ELADIO DIESTE

# ELADIO DIESTE
## Innovation in Structural Art

Stanford Anderson, editor

PRINCETON ARCHITECTURAL PRESS, NEW YORK

Published by
Princeton Architectural Press
37 East Seventh Street
New York, New York 10003

For a free catalog of books, call 1.800.722.6657.
Visit our web site at www.papress.com.



Frontispiece: Eladio Dieste, Church of Christ the Worker, Atlántida, Uruguay, 1958–60. Photograph: Julius Shulman

Support for the Dieste project was significantly provided by the Graham Foundation for Advanced Studies in the Fine Arts, Chicago, and the Batuz Foundation/Société imaginaire, Altzella, Germany.

Editor: Nancy Eklund Later
Associate Editor: Scott Tennent
Designer: Jan Haux

Special thanks to: Nettie Aljian, Nicola Bednarek, Janet Behning, Megan Carey, Penny (Yuen Pik) Chu, Russell Fernandez, Clare Jacobson, John King, Mark Lamster, Linda Lee, Katharine Myers, Jane Sheinman, Jennifer Thompson, Joseph Weston, and Deb Wood of Princeton Architectural Press
—Kevin C. Lippert, publisher

Library of Congress Cataloging-in-Publication Data:

Eladio Dieste : innovation in structural art / Stanford Anderson, editor.
263 p. : ill. (some col.) ; 31 cm.
Includes bibliographical references and index.
ISBN 1-56898-371-9 (hard cover : alk. paper)
1. Dieste, Eladio, 1917—Criticism and interpretation. 2. Architecture—Uruguay—20th century. 3. Architecture—Technological Innovations—Uruguay. I. Anderson, Stanford. II. Dieste, Eladio, 1917–

NA929.D5E39 2004
720'.92—dc22

2003023707

eISBN 978-1-61689-002-5

CONTENTS

## ACKNOWLEDGMENTS

This book's beginnings lie in three serendipitous events, unrelated but almost simultaneous; its publication provides the welcome opportunity to express my deep and continuing gratitude to several colleagues.

In the fall of 1998, the artist Batuz, founder and leader of the Société imaginaire, an intentionally loose organization in which I participate, asked that I host at Massachusetts Institute of Technology a visit by the mayor of Uruguay's capital city, Montevideo, and a number of his colleagues. The mayor, Mariano Arana Sánchez, is an architect and writer on architecture. With our common interests, this was a pleasant meeting but, given the distance between our home cities, might easily have had no further consequence. Batuz was planning a meeting of some members of the Société in Uruguay in November and asked that I join in the activities. Busy with many matters, I did not rush to accept the invitation.

Shortly thereafter, Edward Allen, architect and author, former colleague and long-time friend, gave a lecture at MIT on the use of brick in architecture. In a passing note near the end of his presentation, he offered a few slides illustrating the work in reinforced masonry of the Uruguayan engineer Eladio Dieste. I was struck by the invention and beauty of these works. I was also surprised that I knew nothing of them, and that even so well informed a person as Ed could only tempt us with a few copy photographs, never having visited the buildings themselves. Immediately I knew I had to accept the invitation to visit Uruguay.

I was so importunate as to put a requirement on my participation in the Société imaginaire event: I had to have some time to see the works of Dieste. This agreed, Mayor Arana, who had been a student of Dieste, generously arranged that I be under the informed guidance of the young architects Salvador Schelotto, an assistant to the mayor; Martín Sales; and Alicia Rodriguez. While we toured some of Dieste's major works, including both of the famous churches, another plan was unfolding back in Montevideo. A fellow member of the Société, the engineer and Uruguayan Minister of Transport

and Public Works Lucio Cáceres Behrens (also a former student of Dieste) was arranging for me to meet the architect and engineer. On later visits, Elizabeth Friedheim de Dieste kindly received me at their home—a kindness she extended several times, and one of the many ways in which the Dieste family supported my efforts to learn more about Dieste's career.

The character of the man and his work were so impressive that Minister Cáceres and I soon agreed that my interest had to be projected into a concrete enterprise for the appreciation and propagation of knowledge of Eladio Dieste's work. What we conceived was a symposium that would take place both in Montevideo and at MIT. The meetings would of course attend directly to Dieste's projects, but I felt his work should also be seen as a model for other inventions with traditional materials. Preparations for the symposium thus required finding not only those who were best informed about the work of Dieste but also those who knew about or had done exploratory work with materials such as wood and stone.

Batuz again supported this significant planning effort. Architects and engineers working on the Dieste symposia gathered within a more general meeting of the Société imaginaire at Cadenabbia on Lake Como in 1998, with facilities generously provided by the Konrad-Adenauer-Stiftung. There, Antonio Dieste, an engineer son of Eladio, and Gonzalo Larrambebere, long the chief associate of Dieste and still the lead engineer for the continuing firm of Dieste y Montañez, entered into the heart of the program. We continued on to the Batuz Foundation headquarters at the monastery of Altzella, near Dresden, for more intense planning sessions. The noted Stuttgart engineer Jörg Schlaich joined us, as did the Munich architect Professor Thomas Herzog and architect David Selby of the Michael Hopkins office in London. The result was a preliminary plan for a nine-day excursion, which would take place in late September and early October 2000, beginning in Montevideo with two days of touring Dieste buildings and a two-day symposium, followed by an overnight flight to Boston, a rest day, and a two-day symposium in Cambridge, at MIT.

The symposia successfully cast a conceptual net that reached beyond Dieste's direct accomplishments and brought together in wonderful camaraderie people from various disciplines who, for the most part, had not previously known one another. The participants in Montevideo included Edward Allen, Lucio Cáceres, Carlos Clemente (collaborator with Dieste in the late works in Spain), Edward Cullinan (architect, London), Antonio Dieste, Gonzalo Larrambebere, Julius Natterer (noted timber engineer, Lausanne), Yves Pages (architect, Paris), Remo Pedreschi (engineer, University of Edinburgh), Raj Rewal (architect, New Delhi), Peter Ross (engineer, Arup, London), Roland Schweitzer (architect, Paris), Martin Speth (engineer, University of Hannover), Mark West (architect, University of Manitoba), and myself. These participants were joined by additional speakers at the MIT symposium: Jörg Schlaich, Antony Smith (engineer, Arup, London), Martin Tschanz (ETH, Zurich), Rafael Viñoly (architect, New York), and Robertson Ward (architect and building technologist, Boston).

The Ministry of Transportation and Public Works and the Batuz Foundation supported the symposium in Montevideo. The ministry handled arrangements, assisted by Martha Kohen of the School of Architecture of the University of the Republic and by an executive committee composed of Nestor Castro, Enrique Benech, and Gonzalo Larrambebere. Rosario Olivero, Graciela Iraizóz, Marcelo Dalmases, and Eduardo Rodriguez Briatures provided assistance. Faculty and students of the university mounted an exhibition, with text contributed by Maria E. Yuguero. Nestor Castro of the ministry and Federico Sanguinetti of the Dieste y Montañez office gave generous and sustained attention to the participants.

Planned as an investigation into Eladio Dieste's long and productive career, the Montevideo symposium became rather an homage, after the death of Dieste on July 29, 2000. The Dieste family honored their husband and father, but also their guests, with an evening musical program at Dieste's renowned Church of Christ the Worker in Atlántida.

The Dieste symposia, and in particular the event held at MIT, had many supporters, the most notable of which were the Graham Foundation for Advanced Studies in the Fine Arts; the Arthur H. Schein Memorial Lecture Fund of the

Department of Architecture, MIT; the Pietro Belluschi Lecture Fund of the School of Architecture and Planning, MIT; Ove Arup & Partners, London; Rafael Viñoly Architects, New York; the Weyerhaeuser Company Foundation; the Cold Spring Granite Company; the International Masonry Institute; the Aga Khan Program, MIT; Ann Beha Associates, Boston; Ellenzweig Associates, Cambridge, Mass.; and George and Laura Heery of the Brookwood Group, Atlanta. Many of the participants donated not only their own time but also their travel costs.

My assistant Anne Simunovic managed the MIT symposium energetically and perfectly. She was ably assisted by a battery of people: from the headquarters of the Department of Architecture, Rebecca Chamberlain, Jack Valleli, and Anne Rhodes; from the MIT student body, Ariel Fausto, Nicole Michel, and Ruth Palmon.

Many people also contributed to the realization of this book, which began as an outgrowth of the symposia but necessarily assumed a narrower focus. While I am grateful to all of the contributors, I must give special honor to those who have been constant in the gifts of their knowledge and advice: Edward Allen, Gonzalo Larrambebere (together with his colleagues Eduardo Dieste and Walter Vilche), Remo Pedreschi, and, most recently, John Ochsendorf. Valeria Koukoutsi Mazarakis was of immense help with images and documentation. The greatest number of the color photographs were taken by Yushihiro Asada and were the product of a campaign conducted in October 2002 together with Jun Hashimoto under the sponsorship of *a+u*. This Japanese architectural journal generously made these images available for this publication. The photo campaign was organized and guided by Federico Sanguinetti and Marcelo Marrero of Dieste y Montañez. Many of the other excellent images in this book were taken by the Spanish photographer Vicente del Amo Hernández.

In the many labors a book entails, I again drew on my Department of Architecture colleagues Anne Simunovic, Jack Valleli, Anne Rhodes, Donna Beaudry, Joanna Mareth, and Tijana Vujosevic. Nancy Eklund Later has been the open-minded, demanding, and fulfilling editor for Princeton Architectural Press.

This long list of acknowledgments could only be longer. I must ask the understanding of so many others who have contributed to this enterprise over the years but are not named. It has been very gratifying to receive so much kind assistance from, and now to express my warmest thanks to, the many people who collaborated in a project that came to be very dear to me. I dedicate my efforts in this work to my wife, Nancy Royal.

*Stanford Anderson*

Rafael Dieste, *Obras completas* (Sada/A Coruña, Spain: Ediciós do Castro, 1995), 1/484. English translation by Ann Pendleton-Jullian.

Eladio Dieste, in Antonio Jiménez Torrecillas, ed., *Eladio Dieste: 1943–1996* (Seville: Consejería de Obras Públicas y Transportes, 1997), 218.

## THE MILLER'S SURPRISE

You built a mill
thinking it was only
for grinding wheat.

You diverted the water
thinking it was only
for working the mill.

But the water speaks
sentences and couplets
never asked for.

And is answered
pensively, lyrically,
by the docile mill.

Building a mill
and diverting the water
you drew a sign

And, absorbed
staring at the ground wheat
you seek to know what it means

—*Rafael Dieste*

Surprise. As all art, architecture helps us contemplate. Life wears out our ability for surprise. Surprise is the beginning of a true vision of the world.

—*Eladio Dieste*

Carlos Contrera - CMdF - AFMVD

## INTRODUCTION

*Stanford Anderson*

Eladio Dieste would not have realized his brilliant, innovative works had he relied on the conventions of ordinary practice; rather, he began from first principles. In the hands of this extraordinary engineer, adherence to first principles did not inhibit but rather enhanced the search for sound forms appropriate to the demands put upon them. It is physically possible to do what is unreasonable, but working from physical principles one is not led to the unreasonable. Brilliant work by a man of principle, revealing a process of designing and building that is principled—this is the legacy of Eladio Dieste. From my first encounter with his work, I knew I wanted to spend more time with it and to ask others to know it better as well.

This book must aspire to be inclusive—inclusive, not as an account of Dieste's numerous works, or even as an exhaustive account of individual works. Nor should it be an intimate biography that would have to rest in the hands of those who were close to this remarkable man. Rather, it must seek to be inclusive in an ambition to recognize the wholeness of this man and the integral quality of his life and work. Dieste was an engineer—in Spanish, *ingeniero*. During the last century, the engineering profession allowed that term to lose its sense of the "ingenious." It is to some exemplary individuals that we turn to renew our enthusiasm for inventions that are complex yet, once realized, possess a simplicity and seeming inevitability—for inventions that are not mere novelties.

Dieste embraced a technique—reinforced masonry—that in his day was little known and less exploited. Through that technique he invented appropriate structural types that he employed with daring. He was a builder. Innovations in construction were necessary and integral to his engineering insights. He built prodigiously, mostly humble structures for storing and making. Yet even these humble works were raised to higher levels; the sheer daring of great spans was part of

this, but only part. In all but the most elemental of these structures other qualities emerge: the proportions of the whole; the economy and elegance of the materials; the detail of the parts; and above all, the knowing use of light as it plays on and especially as it is admitted into these buildings. These are the qualities of a building created by a fine architect. Given only a few (all too rare) special opportunities, Dieste was nonetheless undeniably an architect.

The significance of Dieste's life and work does not end there. He was born, lived, and predominantly built in Uruguay, a small country of high educational and cultural levels but not of generous resources. Dieste's choice of materials and the (not exclusively financial) economy of his works systematically address the conditions of his country and potentially those of many under-resourced countries, in an era of superpowers and globalization. Dieste knew full well that resources, wealth, and power are not enough to assure a sound environment or society. Contending with limits may deny many material advantages but not the opportunity to think and contribute substantively to the creation of a fulfilling social state.

Dieste wrote about his engineering innovations and accomplishments, of course. Those accomplishments, however, lay at the core of ever expanding concerns. He was a man of culture. He understood that art and architecture had been integral to the making of the best buildings and cities of the past and had to be part of any desirable future. Although religion makes little appearance in his writings, Dieste was a man of religion who embraced liberalizing forces within the church. His concerns for social justice and for expanding opportunities for less-resourced people and countries were integral to, and integrated with, his work as an engineer.

This book seeks to illuminate the many facets of a remarkable man. It includes essays by historians, practicing engineers, and architects analyzing Dieste's work from still more diverse points of view. It even presents a moving tribute to Eladio Dieste and his work by the distinguished figure Lucio Cáceres, minister of transport and public works of the Republic of Uruguay, a former student of Dieste, and family friend of the engineer. But is this only an homage to a man who worked in a very special way under particular circumstances now vanished? The most recent works illustrated here are less than a decade old, and the firm of Dieste y Montañez continues. Still, even the engineer son Antonio Dieste, in his reflective essay, raises such questions. The comparative economics of several types of construction have shifted, he argues, in both developed and developing countries, mitigating against the continued use of reinforced masonry.

Today, the increasing emphasis on sustainability in architecture gives cause to continue the consideration of reinforced masonry. This building technology employs a material that is local under most circumstances and is remarkably efficient in the use of that material. It has excellent thermal properties. That it is labor-intensive may be altered through innovation, but there are still large parts of the world in which this trait remains an economic and social good. A broader recognition of Dieste's achievements may well suggest continuing opportunities for the use of reinforced masonry construction in certain circumstances—with imagination, perhaps even in situations that at first seem unlikely.

Dieste's accomplishments inspire thoughts beyond the (albeit deserved) attention to the works themselves and to the continued application of his technique. It is stimulating to think that Dieste, with a lifelong devotion that required his mutually reinforcing efforts as engineer, designer, and builder, took such an ancient and elemental material as brick and raised it to unprecedented heights of technical efficiency and aesthetic beauty. The Dieste symposia that marked the beginnings of this publication attempted to open an inquiry into current and possible innovations with other traditional building materials such as wood and stone. In the case of other "old" building materials, such as glass and fabrics, the materials themselves have gone through radical changes in recent years. The example of Dieste's work may yet serve, in the more general sense, to demonstrate how the integration of abstract thought, design, and making can reinforce one another.

Beyond this integration of conception and making, there is also Dieste's cultural and, indeed, philosophical

understanding, not only of his work but also of his métier and of the contributions of engineers, architects, and artists. If one is not attuned to starting with devoted inquiry into the potentials of a particular material or technique, one can do well to consider the higher opportunities and responsibilities advanced by Dieste, and then cycle back to the means for making such contributions. There are ample reasons to come to know Eladio Dieste.

Eladio Dieste Saint Martín was born on December 10, 1917, in Artigas, a town in northern Uruguay on the Brazilian border. His father, also named Eladio, was an atheist who taught history. In 1936, the younger Eladio enrolled in the Faculty of Engineering of the University of the Republic in the capital city of Montevideo, graduating in 1943. The preceding decades had been a time of wealth and growth in Montevideo, still visible today in the fabric of the city and its many fine art deco buildings. In 1944, Dieste, who had accepted the Catholic faith, married Elizabeth Friedheim, a German-Jewish immigrant who converted. The Diestes had twelve children, one of whom died in infancy.[1]

From 1944 to 1947, Dieste worked as an engineer on bridge projects for the Highway Administration of the Uruguayan Ministry of Public Works. For the same ministry he was made head of the technical section of the Architecture Office from 1945 to 1948. In these years he was also associated with the Norwegian contractors Christiane & Nielsen. Between 1949 and 1958, he was the directing engineer for the Viermond piling company. In addition, from 1945 on, Dieste also taught mechanics at the Faculty of Engineering.

In 1946 Dieste realized his first reinforced brick vault while collaborating with the Catalan architect Antoní Bonet on the Berlingieri house in Punta Ballena.[2] In 1956, Dieste and Eugenio Montañez (1916–2001), a fellow graduate of the university, founded the firm of Dieste y Montañez, S.A., through which their great body of work was accomplished. A strong reason for the success of the firm in realizing unprecedented works is that this was a construction as well as design firm. Both of these activities significantly informed the other, encouraging progressive development of the firm's concepts and efficient production. Dieste and his followers are keen to point out that the firm was able to carry out large amounts of what we see as innovative and creative work because it could perform competitively while offering alternative building techniques.

As the firm was engaged in projects from concept to the laying of bricks, many people contributed to its success. Most important was Dieste's partner, Montañez—a balancing figure, astute in the organization of work and the development of the company. The firm began consulting work in Brazil in the 1960s. Early in the 1970s, Montañez moved to Brazil; he took responsibility for massive projects there, including construction by Dieste y Montañez, until his return to Montevideo at the end of the decade. The engineers Raúl Romero, Gonzalo Larrambebere, Ariel Valmaggia, and José M. Zorrilla, the technical assistant Walter Vilche, and the architect Alberto Castro sustained long-term collaborative relationships with the firm. Dieste's son Eduardo continues in its management, and the names of other sons—the engineer Antonio and the architect Esteban—appear in the credits for numerous works.

The high level of craftsmanship exhibited by the firm's work was only possible with a stable crew of expert workers on the building site. The most frequently mentioned of these is

1 Biographical information on Eladio Dieste is owing to several souces, including personal communications from his son Antonio and members of the firm of Dieste y Montañez; also from Antonio Jiménez Torrecillas, ed., *Eladio Dieste: 1943–1996*, trans. Michael Maloy and Harold David Kornegay (Seville: Consehería de Obras Públicas y Transportes, 1997).

All projects discussed in this volume were built in Uruguay, unless otherwise noted.

2 For more on this project, see John Ochsendorf's essay on pages 96–97 of this volume.

the mason Vittorio Vergalito, who spent thirty-eight years with Dieste y Montañez; Edio Vito Pacheco and Alberto Hernandez devoted thirty-six and thirty years, respectively. Eduardo Dieste wrote movingly of these men. Of Vergalito, he said, "To my father, Vittorio is the evidence of what he feels to be the truth. He is the person who best incarnates the philosophy on which his whole work is based."[3] The most commonly mentioned architect collaborator is Alberto Castro, who worked with Dieste on numerous projects, including the Church of St. Peter in Durazno. In a personal communication, Castro assures that the engineers and architects of the Dieste office were truly collaborators but under the "natural leadership of an exceptional man, Eladio Dieste."[4]

Dieste was a corresponding member of the Academy of Sciences of Argentina, honorary professor of the schools of architecture of Montevideo and Buenos Aires, and a member of the Uruguayan Academy of Engineers. He received the Gabriela Mistral Award of the Organization of American States in 1990, the Americas Award in 1991, and an honorary professorship from the University of the Republic in 1993.

Beginning in 1993, Dieste collaborated with the architects Carlos Clemente and Juan de Dios de la Hoz on a "Students' Street" for the University of Alcalá near Madrid, Spain, and on three churches in the same area, each modeled on one of the noted churches he had designed in Uruguay. Dieste continued this association despite a degenerative disease that after 1995 left him confined to his home. Eladio Dieste died on July 29, 2000, in Montevideo. His gentle, accommodating wife still resides in the home he built overlooking the River Plate. The firm of Dieste y Montañez continues today and has been instrumental in the realization of this book; it is represented here in the contributions of the engineer Gonzalo Larrambebere and in many other details.

The first small book on Eladio Dieste was written by the Argentine architect and historian Juan Pablo Bonta. Published in 1963, it included the Church of Christ the Worker at Atlántida and the Dieste house. Indeed, the attention given to these works, rather than the more characteristic warehouses and industrial buildings, is a sign that Dieste had already become a figure in the world of architecture. The bibliography of Bonta's book suggests that the new appreciation of Dieste as architect was, at that time, stronger internationally than in Uruguay. Subsequent extensive (primarily journal) literature by and about Dieste originated almost wholly from South America and Europe. Two monographs—one edited by Antonio Jiménez in Spain in 1996 and the other by Remo Pedreschi in Britain in 2000—never lose sight of Dieste the architect but are organized around the structural typologies found in his work.[5] Despite these recent monographs, the name Eladio Dieste remains remarkably obscure in North America—a failing the MIT symposium of 2000 and this book seek to alter.

What then is the envisioned role of this book? Above all, it looks to the architecture of Eladio Dieste. Early and special attention is given to the Dieste house and the two famous churches in Atlántida and Durazno. The architectural qualities of a broad range of Dieste's production are also emphasized. This is particularly the role of my essay but is reinforced in distinct ways by Remo Pedreschi and Gonzalo Larrambebere and by John Ochsendorf as well.

This book also provides a historical dimension to the study of Dieste, in at least four ways. Dieste's body of work is arrayed in near chronological order in the project portfolio disbursed throughout the volume. This is designed to invite easier consideration of the development of his oeuvre.

Historical context is also provided in a number of essays contained herein. Edward Allen provides a brief overview of the major types of compressive masonry vaults from antiquity to the present day, giving careful attention to the impressive lightweight vaults built without formwork in Catalonia and to the extraordinary elaboration of this technique in the work, mainly in the United States, of the Catalan architect Rafael Guastavino. Knowledge of this history is rewarding in itself and necessary if one is to understand the unique contribution of Dieste's vaulting techniques.

John Ochsendorf places Dieste's work in the context of "structural art." Eduardo Torroja, Eugène Freyssinet, Robert

Maillart, and Heinz Isler are among those noted engineers who have been seen to change our visual culture not only with the technical innovations of their work but also with their coherent aesthetic production. The author gives a fresh assessment of Dieste's accomplishments by comparing his work with that of these other four masters of structural art.

Remo Pedreschi and his colleague Braj Sinha provide our fourth historical account in the appendix of this volume: a thorough review of the literature on reinforced masonry.

In his essay that appears earlier in this book, and with the collaboration of Gonzalo Larrambebere, Pedreschi turns the tables on his own monograph, which was constructed to reveal how the engineer has contributed to contemporary architecture. In this volume, conceived by an architect and built around architecture, Pedreschi's role is to draw due attention to Dieste's technical contributions in the areas of structure and construction.

The argument of the book as outlined here is supplemented by extensive appendices. As previously noted, Eladio Dieste was a profound and socially committed thinker. We reproduce three of his essays here. Timothy P. Becker and Kent Anderson's firsthand description of Catalan vaulting nicely supplements Allen's essay. Antonio Dieste makes the argument that his father's work can have continued life only if technical innovation in reinforced masonry continues, perhaps in unanticipated ways. Finally, the young German engineer Martin Speth draws inspiration from Eladio Dieste's work but finds reason, under the industrialized conditions of his country, to explore prefabricated but unreinforced masonry vaults—not the projection Antonio Dieste sets out but fulfilling one of his expectations, being unanticipated.

To this volume there is another, already somewhat revealed, agenda. At a time when we are encouraged to embrace the idea that digital technologies allow not only the representation but also the physical realization of absolutely any form, for any or no reason, I invite the reader to exercise critical discrimination—between novelties and profound, complex, and responsible innovations, as Eladio Dieste sought and often realized.

3 Eduardo Dieste to Antonio Jiménez Torrecillas, August 1998, quoted in Pedreschi, *Eladio Dieste*, The Engineer's Contribution to Contemporary Architecture (London: Thomas Telford, 2000), 19.

4 See Anderson's essay, 38, n. 14. of this volume. It should be noted that many of the Dieste projects included subsidiary buildings, office components, and the like that required architectural design and were presumably rarely the province of Dieste himself.

5 Jiménez, ed., *Eladio Dieste*. This book is beautifully produced, with fine illustrations and much information by and about Eladio Dieste. It also has a small supplementary technical volume. It is a fundamental resource for the study of Dieste.

Pedreschi, *Eladio Dieste*. The engineer Pedreschi precisely lives up to the series title in which his book appeared, The Engineer's Contribution to Contemporary Architecture. It is not surprising then that the author has been an important resource and collaborator in the production of the current book.

fig. 1

# DIESTE HOUSE

*Montevideo, 1961–1963*

The house Dieste built for himself and his family occupies most of its small site. Three terrace and courtyard areas provide varied associations of exterior and interior for both the public and private spaces of the house. Small self-carrying (or "freestanding") vaults are used throughout, except in the kitchen, corridor, and lower floor areas, where reinforced masonry slabs are used. The vaults provide a sense of release in the small bedrooms and study but also open laterally between rooms and longitudinally, with openwork forming a pergola, into the courtyard.

fig. 1: Dieste House, Montevideo, 1961–63. Street façade with garage and entry below the front garden terrace

fig. 2: (top) Transverse sections through the family room, entrance stair, and study (a-a); courtyard-terrace, dining area, kitchen, and hall (b-b); and bedrooms (c-c)
(center) Longitudinal section through garden-terrace, entrance, dining area, courtyard, "veranda," a children's bedroom, and rear garden (d-d)
(bottom) Lower floor plans and main floor plans

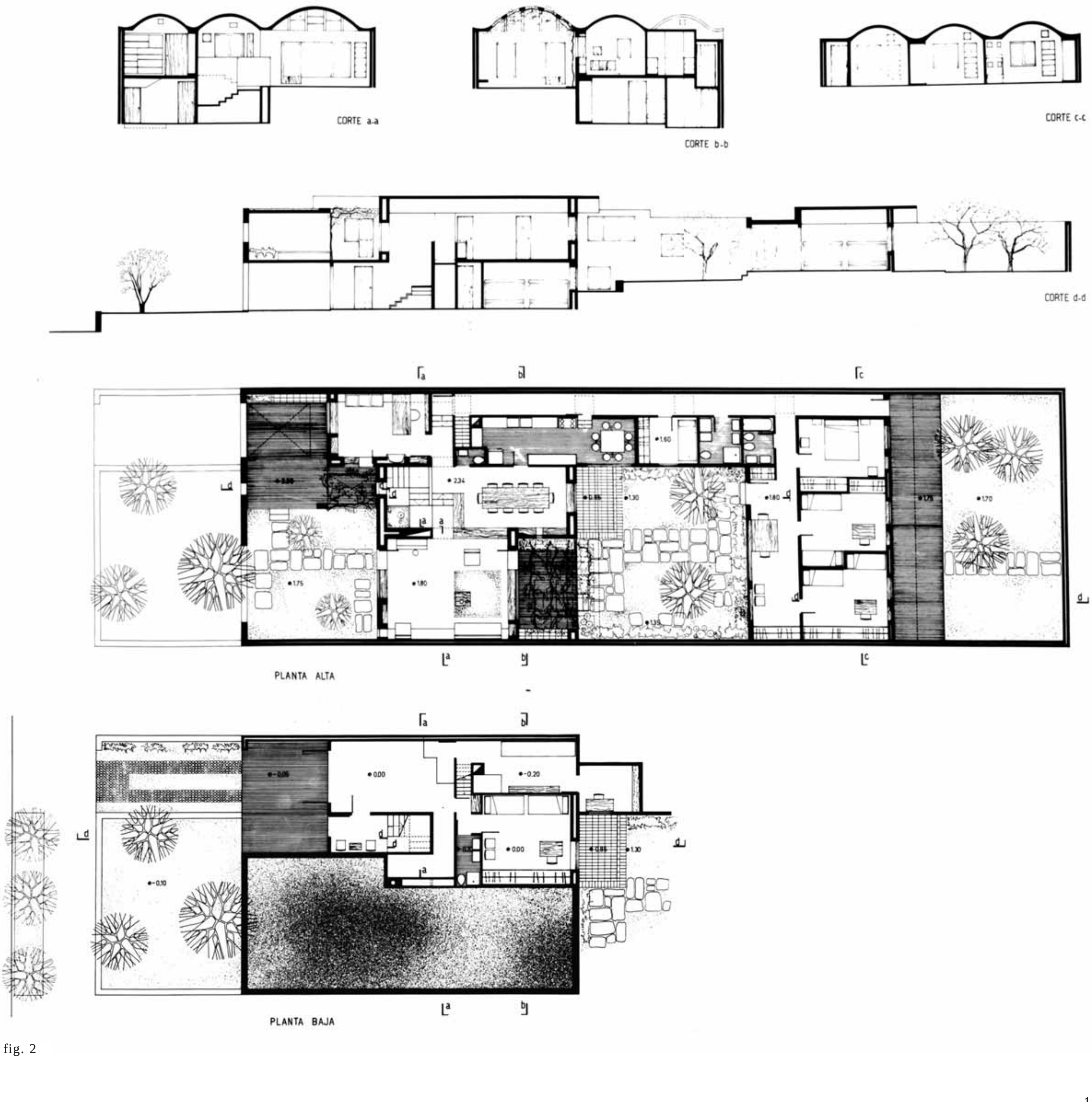



fig. 2

## THE DIESTE HOUSE

Antonio Dieste

*Located on one of Montevideo's high grounds, approximately 100 feet from the shore of the River Plate ("the river wide as the sea"), the Dieste House frames views of the water over its neighbors' rooftops. My father, Eladio Dieste, bought the property in 1952. For financial reasons, construction of the house was delayed until 1961, and the house was completed in 1963.*

*The site is long and narrow. My father had a clear vision of how the house should occupy the terrain. It was designed to provide the largest possible number of rooms with openings to the north and east, clustered around two patios. The windows facing north are surmounted by awnings or gazebos, covered by a deciduous climber, that allow sunlight to enter the rooms in winter and provide shade in the summer.*

*From the entrance, above the street but below the main body of the house, a staircase leads up to the dining room and family room, each a separate but open space facing both the garden-terrace at the front and the inner courtyard, with its brick benches built into the walls.*

*The garden-terrace opens to the sea. From the study, the view is framed by the terrace parapet, designed as an opening in the wall. From his seat at the head of the dining table, my father*

fig. 3

fig. 3: View from near the entrance to the upper terrace

fig. 4: Stairs from front entry to the central point of the house

fig. 5: View from top of entry stairs to the central courtyard

fig. 4

fig. 5

fig. 6: Raised garden-terrace at the front of the house. To the right, the family room doors

fig. 7: Window and opening in terrace wall

fig. 8: Dining area with window and wall opening aligned to the sea. To the left, the family room

fig. 9: View past the entrance stair and dining area to the family room

fig. 6

fig. 7

*could see the outlines of ships on the horizon through the main staircase window and an opening in the garden-terrace wall. Today, this view is blocked by a pine tree.*

*The house appears totally hermetic from the outside, though it is ample within. People walking down the street cannot see into the house except to the garden-terrace. Even there, one may find corners where it is possible to sit and read quietly or enjoy the autumn sun, protected from the outside view. This gives the house a sense of mystery that may have a disquieting effect on passersby.*

*The house was home to a large family: our parents, eleven children, and a maid. On the upper floor, my parents' bedroom and two additional bedrooms—one for the three younger boys and another for the four girls—face the veranda on the far side of the central patio. The children used the veranda, overlooking the patio, as a place to do their homework. It was also used as a sewing room. The elder boys' bedroom was on the lower level and opened to an "English patio," a very self-contained area next to a study.*

*By the time Dieste started working at home, because of health reasons, all the children had left the house. He first used the elder boys' bedroom as his workplace. When he could no longer use the stairs, he worked on the veranda on the upper floor. It was here where he worked on the Spanish projects in the late 1990s.*

fig. 8

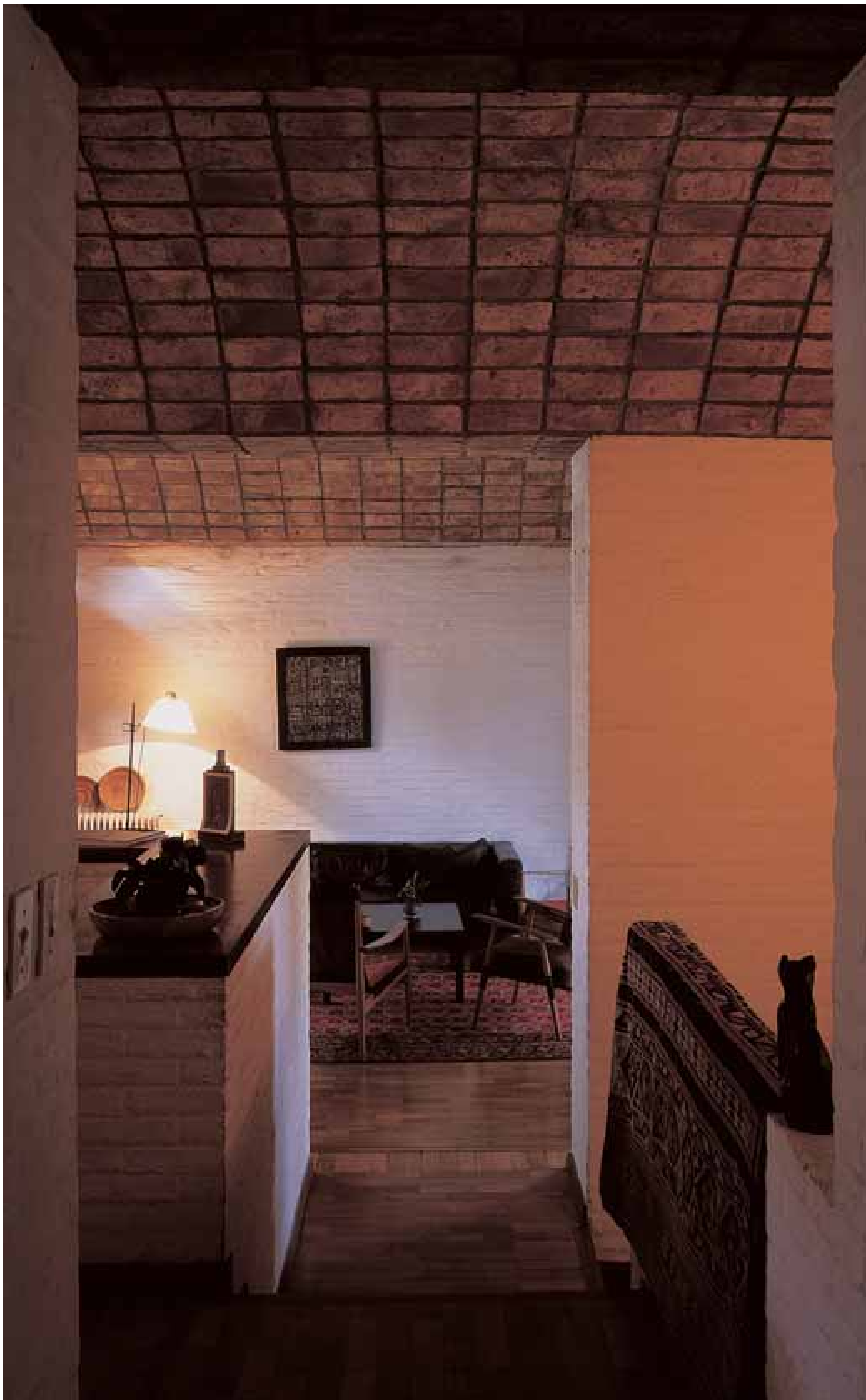


fig. 9

*Dieste justified the use of reinforced ceramic vaults and load-bearing walls—the characteristic elements of his work—as structural elements. Here, however, the formal effects of the vaults prevail over structural reasoning, as the spans involved in building the house are within the range of more economical concrete slabs.*

*The notable thickness of the walls is the result of both formal and functional considerations. Throughout the house, the walls contain boxes for roller-blinds and built-in bookshelves. Vents for the central heating system open through holes cut in the wooden lids of the window sills. In the living room the walls also serve as seats. On a winter afternoon, it is very pleasant to sit there, by a north-facing window, enjoying the sun. In the bedrooms, small light niches reveal the depth of the wall. The seasonal and hourly positions of the sun can be traced through the changing color spots cast on the floor and the adjacent walls. A metal fireplace set into the study wall provides the primitive pleasure of watching a fire.*

*A stereo system is housed in the wall separating the dining room from the living room. The equipment, consisting of a radio and a record player, is placed behind wooden doors, and the speakers are covered with rattan panels. My father had very set views regarding our education. We had a radio at home but no television. He only allowed us to listen to the National Radio*

fig. 10

fig. 10: The secluded house, viewed from the street

fig. 11: View from the front through the family room to the courtyard, with the raised dining area to the left

fig. 11

fig. 12: “Veranda,” a gallery giving access to the bedrooms and with a view to the central courtyard

fig. 13: View from the family room to the central courtyard. Note the openwork brick vault with its climber moderating the light on the paved terrace slightly above the courtyard itself.

fig. 14: Dieste’s study, looking to the raised hard terrace at the front of the house

fig. 12

fig. 13

*Broadcasting Service, which only aired classical music and the news. If he arrived home to find us listening to anything else, he simply said, "National Broadcasting," emphasizing each word. With that, we would have to return to Prokofiev's* Peter and the Wolf *or Bach's Brandenburg concerti.*

*In Uruguay, television transmission began in the mid-1950s. For many years (until 1982), Dieste's house was the only one in the neighborhood without a TV set. My father considered television culturally negative and the TV set itself aesthetically unappealing. Nor were comics allowed in the house (though we managed to obtain and hide them). We did have books, by the likes of Hans Christian Andersen, the Brothers Grimm, and Horacio Quiroga. There was Twain's* Tom Sawyer*, Stevenson's* Treasure Island*, Melville's* Moby-Dick *and books by Dickens, Kipling, and Dumas that we received as birthday presents or as presents on the sixth of January (a Spanish tradition, in which children receive gifts from the Three Wise Men as Jesus did). As time went by and we grew older, we could read from the vast bookcase, where we could find almost anything. Whatever we could not find, we could ask for; we could be denied a pair of new shoes but never a book. Money was no issue when it came to books.*

*Dieste always refused to have decorative elements in the house. Over the years, he only agreed to incorporate the following*

fig. 14

fig. 15: View from the arrival point through the dining area to the family room and court. The table was designed by Dieste.

fig. 16: View of the family room and the dining area. Eladio Dieste, visible through the central window

fig. 15

*objects: a painting and a small sculpture by Joaquín Torres García; two Eduardo Yepes sculptures (Christ on the Cross and The Virgin); a copy of an Egyptian cat; two glass art pieces by Agueda Dicancro; two sculptures by my brother Eduardo (a woodcut of a hake and a mechanical contraption devised by my father himself, rescued from the junkyard by Eduardo and set on a wooden stand); a woodcut of a Franciscan by an unknown artist; and a scale model of a sailing boat. The last two were only partially accepted by Dieste; they were placed so that he could not see them from where he normally sat.*

*This rejection of ornament was not a whim. In my father's architecture there are carefully proportioned volumes and surfaces, both curved and flat, that form spaces we inhabit and that interact with light. He believed that decorative elements become obstacles to our understanding the essential.*

*Each piece of furniture has a precise and defined location. For instance, in the bedroom a recess is carved in the wall behind the bedstead and fitted with a white acrylic panel, a reading light, and a small bookshelf. The rigidity in the location of the beds created a problem, following the adoption of the final scheme for the building, when my youngest sister was born and an additional bed was required. The formal disturbance this caused was only resolved when one of my sisters got married and left the family home.*

fig. 16

*Dieste designed most of the furniture in the house. The breakfast table is an extreme example of a site-specific piece of furniture. Its single leg, which secures the entire table and eight stools, is built into the floor slab.*

*After my father's death, I visited a monastery in the city of Tomar in Portugal, the headquarters of the Order of Christ Templars, built in the twelfth century. In the monastery there is a window from the sixteenth century, reputed to be the most stunning example of Manuelina decoration. In contrast to this window, in each of the monk-knights' cells there is a window seat made of a simple stone slab set within the width of the wall. The white walls of the bedrooms have no decorative elements. The bareness of these cells is the fruit of a religious conviction that ornament is a trick of the devil, used to drive us away from God.*

*I am sure that my father would have spent more time in contemplation of the cells than on the famous window. I can imagine him in the cloister, in spiritual communion with the monks who lived there centuries ago.*

fig. 17

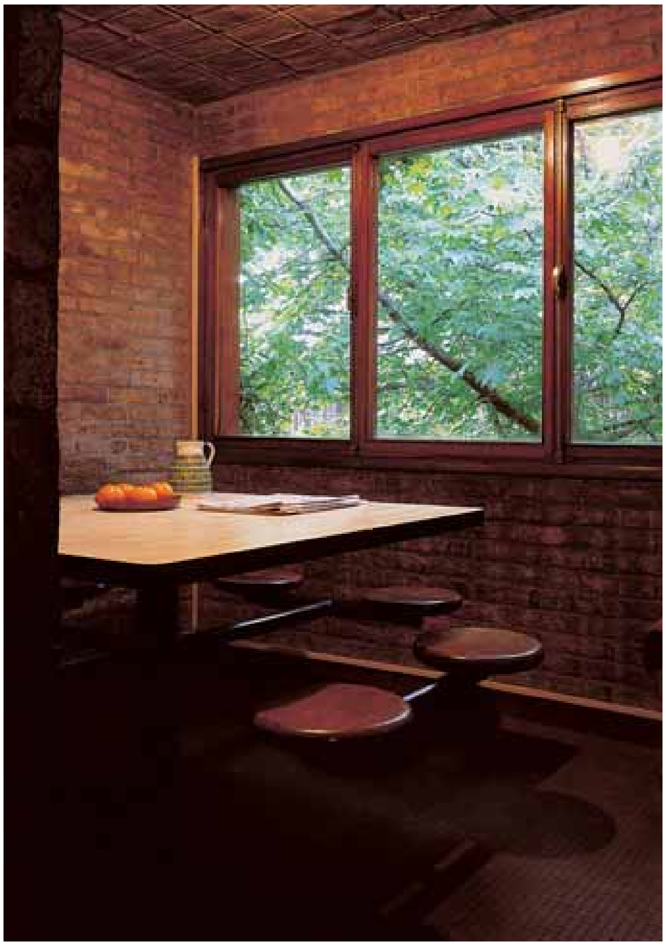


fig. 18

fig. 17: One of the Dieste children's bedrooms
fig. 18: Built-in single-legged kitchen dining table
fig. 19: View from the court through the family room to the front terrace
fig. 20: Rear façade. Note the distinction of the structural vault from the upper profile of the roof.

fig. 19

fig. 20

fig. 21: "Sea Gull" (originally the Barbiere and Leggire Service Station), Salto, 1976. Dieste's Refrescos del Norte complex appears in the distance.
fig. 22: Massaro Agroindustries, Joanicó, Canelones, 1976–80. This view is taken from the five-vaulted main sheds to the three double-cantilever, self-carrying vaults at the entry.
fig. 23: Port Warehouse, Montevideo, 1977–79. Note the double-curvature, or "Gaussian," vaults and detail at an end wall.

## "DANCE WITHOUT EFFORT OR FATIGUE": THE ARCHITECTURE OF ELADIO DIESTE

*Stanford Anderson*

"A lightness, a mysterious ease, a concise simplicity, something like dance without effort or fatigue": these are words that Eladio Dieste used to describe the goals for his work.[1] Such were the necessary conditions, he argued, for convinced acceptance of a building by its users.

Dieste wrote those words out of the specific concern that his work should communicate with ordinary people. In the same essay "Art, People, Technocracy," he tells of his experience of a humble woman with coarse shoes covered in mud at his Church of Christ the Worker in the village of Atlántida: "The itinerary that she followed, the places where she paused, the things that she said with complete simplicity and without accolades: these things that made me realize she was really seeing it."[2] Dieste assures us this was not a singular experience. He was certain that people are not moved when a difficulty is resolved by brute force but rather want to perceive a problem resolved with the effortlessness of a hawk soaring in the sky or a flower unfolding in the sun. It is one thing to have such an ethereal ambition and quite another to achieve it. Yet that is what Dieste achieved in his buildings. It is no accident that the phrase "light as a brick" was invented for his work.[3] The buildings of this master and innovator of reinforced brick construction address us so effortlessly, and yet forcefully, that a brief first exposure suffices to assure a deep engagement.

The inexplicable neglect in North America of Eladio Dieste accounts for the fact that my own exposure to his work came late in a long career involved with modern architecture and then, incidentally. In 1998 I received an unanticipated invitation to visit Uruguay, followed a few days later by a coincidental, brief exposure to two or three images of Dieste's buildings. One incident informed the other; soon I found myself touring the work of Dieste and then taken to visit the engineer at his home by one of his former students, Lucio Caceres, a civil engineer and the Minister of Public Works of Uruguay.

Inserted into this meeting of friends, I was soon able to reveal, in effect, my own conviction about Dieste's work as a "dance without effort or fatigue"—though these were words I had not yet had occasion to learn. As genuine and motivated as were my first words to Dieste, perhaps I was too enthusiastic in my appreciation. Though suffering the effects of a degenerative disease, Dieste, with a knowing and friendly sparkle in his eyes, calmed me with the words: "I too obey the laws of physics!"

In the presence of Dieste's buildings, one may sometimes wonder if he truly obeyed those laws. But, yes, he was an engineer, and there the buildings stand. The laws of physics are satisfied. Nonetheless, we must also observe that there is all the difference in the world between engineering work that remains safely controlled within the conventions of ordinary practice and that which challenges convention. Dieste imagined new possibilities and then, yes, observed *only* the laws of physics, not standard practice, both as a critic and a facilitator. Additionally, it must be emphasized that Dieste's innovations are not for the sake of novelty. They are rather the result of a continuous quest, a reasoned approach to building well, addressing the pragmatic problems at hand but also satisfying his own profound demands, ethical and spiritual, that lay behind his dance.

Dieste made himself the master of reinforced ceramics, virtually the only mode in which he built. The vast majority of his structures serve everyday purposes of work and storage. He invented two distinctive forms of reinforced brick vaulting that were instrumental in winning the economic competition to build these utilitarian structures. Serving pragmatic purposes and doing so economically (in terms of time and cost) was the fundamental business model of the engineering firm of Dieste y Montañez. It is not despite these constraints but largely because of them that these buildings rise above their quotidian settings and achieve an ennobling architectural presence.

Of Dieste's two major innovations in structural types in reinforced brick masonry, consider first what he termed "self-carrying vaults." These are barrel vaults with none of the usual


fig. 21


fig. 22


fig. 23

conditions of support for such a vault: no continuous side wall supports or buttresses, no tympanum or arch under the vault at its ends. Dieste's vaults rest on columns—or even a single column (fig. 21)![4] Less demonstrative but equally impressive are the true self-carrying vaults whose basic variants are well illustrated by the sheds for Massaro Agroindustries. The main storage area is formed by a set of five parallel barrel vaults carried on a sparse grid of columns, with a cantilever of 54 feet at one end. Freely sliding under that cantilever are three still more astounding vaults with 43-foot cantilevers in both directions, carried on a single row of four columns (fig. 22).

Such minimal support is only possible, of course, if the vault, unlike traditional masonry vaults, can resist bending forces. This Dieste accomplishes by introducing pre-stressing steel that pre-compresses the vault. In cross section, the vaults are given the most effective structural form—a catenary. This, together with ordinary reinforcing bars between rows of bricks, yields a thin and light vault. This lightness reduces the lateral forces but, of course, the forces are there and must be counteracted. Dieste's characteristic elegant solution is a horizontal edge beam at the outer limit of any group of vaults—a beam that collects the lateral forces and brings them back to vertical buttresses at point supports. In the long direction of a barrel vault supported on columns, the vault acts as a beam, and it is here that the pre-stressing becomes necessary. Atop the brick masonry, successive loops of steel are tensed and then imbedded in a thin concrete layer, applying high compressive forces to resist tension in the finished vault. In these self-carrying vaults, the few and distant points of support and the thin, unsupported ends of the vaults convey directly the seemingly effortless lightness of these constructions.

Dieste's second major structural innovation was in what he termed "Gaussian" double-curvature vaults. Barrel vaults rise high in relation to their transverse span and thus are not well suited to broad spans. However, a thin vault of long span and low rise is susceptible to buckling and thus not sound structurally. Dieste gave strength to such vaults not by making the vault more massive (a solution by brute force that he naturally resisted) but by making the vault in successive transverse bands, each of which was given a greatly increased bending stiffness by means of three-dimensional curvature. At the center of the span where the forces to be resisted are greatest, the band has as its cross section (in the longitudinal direction of the building) a reclining S-shape (fig. 23).[5] Dieste configured the S-shape to be lower and flatter at one side than at the other; when such bands of vault are built next to one another, the disparity of the edges of the neighboring S-shapes leaves a long, curving lunette ideal for illumination at frequent intervals and across the width of the building. Because the vaults are carried on edge beams, Dieste often introduced continuous windows in the walls below the beams. Recurrently, Dieste framed these glazed openings with the simplest of small steel bars. Ever attentive to simplified systems of support, he progressively flattened the full S-shape of mid-span until the vault became a continuous horizontal line at its outer supports. The long span and low rise of these Gaussian vaults result in significant lateral thrusts that were usually resolved with exposed horizontal tie-bars, though Dieste had no love for them. By extending the columns of the Don Bosco school gymnasium in Montevideo, he succeeded in placing the ties above the roof where they are effectively invisible from within. In a variant of the Gaussian vault used in his horizontal silos, where a higher pitched vault reaches the ground, Dieste absorbed the horizontal thrust in the floor or foundation.

1 Eladio Dieste, "Art, People, Technocracy," 194 of this volume. Originally published as "Arte, pueblo, tecnocracía," in *Eladio Dieste: La estructura cerámica*, ed. Galaor Carbonell, Colección Somosur (Bogotá, Colombia: Escala, 1987).

2 Ibid.

3 Juan Martín Piaggio, *Leggero come un mattone: L'Architettura de Eladio Dieste* (Parma, Italy: Industria Leterizi Giavarini S.p.A., 1997).

4 The "Sea Gull" is not, strictly speaking, a vault since the cross section cannot act in compression. Its form and construction do, however, owe much to Dieste's self-carrying vaults.

5 There are also those constructions, as at the church at Atlántida, where the Gaussian vaults are a continuous surface, at times penetrated to provide light.

That Dieste built with brick is one of the reasons for his neglect in architectural history and criticism. His career coincided with the prominence of theories of architecture and its history that embraced dubious notions of a modern zeitgeist. An inevitable evolution toward a technologically advanced society demanded, it was said, the use in architecture of “modern materials” such as steel, concrete, and glass. Dieste was educated in the emerging practices of framing and vaulting with reinforced concrete, yet he chose to build in brick. While his innovative brick structures grew out of precedents and practice in reinforced concrete, Dieste quite reasonably argued that new materials do not necessarily displace earlier materials of demonstrated effectiveness.

Dieste found compelling reasons for the use of ceramic materials in the marginalized economy of Uruguay. However, he also supported brick construction for reasons that rely only partially on that local condition. He claimed advantages for brick over concrete, including relative strength for weight, better resistance to temperature changes and aging, better acoustic and environmental qualities, and, in comparable quality, lower cost.[6] In this Dieste provided good, hardheaded reasons for preferring to work in brick. Further, he believed that the tectonic sense of a durable material with agreeable qualities of color and texture, worked with sound craftsmanship, had a general appeal.

A claim for the architectural quality of Dieste’s utilitarian buildings, however, goes beyond both the performance characteristics and agreeable qualities of brick. Dieste’s effortless dance relies, of course, on the structural innovations we have rehearsed, but belief in the dance relies on the intrinsic architectural quality of his achievement. In those buildings of a single volume, the space is generous and well proportioned; the structure itself is articulated in smaller elements, down to the handheld, often handmade, brick itself. In the buildings of multiple bays, both the clarity of each bay and the associations among them offer compelling spatial experiences. When, as at Massaro, impressive cantilevers overhang one another, there is a wonderful sequencing of open to covered and finally enclosed spaces. Another aspect of this sequencing is natural light. The self-carrying vaults admit light where they overlap or stop short of one another, or where they are simply penetrated. The Gaussian vaults yield very special qualities of light. In addition to the effective dispersion of light throughout these buildings, there is the virtually sentient way in which different aspects of the vaults are revealed as one moves beneath them. From one direction, there is the soft lighting over the curving surfaces of the vaults; from the other, the repetition of the glazed lunettes with views of the sky. The last vault at either end of the series poses here the lower, flatter arch, and there the higher arch of either side of the S-shaped vault section. Characteristically, Dieste demonstrates the difference of the two ends of the series of vaults with different heights of glazing above the opposite end walls. That glazing also allows emphasis of the thin end of the vault and the absence of a tympanum or other structural support.

We know there are buildings that are technically sound without becoming architecture. And there are buildings of widely recognized architectural standing that are open to technical and tectonic criticism. There remains a special place for technically sound buildings that achieve high tectonic standards and thus deserve to be recognized as architecture. This is all the more true when the designers of these buildings also ran the risks inherent in technical and tectonic innovation. Dieste successfully took such risks. His are works that do not indulge the arbitrary, works in which the form of the structure is also the form of the building and the delimiter of space. Dieste stated this more strictly:

> A building cannot be profound as a work of art unless it has an earnest and subtle fidelity to the laws of matter. Only the reverence that this fidelity requires can make our buildings serious, lasting, and worthy partners in our contemplative journey.[7]

The utter directness of Dieste’s work—its “earnest and subtle fidelity to the laws of matter”—moves us.

Within his oeuvre and beyond the types of buildings already mentioned are a few works that are especially integral

to Dieste's contemplative journey. Dieste's best-known work is the Church of Christ the Worker in Atlántida. It is all the more remarkable for having been created early in his career. It is both proof of Dieste's architectural capacity from the outset and an inventive variation on the system of Gaussian vaults. A detailed discussion of this impressive structure can be found in the essays of John Ochsendorf and Remo Pedreschi contained in this volume.

The Dieste House in Montevideo, built between 1961 and 1963, is located on a street that parallels the River Plate.[8] The house rests on steeply rising ground on the landward side of the street, providing a view south to the sea. The house with its courtyards occupies most of a narrow but deep lot, as was necessary for a large family of eleven children, even if the accommodations are economically organized.

The driveway makes a steep ascent to a broad terrace that is both carport and entry to the lower level of the house. The entrance is compact but ascends immediately via an L-shaped stair to the living room, built on grade less than a full story above. The living room is truly the center of the house and possesses varied and excellent relations to the exterior. To the south is a two-level open space, planted as it extends from the living room; and a hard-surfaced, partially covered terrace, which forms a roof over the entrance. To the north (which here, in the Southern Hemisphere, is the direction of the sun) is a constructed terrace under an openwork brick vault that opens to a generous courtyard garden.

Back in the living room, three steps bring one up to the dining space that is continuous with the living room except for the low storage units that further define the change of level between the two areas. This main level of the house is roofed with self-carrying vaults of a small span. Even at this scale, these vaults fulfill most of the claims Dieste had made for brick construction.[9] They serve important architectural purposes as well. The continuity of the living and dining areas is also articulated with their separate vaults. These main spaces of the house, with their undulating vaults, achieve both an intimacy and a generosity that no flat ceiling, high or low, would offer. From the living room to the sunny courtyard, the vault first offers a high, protected source of balanced light, beyond which is the perforated vault of the terrace that nuances the light both of the terrace and the interior. The shape and the perceived warmth of the vaults significantly ease the compactness of smaller spaces like the bedrooms and Dieste's study.[10]

There is reason to suppose that Dieste knew of Le Corbusier's famed Jaoul houses, built between 1954 and 1956 in Neuilly, outside Paris, which use walls of brick and thin-tile vaults.[11] The structures are, however, very different than Dieste's. The vaults of the Jaoul houses are not reinforced and

6 The full list of advantages appears in Antonio Jiménez Torrecillas, ed., *Eladio Dieste: 1943–1996*, trans. Michael Maloy and Harold David Kornegay (Seville: Consejería de Obras Públicas y Transportes, 1997), 34–36. This list, lacking a final point on low cost, first appeared in Eladio Dieste, "Acerca de la cerámica armada," *Summa* (Buenos Aires) 70 (Dec. 1973). It is considered more fully here in John Ochsendorf's essay on page 103 of this volume.

7 Eladio Dieste, "Architecture and Construction," 188 of this volume. Originally published as "Arquitectura y construcción," in "Eladio Dieste, el Maestro del Ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 84–93.

8 An essay by Antonio Dieste, one of Eladio Dieste's sons and himself a civil engineer, provides a description of the family home and insights that only a family member could give. See 18–31 of this volume.

9 Antonio Dieste notes that these spans could have been achieved more efficiently and economically with prefabricated concrete slabs. Of course here Dieste was not in economic competition for the commission, but neither was he merely advertising his business of building vaults.

10 Dieste's sense for the making of domestic space is revealed in his story of his encounter with an elderly woman in her humble, but humane and beautiful, room. See Dieste, "Art, People, Technocracy," 196 of this volume.

11 Aside from the renown of Le Corbusier and the Jaoul houses, Dieste, through the design of his first reinforced brick vaults for the Berlingieri house in 1946, had early association with the Catalan architect Antoní Bonet, who had moved in the circle of Josep Lluis Sert and Le Corbusier. See Ochsendorf's essay on page 96 of this volume.

fig. 24: Church of St. Peter [San Pedro], Durazno, 1969–71, axonometric section
fig. 25: Church of St. Peter, axial view from the nave to the sanctuary
fig. 26: Church of St. Peter, axial view from the nave to the rose window over the narthex
fig. 27: Church of St. Peter, view up into the light tower of the sanctuary
fig. 28: Church of St. Peter, angle view from the west side aisle to the sanctuary

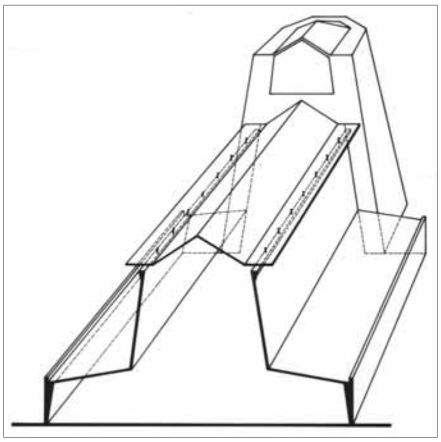


fig. 24


fig. 25

thus span between heavy walls or concrete beams and employ exposed tie-rods. The structural system is conventional and strongly cellular in its definition of space. The materials of the two houses suggest a relation, but Dieste's structural innovations opened new architectural potentials that he realized.

Beyond such claims for the vaulting, the architectural achievement of the Dieste House also rests on the compelling organization of the site and the house. The positive potential of the sloping site is realized. The changes of level, the several special relations of house and garden, the knowing use of light, and—employing all of these features and more—the appropriate distinctions of public and private are all the marks of a fully realized architectural proposition.

The most uncharacteristic work by Dieste is also the most subtle architectural achievement of his career: the Church of St. Peter in the provincial city of Durazno. The task at hand may well have seemed unpromising at first. In 1967, the original timber roof of St. Peter burned and only its replacement was envisioned. The church is located on the south side of the town's principal plaza, and presents only a façade to the square. The façade bears relation to both Romanesque and Renaissance precedent. Its gable top rises sheer into a square bell tower topped by a cylindrical colonnade with a high, stilted dome. The cubic bell tower directly over the entry requires a second strong wall parallel with the façade for support, the two walls framing the narthex. All this survived the fire and was incorporated into the new design.

The plan of the old church was a simple, three-aisled basilica with lower side aisles beyond a row of columns. Had the intention for rebuilding remained solely the addition of a fireproof roof, there would have been little of architectural consequence. However, the intention came to be a rebuilding of everything beyond the narthex, and Dieste made the most of this opportunity.

Any new design was constrained by the rectangular site in the middle of the block. Dieste's design has a deceptively simple plan (see fig. 56). It is a squat rectangle of a ratio of approximately 4:5, suggesting no strong directionality. To the south, the nave continues into a sanctuary that is five sides of a slightly irregular octagon. The transverse section of the nave is also simple, yet this is the first step in achieving a remarkable spatial organization (fig. 24). The section is once again basilical; however, no columns or piers—remarkably nothing—separates the nave from the long, broad side aisles. Since the side aisles together are wider than the nave and comparatively low, the central vessel, the nave, does achieve a strong horizontal directionality. The high side walls of the nave tilt inward such that the width of the nave at the roof line is only about half that of the nave height, and the apparent height is intensified. The horizontal and vertical directionalities obtained with the high, inclined side walls of the nave are all the more emphatic and resonate with symbolic significance by flowing seamlessly into the walls of the octagonal sanctuary. These walls rise well above the roof of the nave, sheltering a large concealed north window that brings direct sunlight streaming down the windowless south wall.

The roof of the nave is a strong complement to the powerful walls, with their continuity into the seemingly boundless height of the sanctuary. Like all other surfaces, the roof is wholly of brick, fashioned into long folded plates that form a low gable (fig. 25). The end of that low gable at the south provides a strong central focal point and sharp shadow line against the light in the sanctuary. The broad gable plates of the roof are stabilized laterally by horizontal plates that extend beyond the nave walls, acting as horizontal beams. To our surprise, there is a thin continuous band of light between the top of the nave wall and the roof, giving a soft illumination throughout the church without competing with the focal light over the altar. The horizontal band of clerestory windows does more than admit light. In this building so redolent of craftsmanship and sound tectonics, the seeming impossibility of that light source leaves the viewer with a conviction that here the material world itself has been overcome.

Due to the ingenious section and structure, the nave is, after all, a powerful directional force where form, tectonics, and light are in total congruence, subtly focusing attention on the most sacred part of the church. The spatial continuity of

fig. 26

fig. 27

fig. 28

the nave and side aisles is a secondary phenomenon but still vitally important to creating a sense of oneness between the congregants and the religious celebrants, in accord with Dieste's religious convictions.

A final surprise remains. Turning to leave, we see the third, and only other, source of light through an opening that is a tour de force in brick masonry (fig. 26). The old façade facing the square contains large lancet windows that give generous light into the high narthex. In Dieste's new inner wall of the narthex (the back wall of the nave), he suspends on tiny steel rods five concentric "rings" of brick in an irregular hexagon, creating a rose window that borrows light from the façade. Here too the beauty of the light and the improbability of the material phenomenon challenge our comprehension (fig. 27).

The folded plate construction used in Dieste's church at Durazno is all but unique in the engineer's work; indeed, it is unique among the great buildings of the world. The side walls of the nave are over 100 feet in length. How can it be that there are no columns to support them? How can it be that there is a continuous source of light between the walls and roof of the nave? The answer is that the side walls of the nave and the folded planes of the roof are beams spanning the length of the church! They are supported on the reinforced inner wall of the narthex and a reinforced concrete portal frame at the sanctuary.

Placing structural members in the long direction of the space is itself counterintuitive, but if you would stretch your intuition, examine the transverse section of St. Peter. In taking the apparently difficult path of spanning the church in the long direction, Dieste did not solve the problem with brute force. Observe the thinness of these wall/beams and roof plates! The nave wall—a slightly inclined beam—is a composite of brick and concrete, about 26 feet high and only about 10 inches thick, a ratio of 1:30. The principal roof plates, resting only 34 degrees off the horizontal, are even more amazing: little more than 3 inches thick, they too span over 100 feet. The ratio of thickness to span is approximately 1:400. The structural adequacy of these members is due to their form (the 26-foot height of the beam and the effective depth of the folded roof plates), but the actual and conceptual thinness of the structural elements remains striking. While the impressive span of the nave walls and the virtual independence of the roof from the nave walls are visible to the viewer, it is true that the extraordinary thinness of wall and roof is not directly given to view. Yet the taut brick surfaces in this building convey a clear sense of an economy of means that is much more than a mere material matter (fig. 28). Here again, Dieste has performed a "dance without effort or fatigue." He explains:

> The resistant virtues of the structures that we are searching for depend on their form. It is through their form that they are stable, not because of an awkward accumulation of matter. . . . there is nothing more noble and elegant from an intellectual viewpoint than this resistance through form.[12]

Dieste's resistance through form was a matter of spanning space. The centrality of this evident fact entails an important and less obvious aspect of his work. Virtually all of his buildings have the simplest of rectangular plans—in the greatest of his buildings, the Church of Saint Peter, even an obtuse, unpromising rectangle. Where the walls are curving, ruled surfaces, they are bounded by a real or implied rectangle. With the exception of his house, it is not the plan that sets his buildings apart. Nor are their exteriors elaborated. It is the section that is the telling feature of Dieste's buildings

12 Dieste, "Architecture and Construction," 187 of this volume.

and, through the section, that his innovations of space, light, and structure are achieved. Despite the excellence and centrality of structure and construction, with Dieste, a building offers little as an object and much as a space articulated for life.

Dieste's innovations in structure also entailed quite exceptional innovations in construction: movable formwork, simple pre-stressing techniques, rapidity of construction, and the like. What is so evident in the Church of St. Peter is the exquisite brickwork. The overall impression is of such perfection that one is convinced of the precision and economy of the thinking and performance that must lie behind such a work. This precision can be pursued down to details. At the junction of the nave, side aisle, and sanctuary, no two of these surfaces are at right angles to one another, yet the bonding here, as elsewhere, is perfect in its transitions.[13] To achieve such perfection requires deeply informed planning on the part of the designer, but it will never be achieved without excellent collaborators during the design and construction process and, needless to say, skilled and devoted craftsmen.[14]

Early in his career, Dieste courageously disciplined himself, his client, and his collaborators to achieve in the church at Atlántida a challenging work that went far beyond the initial program and established Dieste as an architectural force. The church at Durazno, with its intellectual as well as spiritual power, its refinement in both thought and execution, make it, I would argue, one of the major architectural achievements of the last half of the twentieth century. Dieste knew this and was willing to recognize that he had achieved architectural works, even if he was loath to title himself an architect.

Dieste was still more than an engineer and architect; he was a man with deep ethical concerns and broad intellectual interests. In his two churches he sought to unify the congregation and the priest and liturgy for the well-being of people, especially those who labored or were dispossessed. At Atlántida, Dieste had fulfilled this ideal prior to the dictates handed down by the Second Vatican Council. He was a religious man; you will find a crucifix on the wall of his study. But his concerns were not framed by the Church or even by religion more generally. His was a concern for humanity, expressed in both political and humanistic terms. He wrote, "I think that we would reach a wide consensus if we proposed as a common aim the fulfillment and happiness of mankind. This is an aim that would certainly produce different principles in accordance with each individual's philosophy of life and his religion."[15] After noting that "what we see around us is not acceptable," he continued, "The industrial revolution took place with such great injustice that the repercussions from the fierce indignation that its inequities produced in mankind are the reason for the destructive madness that has spread throughout the world."[16]

Deeply concerned for the inequities suffered by the majority of the world population, and committed to the maintenance of well-being in countries like his own that were buffeted both by local constraints and the harms of international development activities, Dieste did not lose sight of the higher goals of humankind. In his essay "Technology and Underdevelopment," he maintained:

> Efforts that are put to good use are efforts that help man to be happier, to be more himself. Efforts dedicated to science, art, health care, and efforts to make the earth, our countryside and cities, the true home of mankind, are efforts that are put to good use. If we understand development in this way, then it is both good and desirable.[17]

13 In Remo Pedreschi and Gonzalo Larrambebere's essay in this volume, the authors make this point. See page 148.

14 Gonzalo Larrambebere, a longtime key member of the Dieste y Montañez office, confirms that the architect Alberto Castro Oyola and the engineer Antonio Raúl Romero Riveiro collaborated with Dieste both in the design and the direction of the construction of St. Peter. Gonzalo Larrambebere to Stanford Anderson, electronic communication, 28 May 2002.

Castro explains that both he and Romero were "immediate collaborators," working independently but from an initial idea that Dieste had, as usual, given in a small (now lost) sketch. He states:

> My initial participation was the architectural elaboration of the preliminary design based on Dieste's original idea. When this phase was completed, the engineer Romero worked

Embracing this general position, Dieste's own efforts were conducted as both science and art, and were directed not only to the home of mankind but to our edification.

Recognizing that calls for simplicity usually entail unjustified simplification and that those for economy address merely money and its movement, Dieste advanced a much larger cause: "The things that we build must have something that we could call a cosmic economy, that is, to be in accord with the profound order of the world. Only then can our work have the authority that so surprises us in the great works of the past."[18] While here Dieste refers to structures, we should see his notion of "cosmic economy" in terms of that "profound order of the world." The inexplicable harmonies of the Church of St. Peter are the fundamentals of his cosmic economy, but so too are his understandings of how his country should operate within a world of disparate opportunities, and how genuine goods must reach equitable distribution.

Dieste's thought and work are undeniably metaphysical. Yet he rejects any teleology and his ambitions are always grounded:

> It is not easy to have a clear image of the goal. On the other hand, it is much easier to have a clear image of the foundations and principles that will shape that goal. This is why the idea that "the ends justify the means" is a drastic mistake. We do not know what the end will be. We have an image of our goals, but these will never be realized if in our actions we betray the principles that will shape and form these goals. We cannot postpone for the future city the beauty and dignity that we need so badly to endure the severities of life. We cannot postpone them as principles even though we might have to compromise in practice. When we have no other choice, we will have to compromise, but we should always continue to try to achieve the principles that will shape the goal, our future.[19]

With this confrontation of principles and reality, it is tempting to recall Dieste's story of one of his professors, who, hearing the word "theoretical" used with disdain, retorted, "Theoretical, theoretical, the theoretical that fails in reality, fails because it isn't theoretical enough!"[20] Dieste's thought, his search for "cosmic economy," takes him readily to large and small issues in quite different domains, but there remains a selective and rational mind behind these ambitions.

Dieste's achievement has a strong moral and intellectual basis. It offers fundamental lessons. Within a period marked by naïve modernist determinisms and conservative resistances, Dieste provided an unusual and strong counterexample. He was an engineer working rationally from first principles, but he was also a pragmatic humanist who chose his course in accord with both limiting conditions and social ideals. He knew how to make his situation work for him and others

> closely with Dieste to define the structure of the project . . . . Dieste directed the construction phase with Romero's support in structural issues and my support in architectural issues. At this point, the site superintendent Vittorio Vergalito was integrated in the team.

Castro also emphasized that this had been an exceptional team effort but (as with other projects in the office) under the natural leadership of an exceptional man, Dieste. Alberto Castro to Stanford Anderson, electronic communication, 5 June 2002. Dieste's recognition of Castro's and Romero's construction appears in Jiménez, ed., *Eladio Dieste*, 174. Vergalito was also a trusted collaborator, having long superintended the construction of Dieste's works.

15 Dieste, "Architecture and Construction," 188 of this volume.

16 Ibid.

17 Eladio Dieste, "Technology and Underdevelopment," in Jimenez, ed., *Eladio Dieste*, 261.

18 Dieste, "Architecture and Construction," 186 of this volume.

19 Dieste, "Art, People, Technocracy," 197 of this volume.

20 Eladio Dieste, quoted in Jiménez, ed., *Eladio Dieste*, 160.

without appeal to invented temporal imperatives. In the end, he was the author of innovations that are undeniably modern, socially responsible, and of high environmental quality.

Successively stepping down from these flights, consider a word that may still alarm the fastidious: form. Dieste introduced his essay "Architecture and Construction" with these words:

> [These] are reflections of an engineer who found in the process of building warehouses, he was creating architecture, even though that was not his object. He also found that he had an awareness of form and in confronting this awareness, he discovered that it helped him to solve problems that were strictly structural.[21]

Form is antecedent to Dieste's structural discoveries. I do not think he is referring to such knowledge as the structural efficiency of catenary curves; this is too well known in his discipline and too intimately related to structure to elucidate this passage. On the other hand, Dieste criticized the arbitrariness of architectural formalism, so his "awareness of form," though apparently susceptible to abstract exploration, is certainly part of a discipline. We are surely inserted once again in Dieste's "cosmic economy," but how can we understand this in a more concrete way?

A clue to answering this question appears in Dieste's comment, "If I had to synthesize what has driven our search, I would say that it is the perennial value of the surface itself."[22] "Surface" at first seems a dangerous word: "surface treatment," "surface coating," and the like suggest superficiality. We do not want to remain at the surface of a matter when it can be probed profoundly. Surely Dieste found something profound in the "perennial value of the surface," and it is here that he recognized a realm of formal exploration that could in turn solve structural problems.

Dieste rejected reliance on rectilinear frame systems.[23] He also resisted structural solutions that relied on two-dimensional curved forms such as arches and ribs.[24] Such approaches invited solutions based on additional material rather than on structural efficiency. To the contrary, Dieste's principal structural innovations relied on the efficacy of surfaces with particular formal properties. The simple curve of the self-supporting vaults allowed them to perform as beams. The S-shape of each band of Gaussian vaults gave it the stiffness to span great distances. Of course, these vaults are of material and have thickness, but their shape is still more fundamental to their capacity. Dieste carefully detailed his buildings to facilitate the viewer's recognition of the literal and affective power of form. Simply examine again how the cantilever of a self-carrying vault terminates: so thin relative to the span that we think of line and surface rather than of mass.

The two vault systems that recur in Dieste's work deserve acclaim within his "awareness of form," but he had internalized these solutions so fully that he must have been thinking of still other formal explorations that helped him solve structural problems. I return to the planar beam and the folded roof plates of the Church of St. Peter. Planar forms can now be explored, but in assemblies where two or more planes work integrally to perform far beyond what they could achieve separately. The thickness of the walls and roofs is so slight relative to their extent that, again, we are inclined to think of them as surfaces. That reading is further motivated by the careful bonding and grouting of the bricks, turning the materiality of brick into elegant surfaces made evanescent by the effects of natural light.

21 Dieste, "Architecture and Construction," 182 of this volume.
22 Eladio Dieste, quoted in Jiménez, ed., *Eladio Dieste*, 218.
23 Dieste, "Architecture and Construction," 182 of this volume.
24 Eladio Dieste, in Jiménez, ed., *Eladio Dieste*, 218.
25 Alberto Petrina, "From the South," in Jiménez, ed., *Eladio Dieste*, 18.

Light, so effective in Dieste's most utilitarian buildings, is transcendent in St. Peter. The Argentinean architect Alberto Petrina gave a compelling appreciation of Dieste's use of light in the Church of Christ the Worker in Atlántida and, I would say most appropriately, of St. Peter:

> In these churches light is an irreplaceable ingredient without which the buildings would fall as if the structure had given way. Light is pulled toward the chosen points as if by a magnet; it is kneaded and mixed with the materials until it is part of them, it is exalted and transfigured. Light announces the Divine Presence, or at least simulates perfectly that presence.[25]

Ultimately, it is by the play of light on surfaces of material and structure, as well as by resisting through form, that Dieste achieves "a lightness, a mysterious ease, a concise simplicity, something like dance without effort or fatigue."

fig. 29

## CHURCH OF CHRIST THE WORKER

*Atlántida*, 1958–60

Remarkable but true, this church is Eladio Dieste's first architectural work, evolving from an initial contract for a simple vault in 1952. It is located in a formless village populated by agricultural and manual laborers.

At floor level, the plan of the church is a simple rectangle, from which undulating walls rise to the maximum amplitude of their arcs. These thin but self-stabilizing walls carry continuous double-curvature vaults with tie-rods concealed in the almost-level troughs that are anchored in the brick edge-beams projected beyond the walls. These complex forms achieve a stunning simplicity as the walls and roof meet in a level plane.

Dieste wrote of his desire to unite the congregants with the officiants in a single space, which the nave of this church provides. The space also presents a spiritual itinerary for the rite of baptism, symbolizing acceptance into the family of the church: parallel to the main entrance, a projected, tunnel-like entry descends to the circular baptistery, from which another passage ascends to join the congregation in the unified space. The realm of the altar is demarcated through a slight change of level and careful use of light.

Light is a compelling force on the interior of the church. The accent at the altar and the suffused light throughout the nave emanate from obscured origins: shielded light sources at the choir above the entry; multiple small windows cut into the curves of the brick wall that orient toward the altar; and a small crown of skylights let into the vaults above the altar. Revealing of the structure is the perimeter of light, which separates the structurally complete nave walls and roof from the freestanding entrance wall.

fig. 29: View of the north-facing entrance façade
fig. 30: Raking view of the west wall

fig. 30

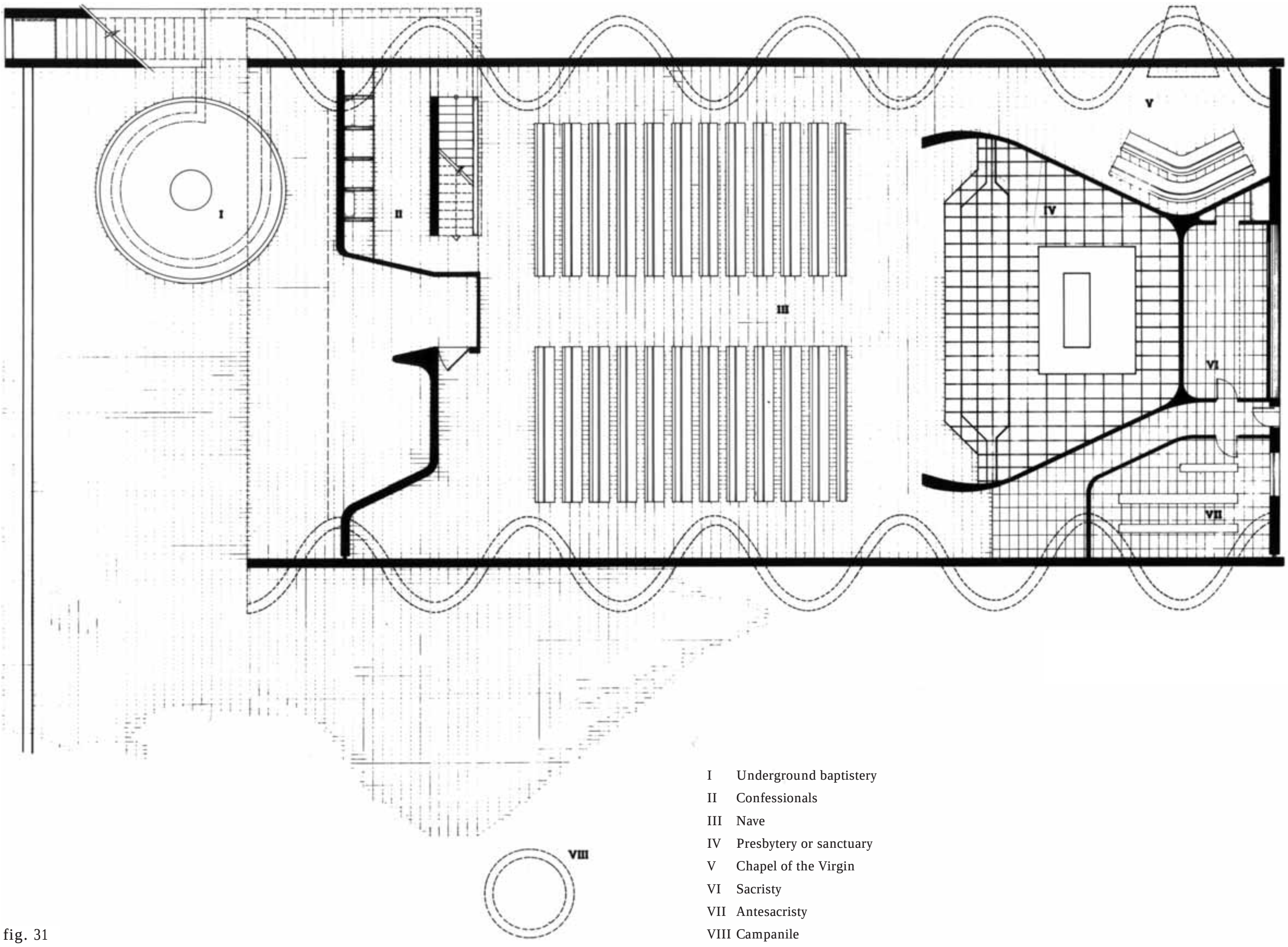



fig. 31

fig. 31: Plan of the church. The church is “oriented” to the south.

fig. 32: Vittorio Vergalito, master mason with Dieste y Montañez. The walls of the church are ruled surfaces, the bricklaying controlled with straight lines established within the construction framework.

fig. 33: Sinusoidal walls and roof, before end walls were added

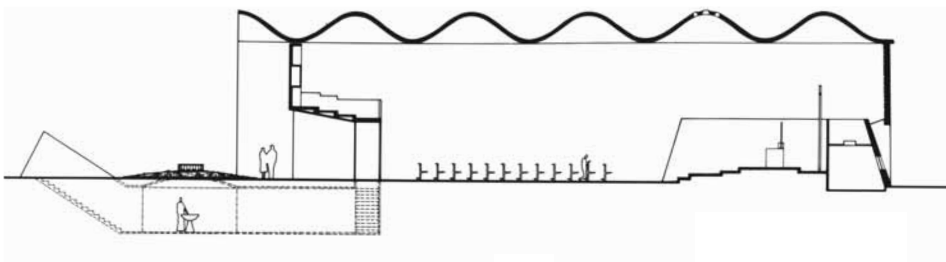
fig. 34: a) Longitudinal section. The continuous double-curvature vaults are perforated to admit light over the sanctuary.
b) Transverse section, which to a technical eye reads as the moment diagram of the structure

overleaf

fig. 35: East wall. The curvature of the walls renders the windows invisible as one enters the church.

fig. 32

fig. 33



a)

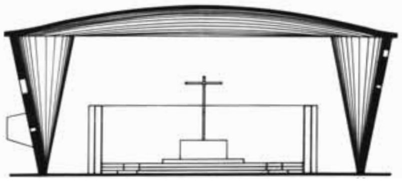


fig. 34 b)

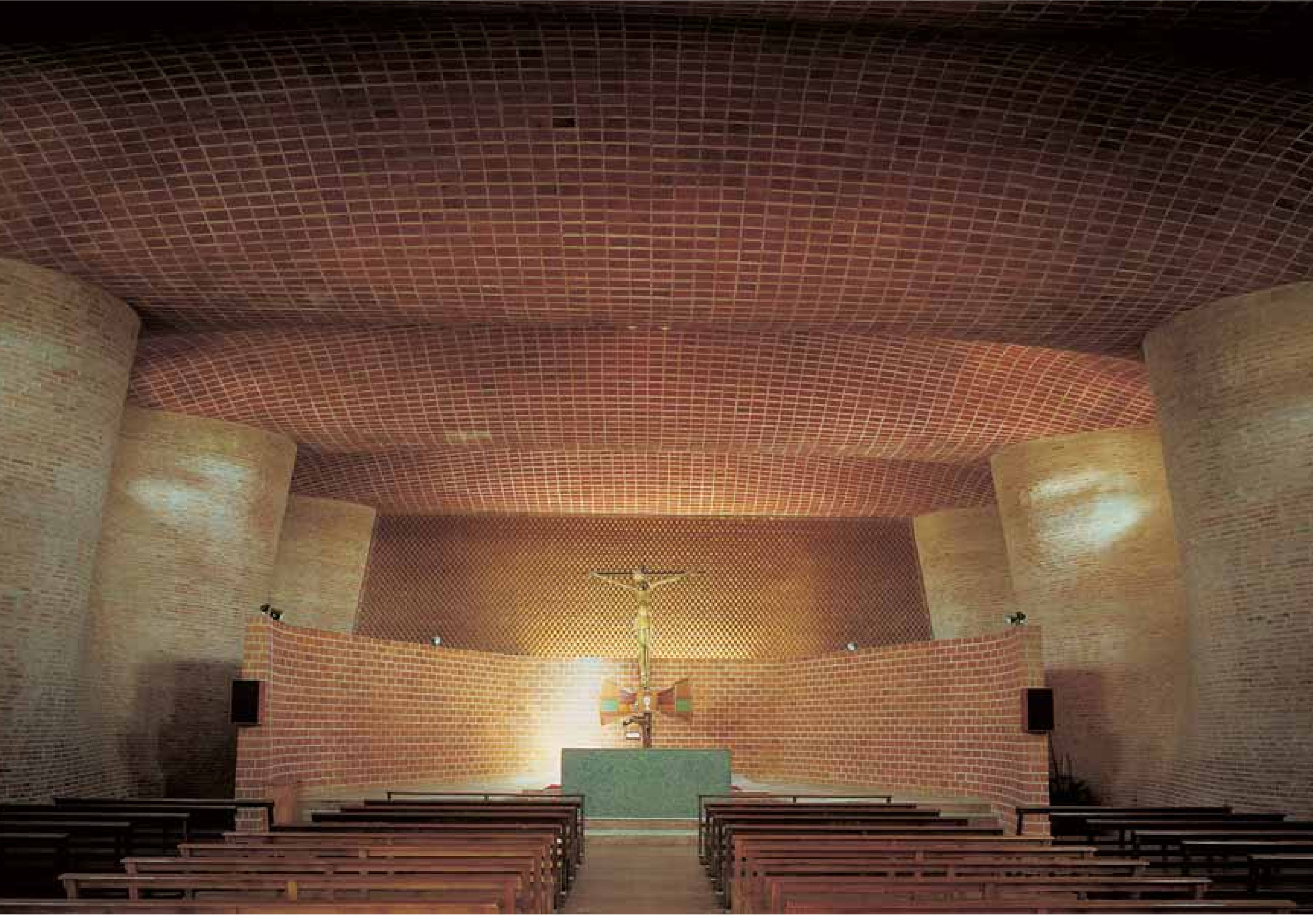


fig. 36

fig. 37

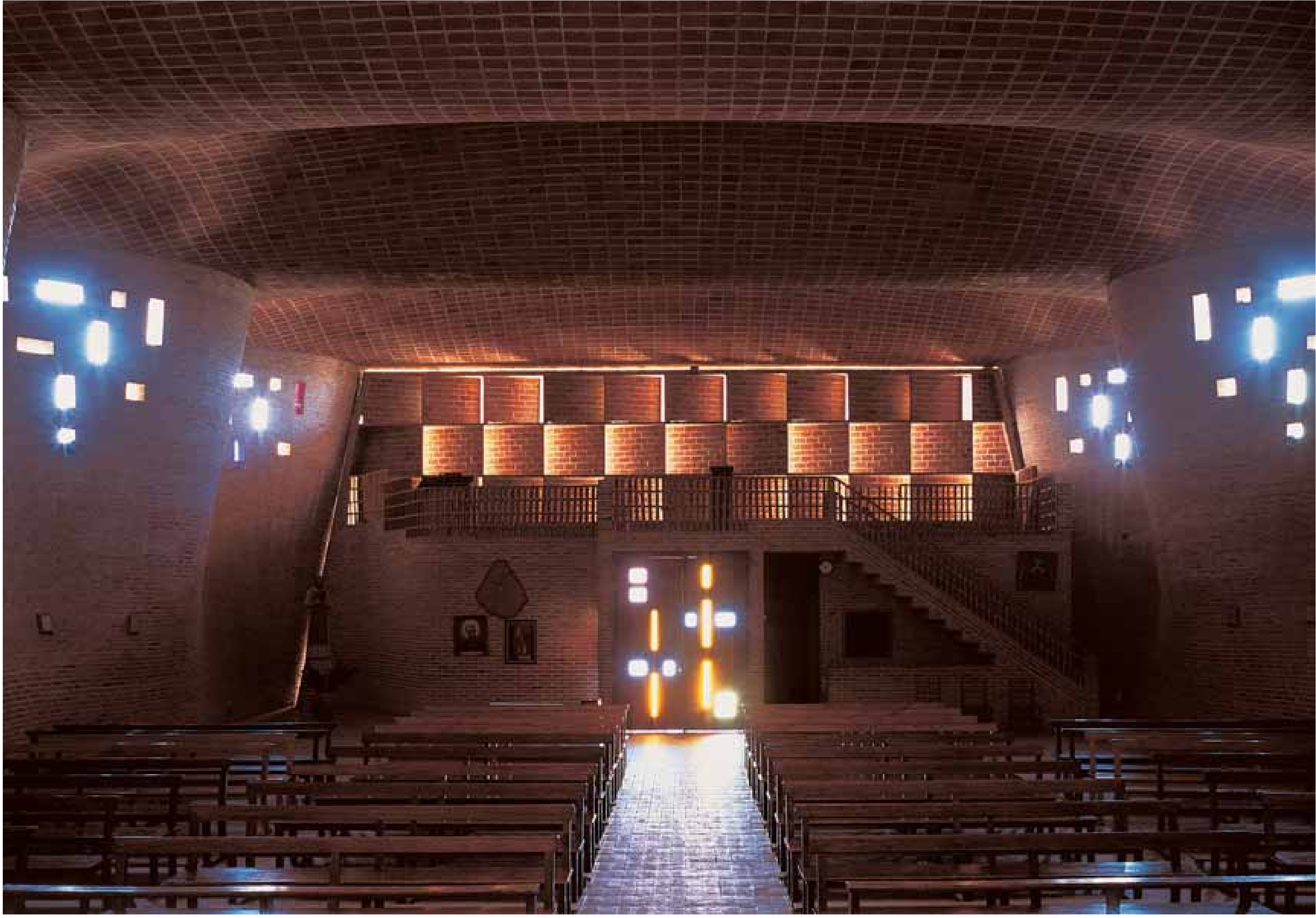


fig. 38

fig. 36: Axial view of the interior, from the entrance

fig. 37: Independent entrance. A passageway descends from here to the baptistery and continues into the church, a symbolic entrance to Christian faith.

fig. 38: Axial view toward the entrance, showing the light sources

fig. 39: View along the east wall toward the choir stair

fig. 40: View along the west wall revealing the independence of the end wall from the structure of the church

fig. 41: Diagonal view, illustrating how the sinusoidal walls and roof meet in a horizontal curved line

fig. 42: Chapel of the Virgin with a devotional window, a perspectivally exaggerated box that penetrates the wall. At the near, non-structural brickwork

fig. 39

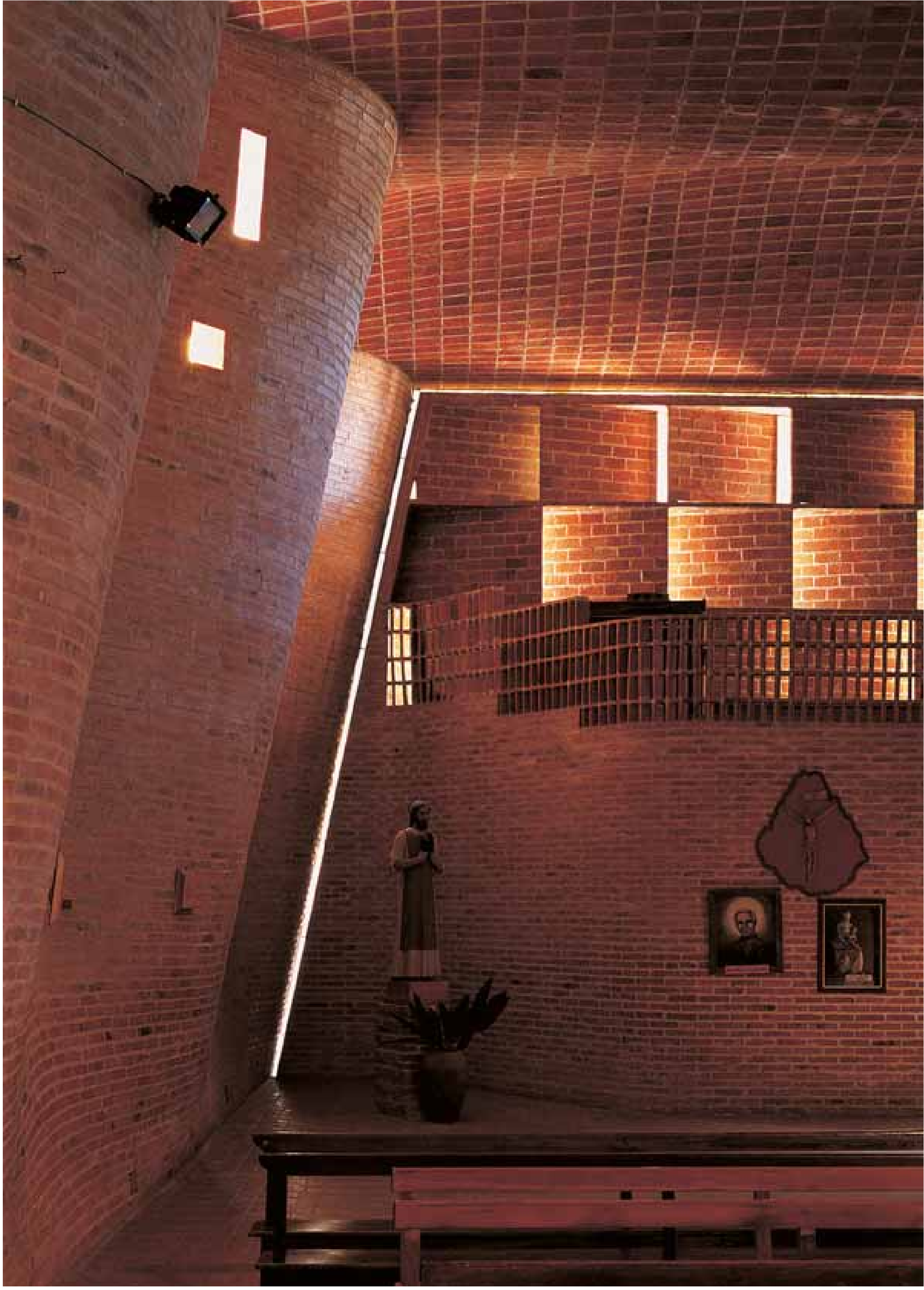


fig. 40


fig. 41


fig. 42

fig. 43

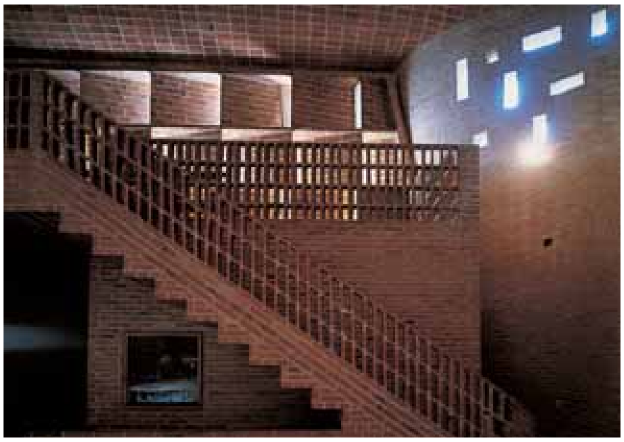


fig. 44

fig. 43: Lateral view in the church

fig. 44: Stair and choir railings

fig. 45: Canted brick grille with alabaster windows, which controls the strong north light from the entrance wall

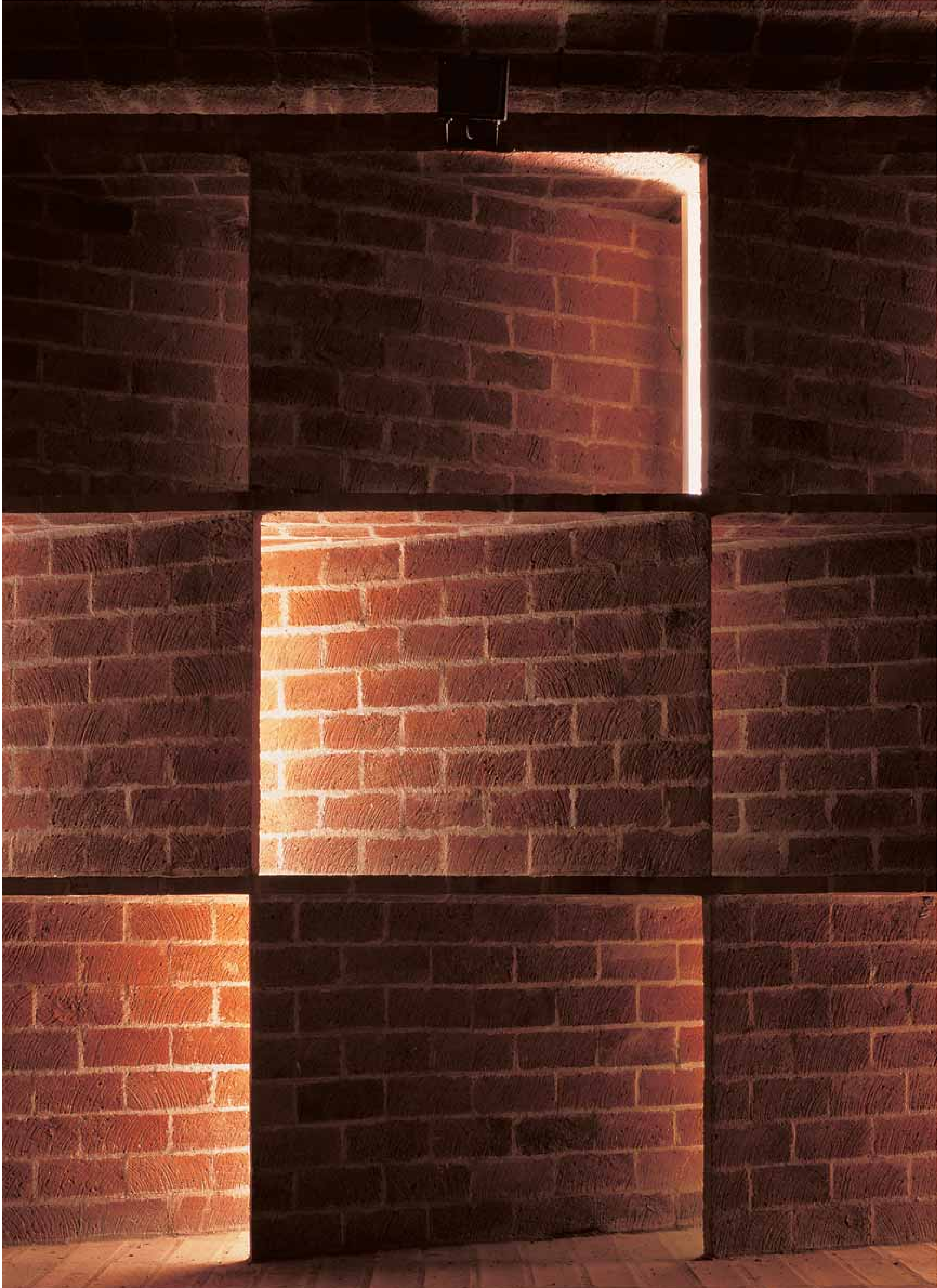


fig. 45

fig. 46: Campanile interior, illustrating prefabricated, cantilevered brick steps

fig. 47: West of the church, a campanile of penetrated brick

fig. 48: Late-afternoon sun, creating strong contrasts through the campanile on the form of the church

fig. 46


fig. 47


fig. 48

fig. 49

## CHURCH OF OUR LADY OF LOURDES

*Malvín, Montevideo*, 1965–68

A large new church, projected in 1961, was to envelop the existing church before its planned destruction. The new parish house and a fragment of the high walls of the sanctuary were built before economic conditions and the death of the supportive Father Freire halted the work. This towering construction is a double brick wall with internal stairs, which eliminated the need for scaffolding during its construction. Drawings show a clerestory window of simple geometric pattern giving light from the tower onto the chancel. This was not a definitive design; there are also photographs of a model that showed an alternative of three, lightly scaled cruciform windows. The nave walls of the Malvín church were to have been of a greater height than those at Atlántida, and their ruled surfaces were to begin and end in undulating lines.

*Collaborator: Architect Alberto Castro*

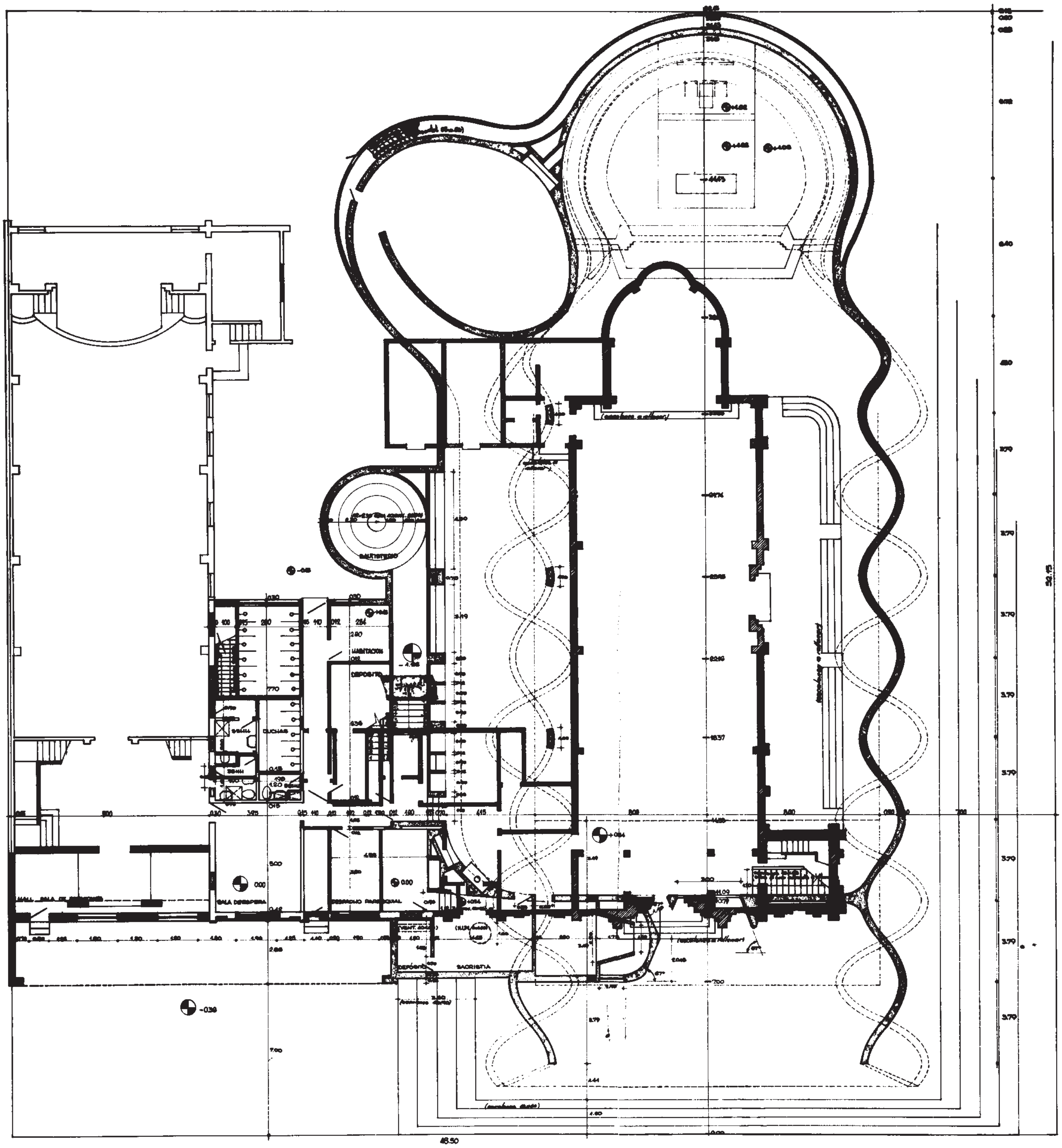


fig. 50

fig. 49: View of the parish house, with its perforated, self-carrying barrel vaults

fig. 50: Plan of the church and parish house, which were to envelop the existing church

fig. 51: Detail of the perforated vaults of the parish house

fig. 52: Fragmentary construction of the sanctuary of the church, with its double wall

fig. 51

fig. 52

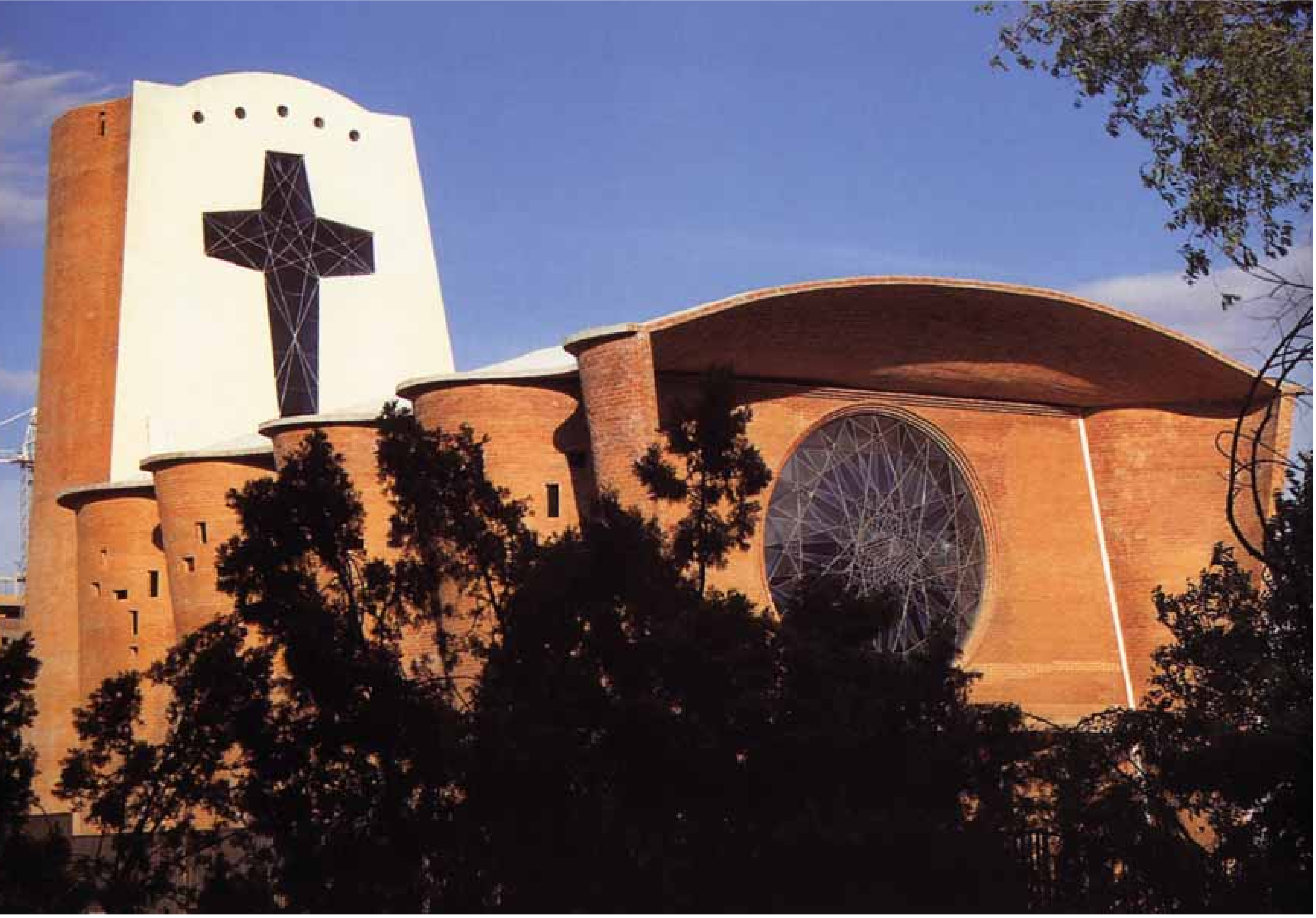


fig. 53

## CHURCH OF SAN JUAN DE ÁVILA

*Alcalá de Henares, Madrid, Spain,* 1996ff.

Dieste's late collaborative works built near Madrid include this church, designed in 1993 and based on the plans for the unfinished church in Malvín. The large rose window and the large cross as the clerestory window are not wholly satisfactory resolutions of what had remained uncertain in the original design nearly thirty years earlier.

Clemente and others also collaborated on additional churches in the same area of Madrid based on Dieste's designs. The Church of the Sagrada Familia in Torrejon de Ardoz and the Nuestra Madre del Rosario in Mejorada del Campo are close emulations of the churches in Atlántida and Durazno, respectively. Three more churches have since been built in the Diocese of Alcalá using Dieste's techniques.

*Collaborators: Architects Carlos Clemente and Juan de Dios de la Hoz*

fig. 53: View of the Spanish church based on the Malvín church design
fig. 54: View up in the light tower above the sanctuary and to the first vaults of the nave

fig. 54

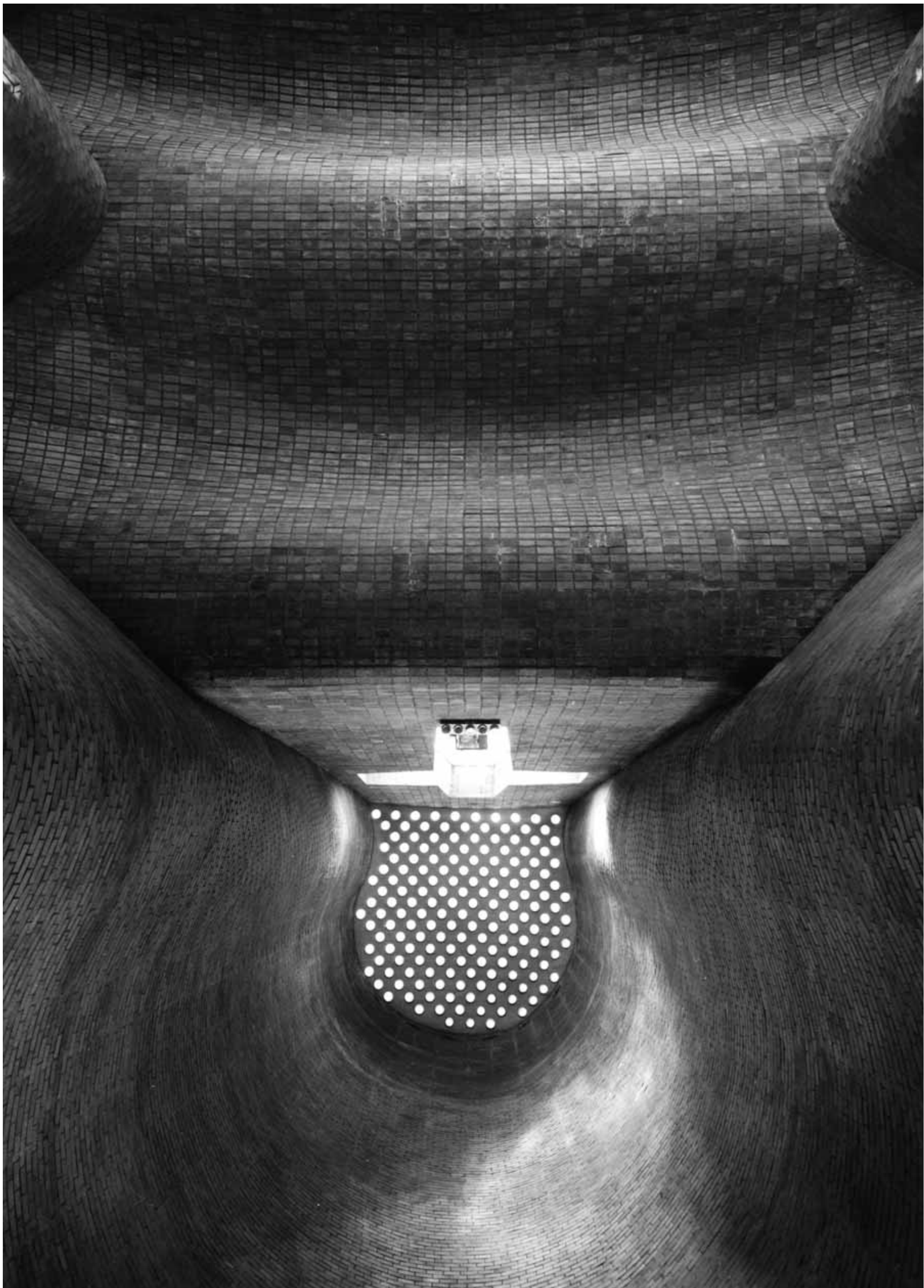


fig. 55

# CHURCH OF SAINT PETER [SAN PEDRO]

*Durazno,* 1969–71

The neo-Romanesque façade, narthex, and outer walls of the Church of St. Peter (San Pedro) survived a fire that otherwise demolished the building. Dieste transcended the initial call for a new roof by conceiving a church with unique space and light that deserves to be counted among the best modern churches in the world.

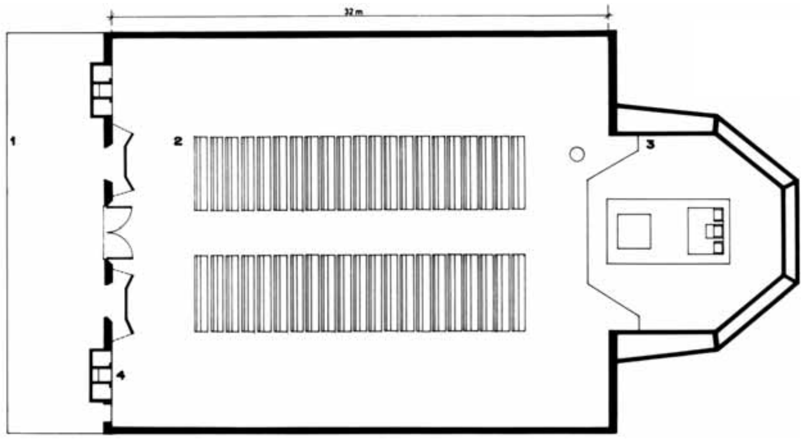
The structural technology of St. Peter is all but unique in Dieste's work. It is built entirely of very thin folded plates that span over 100 feet between the narthex and sanctuary walls, allowing a completely open plan contrasting with a basilical cross section that would usually be divided by rows of columns. The plates that form the nave walls and side aisle roofs, and those that form the high roof, are joined only by small steel, recessed posts. A narrow band of light between these plates simultaneously reveals this remarkable structural feat and more importantly provides an evocative, even light throughout the nave. This controlled light creates the ambience against which the drama of the sanctuary light is played. The sanctuary walls rise high to open a large clerestory window, out of sight above the plates of the nave roof. Opening from the direction of the sun, the high window floods the sanctuary with light that varies in intensity, direction, and pattern, a moving complement to the still environment of the nave. On the wall above the entrance, the ethereal brick of the rose window filters light from the narthex and original façade.

*Collaborators: Architect Alberto Castro and Engineer Raúl Romero*

fig. 55: Façade and narthex/tower of St. Peter, located on the south side of the main square of Durazno

fig. 56: Plan of the church, with the existing façade and narthex only outlined

fig. 57: Axial view from the entrance, illustrating the continuous light source between wall and roof, and the dramatic lighting of the sanctuary from the high clerestory window




1 Existing narthex
2 Nave
3 Presbytery or sanctuary
4 Confessionals

fig. 56

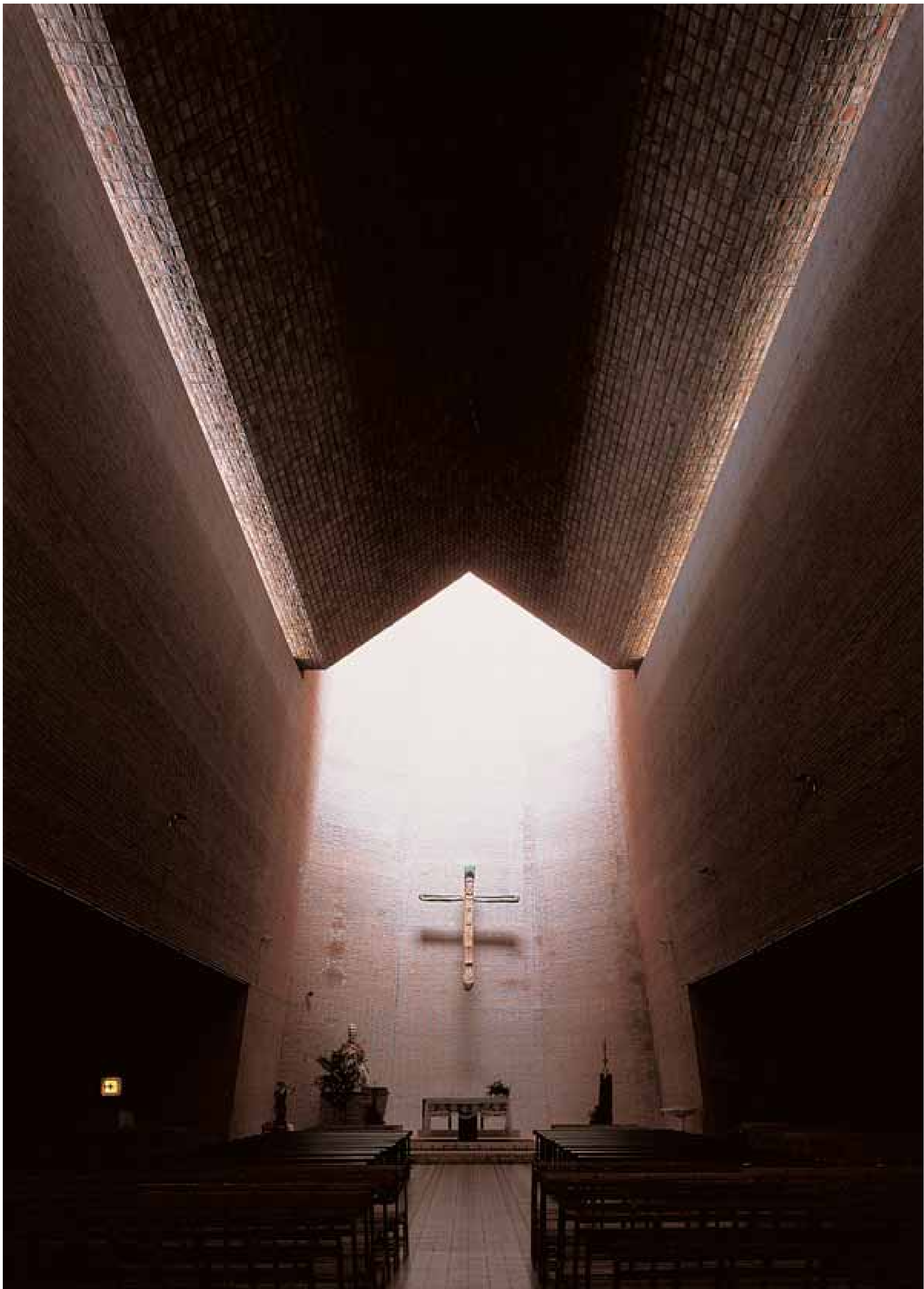


fig. 57

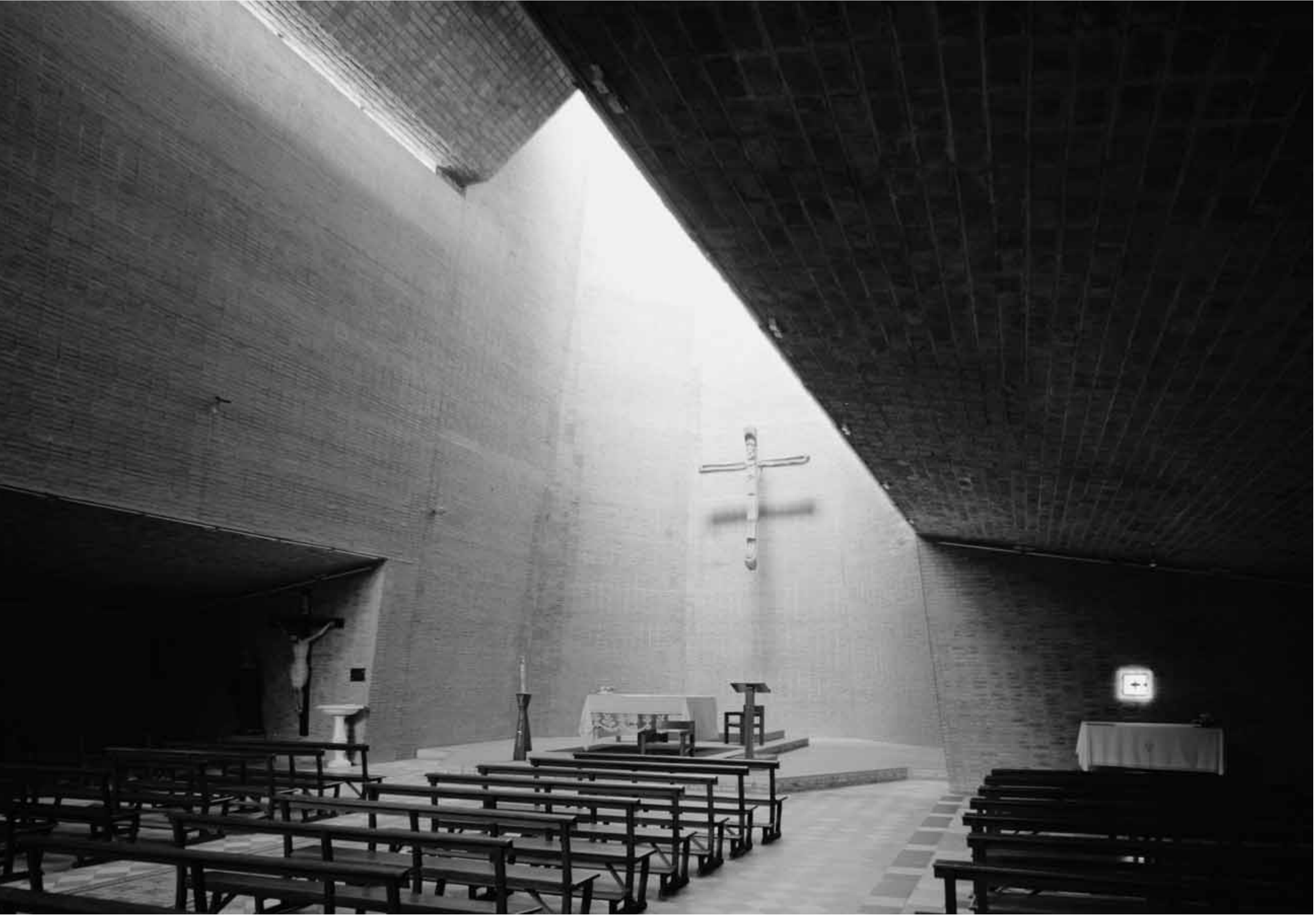


fig. 58

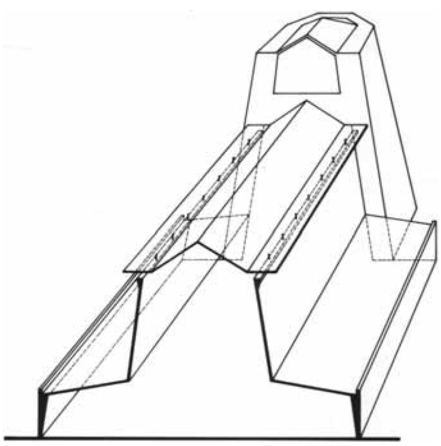


fig. 59

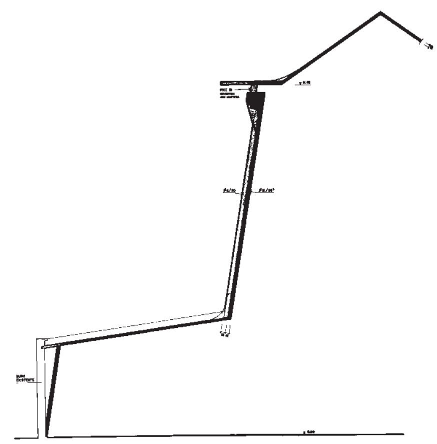


fig. 60

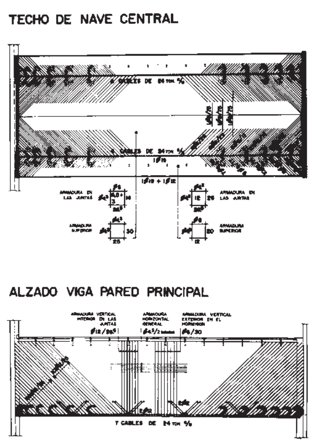



fig. 61

fig. 58: Angled view showing the continuity of space from the side aisles and the fine brickwork from the spanning wall/beam into the support of the sanctuary walls
fig. 59: An axonometric section, revealing the extreme thinness of the folded plates, their long span, and the open plan of the church
fig. 60: Partial transverse section.
fig. 61: (top) Reinforcing pattern for the roof, (bottom) reinforcing for the nave walls
fig. 62: View of the sanctuary, with crucifix by Claudio Silvera Silva, originally from Durazno

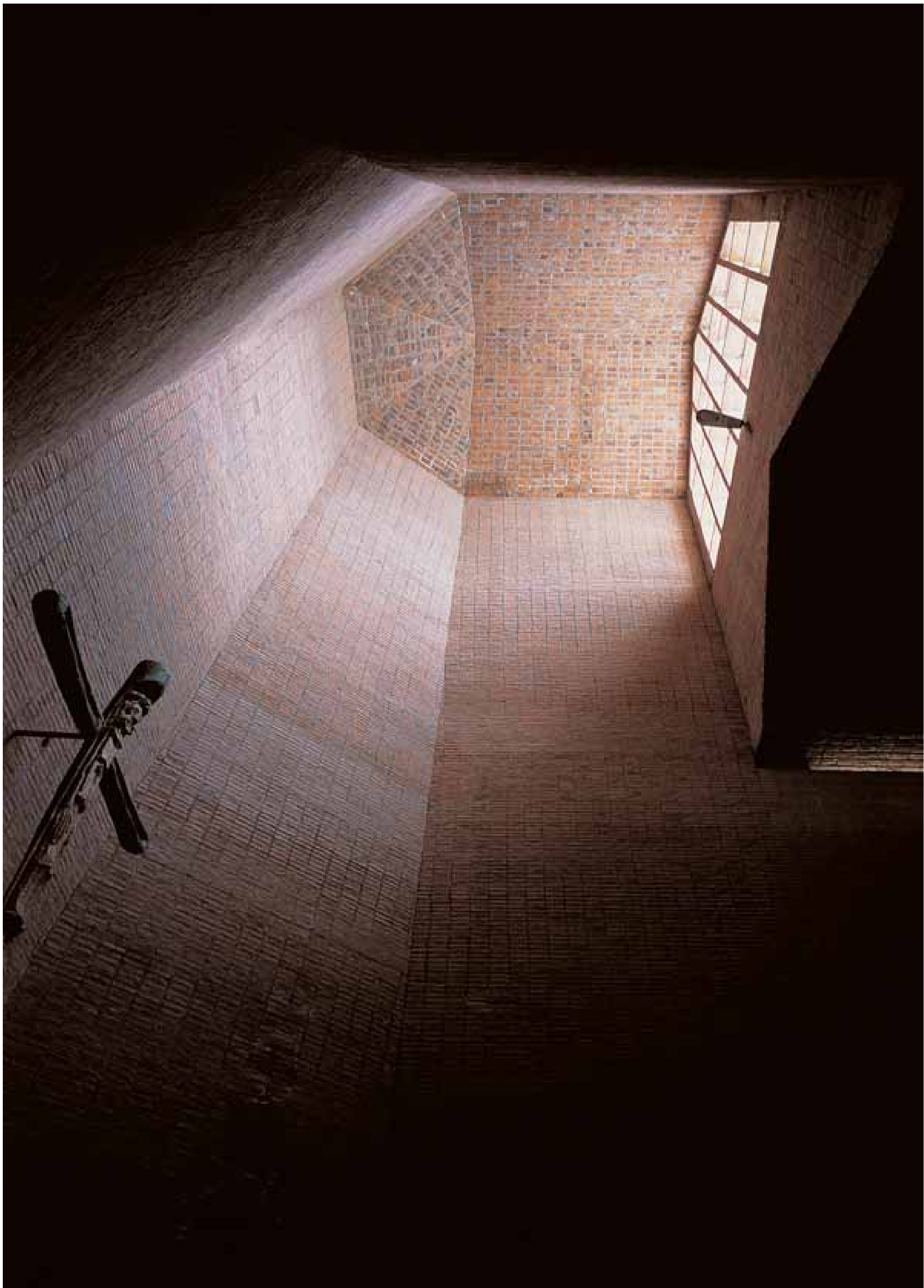


fig. 62

fig. 63

fig. 64

fig. 63: View of the narthex, with the old façade to the left and the new wall with rose window to the right

fig. 64: Looking back through the nave, with its continuous surfaces of simple brickwork, to the rose window above the entrance

fig. 65: Longitudinal section, showing the clarity and simplicity of the church that nevertheless contains so many effective nuances

fig. 66: The seemingly free-floating brick of the rose window

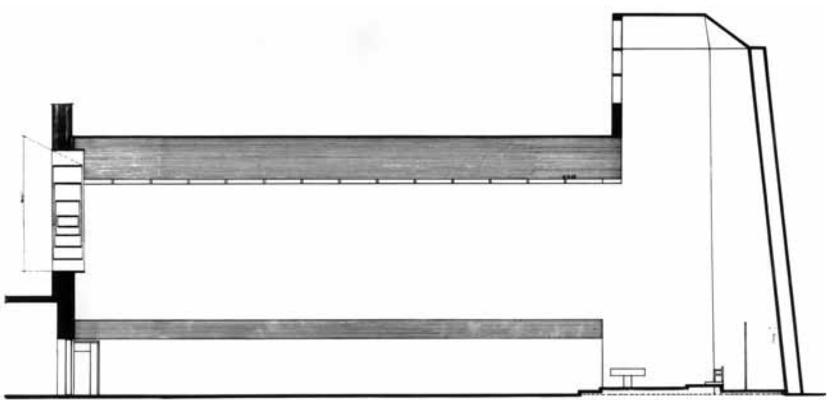


fig. 65

fig. 66

fig. 67: The three types of traditional masonry vaults: European, Middle Eastern, and Catalan

## GUASTAVINO, DIESTE, AND THE TWO REVOLUTIONS IN MASONRY VAULTING

*Edward Allen*

Two successive revolutions transformed masonry vaulting from the thick, handcrafted roofs of the ancients, shaped and proportioned by intuition, to the steel-reinforced, mathematically designed, thin brick shells of the late twentieth century. The first revolution began in the late nineteenth century in Catalonia, where Rafael Guastavino applied the then-new discipline of graphic statics to traditional Catalan vaulting to produce the first scientifically engineered masonry structures. The second was wrought in the last half of the twentieth century by Eladio Dieste who, with the numerical theory of reinforced concrete shells as his point of departure, designed and built clay masonry roofs in daring new forms that spanned unprecedented distances. This discussion will focus on Guastavino's work and its relationship to that of other architects and engineers of his time. It will conclude by contrasting Guastavino's innovations with those of Eladio Dieste.

### The Application of Graphic Statics to the Development of Masonry Vaults

Historically, masonry vaulting developed along three paths: the European, the Middle Eastern, and the Catalan (fig. 67). The European path included Roman, Romanesque, Gothic, and Renaissance vaulting. The design of European vaults was generally based on the geometry of the circle, and the vaults were erected over temporary centering or formwork. Working in this fashion resulted in relatively thick vaults, with the long dimensions of their stones or bricks lying along radial lines. The inclined thrusts of the vaults are resisted by either engaged or flying buttresses.

The second path of development took place in the Middle East, where both barrel vaults and domes were erected without the use of centering. For vaults, centering was eliminated by inclining the courses of bricks against an end wall and for domes, by building in a spiral pattern. The resulting vault shapes often tended toward a parabolic geometry rather than a circular one, probably because it was easier for the mason, when working without centering, to keep bricks in place in a partially completed vault if they were laid along a parabolic line. Middle Eastern vaults are about as thick as European ones. Their thrusts are resisted by thick walls or engaged buttresses.

The third path of traditional masonry vault development—the Catalan vaulting technique—emerged in the region around Barcelona and is distinctly different from the other two. It utilizes multiple, overlapping laminations of thin tiles whose long dimensions lie in the curving surface of the vault. Catalan vaults are much thinner and lighter in weight than either European or Middle Eastern vaults. They are often also much shallower, sometimes rising as little as 10 percent of the span. They are extremely strong due to the staggering of joints between one tile lamination and the next. They are sometimes called timbrel vaults in reference to their extreme thinness, which is likened to that of the head of a timbrel, a small hand-drum or tambourine.

Vault forms commonly constructed in Catalonia included domes, barrel vaults, pillow-shaped vaults, and helical stairs. Even "flat vaults," planar laminated tile slabs, were often built to span very short distances, usually not more than three feet or so. All the Catalan vault forms were erected without centering by using ingenious construction procedures.[1] These procedures are made possible by joining the tiles edge to edge in the first layer with plaster of Paris (pure gypsum), which is very fast-setting and highly adhesive. Because this material weakens when wetted, it is unsuitable for use as the primary mortar in a vault. Subsequent layers of tile are bonded to each other and to the first layer with portland cement mortar, which is water resistant and much stronger than plaster of Paris.

Until late in the nineteenth century, masonry vaulting was shaped and proportioned by guesswork or rules of thumb. As a consequence, vaults based on the European or Middle Eastern precedents tended to be not only thick but also heavy and expensive. Catalan vaults were much thinner but were also designed by wholly intuitive methods. A correct understanding of vault shapes and forces had been formulated as

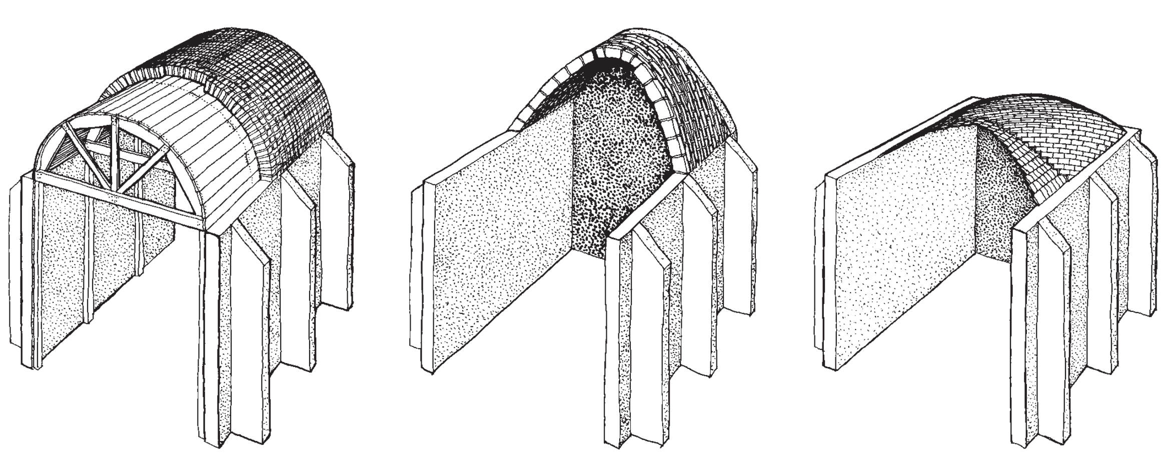


fig. 67

early as the end of the seventeenth century, as demonstrated in a treatise by Giovanni Poleni (1683–1761), published in 1748, on finding the ideal shape for a dome.[2] It was not until Karl Culmann (1821–1881) transformed Poleni's hypothesis into a simple and powerful working method, however, that it became easy to find correct shapes and forces for masonry arches and vaults. Culmann's *Die graphische Statik*, published in 1866 by the Swiss Federal Technical University (ETH) in Zurich, was the first comprehensive presentation of graphic statics, a method of structural design that employs scaled drawings rather than numerical operations.[3] Graphic statics made it possible to determine the ideal form for a masonry vault and the forces within the vault quickly and simultaneously.

The use of graphic statics to find the form and forces for a vaulted roof that spans 280 feet over an athletic arena is illustrated in figures 68–71. The given conditions are that the vault must spring from abutments *X* and *Z* and it must pass through point *Y* on its vertical centerline. In order for a vault to be stable under a uniform gravity load, each segment of it must be in static equilibrium. This requires that three forces—the pull of gravity on the segment and the two inclined compressive forces exerted on it by the segments on either side—must balance one another. It is a fundamental axiom of physics that when the vectors of these three forces, connected tip to tail, form a closed triangle, this equilibrium is achieved.

The goal of this design procedure is to find a funicular shape for the vault. The word "funicular" stems from the Latin *funiculus*, meaning "string," and a funicular shape for a vault that is subjected to a given pattern of loads is the inversion of the shape that is assumed by a flexible string or cable when it is subjected to the same pattern of loads. For a single, concentrated load, a funicular shape for a cable will resemble the letter V; the funicular shape for a vault will resemble an inverted V. For a load uniformly distributed over the horizontal projection of a vault, a funicular shape will be a parabola; for a vault that carries its own weight only, a funicular shape is a catenary, which is very close in shape to a parabola (although much more complex to represent mathematically). The advantage of a funicular shape is that the vault experiences only pure compression, and not bending, when it is subjected to the load for which it was designed. This allows it to be built with a minimum of material. More often than not, it also produces a shape that we perceive as being elegant.

In this illustrative example, the total vertical load on a one-foot strip of vault has been estimated to be 21,000 pounds. At the top of figure 68, this load is divided into a convenient number of segments: seven of 3,000 pounds each in this case. Each segment is then represented just below on the drawing by a concentrated force of the same magnitude that is centered on the segment. The lines of action of these forces are extended downward over a section view of the arena. The magnitudes and directions of these forces are represented on a vertical load line to the right, where they are drawn tip-to-tail to a convenient scale of pounds to inches. The overall length of the load line at this scale is equal to the total load on the entire span of the one-foot strip of vault.

Because the vault is uniformly loaded in horizontal projection, we know that the funicular shape is a parabola. A parabola has the useful property that lines that are tangent to its ends will intersect at a point on its vertical centerline. This point lies at a distance above the parabola's closing string (baseline) that is exactly twice the parabola's altitude. In figure 68, the baseline or closing string of the parabola is drawn between its endpoints, *X* and *Z*. The altitude of point *Y*,

1 A number of these procedures are illustrated in Timothy P. Becker and Kent Anderson's essay on pages 202–07 of this volume.

2 Giovanni Poleni, *Memorie Istoriche della Gran Cupola del Tempio Vaticano* (Padua, 1748), quoted in Hans Straub, *A History of Civil Engineering* (Cambridge, Mass.: MIT Press, 1964), 140–42.

3 Karl Culmann, *Die graphische Statik* (Zürich: ETH, 1866).

An example of the use of graphic statics to find the form and forces for a vaulted roof. Each arrow is a vector. The direction of the arrow indicates the direction of the force, and the length of the arrow is proportional to the magnitude of the force.

fig. 68: Setting up the graphical solution

fig. 69: The first segments of the vault, oa and ob, are constructed

fig. 70: Another segment of the vault, oc, is added

fig. 71: The finished solution

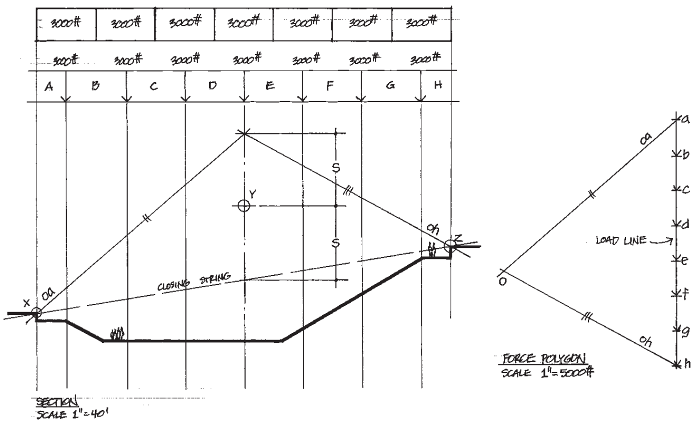



fig. 68

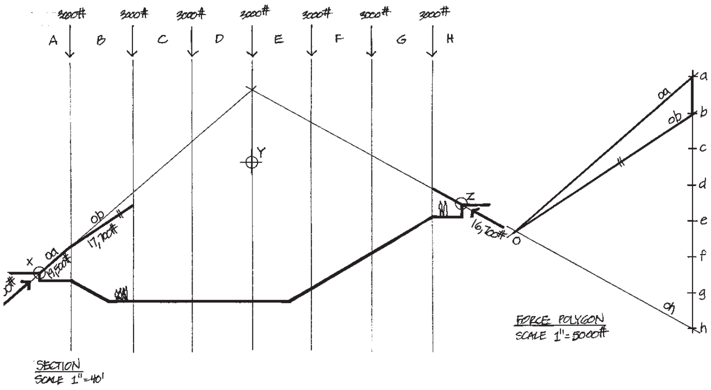



fig. 69

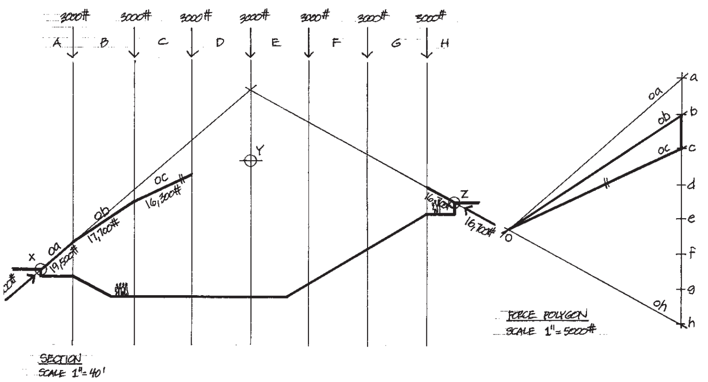



fig. 70

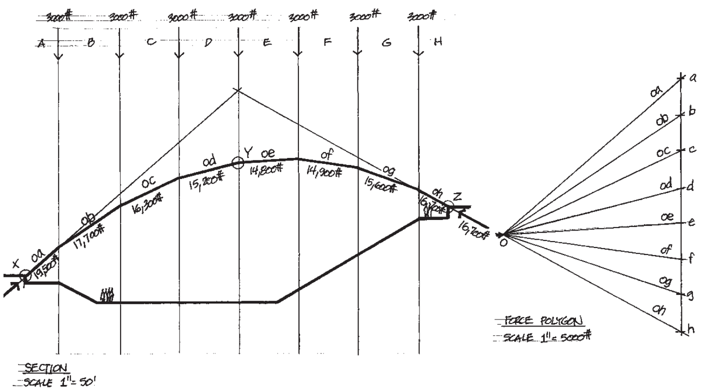



fig. 71

through which the parabola must pass, is measured as distance *s*. Another vertical distance of *s* is laid off above *Y*, and lines are drawn to connect this point to *X* and *Z*. These two lines are tangents to the ends of the parabolic vault. They are therefore the directions of the forces that the foundation abutments must exert upon the vault.

To the right in figure 68, a line is drawn through point ***a*** at the top of the load line, parallel to the left-hand tangent line, and another through the other end of the load line, ***h***, parallel to the right-hand tangent. These intersect at a point labeled *o*.

The resulting triangular diagram is an equilibrium triangle for the vault strip as a whole. The load line represents the total load on the strip of vault, and line segments *oa* and *oh* represent the forces exerted on the ends of the strip by the abutments. We can measure the lengths of *oa* and *oh* on this diagram at the given scale to determine the magnitudes of the forces that they represent. This diagram is also the first stage in the construction of what is called the force polygon, a scaled diagram that will eventually include line segments that are proportional in length to the internal forces in every part of the vault.

In figure 69, line *ob* is drawn on the force polygon to complete an equilibrium triangle for the point on the vault under the leftmost 3,000-pound load. Then segment *ob* is drawn parallel to this line on the section view to the left, starting from the point where line *oa* intersects the line of action of the leftmost load. The heavy lines *oa* and *ob* on the section are both tangent to the curve of the vault. By scaling the lengths of segments *oa* and *ob* on the force polygon to the right, we determine the magnitudes of the forces in these two regions of the 1-foot strip of vault.

In figure 70, these same steps are followed for the vault's next point of loading. In the equilibrium triangle on the force polygon to the right, which is drawn with heavy lines, the first and second equilibrium triangles share a common force, *ob*. Segment *oc* is scaled to determine the force in the vault segment that has just been drawn.

This process is repeated until the force polygon and section drawing are complete (fig. 71). The actual curve of the

fig. 72: Composite drawing of a selection of masonry domes constructed in North America by Rafael Guastavino

fig. 73: Construction drawing for the dome of St. Paul's Chapel, Columbia University, by Rafael Guastavino's consulting structural engineer, Nelson Goodyear. The several fan-shaped diagrams were used to find an optimum form for the dome and to determine the forces within it.

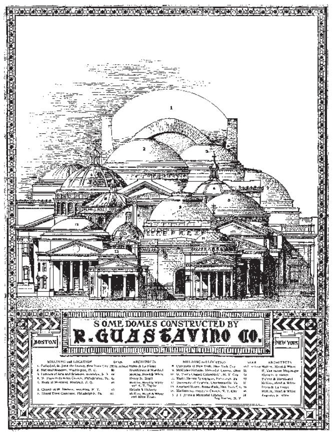



fig. 72

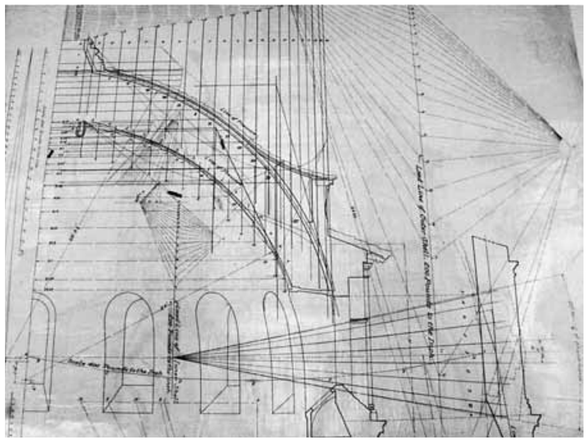


fig. 73

vault will be a smooth curve that passes through *X* and *Z* and is tangent to the midpoints of the other plotted segments. Without using numerical mathematics, we have found a funicular shape for this vault, and we have determined the forces in it with a maximum error of about 1 percent.

The payoff for constructing a vault in a funicular shape rather than as a segment of a circle is that it can be built with great economy of materials. The vault that was designed in figures 68-71, for example, would, in theory, if constructed of masonry with an allowable stress of 600 psi, span the 280 feet with a thickness of only 2.7 inches, which is about 1/1200 of its span.[4]

This technique for designing a funicular vault is remarkably fast and effective: it simultaneously finds a funicular form for the vault and the magnitudes of the forces in its various segments. Of the various closely related techniques that make up the repertoire of graphic statics, this is typical. They were adopted by engineers and architects around the world as soon as they were introduced.

### The First Revolution: Rafael Guastavino and Graphic Statics

Beginning in the late 1860s, Rafael Guastavino (1842–1908) designed and constructed a number of large industrial buildings in Barcelona in which he used traditional Catalan laminated tile vaulting for the floor and roof structures. In 1881 he left Barcelona and emigrated to New York, where he established a company that over the ensuing seven decades created well over one thousand vaulted structures across North America. Many of these were incorporated into buildings by such well-known architects as McKim, Mead, and White, Ralph Adams Cram, Bertram Goodhue, Warren and Wetmore, Ernest Flagg, Cass Gilbert, and Carrère and Hastings. In Manhattan, Guastavino constructed vaults in more than three hundred buildings, including Grant's Tomb (1890), the Cathedral of St. John the Divine (1908–11), Grand Central Station (1909–13), the Ellis Island Immigrant Hall (1917), the Federal Reserve Bank (1923–24), and Riverside Church (1930), to name only a few prominent examples. The Boston Public Library (1887–98) and several Boston-area churches also feature Guastavino vaulting, as well as the state capitol buildings of Minnesota (1895–1903) and Nebraska (1920–32). Guastavino's work can be found in forty-one U.S. states, five Canadian provinces, and nine other countries (fig. 72).[5]

Before Guastavino began his career, masonry vaults and domes—whether European, Middle Eastern, or Catalan—were shaped and proportioned by intuition and tradition and tended to be heavy and wasteful of material. By applying graphic statics to Catalan laminated tile vaulting techniques, Guastavino was able to design and build thin, sleek, economical, scientifically engineered masonry shells (fig. 73). Graphic statics permitted Guastavino to give a funicular shape to each of his vaults. This minimized bending stresses while producing shapes that were generally parabolic or catenary in section rather than circular. Graphic statics also permitted the determination of the minimum permissible thickness for each structure, allowing Guastavino to use only as much material as was absolutely required to support the load with a suitable factor of safety. He was thus able to build vaults that were thin, graceful, and so durable that most survive in excellent condition today. They are typically only 3 inches thick and weigh a fraction of what traditional vaults weigh. Because they were made of fired clay tiles, they are also highly resistant to fire. Furthermore, they were often lower in initial cost than any other spanning method, and given their obvious durability

4 In practice, this dimension would have to be increased somewhat to provide sufficient protective embedment for reinforcing bars, and the vault would have to be stiffened with ribs, folds, or corrugations to help it resist wind loads and unbalanced snow loads.

5 For a comprehensive study of Guastavino's life and work, see George R. Collins, "The Transfer of Thin Masonry Vaulting from Spain to America," *Journal of the Society of Architectural Historians* 27, no. 3 (October 1968): 176–201.

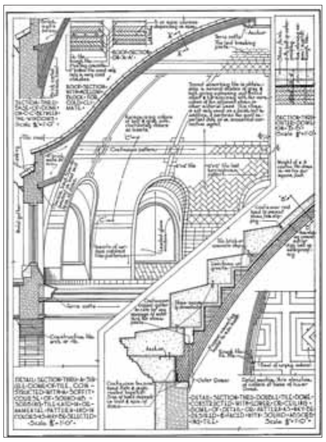


fig. 74

fig. 74: A Guastavino Company detail sheet for a typical Renaissance dome. The total thickness of the structural tiles is 5 to 6 inches, depending on span and load.

fig. 75: Rafael Guastavino (right), inspecting laminated tile arches that will support floor vaults at the Boston Public Library

fig. 76: Laminated tile domes, built without using formwork and supported by the tile arches, beneath the front stairs of the Boston Public Library

fig. 77: Semicircular vault in the Boston Public Library. Because a semicircle is not an ideal shape for a vault, stiffening ribs and transverse stiffening walls were necessary to assure the stability of the vault.

fig. 78: Guastavino tile vaults in the Boston Public Library, finished with decorative tiles and exposed to view


fig. 75

fig. 77


fig. 76


fig. 78

fig. 79: Graphical computation for finding the form of the retaining wall vaults in the Parc Güell, Barcelona. This is one of the few drawings by Antoni Gaudí to survive the Spanish Civil War.

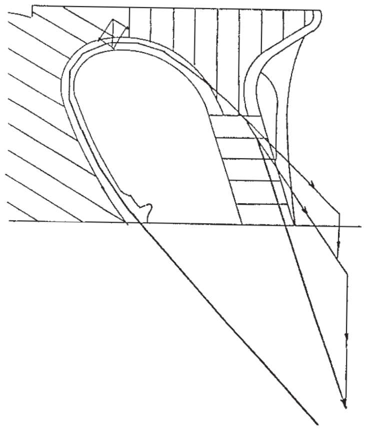


fig. 79

(in a number of recent restorations of Guastavino buildings, few tiles have needed replacement), their life-cycle cost has proved to be extremely low (fig. 74).

The Catalan technique was indispensable to Guastavino because it enabled him to build as thin a vault as his graphical calculations indicated. It also permitted him to build without the expense and delay of having to erect and remove temporary formwork, except for simple forms needed to support planar arches during construction. Guastavino's workers assembled his vaults in midair, starting from the perimeter and working toward the center (figs. 75–8). Wires, strings, and templates were used as guides to produce accurate vault shapes. Guastavino's crews avoided the need for scaffolding by laying tiles "overhand"—standing on the work they had already put in place to gain access to the working edge of the vault. Their standard of workmanship was very high, as can be observed in any of the perfectly formed, highly finished vaults that they constructed.[6]

## After Guastavino: Other Users of Graphic Statics

Guastavino's factory for the Batllo Company in Barcelona, constructed between 1869 and 1875, was visited each year by students from the local architecture school, among them the young Antoni Gaudí (1852–1926),[7] who would soon embark on his lifelong search for a "natural" architecture. Having learned graphic statics from his friend Joan Martorell shortly after graduation, Gaudí used the technique throughout his career to find "natural" (meaning funicular) shapes for the Catalan laminated tile vaults of his roof and floor structures, just as Guastavino did contemporaneously in the United States.[8] But Gaudí went one step further, using graphic statics also to determine the directions of the thrusts that emerged from the bases of his vaults and to align the supporting columns along these lines of thrust. He was thus able to avoid constructing buttresses, which he considered unnatural. The inclined columns that result from this procedure are particularly prominent in his Parc Güell (1900–14), Güell Chapel (1898–1915), and Expiatory Temple of the Sagrada Familia (1884ff) (fig. 79).

It is widely known that Gaudí employed an elaborate hanging string model to find the structural form for his Güell Chapel. However, it is well documented that he, like Guastavino, did most of his structural design by means of graphic statics. He said of the two methods, "The curves of the vaults of the Sagrada Familia were found graphically, and those of the Güell Chapel were arrived at experimentally; however, it turns out that both procedures produce the same result, and that the one is the child of the other."[9]

Gaudí was but one of a large group of gifted architects who worked in and around Barcelona in the late nineteenth and early twentieth centuries, most or all of whom used graphic statics to design their vaulted masonry structures. Among the finest of the structures built by this group are the works of Luis Moya Blanco (1904–1990) and the more than thirty agricultural cooperative buildings by César Martinell Brunet (1888–1973), which adhered closely to the "natural" approach championed by Gaudí.[10]

In using graphic statics, Gaudí and Guastavino placed themselves in the mainstream of the structural engineering practice of their time. Gustave Eiffel (1832–1923) employed as his assistant Maurice Koechlin (1856–1946), who had been Karl Culmann's student at the ETH. Koechlin applied Culmann's graphic statics to find forms and forces for Eiffel's structures. The form of the Eiffel Tower, a symmetrical

6 See Janet Parks and Alan G. Neumann, *The Old World Builds the New: The Guastavino Company and the Technology of the Catalan Vault, 1885–1962* (New York: Columbia University, 1996).

7 Collins, "The Transfer of Thin Tile Vaulting," 191.

8 Joan Bassegoda Nonell, *A Guide to Gaudí* (Barcelona: Edicions de Nou Art Thor, 1989), 8.

9 César Martinell Brunet, *Conversaciones con Gaudí* (Barcelona: Ediciones Punto Fijo, 1969), 39. Translation by the author. For further insights into Gaudí's structural design methods, see Santiago Rubió, *Cálculo funicular del hormigón armado* (Buenos Aires: Ediciones Gustavo Gili, 1952). Rubió's father was Gaudí's structural engineer.

10 See Luis Moya Blanco, *Bóvedas tabicadas* (Madrid: Dirección General de Arquitectura, 1947), and César Martinell Brunet, *Construcciones agrarias en Cataluña* (Barcelona: La Gaya Ciencia, 1976).

fig. 80: Simple graphical construction, used by Gustave Eiffel to find the form of the Eiffel Tower. More complex graphical analyses were used to verify the design for every part of the tower.

fig. 81: Fan-shaped force polygons, used by Robert Maillart to find the pressure lines and internal forces in the arch of the Salgina Bridge for various loading conditions. The tapering arches of the bridge were shaped to contain these pressure lines.

fig. 82: Antoní Bonet, Berlingieri house, Punta Ballena, with vaults by Dieste, 1946–47

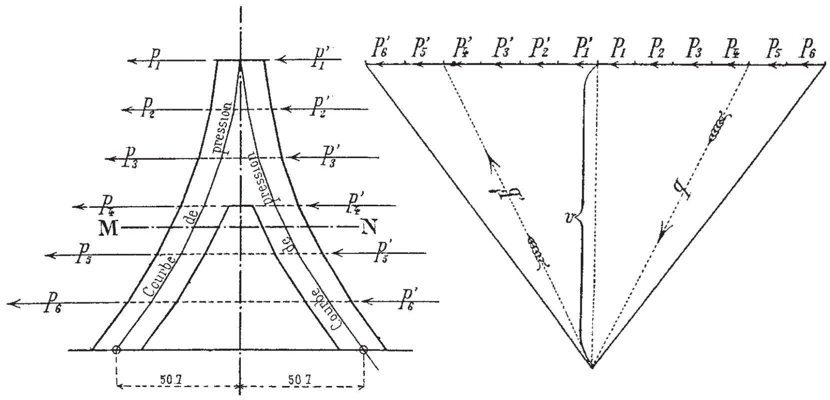



fig. 80

cantilevered truss that is funicular for its assumed wind loading pattern, was found through a simple graphical procedure (fig. 80). Employing this form permitted Eiffel to avoid including major diagonal braces in the bottom two panels of the tower, thus maintaining the open appearance essential to the tower's aesthetic success.[11] His Garabit and Douro River bridges are supported by trussed funicular arches whose boomerang shapes were determined graphically so as to contain the pressure lines for all the loading patterns exerted by moving trains.

Swiss engineer Robert Maillart (1872–1940) learned graphic statics from Culmann's successor at the ETH, Wilhelm Ritter (1847–1906). Maillart used the techniques to shape his concrete bridges along the paths of the forces that they conduct and to find the forces in them (fig. 81).[12] Like the iron and steel arches of Eiffel's bridges, the concrete arches of Maillart's box-arch bridges, such as the Salgina Bridge, are shaped to contain all possible pressure lines. In his deck-stiffened arch bridges, such as the Schwandbach Bridge, the shape of the daringly thin arch was based on a symmetrical loading condition found by graphic statics. Asymmetrical loadings were accommodated by stiffening the deck so that it distributes the loads and restrains the arch from excessive deformations. The resulting forms continue to be admired to this day.

## Eladio Dieste and the Second Revolution in Masonry Vaulting

Eladio Dieste studied graphic statics at the Facultad de Ingeniería de Montevideo, an experience that contributed to the formation of his structural intuition and made him conscious of the economy and beauty that can result from aligning the elements of a structure along lines of force. He also learned numerical methods for engineering calculations, including the theory and practice of designing concrete structures with steel reinforcing, prior to his graduation in 1943.[13]

Brick masonry was the most economical mode of construction in Uruguay, and Dieste chose from the outset to build almost all of his works in this material. At the time, engineers such as Felix Candela (1910–97) and Eduardo Torroja (1899–1961) were enjoying worldwide fame for their sleek shell structures made of reinforced concrete—the favored material of the modern movement. In choosing brick over concrete, Dieste swam against a strong current of fashion, virtually guaranteeing his own obscurity: "I discovered in brick," Dieste wrote,

> a material with unlimited possibilities, almost completely ignored by modern technology, and began to use it structurally....I am convinced that structural brick has the same great possibilities that reinforced concrete has....The fact that this technology leads to the predominance of varied surfaces tends to produce more magnificent, or we could say symphonic, spaces. This contrasts with the rather elemental spaces that contemporary architecture produced in its beginnings.[14]

Dieste's first, tentative steps in this direction were taken just three years out of engineering school, in 1946, with the cylindrical, reinforced brick roof vaults of the Berlingieri house.[15] His powers developed at such a pace thereafter that only a decade later, Dieste was able to design the doubly curved, post-tensioned brick shells and sinusoidal walls of the Church of Christ the Worker in Atlántida (designed 1955–57, constructed 1958–60), which is considered by many to be his greatest architectural achievement.

Antoní Bonet (1913–1989), the architect of the Berlingieri house, proposed to Dieste that he should structure the house in Punta Ballena with vaults of thin tiles, built with-

11 For an example of Eiffel's use of graphic statics, see Gustave Eiffel, *La Tour de trois cents metres* (Paris: Imprimerie Mercier, 1900), 36.

12 David Billington, *Robert Maillart's Bridges: The Art of Engineering* (Princeton, N.J.: Princeton University Press, 1979), 7.

13 Antonio Dieste, note to the author, summer 2000.

14 Eladio Dieste, in Antonio Jiménez Torrecillas, ed., *Eladio Dieste 1943–1996*, trans. Michael Maloy and Harold David Kornegay (Seville: Consejeria de Obras Públicas y Transportes, 1996), 27, 30.

15 For a detailed discussion on this project, see John Ochsendorf's essay on pages 96–97 of this volume.

16 Gonzalo Larrambebere, Dieste's longtime associate, communicated this insight to the author in a conversation that took place at Altzella, near Dresden, Germany, in June 1999. Larrambebere further stated that he did not know why Gauss's name would be related in Dieste's mind to cylindrical

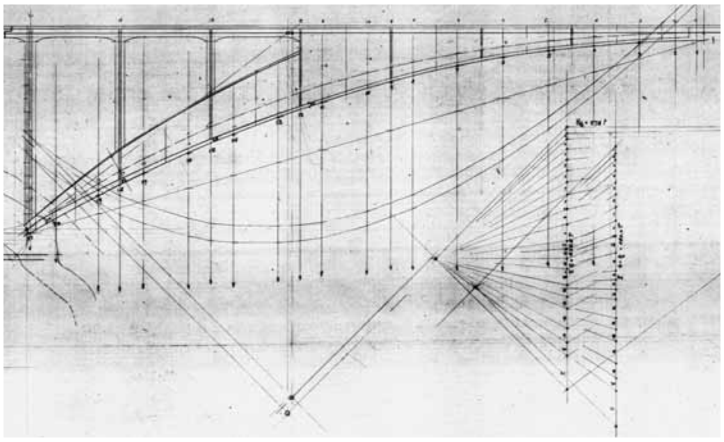


fig. 81

fig. 82

out formwork in the Catalan tradition, much as Guastavino had done. Instead, Dieste chose to build with conventional bricks, using formwork for temporary support during construction (fig. 82). His work differed from that of Guastavino in other important ways, as well. Although Guastavino patented techniques for both reinforcing and post-tensioning, most of his roofs were constructed of unreinforced masonry, whereas Dieste nearly always used steel reinforcing, often in combination with post-tensioning. Guastavino's structures were mostly shaped as traditional vaults and domes, whereas Dieste adopted and improved upon some of the new structural forms that had become popular in the twentieth century. Furthermore, Guastavino did his engineering with graphical methods, and Dieste with numerical methods, which were much better suited to the design of his *cascaras autoportantes* ("self-supporting shells"), which act in bending rather than pure compression.

### Eladio Dieste's Structural Forms

Dieste's building structures fall into four general categories, none of which was feasible in Guastavino's time. His largest industrial roofs, which span up to 180 feet, are essentially shallow barrel vaults that act entirely in compression. For these he coined the name *bóvedas gausas,* which translates literally as "Gaussian vaults"—apparently an admiring reference to Carl Friedrich Gauss (1777–1855), the great mathematician of Göttingen (fig. 83a).[16] Dieste's second building type, his *cascaras autoportantes*, is made up of cylindrical barrel shells (fig. 83b). In their curved direction, these act in compression, just like the *bóvedas gausas*, whereas in their longitudinal axes, they act as beams, deriving bending strength from their shape. The largest spans Dieste achieved with these structures were 43 feet between columns in the curved direction and 108 feet in the longitudinal direction, with longitudinal cantilevers as great as 54 feet. Of the third category, *estructuras plegadas* ("folded structures"), only two examples rank among his major works. One of these—the Church of St. Peter at Durazno (fig. 83c)—is noted proudly by the Dieste office in the list of their works as "technically the highest-ranking work built by our firm."[17] It is composed entirely of planar surfaces that join one another in the same way as the planes of a folded piece of cardboard, and it is from this folding that the structure derives its strength and stiffness. The fourth category of building structures, *superficies regladas* ("ruled surfaces"), is represented by the walls of the Atlántida church; as well as its much later sequel, the Church of San Juan de Ávila, constructed in Alcalá de Henares, near Madrid, in 1996; and the shopping center in Montevideo (fig. 83d).[18] The shapes of these walls were generated by straight line segments whose ends were translated along sinusoidal paths.

vaults. Subsequently, Stanford Anderson called the author's attention to a passage from Mario Salvadori's ***Why Buildings Stand Up: The Strength of Architecture*** (New York: W. W. Norton, 1980), in which Salvadori recognizes Gauss for the "discovery that all the infinitely varied curved surfaces we can ever find in nature or imagine belong to only three categories, which are domelike, cylinderlike, or saddlelike" (188). Domelike curvature is commonly referred to as "synclastic," meaning that at every point on its surface, all curvatures are in the same direction. Saddlelike curvature is "anticlastic," which indicates that at every point, curvatures along mutually perpendicular axes are in opposite directions. Dieste's Gaussian vaults are fundamentally cylindrical in shape. However, in order to remain stable under asymmetrical loading conditions such as drifting snow or strong winds, a cylindrical vault would have to be very thick. Dieste's response is to keep the vault thin and slice it into strips. The cross section of each strip begins at its springings as a straight, horizontal line that soon morphs into an s-shape whose depth increases until it reaches a maximum at the crown of the vault. In the higher portion of each strip, curvature of the masonry surfaces is domelike or synclastic. In the lower portion, it is saddlelike or anticlastic. The net effect is that the strip is stiffened by two different kinds of curvature at any point on its span. Additionally, of course, this shape provides daylight and sheds water to a built-in gutter. Structurally and functionally, it is a clever solution that also looks very elegant and graceful.

17 Jiménez, ed., *Eladio Dieste*, 293.

18 Dieste never used the saddle-shaped hyperbolic paraboloid, the ruled surface that made Felix Candela famous, even though from a technical standpoint he could have done so. Perhaps he disliked its appearance, but it seems more likely that he simply did not find it as useful as other structural forms for the work at hand.

fig. 83: The four primary structural types built by Eladio Dieste:
a) *bóvedas gausas* (Gaussian vaults);
b) *cascares autoportantes* (self-supporting shells);
c) *estructuras plegadas* (folded structures); and
d) *superficies regladas* (ruled surfaces)

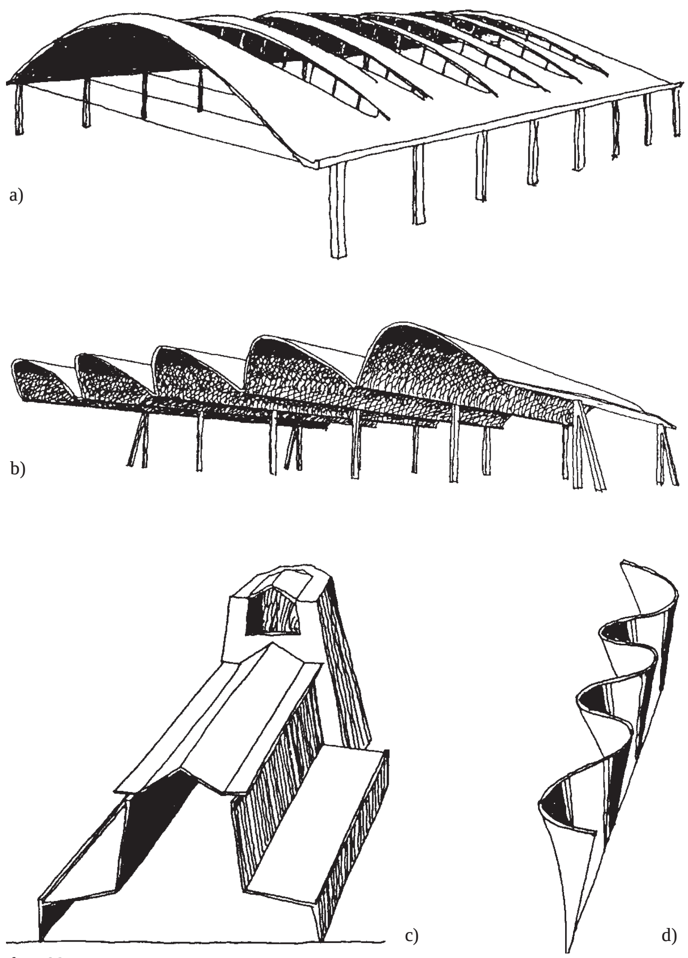


fig. 83

Dieste was not the only designer to work in reinforced masonry during the years immediately following World War II. I. Sanchez del Rio de Pisón designed and constructed many innovative reinforced clay tile structures in Spain.[19] Torroja, a structural engineer like Sanchez and Dieste, built several brick-vaulted churches and water towers.[20] There were others as well who built with reinforced brickwork, but two things set Dieste's work above the rest. One is his unmatched use of masonry in structures subject to bending, such as cantilevered barrel shells, tanks under hydrostatic pressure, and folded plates. The other is the power and poetry of his masonry architecture. Dieste's mind seemed to move effortlessly from the mathematical to the ethereal, from the mechanical to the philosophical. He saw all of his efforts as a seamless whole, never separating the technical concerns from the artistic. Even in his churches, structure, form, and space are one: there are no non-loadbearing elements added (or needed) to sculpt the interior space. One need only compare his Atlántida and Durazno churches to any of the masonry churches designed by the far more famous Torroja to understand that Dieste was an authentic genius, both as an engineer and as an architect.[21]

In Rafael Guastavino's time, the discipline of graphic statics was the most expedient means of finding a theoretically correct form for a vault and for finding the forces within it. By the time Eladio Dieste began his work, graphic statics was

19 See I. Sanchez del Rio de Pisón, *Estructuras "laminares cerámicas"* (Madrid: Río-Cerámica, S.A., 1959).

20 Eduardo Torroja, *The Structures of Eduardo Torroja* (New York: F. W. Dodge, 1958), 168–87.

21 For an insightful comparison of Dieste's and Torroja's masonry churches, see Ochsendorf's essay on pages 97–100 of this volume.

falling gradually into disuse, in part because it was ill-adapted to the new forms of shells that were then being built and because numerical methods of analysis were becoming the norm. But the works of the great engineers and architects of the late nineteenth and early twentieth centuries—including those of Guastavino, Eiffel, Gaudí, and Maillart—were all structures that worked in pure compression and were all designed through graphic statics. These provided the foundation of theory and experience upon which Dieste's generation of designers would develop their unprecedented structures.

The author wishes to thank Janet Parks and Jim Epstein of the Guastavino Archive, Avery Architectural Library, Columbia University; Professor Joan Bassegoda i Nonell of the Gaudí Archive, Barcelona; Christiane Crasemann Collins; Aaron Schmidt of the Print Department, Boston Public Library; Professor Stanford Anderson of MIT; all the members of the Dieste y Montañez office in Montevideo, Uruguay; Professor María E. Yuguero; Amanda Miller; Timothy Becker; and Waclaw Zalewski.

fig. 84

## TEM FACTORY

*Montevideo*, 1960–62

The TEM factory provides a classic example of one of Dieste's two basic vault types: the Gaussian, or double-curvature, vault. As early as 1955, Dieste built discontinuous vaults that provide clerestory lighting between the vaults, but they were heavy and not of a very great span. At 140 feet, the TEM factory became the first of Dieste's Gaussian structures with a truly breathtaking span. In the cross section of such a construction, the arc of the vault is a catenary and thus, under dead load, generates only compressive forces. At longer spans, however, and particularly where the rise of the vault is shallow, the vault becomes subject to buckling and collapse. In the longitudinal section of the building, at the crown of the vaults, Dieste developed an S-shaped undulation that increased the moment of inertia with little increase in weight. The vault being level at its springing also simplifies support conditions and drainage.
In 1975, the factory suffered a catastrophic fire, with gas explosions and extremely intense heat. Two of the vaults collapsed and pulled down a large piece of a third. Dieste spoke of this with pride, as the partially destroyed vault retained its integrity and was easily repaired.

*Architects: Studio Clerk and Guerra*

fig. 85

fig. 84: Interior view showing windows between vaults and lining the side and end walls of the building

fig. 85: Rooftop view of discontinuous double-curvature vaults

fig. 86

## CEASA PRODUCE MARKET

*Porto Alegre, Brazil*, 1969–72

This vast project, built for the Centro de Abastecimiento, S.A., includes a central 150- by 900-foot “Growers’ Pavilion” of long-span double-curvature vaults with side wings serving as broad edge beams to resist the lateral thrust. The nearby “Traders’ Pavilions” employ a large array of simple self-carrying vaults, and a vehicular entrance portico is constructed with double-cantilever self-carrying vaults.

Self-carrying vaults are catenaries in their transverse section. As single curvature-vaults, the transverse spans are small. Adjoining vaults create valleys that jointly resolve lateral thrusts. Dieste was ingenious in solving the lateral thrusts at the end of such a series of vaults, notably with pre-stressed masonry edge beams cantilevered from the vault and carried by the same support or supports as the vault itself. Long spans are achieved in the longitudinal direction of the vault through the performance of the entire vault as a beam that, for the same reason, can be an extensive cantilever. Acting as a beam introduces tensile bending stresses that are resolved by pre-stressing.

Dieste expressed special satisfaction in collaborating with the architects of the Growers’ Pavilion, whose work can be seen, for example, in the variation of the vaults at both ends of the series.

*Architects: Carlos Maximiliano Fayet and Claudio Araujo*

fig. 87

fig. 86: View of the Growers' Pavilion, from the northwest

fig. 87: Aerial view of the CEASA complex, which employs both self-supporting and Gaussian vault types

fig. 88: Growers' Pavilion, partial longitudinal section, at northern end

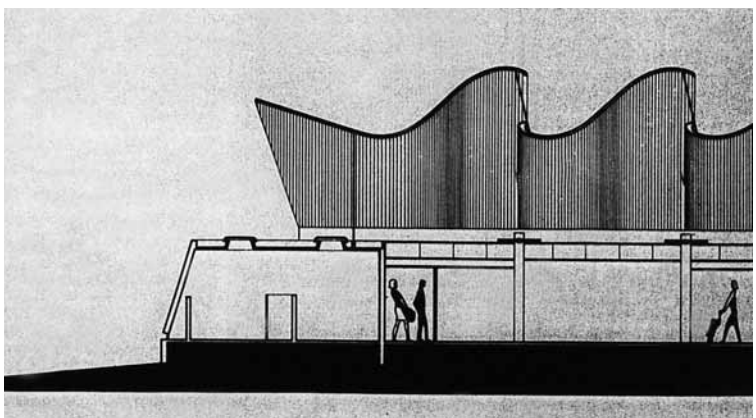


fig. 88

fig. 89

# CÍTRICOS CAPUTTO FRUIT PACKING PLANT

*Salto*, 1971–72, 1986–87

The principal space of this packing plant is a series of large discontinuous double-curvature vaults spanning approximately 150 feet. The illustrations of this work show well the light qualities of this vaulting system: the effective and pleasing lighting of the vaults seen in both directions, and the diffusion but also vivacity of light throughout the space.

The later dates of the project correspond to the construction of a cold storage facility with a continuous double-curvature vault. A characteristic Dieste water tower with a perforated shaft was also built nearby.

fig. 90

fig. 89: Transverse view, showing the array of lighting conditions
fig. 90: General view of the complex with the principal space of discontinuous double-curvature vaults in the distance
fig. 91: Work space during the off-season, lit by diffused and concentrated light

fig. 91

fig. 92

fig. 93

fig. 92: Impression of an almost-continuous light source, created by the curvature of the discontinuous vaults

fig. 93: Detail of vaults

fig. 94: Detail of vaults and windows

overleaf

fig. 95: Varied color and texture of the ceramic units under the play of light

fig.94

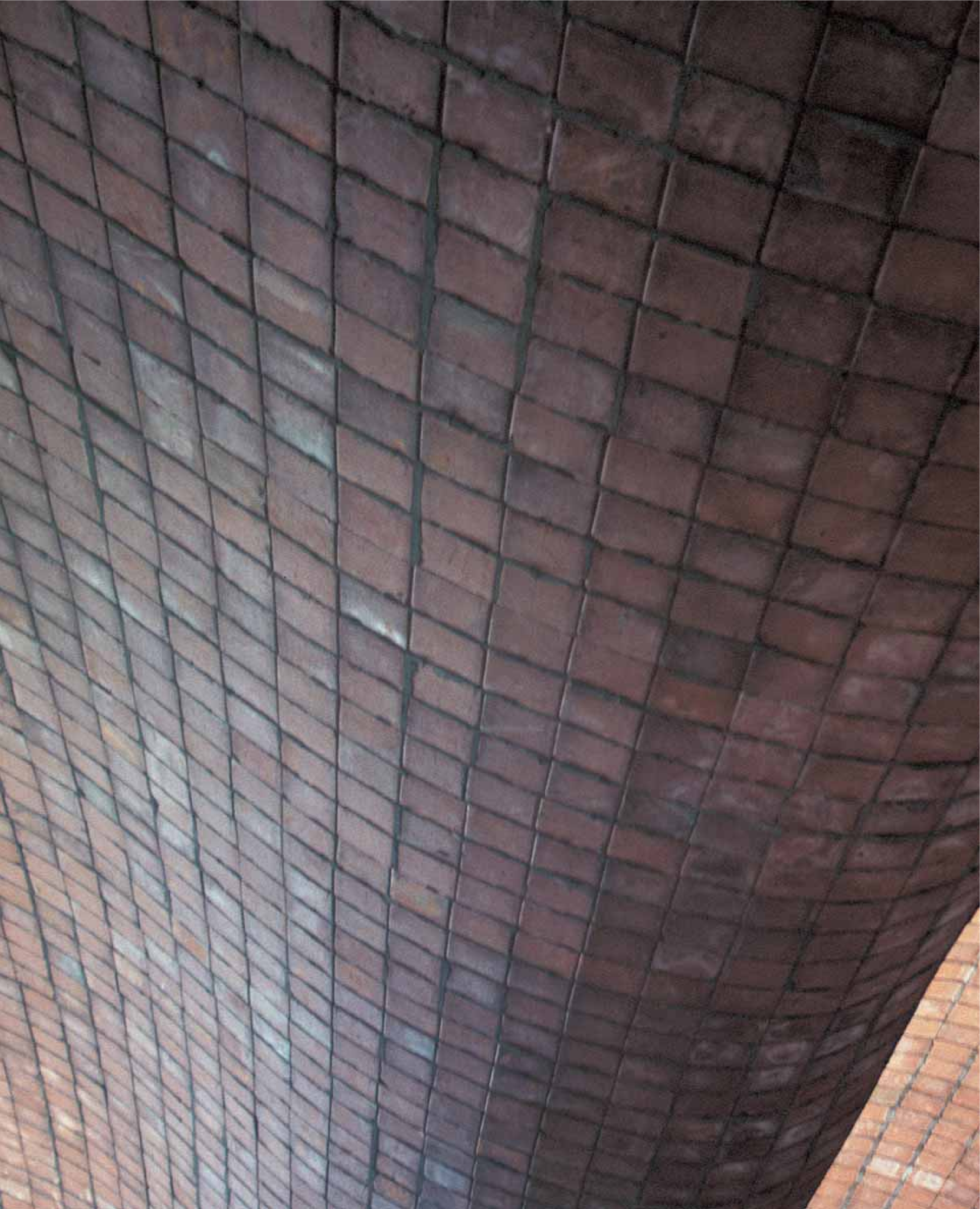


fig. 96

# LANAS TRINIDAD WOOL INDUSTRIAL COMPLEX

*Trinidad*, 1965, 1979, 1986–87, 1988–89

This complex was built in four stages using self-carrying vaults, such as appeared at a small scale at the Dieste house in 1961. Illustrated here is the third stage of Lanas Trinidad, with bays of 26 by 131 feet. The vaults are stable without beams or tympana; consequently, the structure is very light for such a long span, and good lighting is achieved through change in the height of the vaults.

*Architects: Lorieto and Queirolo*

fig. 96: General interior view of the self-carrying vaults. At the right, the flat edge-beam and the column of altered shape receive the lateral thrust that elsewhere is balanced by adjoining vaults.

fig. 97: Drawing containing plan of reinforcing for one group of eight bays plus edge beams, transverse sections, and structural details of the edge beam and valleys

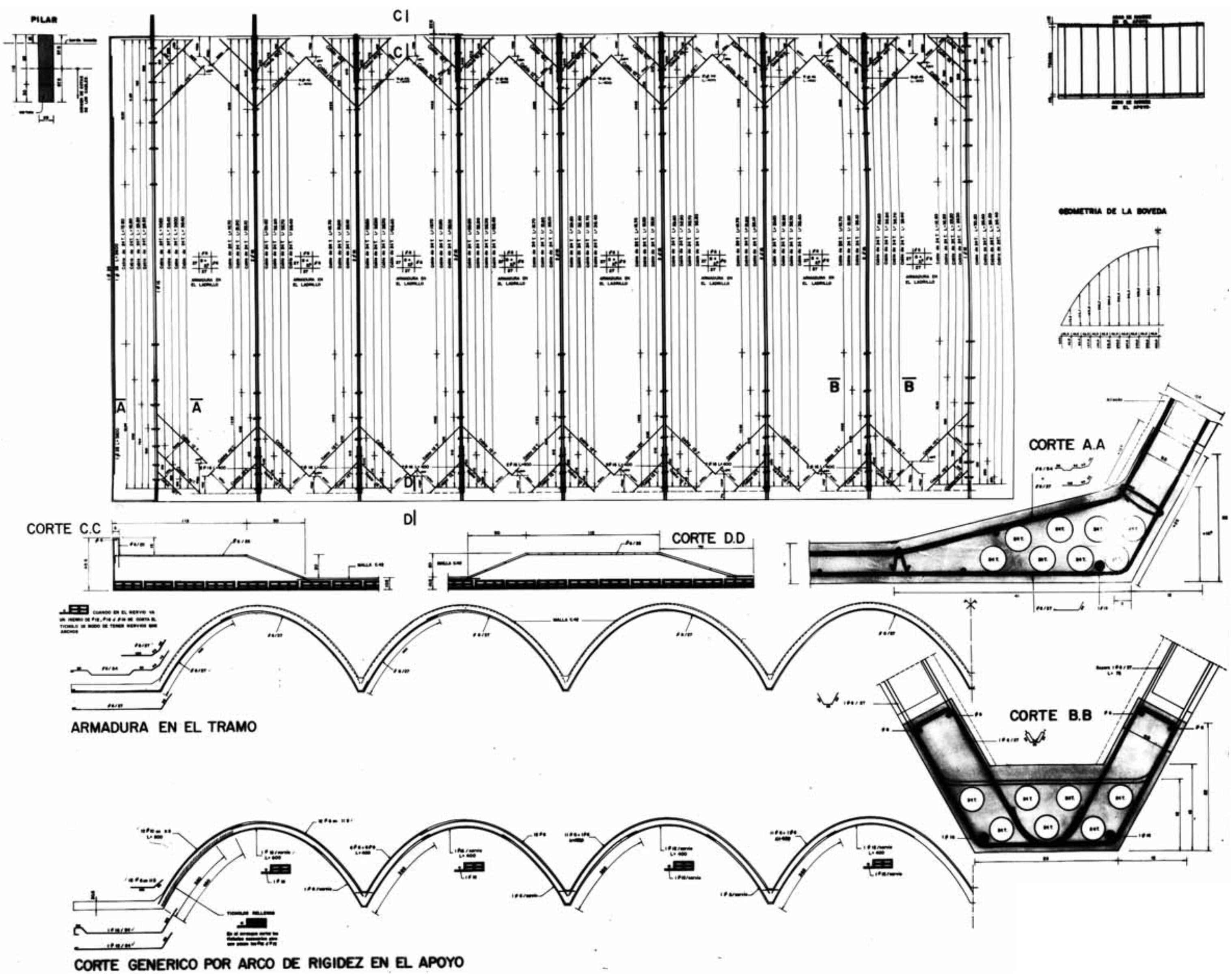



fig. 97

fig. 98

# RIO METRO MAINTENANCE HANGAR

*Rio de Janeiro*, 1971–79

Subway trains are brought to this 560,000-square-foot facility for maintenance and repair. The structural system employs self-carrying vaults and gains natural light through both alternating heights and penetrations in the vaults. The engineering was done in the Montevideo office and construction was overseen by Dieste's partner, Eugenio Montañez, in Brazil.

fig. 99

fig. 98: Self-carrying vaults, extending in both directions without loss of natural light

fig. 99: Subway train, sheltered by cantilevered self-carrying vaults


fig. 100

# MUNICIPAL BUS TERMINAL

*Salto*, 1973–74

Supported by a single row of columns are long self-carrying vaults with equal cantilevers of 40 feet. Such cantilever vaults are ideal for sheltering (as opposed to enclosing) structures and thus are perfect for bus stations. At the lateral outer edge of the vaults, Dieste sought a more gradual and spatial termination in consideration of people's passage through the space. He did not adopt his most structurally efficient solution of a tapered edge beam but rather an edge slab, the outer half of which is carried by a thin, cantilevering concrete beam, separated from the central concrete outrigger by steel pins.

*Collaborator: Architect Nestor Minutti*

fig. 100: General view of the bus terminal, with its double-cantilevered self-carrying vaults

fig. 101: The sheltering character of the vaults

fig. 101

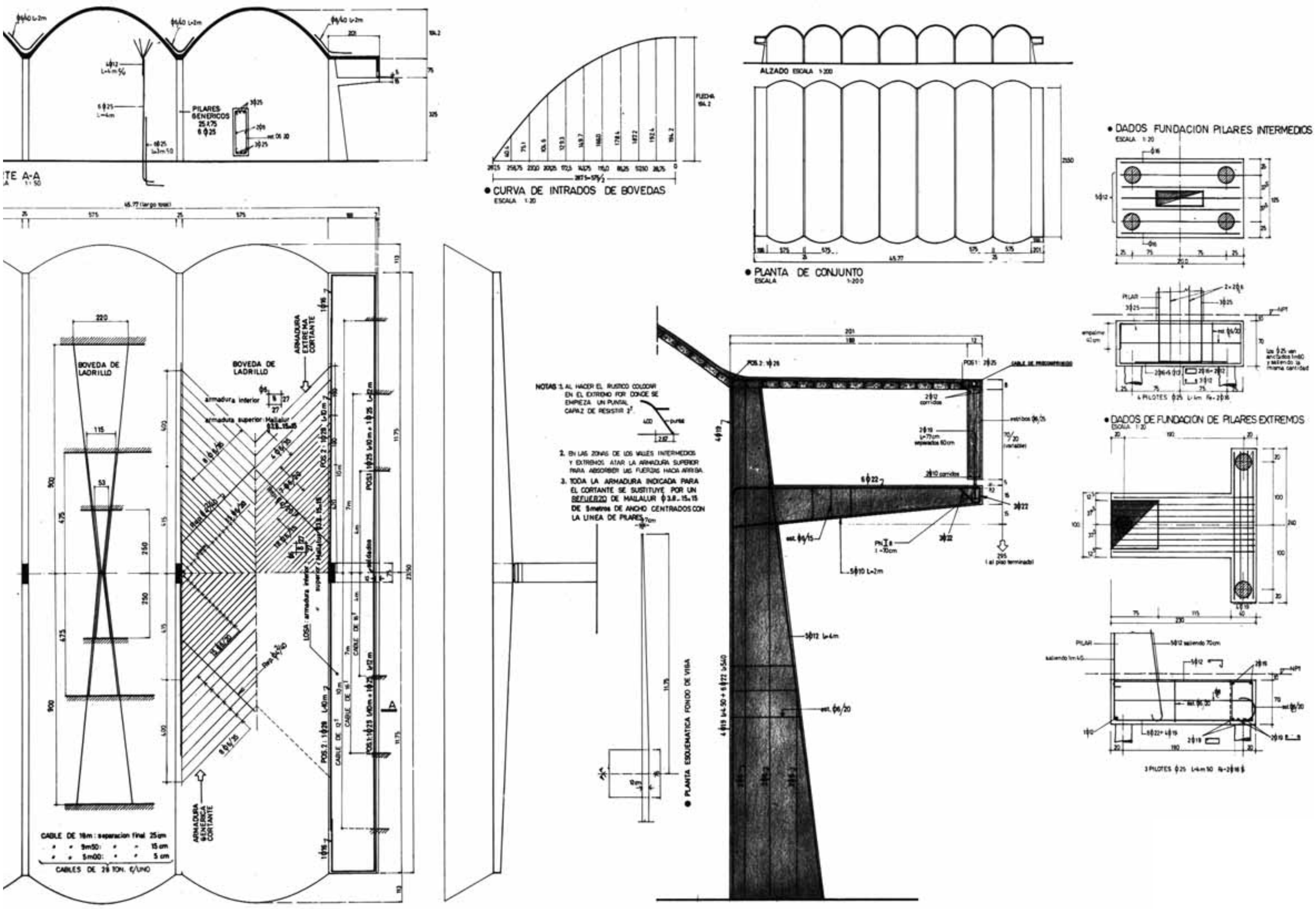



fig. 102

fig. 103

fig. 104

fig. 102: Partial plan, sections, and details showing reinforcing and pre-stressing steel. At upper right, plan and elevation

fig. 103: General view from the south

fig. 104: Special edge condition at the west

fig. 105: Rafael Guastavino, Jr., patent for reinforced ceramics illustrating metal reinforcing near the base and crown of the dome, 1910
fig. 106: Influence of curvature in membranes: a) with curvature, and b) without curvature

## ELADIO DIESTE AS STRUCTURAL ARTIST

*John A. Ochsendorf*

The discipline of structural engineering encompasses the design of structures that are efficient in their use of materials and economical in their methods of construction. In addition to the constraints of efficiency and economy, the best engineers seek to create forms that are elegant in their appearance. In his book *The Tower and the Bridge*, the structural engineering historian David Billington argues convincingly that the leaders in this field of design are "structural artists," who develop works of art through their pursuit of efficiency, economy, and elegance in construction.[1]

Among the most admired structural artists are John A. Roebling (1806–1869), for his masterful long-span suspension bridges; Gustave Eiffel (1832–1923), for his elegant structures in iron; and Robert Maillart (1872–1940), for his pioneering forms in reinforced concrete. These designers succeeded primarily because they produced structures at a significantly lower cost than their competitors. Technically, they were working at the forefront of the profession, and they produced unprecedented works with minimum materials. Yet they were deeply concerned about the appearance of their designs and pursued clear structural expression as a guiding aesthetic principle. The constraints of economy led each to develop new forms, which are striking for their originality. As artists, they criticized and refined their own works, developing clear personal styles.

To create works of structural art, the designer must know the construction process intimately. Roebling, Eiffel, and Maillart were responsible for their own companies, and they were often present on the construction sites of their projects. These designers produced structures at low cost because they mastered the construction process through years of experience in the field and sought suitable methods for dealing with local circumstances. Furthermore, each concentrated on one specific material and extended that material to impressive new applications by developing new methods of design and construction. For structural artists, the process of design is never disconnected from the process of construction.

Many leading structural artists began by constructing their works outside of the mainstream: Roebling, in the midwestern United States; Eiffel, in rural France; and Maillart, in remote regions of Switzerland. Initially, their works were noteworthy only for their novelty, and the structures were not recognized for their aesthetic appeal. Widespread artistic recognition of these designers was not forthcoming in their lifetimes. Structural artists challenge the limits of design and construction and often fight a solitary battle to construct their unconventional works outside of the established methods.

Eladio Dieste (1917–2000) belongs to this pantheon of great structural artists. Just as Roebling pioneered with wire cable, Eiffel with iron, and Maillart with reinforced concrete, Dieste led the way in developing economical, efficient, and elegant structures in reinforced brick. Like his predecessors, he owned his own construction company and received commissions primarily because he proposed the least expensive option. Dieste's detailed technical knowledge and extensive experience enabled him to extend vaulting in reinforced brick to a new scale. As with Roebling, Eiffel, and Maillart, he did not receive the recognition of critics for the aesthetic power of his work until very late in life.

1 David P. Billington, *The Tower and the Bridge: The New Art of Structural Engineering* (Princeton, N.J.: Princeton University Press, 1985).

2 Eladio Dieste, interview by Damián Bayón and Paolo Gasparini, *The Changing Shape of Latin American Architecture: Conversations with Ten Leading Architects* (New York: John Wiley, 1979), 210–11.

3 Ibid., 209–10.

4 The engineer Marc Isambard Brunel (1769–1849) constructed with reinforced brick in England in the early nineteenth century. See Tom F. Peters, *Building the Nineteenth Century* (Cambridge, Mass.: MIT Press, 1996), 66–70. Joseph Eugène Anatole de Baudot (1834–1915) promoted reinforced masonry as a material of choice for architects in France during the late nineteenth century. See Kenneth Frampton, *Studies in Tectonic Culture* (Cambridge, Mass.: MIT Press, 1995), 54–57.

5 For vaulting in France, see Turpin C. Bannister, "The Roussillon Vault:

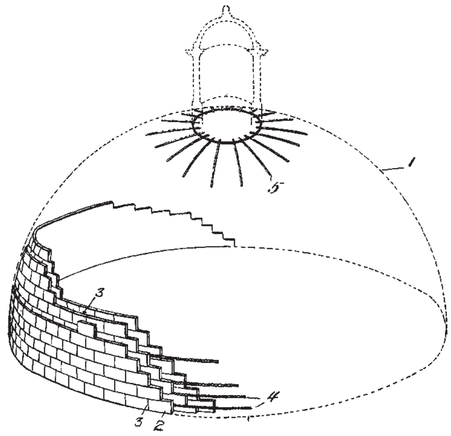


fig. 105

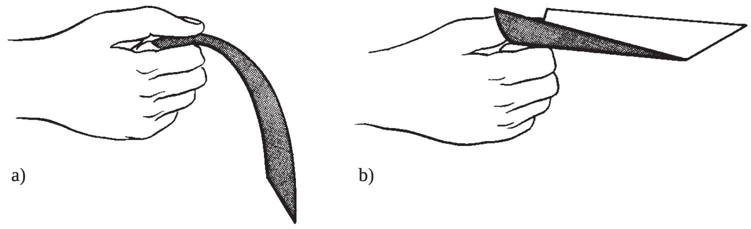



fig. 106

Dieste designed according to the ideals of structural art, taking "jointly into account" the validity and efficiency from the structural point of view, the efficiency from the economic point of view, the efficiency in the conditioning of the spaces enclosed, and the aesthetic value, which for me, really, is a sort of ultimate summary, the ultimate synthetical value judgment of all this series of factors.[2]

He was deeply critical of his own designs. In his concern for aesthetic values he searched for structural honesty, maintaining that "one thing that the spirit perceives about a form is the adequate or inadequate way in which it bears a load. In other words, the spirit is deeply sensitive to the fact of knowing if a form is completely successful from the structural point of view."[3] Like the best engineers, he sought elegant forms that expressed their structural function. By tracing the development of Dieste's career and examining his works alongside the designs of other leading structural artists, the accomplishments of this underappreciated figure will hopefully claim their rightful place in the context of engineering history.

### The Development of Thin Shell Structures in Reinforced Brick

Dieste's formation as a designer is directly linked to his use of reinforced brick as a structural system. Thus, it is worthwhile to trace the development of this system. Beginning in the nineteenth century, architects and engineers experimented with the concept of reinforced brick as a building material.[4] In the twentieth century, lightly reinforced brick shells were inspired by timbrel vaulting, a common building method in the Mediterranean.[5] Rafael Guastavino (1842–1908), upon emigrating to the United States from Catalonia in 1881, introduced the method with great success.[6] His son, Rafael Guastavino, Jr. (1872–1950), continued constructing vaults well into the twentieth century, and he appears to be the first to have introduced steel reinforcing to thin brick shells. In two patents, issued in 1910 and 1913, Guastavino, Jr. documented this system, which is a precursor to the thin shells of reinforced concrete developed widely in the ensuing decades (fig. 105).[7]

Two leading engineers explored methods of constructing thin shells in reinforced brick: Eduardo Torroja (1899–1961) in Spain and Eladio Dieste in Uruguay. Thin brick timbrel vaults of the type constructed by Guastavino played a role in the development of both engineers' work.

The leading figure in the Spanish school of thin shell vaulting, Torroja is most famous for demonstrating new possibilities in reinforced concrete.[8] Yet he also recognized bricks as "adequate materials for shell structures, slabs, and membranes."[9] He introduced steel reinforcing in the traditional timbrel vault,[10] designing reinforced brick shells as early as 1926. Openly acknowledging the influence of Catalan vaulting on his methods, Torroja wrote,

The Apotheosis of a 'Folk Construction,'" *Journal of the Society of Architectural Historians* 27, no. 3 (1968): 163–75. For Spanish vaulting, see Fray Lorenzo de San Nicolás, *Arte y uso de arquitectura*, 2 vols. (Madrid: Albatros, 1989), and Santiago Huerta, "The Mechanics of Timbrel Vaults: A Historical Outline," in *Between Mathematics and Architecture*, ed. Antonio Becchi et al. (Basel: Birkhäuser, 2003). The term *bóveda tabicada*, or "timbrel vault," is used in Spain, though the method is often called "Catalan vaulting" as well. See also Timothy P. Becker and Kent Anderson's essay on pages 202–07 of this volume.

6 George R. Collins, "The Transfer of Thin Masonry Vaulting from Spain to America," *Journal of the Society of Architectural Historians* 27, no. 3 (October 1968): 176–201. See also Janet Parks and Alan G. Neumann, eds., *The Old World Builds the New: The Guastavino Company and the Technology of the Catalan Vault, 1885–1962*, exhib. cat. (New York: Columbia University, Avery Architectural Library and the Miriam and Ira D. Wallach Art Gallery, 1996); Santiago Huerta, ed., *Las bóvedas de Guastavino en América*, exhib. cat. (Madrid: Instituto Juan de Herrera, 2001). In his *Essay on the Theory and History of Cohesive Construction, Applied Especially to the Timbrel Vault*, Rafael Guastavino preferred the terms "timbrel vault," or "cohesive construction," to "Catalan vault." (Boston: Ticknor, 1893). See also Edward Allen's essay on pages 66–75 of this volume.

7 United States Patents 947,177 and 1,052,142 were published along with Guastavino's other patents in the *APT Bulletin: The Journal of Preservation Technology*, special issue, *Preserving Historic Guastavino Tile Ceilings, Domes, and Vaults* 30, no. 4 (1999): 59–156.

8 For a survey of the work of Eduardo Torroja, see the engineer's *The Structures of Eduardo Torroja*, 2nd ed. (Madrid: CEDEX, 2000), and José

fig. 107: Antoní Bonet, Berlingieri house, Punta Ballena, 1946-47
fig. 108: Eladio Dieste, vault solution for the Berlingieri house
fig. 109: Eduardo Torroja, Church of Pont du Suert, Spain, 1955

fig. 107

> The Catalonian brick vault is as typical of the region as the carob tree in its fields and just as marvelous. Modern theory finds it difficult to explain and measure the phenomenon of its resistance, and the builders who showed their genius in understanding [brick vaults] are dead and buried beneath the clay which they used to make the brick centuries ago.[11]

The resistance of thin brick vaulting comes from the form of the vaulting, as the art historian George Collins described in his landmark discussion of Guastavino's construction methods. By creating curvature in the vault, a thin surface can resist forces as a membrane and will have a much higher resistance to loads than a thin surface without curvature.[12] This can be illustrated by comparing the stiffness of a piece of paper with curvature to a piece of paper without curvature (fig. 106). As Dieste said in relation to thin shells,

> The resistant virtues of the structures that we are searching for depend on their form. It is because of their form that they are stable, not because of an awkward accumulation of matter....there is nothing more noble and elegant from an intellectual viewpoint than resistance through form.[13]

Thus, the curved piece of paper develops load capacity due to the form of the structure.

Dieste's link to timbrel vaulting is more tenuous and can be traced to the interest shown by modernists in traditional Catalan vaulting. At approximately the same time that Torroja began building shells in reinforced brick, modernist masters Le Corbusier (1887–1965) and Josep Lluis Sert (1902–1983) became interested in tile vaulting, largely through their exposure to the works of Antoni Gaudí (1852–1926). The young Catalan architect Antoní Bonet (1913–1989), who collaborated with Le Corbusier and Sert in the 1930s, brought with him a knowledge of timbrel vaulting methods when he emigrated to Argentina during the Spanish Civil War (1936–39). Bonet met Dieste in 1946, and Dieste's development is due in part to Bonet's earlier experience with timbrel vaulting in Catalonia.[14]

In 1946, Bonet designed the Berlingieri house at the resort of Punta Ballena in Uruguay (fig. 107). While seeking local assistance on a structural problem posed by the barrel vaulting for the house, Bonet met the young engineer Dieste, and their collaboration on this project led to Dieste's first application of reinforced brick.[15] According to the German historian of construction Jos Tomlow, Dieste rejected Bonet's initial concept of a barrel vault with a reinforced concrete roof because the form was poor and overly expensive. He suggested instead a wooden roof with tiles as a more rational solution, but Bonet disliked this idea. Dieste then suggested that the roof be vaulted in brick, and both agreed to pursue this option. Dieste suggested that thin barrel vaults of brick be reinforced so as to function as shell structures. Bonet described the Catalan vault to Dieste, who knew nothing of timbrel vaulting at this point, and both agreed to proceed.

Dieste described his final solution of reinforced brick vaults in his 1947 article "Bóveda nervada de ladrillos 'de espejo.'" [16] It is significant that in this first project he chose to construct the vaults in a catenary form, so that the vault would function in pure compression under the vertical load of its own weight.[17] Dieste was clearly thinking in terms of structural, rather than geometrical, forms; this choice of form allowed him to achieve a remarkable thinness of only 2 inches over a span of 20 feet (fig. 108).[18] A geometrical form, such as a cylindrical barrel vault, would have required much more material and was therefore unsatisfactory to Dieste.

Antonio Fernández Ordóñez, *Eduardo Torroja* (Madrid: Ediciones Pronaos, 1999). See also Billington, *The Tower and the Bridge*, 183–93.

9 Fernández, *Eduardo Torroja*, 30.

10 John Ochsendorf and Joaquín Antuña, "Eduardo Torroja and *cerámica armada*," in *Proceedings of the First International Congress on Construction History*, ed. Santiago Huerta (Madrid: Instituto Juan de Herrera, 2003), III: 1527–36. See also José María Cabeza Lainez and José Manuel Almodóvar Melendo, "Las bóvedas de cerámica armada en la obra de Eladio Dieste," in *Actas del tercero Congreso Nacional de Historia de la Construcción*, ed. Amparo Graciani Garcia (Madrid: Instituto Juan de Herrera, 2000), I: 135–42.

11 Torroja, *Structures of Eduardo Torroja*, 30. The great virtue of timbrel vaulting is that it can be built with no supporting formwork.

12 Collins, "Transfer of Thin Masonry Vaulting," 176. See Huerta, "The Mechanics of Timbrel Vaults," for an excellent discussion of the structural

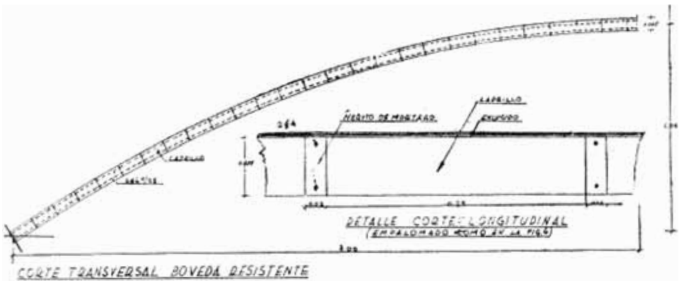


fig. 108


fig. 109

Significantly, the exterior view of the completed Berlingieri house does not express the thinness of the structural vault. Bonet's design called for an insulating space and an additional layer of roof tiles on top of the thin vault, resulting in a heavy appearance for the completed roof that obscures Dieste's elegant structural solution. For Dieste, expressing the thin structure was a priority in almost all of his later work. The Berlingieri house is a work of architectural art but not of structural art, and this illustrates the difference in aesthetic priorities between the engineer Dieste and the architect Bonet. Like other structural artists, Dieste preferred to expose the structure as an important aesthetic aim in construction, as may be seen in the exposed vault detail at the north elevation of his own house.

With the Berlingieri house, Dieste invented *cerámica armada* in South America. He went on to build shells of unprecedented scale in reinforced brick. Although Bonet described the project as a rebirth of Catalan vaulting, Dieste distanced his system from that of unreinforced brick vaulting.[19] Dieste worked in the tradition of the structural engineer to create his thin shells in brick, using steel reinforcement to carry tensile stresses rather than in the ancient tradition of unreinforced timbrel vaulting, which creates shells whose forces act only in compression. The origin of Dieste's work is more closely linked to thin shell concrete construction, known to him from his studies in civil engineering and his earlier design experience.[20]

Though few other South American engineers pursued reinforced brick as a structural material, Torroja applied it throughout his career. The ideas of Dieste and Torroja were strikingly similar. Both sought out inexpensive methods of construction to create elegant structural forms. Their efforts would culminate in the 1950s in the design and construction of small parish churches employing innovative structural systems and similar construction methods. Remarkably, Torroja was nearing the end of his career, while Dieste was entering the early stages of his.

### Torroja and Dieste: Structural Forms in Church Design

Although best known for his designs in reinforced concrete, Torroja built elegant structures in reinforced brick.[21] The construction of thin concrete shells requires the use of extensive formwork, which is costly to build, so Torroja employed reinforced brick as an economical alternative. Asked to design a church for the small town of Pont du Suert in the Pyrénées, he produced a unique structure in reinforced brick that incorporated double-curved surfaces (fig. 109).[22] By repeating the curving form and leaning one against the other, the surfaces serve as both walls and roof of the church. An affinity between this work and that of Dieste, as demonstrated in his

behavior of unreinforced timbrel vaults, which must act in pure compression. Shells reinforced with steel are capable of resisting tension and can act as a membrane. The membrane theory, which assumes that the shell has no resistance to bending, can demonstrate the resistance of a curved shell by finding a pattern of membrane forces that are in equilibrium with the applied loads.

13 Eladio Dieste, "Architecture and Construction," 187 of this volume. Originally published as "Arquitectura y construcción," in "Eladio Dieste, el Maestro del ladrillo," sp. no. *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 84–93.

14 Jos Tomlow, "La bóveda tabicada y el nacimiento de la cerámica armada," in Huerta, ed., *Las bóvedas de Guastavino*, 241–51.

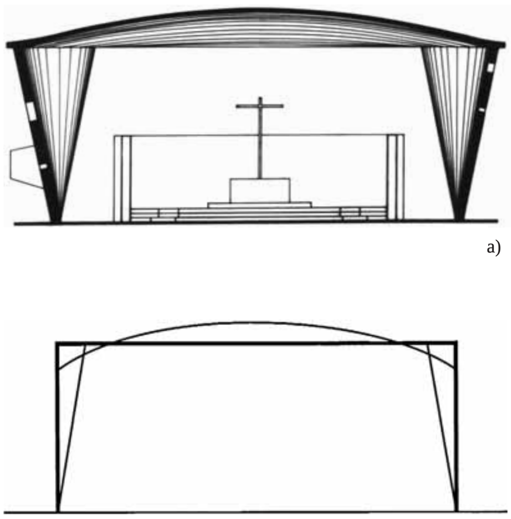
15 Ibid., 244–45.

16 Eladio Dieste, "Bóveda nervada de ladrillos 'de espejo,'" *Revista de Ingeniería* [Montevideo] 473 (Sept. 1947): 510–12.

17 A catenary is the shape taken by a cable hanging under its own weight. If this hanging cable is frozen and inverted, it gives the shape of an arch acting in pure compression. The English scientist Robert Hooke (1635–1703) proposed this idea in 1675: "As hangs the flexible line, so but inverted, will stand the rigid arch." For the source of this quotation, see Jacques Heyman, *Structural Analysis: A Historical Approach* (Cambridge: Cambridge University Press, 1998), 79.

18 The vault was constructed of a thickness of only one brick (about 2 inches). It has a rise of one sixth of the span (approximately 3 feet). The thrust of the vault is resisted by steel ties spaced every 10 feet, so that the resultant load on the walls is purely vertical. See Tomlow, "La bóveda tabicada," and Dieste, "Bóveda nervada," for more complete descriptions of the system.

fig. 110



a)

b)

fig. 111

fig. 110: Eladio Dieste, Church of Christ the Worker, Atlántida, 1958–60
fig. 111: Church of Christ the Worker: a) transverse section, and b) moment diagram of a pinned frame due to self-weight

Church of Christ the Worker in Atlántida, is readily apparent. Intriguingly, Torroja designed the church—and a second, which similarly relies on reinforced brick—immediately upon his return from a tour of South America in early 1952, over twenty-five years after he first experimented with reinforced brick shell construction.[23]

As Torroja designed the church of Pont du Suert, Dieste began work on the church in Atlántida. Like Torroja, Dieste's thinking as a structural engineer governed his architectural concepts, and in his search for economy he created a new form. After years of study, Dieste completed the famed church in 1960 (fig. 110).

The walls of the church were built in reinforced brick without formwork by using an undulating surface to provide lateral stiffness. The walls begin in two parallel lines and rise upward in a ruled surface, following a series of parabolas in plan. The walls are topped with an edge beam in reinforced concrete that helps to transfer the load from the roof. The roof is made of a series of repeating brick vaults that contain steel reinforcement to reduce the thrust on the walls. The transverse section follows the moment diagram for a pin-supported portal frame under its own weight and therefore provides for an efficient use of material (fig. 111).[24] Derived from purely structural considerations, this innovative solution clearly demonstrates the thinking of a structural artist.

Dieste's church in Atlántida shares a number of similarities with Torroja's church in Pont du Suert. Both were constructed of thin shells of reinforced brick with the goal of producing a low-cost parish church in a structural form. Both churches use curving lateral walls to increase the structural stiffness and reduce the amount of material required. In addition, both engineers designed a separate bell tower in reinforced masonry. The overall projects have the same scale.[25] Finally, both churches incorporate sections of glass inserted in the brick to admit natural lighting. Significant differences exist between the works as well. In Torroja's church, the walls curve inward to become the roof, while in the Atlántida church the roof vaults and walls are visually separated. Unlike Torroja's freestanding construction method,

Dieste's method required formwork to create the roof vaults of his church. While Torroja hides the construction method by covering the brick with plaster on the inside and stone on the outside, Dieste leaves the brick exposed. Overall, Dieste worked under much stricter economical constraints, and he produced a more innovative structure as a result.[26]

As a work of structure, Dieste's Atlántida church is superior to Torroja's Pont du Suert church. Dieste's work cost less, used less material, and is more visually striking in its final form. In particular, Dieste illustrated the structural efficiency of a thin membrane by exposing the edges of the brick shell. This expression of edge thinness is a characteristic of structural art in reinforced concrete shells by Maillart, Felix Candela (1910–1997), Heinz Isler (b. 1926), and other masters.[27] Torroja's church at Pont du Suert is not as expressive, and his structure is more of a curiosity than a work of art.

The structural artist always seeks to express the structural function of the elements as clearly as possible. This is exemplified by comparing the bell towers at Atlántida and Pont du Suert. Torroja's tower narrows at the base, and the tapered form does not express the load-carrying function of the tower. Dieste illustrates the flow of gravity loads in his tower with vertical columns in brick. He explained,

> Coherence between the appearance of the form and the constructed reality is also important. Coherence makes the form intelligible to us. In the Maldonado television tower . . . the horizontal elements were placed in a discontinuous manner. The alternative solution, which was the first that occurred to us, was much simpler. This solution would make a ring from each group of horizontal elements . . . . With much effort, I realized that the rings would divide the surface of the discontinuous shell that was the tower; they would not have been expressively appropriate to the structural unity of the surface.[28]

By emphasizing the vertical load-bearing system in the tower, Dieste reveals the importance of structural expression in his built works. Both solutions would cost approximately the same and would use the same amount of material, but in staggering the horizontal elements Dieste made a conscious aesthetic decision that would better illustrate the flow of forces in the tower. Here Dieste speaks the language of the structural artist: "Form is a language, and this language should be intelligible to us."[29]

From the very beginning of his career, Dieste showed an affinity for structural forms and a desire to express these forms clearly. With the Atlántida church, Dieste began to explore the possibilities of *cerámica armada.* He went on to set new precedents in reinforced brick vaulting. By comparing Dieste's work to pioneering structures in reinforced concrete, the design philosophy of this structural artist can be further illuminated. In particular, the reinforced concrete shells of

19 Tomlow, "La bóveda tabicada," quoting a conversation with Dieste, 247.

20 See ibid., and Remo Pedreschi, *Eladio Dieste* (London: Thomas Telford, 2000), for more on Dieste's education.

21 Torroja, *Structures of Eduardo Torroja*, and Billington, *The Tower and the Bridge*, 183–93.

22 For more on this project, see Fernández, *Eduardo Torroja*, 152–59.

23 Torroja's renewed interest in reinforced brick may have been directly inspired by Dieste. For one month in early 1952, Torroja traveled throughout Argentina, Chile, Peru, and Colombia. While Torroja does not seem to have visited Uruguay or met Dieste personally, there is a strong possibility that he learned of the engineer's early work during his travels. A recent dissertation on Torroja mentions this possibility, although further research will be required to substantiate this claim. See Joaquin Antuña Bernardo, "Las estructuras de edificación de Eduardo Torroja Miret" (Ph.D. diss., Escuela Técnica Superior de Arquitectura, Universidad Politécnica de Madrid, 2002), 191. Torroja experimented with reinforced brick as early as 1925 in the construction of bridge caissons. See John Ochsendorf and Joaquín Antuña, "Eduardo Torroja and *cerámica armada*," in Huerta, ed., *Proceedings*, III: 1527–36.

24 Pedreschi, *Eladio Dieste*, 67.

25 The church in Pont du Suert measures 43 feet by 108 feet in plan, and the church in Atlántida measures approximately 50 feet by 100 feet.

26 Pedreschi, *Eladio Dieste*, 67. Billington notes that greater economical constraints generally lead to greater originality and to better works of structural art. See Billington, *The Tower and the Bridge*, 210–11.

27 Billington, *The Tower and the Bridge*, 190–92.

28 Eladio Dieste, "Awareness of Form," 191–192 of this volume.

fig. 112: Eugène Freyssinet, railway repair shop, Paris, 1927
fig. 113: Eladio Dieste, Cítricos Caputto Plant, Salto, 1971–72
fig. 114: Robert Maillart, Cement Hall, Swiss National Exhibition, Zurich, 1939, under construction
fig. 115: Eladio Dieste, Massaro Agroindustries, Joanicó, Canelones, 1976–80

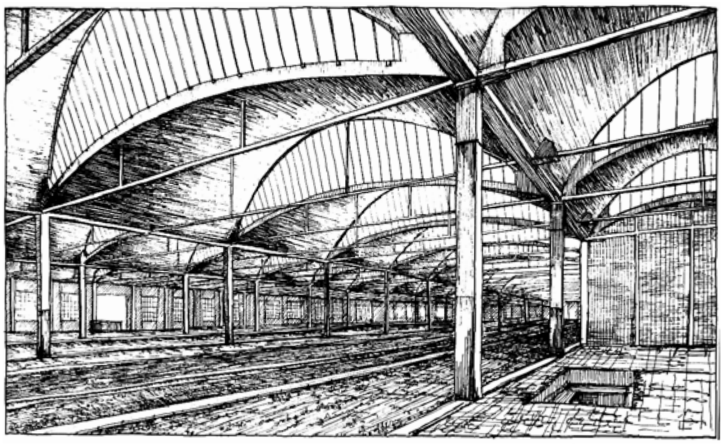


fig. 112

Eugène Freyssinet, Maillart, and Isler illustrate a similar search for new structural forms and provide a context for judging the historical importance of Dieste's work as a structural engineer.

### Freyssinet and Dieste: Thin Shells and Steel Ties

French engineer Eugène Freyssinet (1879–1962) was a master of construction, and he described himself and his people as universal artisans.[30] By becoming a builder, he advanced his goal of creating a society with "an extreme concern for the simplification of forms and economy of means."[31] In the first half of the twentieth century, Freyssinet developed the concept of pre-stressed concrete, his greatest contribution to the construction world. Early in his career, he designed in reinforced concrete and completed two major projects showing new possibilities for thin shell structures. The first work was a pair of large dirigible hangars at Orly in France, which became known around the world upon their completion in 1921. The second work, less well known, was a railway repair shop at Bagneux, near Paris, completed in 1927 (fig. 112). Both works demonstrate an affinity with later shells by Dieste, the latter design being particularly relevant.

For the railway repair shop, Freyssinet used a series of small conoid shells supported on thin columns to create a large space, open in feeling. The thrust of the vaults is resisted by a series of tension ties. Looking in one direction, the structure appears almost transparent, while looking in the opposite direction, the shells appear solid. The construction of these shells was made economical through the reuse of formwork from bay to bay.

Dieste designed many buildings in forms similar to Freyssinet's at Bagneux. His packing plant for Cítricos Caputto, completed in 1972, serves as a typical example (fig. 113). Here, brick vaults span 148 feet without the support of internal columns. Steel tension ties resist the thrust of the vaults, and glazing admits light between the repeating shells. The brick shells act as an arch, and the undulating cross section provides resistance to asymmetrical loading and to buckling. By combining catenary forms in a smooth shell, Dieste produced structural shapes that allowed him to span great distances with minimum material.

The external views of these shells by Freyssinet and Dieste are not as expressive as their interior views, which are striking in light of their minimalism. Both designers incorporated repeating forms in order to economize on construction costs, while they used different structural ideas to generate shell shapes. Freyssinet used the conoids, a geometric form, and Dieste used the catenary, a structural form, but both conceived the overall problem as one of arches rather than of freestanding shells—that is, of structural forms acting primarily in two dimensions rather than in three—and called upon steel ties to restrain the thrust of these arches.

Like other leading engineers, Dieste tried to avoid using unnecessary tie-rods and stiffening beams that did not integrate visually with the thin structural shells.[32] Indeed, he used fewer ties per bay in his Cítricos Caputto Plant than did Freyssinet in his railway repair shop. The aesthetic impact of both Freyssinet's and Dieste's shells is compromised by the use of numerous steel ties on the interior.[33] In later works, such as the Don Bosco school gymnasium of 1983, Dieste obscured the steel ties in order to reduce the visual clutter. He was constantly looking to refine his solutions to achieve greater structural integration.

### Maillart and Dieste: The Vault as a Cantilever Beam

While Freyssinet turned his primary focus to pre-stressed concrete by 1930, other engineers continued to advance the construction of thin shells in reinforced concrete during the subsequent decade. The Swiss engineer Robert Maillart led the way. Maillart was the first great structural artist to work in reinforced concrete; best known for his bridges, he also produced a series of structures with stunning and innovative roof forms in the material.[34] The engineering establishment often rejected his unorthodox and original forms because they could not be analyzed by conventional methods, but in his design philosophy, Maillart exemplified the goals, and the difficulties, of the structural artist.


fig. 113


fig. 114


fig. 115

For the 1939 Swiss National Exhibition in Zurich, Maillart designed the Cement Hall, a thin shell vault of purely structural form (fig. 114). In his *Space, Time, and Architecture,* Sigfried Giedion recognized that "in the hands of a great engineer, this pavilion, conceived only to combine strength and the utmost lightness, became at once a work of art."[35] The structure is both expressive and integrated. The thin shell of the vault is fully exposed, yet the vault could not stand without the accompanying structural elements. The lateral thrust of the vault is resisted by the horizontal slabs, and the central walkway acts as a tension tie. The arch ribs stiffen the vault over the central supports, and the vault acts as a cantilever beam in the longitudinal direction, with bending resistance provided by the vault's great depth. Each element is necessary, and thus Maillart reduced the structure to a remarkable thinness. This is the work of a mature structural artist, completed when Maillart was sixty-seven years old; it was one of the final projects in his impressive career. The Cement Hall was destroyed after the 1939 fair, but its legacy has been perpetuated by the popularity of Giedion's seminal work, which recognized the aesthetic potential of engineering structures.[36]

It is possible that Dieste was familiar with this integrated structural form by Maillart, although he does not refer to the Zurich Cement Hall in his writings. Regardless, one of Dieste's most prominent structural devices—the post-tensioned cantilever vault—is based on very similar ideas.[37] Beginning in the 1960s, he designed a series of such vaults for structures ranging from factories to bus stations to train terminals. Dieste's project for Massaro Agroindustries in rural Uruguay, completed in 1978, provides an elegant example of this form (fig. 115). The double-cantilevered vaults at the north front of this warehouse are comparable structurally to Maillart's vault for the Cement Hall.

Like Maillart's thin shell, Dieste's structure is a barrel vault that acts as both a thin shell and a cantilever beam. At each end, the thrust of the vault is resisted by a tapered horizontal edge beam supported on a diagonally-braced reinforced concrete column. Both designers reduced the area of the slabs to make the horizontal beam more efficient: Maillart, by opening circular holes in the slabs; and Dieste, by tapering the horizontal slab to a minimum at the end of the cantilever. Overall, both designers used structural forms for the vault: Dieste's vaults take a catenary form in cross section, while Maillart's vault resembles a parabola, which narrows toward the end of the cantilever.

Although these shells function in a similar way, significant structural differences also exist. Dieste used post-tensioning in his shells, which allowed him to cantilever 54 feet with a relatively small rise in the shells. Maillart used a much deeper vault to span roughly the same distance in

29 Ibid., 192 of this volume.

30 In his essay "La invención inevitable," Dieste wrote, "Freyssinet claimed that he never learned more from anyone than he did from the artisans who maintained his grandmother's windmill once a year." Published as "The Inevitable Invention," in Antonio Jiménez Torrecillas, ed., *Eladio Dieste: 1943–1996*, trans. Michael Maloy and Harold David Kornegay (Seville: Consejería de Obras Públicas y Transportes, 1996), 246. Published as "La invención inevitable," *Summa: Colección Temática* (Buenos Aires) 19 (June 1987): 43–47, and, in part, in "La inevitable invención tecnológica," *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 93–95.

31 Eugène Freyssinet, "Freyssinet by Himself," in *A Half-Century of French Pre-stressing Technology*, special English ed., *Travaux* 50 (April–May 1966): 18.

32 Two of the most prolific engineers in thin concrete shells, Felix Candela and Heinz Isler, both sought to eliminate stiffening beams as well as exposed tension ties in their designs. See Billington, *The Tower and the Bridge*, 208.

33 Billington argues that shell structures with steel ties do not express an integration of form, and he has described the effect as "a disquieting maze of thin linear elements hovering beneath the smooth surfaces of shell and glass." Ibid., 207.

34 For a comprehensive survey of Maillart's work, see David P. Billington, *Robert Maillart: Builder, Designer, Artist* (Cambridge: Cambridge University Press, 1997).

35 Sigfried Giedion, *Space, Time, and Architecture*, 5th ed. (Cambridge, Mass.: Harvard University Press, 1967), 473.

36 Ibid., 463–73. See Billington, *Robert Maillart*, 234–42, for a discussion of the historical importance of the Cement Hall.

37 Dieste called them *autoportantes*, or self-supporting vaults. Jiménez, ed., *Eladio Dieste*, 89–145. The German engineer Rainer Barthel has noted

fig. 116: Heinz Isler, Heimberg Tennis Center, Switzerland, 1979

fig. 117: Eladio Dieste, CADYL horizontal silo, Young, 1976–78

reinforced concrete. Dieste's use of post-tensioning and the smaller scale of his shells allowed him to avoid the heavy rib arches that Maillart required on the outer surface of his shell. Maillart minimalized column size by using the horizontal walkway to reduce the horizontal force on the columns. By contrast, Dieste relied on the exterior columns to resist the lateral forces and therefore required heavier structural elements, including an inclined supporting member to carry the thrust of the vaults to the foundations. The abrupt junction between the visually powerful shell and the minimal exterior column may be considered a minor aesthetic flaw in Dieste's work. The shell and the column have important structural functions, but they are not visually integrated. In the Cement Hall, Maillart reduced the complex forces from the vault to four small hinges at the foundations, and his columns are more carefully integrated within the overall form.

While aesthetic ideas governed the final design decisions made by both Maillart and Dieste, these ideas never violated the engineers' technical goals. As Jiménez Torrecillas wrote, "Only the essential finds a place in Dieste's work"[38]; this statement applies to the work of Maillart as well, and to that of the best engineers in the Swiss tradition, who labor to derive elegant new forms from purely structural requirements.

### Isler and Dieste: New Shell Forms

In the tradition of Swiss engineering excellence, Heinz Isler has designed some of the most striking thin shells in reinforced concrete of the second half of the twentieth century.[39] He creates thin shells by hanging small membranes in tension and creating smooth curving surfaces that are then inverted and scaled up to create large-scale structures in compression. Like other leading structural artists, Isler owns his own design office and works closely with a local builder to produce economical forms. Within the constraint of economy, he discovered new forms from purely structural considerations and demonstrated the unlimited possibilities for thin compression shells to be found in hanging models.

A typical example of Isler's surprising forms can be seen in the Heimberg Tennis Center, completed in Switzerland in 1979 (fig. 116). This thin-shell reinforced concrete roof is made up of four repeating vaults, each spanning 154 feet. The form of the vaults is derived from hanging membrane models, so that the shells act in pure compression under dead load. Through experimentation, Isler developed a form, providing the necessary stiffening at its upturned edges and preventing any danger of buckling in the thin shell. As Billington notes, these are not "the beaux-arts spaces of high architecture built in spite of cost and the nature of materials; rather, they are only built because they reorder materials in new ways and at low costs."[40]

Dieste and Isler solved similar problems with similar forms. Billington's description of Isler's vaults also applies to the thin shells designed by Dieste, whose large horizontal silos echo the form of Isler's buildings. One year before the opening of the Heimberg Tennis Center, Dieste completed a horizontal silo for CADYL, an agricultural cooperative in Young (fig. 117).[41] This large-scale shell in reinforced brick represents another example of the economical forms developed by Dieste to solve structural problems. To cover a large area and resist the lateral thrust of the grain stored inside, Dieste designed an undulating vault spanning 95 feet. The cross section of the horizontal silo is a catenary, the shape of a hanging chain, so that like Isler's shells, the vault will function in pure compression under the vertical load of its own weight. By undulating the shell, Dieste increased the stiffness of the membrane and decreased the amount of material necessary. Finally, like Isler, Dieste designed the vault to be constructed economically by constructing one bay at a time using movable formwork.[42] After completing this project, Dieste went on to build a number of larger structures using the same system, such as the 1997 silo in Nueva Palmira, which spans 148 feet.[43]

The principal difference between Isler's tennis center and Dieste's horizontal silo designs is the type of loading, and it is interesting to note how each engineer shaped their form in response to this consideration. In the case of Isler's shells, the dominant load is vertical and therefore the form of the structure is governed by the vertical loading. For Dieste's silo,


fig. 116


fig. 117

the dominant load is horizontal—created by the thrust of the grain on the inside of the silo, which must be resisted by the walls.[44] To solve this problem, Dieste began with the appropriate form for controlling vertical loads, the catenary, and added a series of undulations to stiffen the walls against the lateral thrust of the grain. The greater number of undulations in the shell of Dieste is justified by its structural requirements. Isler's thin shells have a larger span but the loading is not as severe, and their form reflects this fact. While Isler derives his structural shapes from three-dimensional experiments, Dieste assumes two-dimensional arch behavior, following the simpler form of the catenary. In the case of a shell supported on corners, Isler's three-dimensional approach is appropriate; for the continuous foundation support of the horizontal silo, Dieste's two-dimensional approach is also appropriate. Both forms are derived from structural principles, their aesthetic ideas shaped purely by structural needs. In his essay "Architecture and Construction," Dieste described himself as an engineer who "found in the process of building warehouses, he was creating architecture, even though that was not his object. He also found that he had an awareness of form and in confronting this awareness, he discovered that it helped him to solve problems that were strictly structural."[45]

### The Future of Brick Vaulting

Dieste discovered new methods to solve "strictly structural" problems and in the process, developed his own aesthetic ideas and artistic style. Dieste's solution is closely linked to the use of *cerámica armada* and suggests that contemporary engineers have neglected a viable construction material in brick. By exploiting the structural potential of brick, Dieste demonstrated by extension the vast and as yet unrealized possibilities for using traditional materials in conjunction with modern engineering methods. Dieste's work raises the question, what is the value of brick in construction?

Dieste believed that brick was superior to other construction materials, and argued for its use for numerous technical reasons.[46] In comparison to reinforced concrete for thin shell construction, he advocated the use of brick for the following four reasons:

> Brick weighs less than concrete, reducing the cost of the supporting structure during construction.
> Brick is easier than concrete to shape into double-curvature vaults.
> In a brick vault, the vast majority of the material is already dry and the small amount of mortar sets quickly, allowing the forms to be stripped earlier.[47] The dry brick absorbs moisture, speeding up the setting of the concrete mortar.
> Brick construction uses less cement.

the similarities between the concrete shell structure by Maillart and the cantilevered shells by Dieste. Rainer Barthel, *Eladio Dieste: Form und Konstruktion* (Munich: Lehrstuhl für Hochbaustatik und Tragwerksplanung, Technische Universität München, 2001), 29.

38 Jiménez, ed., *Eladio Dieste*, 15.

39 See John Chilton, *Heinz Isler* (London: Thomas Telford, 2000); Billington, *The Tower and the Bridge*, 222–32; and David Billington, *The Art of Structural Design: A Swiss Legacy* (Princeton, N.J.: Princeton Art Museum, 2003), 128–62.

40 Billington, *The Tower and the Bridge*, 231.

41 Jiménez, ed., *Eladio Dieste*, 70

42 Freyssinet pioneered this method of construction in the Orly hangars of 1921. See José Antonio Fernández Ordóñez, *Eugène Freyssinet* (Barcelona: 2c Ediciones, 1978), 30.

43 Pedreschi, *Eladio Dieste*, 60–62.

44 Jiménez, ed., *Eladio Dieste*, 70.

45 Eladio Dieste, "Architecture and Construction," 182 of this volume. Originally published as "Arquitectura y construcción," in "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980).

46 For a complete list of reasons, see Eladio Dieste, "La cerámica armada," in Jiménez, ed., *Eladio Dieste*, 34–36. Originally published as Eladio Dieste, "Acerca de la cerámica armada," *Summa* (Buenos Aires) 70 (Dec. 1973), 45.

47 Formwork can be stripped in a matter of hours in brick construction, compared to days for formwork used in reinforced concrete construction. Jiménez, ed., *Eladio Dieste*, 46–47.

48 Dieste addressed the appropriateness of technology in several essays.

An additional benefit, not mentioned by Dieste, regards the compressive stresses in a well-designed shell, which are relatively low compared to the strength of brick or concrete; provided that an appropriate structural form is used, brick provides a suitable material for thin shell construction.

Dieste's work reveals new possibilities for brick in vaulting, but significant barriers continue to prevent the widespread use of this material as a structural component. The construction industry in North America lacks expertise and experience with brick as a structural material, particularly in vaulting applications. Furthermore, few engineers are trained to work in structural masonry, and codified calculation methods are unsatisfactory. Finally, large companies look for general solutions to construction problems and do not encourage local solutions, which depend on local expertise.

Dieste personally devised ways around each of these problems. He directed and trained a generation of workers in the construction of brick structures. He worked outside of conventional regulations and developed his own design methods to demonstrate the safety of thin shells constructed in brick. He pursued practice locally and remained personally responsible for the work. To apply brick vaulting in the future, designers can follow Dieste's example to overcome similar obstacles.

### The Ecological Engineer

If Eladio Dieste ably represents the structural artist of the past, he also provides a glimpse of the engineer of the future. Structural artists have always seen themselves as public servants, building public works that are both affordable and beautiful, but Dieste took this concept further. For Dieste, a work of technology must answer a series of pointed questions: Does the solution use local resources? Is it just? Is it ecologically sensitive?[48] Dieste built not only elegant structural forms but ones that considered the local community, the environment, and the wider social implications involved in their construction.

As engineers and architects move toward methods of sustainable building, the lessons of structural art are particularly relevant. Most importantly, the ideals of engineering should not oppose the protection of the environment and the efficient use of natural resources. Sustainable building requires local methods and materials, and structural art is a *local* practice of construction; as Billington summarized: "such designs depend upon their designers' first-hand experience in the field....There is no such thing as an international style of structural art; its integrity depends upon its integration into local building practice."[49]

The final works by Dieste, a series of structures in Alcalá de Henares in Spain, illustrate Billington's point; when Spanish architects imported his construction system in the 1990s, inexperience led to numerous problems in construction. Without local expertise to oversee construction, the system failed.[50] Like structural art, ecologically responsible structural design is most successful when created by engineers and craftsmen with local circumstances in mind.

Dieste's life and work offer three important lessons for designers and educators, the first being that understanding the construction process is crucial to creating exceptional works of structure. All structural artists are builders as well as designers. Secondly, Dieste's work demonstrates the possibility of constructing with a combination of traditional materials, such as brick, and high-strength industrial materials, such as steel. Structural experimentation, particularly with locally

See Dieste, "La inevitable invención tecnológica," in "Eladio Dieste, el maestro del ladrillo," 93–95.; and "Technology and Underdevelopment" in Jiménez, ed., *Eladio Dieste*, 259–66. Originally published as "Técnica y subdesarrollo," *CEDA:* Revista del Centro de Estudiantes de Arquitectura, Montevideo 34 (Feb. 1973): 1–5. See also Dieste's "Art, People, Technocracy," 194–97 of this volume.

49 Billington, *The Tower and the Bridge*, 268–69.

50 A series of three Spanish churches were built between 1996 and 1997; they are near replicas of Dieste's famous earlier churches. See Pedreschi, *Eladio Dieste*, 122-39. The Spanish churches experienced serious problems with water penetration.

produced materials, should be encouraged. Finally, Dieste's success illustrates that good design must be adapted to local conditions.

As designers look to a future of increasing populations and decreasing natural resources, they would benefit from adopting new role models in design and construction. The ecological engineer must work together with the architect to solve the problems of limited resources through intelligent design. As an engineer, Dieste addressed the great challenge of the future: to create economical, efficient, and elegant structures in an ecologically and socially responsible manner. His life and career serve as a valuable example for engineers and architects alike.

The author would like to thank Joaquín Antuña Bernardo, Jos Tomlow, Santiago Huerta Fernández, Fernando Pérez Oyarzun, David Billington, and Heinz Isler for their assistance, as well as the J. William Fulbright Scholarship Board for providing funds for a year of research in Spain.


fig. 118

## "SEA GULL"

(Barbiere and Leggire Service Station), *Salto*, 1976

This brick canopy carried on a single support is one of the best-known and most remarkable of Dieste's structures. While based on Dieste's self-carrying vaults, it is not properly a vault: it is effectively two counterbalanced wings. Thanks to a heavier section, reinforcing in the valley, and pre-stressing in the long dimension, the entire construction acts as a cantilever beam. This elegant work moves away from structural rationalism. At the same time, however, the canopy with centralized support provided the most effective form of protection at the gas pumps of a service station it originally served.

So distinctive and beloved was this work that when threatened with destruction in 1996, the mayor of Salto stepped in to save it. Transported to the south entrance of Salto (Puerta de la Sabiduría), the "Sea Gull" (as it was nicknamed) now serves as a greeting to the city and as a memorial to Eladio Dieste. The mayor's action was especially appropriate as Salto gave Dieste more commissions than any other city, with the exception of Montevideo, and Dieste responded with some of his best works.

fig. 119

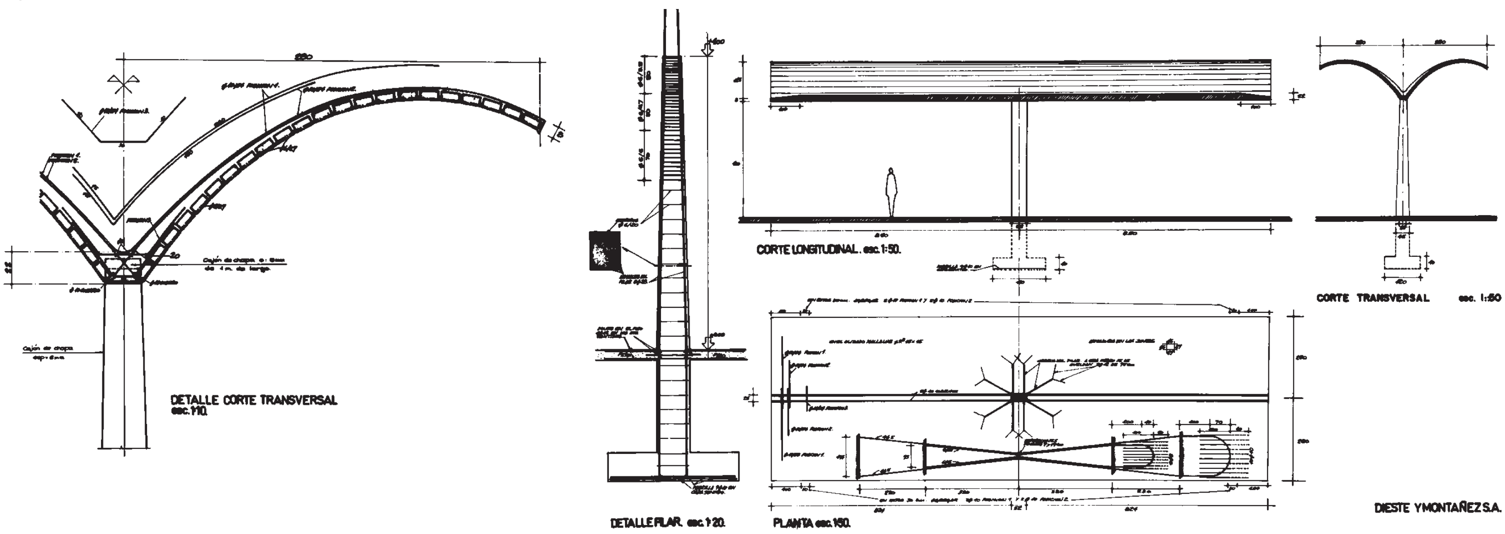



fig. 120

fig. 118: The “Sea Gull,” in its original location and performing its intended use. The cantilevered self-carrying vaults at the left are also by Dieste y Montañez.

fig. 119: The “Sea Gull” in its new installation as a formal welcome to the city. In the distance, vaults and water tower of Refresco del Norte, by Dieste

fig. 120: Drawings of the “Sea Gull” in plan and section. Note the reinforcing and pre-stressing details on the plan and half-section

fig. 121: The remarkable coverage of the “Sea Gull”—18 by 56 feet

fig. 121

fig. 122

# AYUÍ PARADOR

*Salto*, 1976–77

A summer café on the banks of the Uruguay River in Salto, the Ayuí parador represents another atypical structure in Dieste's oeuvre. The truncated cone of single-brick thickness covering a 49-foot diameter enclosure has a 10-foot cantilevered "brim." The structure is ingeniously self-pre-stressed, as the deflection of the cantilever eliminates the need for an edge beam with heavy supports. The roof is carried on 24 very light columns—1 5/8-inch square folded sheet-metal tubes that also act as glazing mullions.

*Collaborator: Architect Nestor Minutti*

fig. 122: General view of the lightly supported conical brick vault of the Ayuí parador

fig. 123

## CADYL HORIZONTAL SILO

*Young,* 1976–78

Dieste's horizontal silos, from those for Fosfato Thomas in Montevideo of 1965 to the largest at Nueva Palmira of 1996, are formed by continuous double-curvature vaults. Dieste indicated that buckling and wind loads were not critical in these structures, but the double-curvature in the lower part of the vaults was calculated to resist any outward thrust of a heavy loading of stored materials. The lateral thrust of the vault itself is resisted by pilings.

The silo at Young has a span of 99 feet, an area of 39,000 square feet, and a capacity of 30,000 tons. Grain is supplied by mechanical feeds at the top and withdrawn at the bottom.

fig. 123: General view of the silo

fig. 124: Transverse section and foundation details

fig. 125: The silo in construction. At the far left, a completed section of the vault; from the left to the center, completed brick vaults without the cement covering; at the right, the large movable form in the process of being relocated. Note the small sticks on the surface of the form to locate precisely the bricks and reinforcing.

fig. 126: Concrete foundation and the springing of the vaults

fig. 127: General interior view, after having been given a flat floor

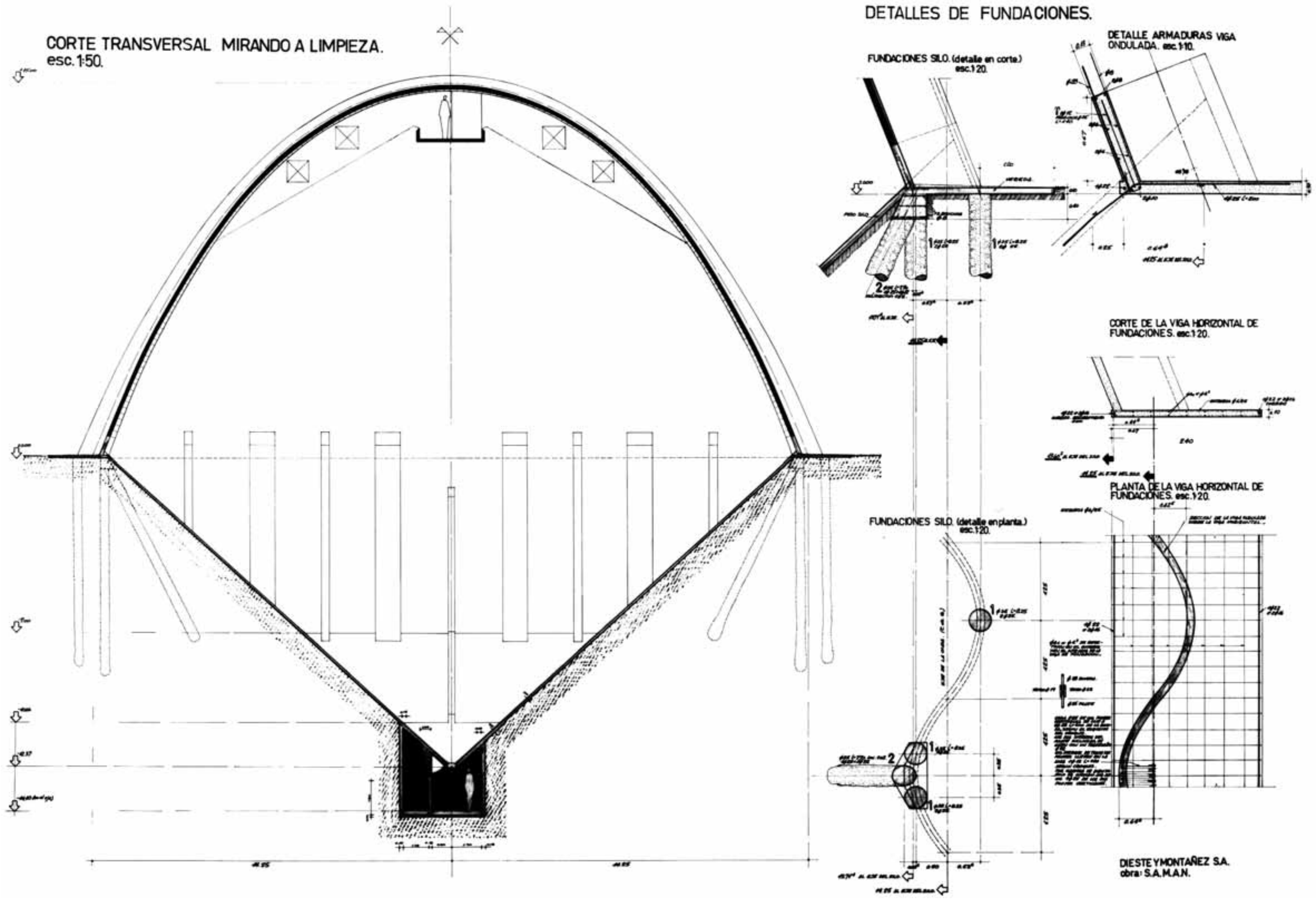



fig. 124

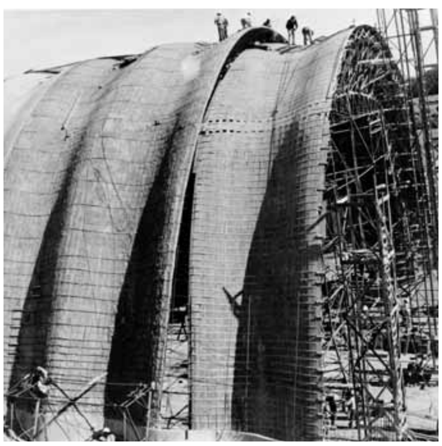


fig. 125

fig. 126

fig. 127

fig. 128

## MASSARO AGROINDUSTRIES

*Joanicó, Canelones*, 1976–80

In their lightness and spatial organization, the self-carrying vaults at Massaro Agroindustries create one of the most dramatic effects of Dieste's many constructions. The main working space of the approximately 97,000-square-foot warehouse is covered in five bays. Each 42-foot-wide bay is comprised of two double-cantilever self-carrying vaults, with columns spaced 115 feet apart. In the three central bays, the north and south vaults stop short of one another, admitting light to the center of the space. To the north, the main working area ends in 54-foot cantilevers that overlap another set of lower self-carrying vaults of the same width. The lower vaults, 82 feet long, are carried on a single row of columns. These vaults end in concave and convex cantilevers, placing their centers of gravity off center, as then are the columns.

As with most of Dieste's buildings, the plan of Massaro is very simple; it is the quality of space and light that he creates with his vaults that sets his work apart. Here, the magnitude of the cantilevers, the sparseness of supports, and the thinness of the vaults create the drama of the grouping.

fig. 129

fig. 128: General view from the northwest, with the water tower also by Dieste

fig. 129: Spatial and light qualities under the three central bays

fig. 130: Longitudinal section and transverse section of the main working space; north and west elevations

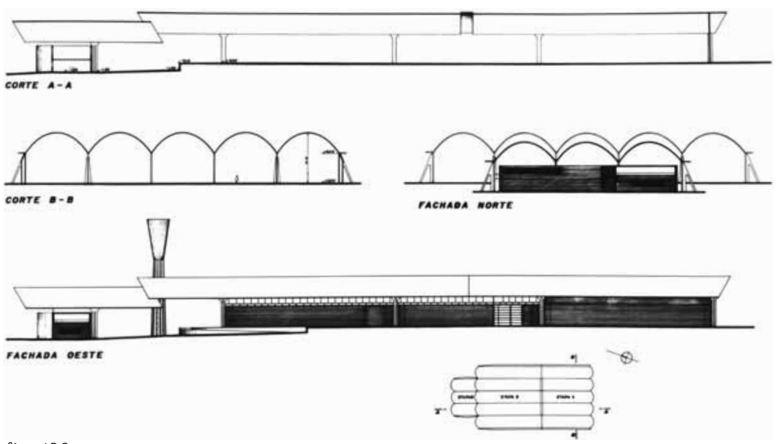



fig. 130

fig. 131

fig. 131: View of the interior from the southerly main vaults, past the skylight between the meeting of the north and south vaults, and on to the lower entry vaults
fig. 132: View from the central main vault to the lower entry vaults
fig. 133: Overlapping sets of vaults
fig. 134: The remarkable thinness of the vaults

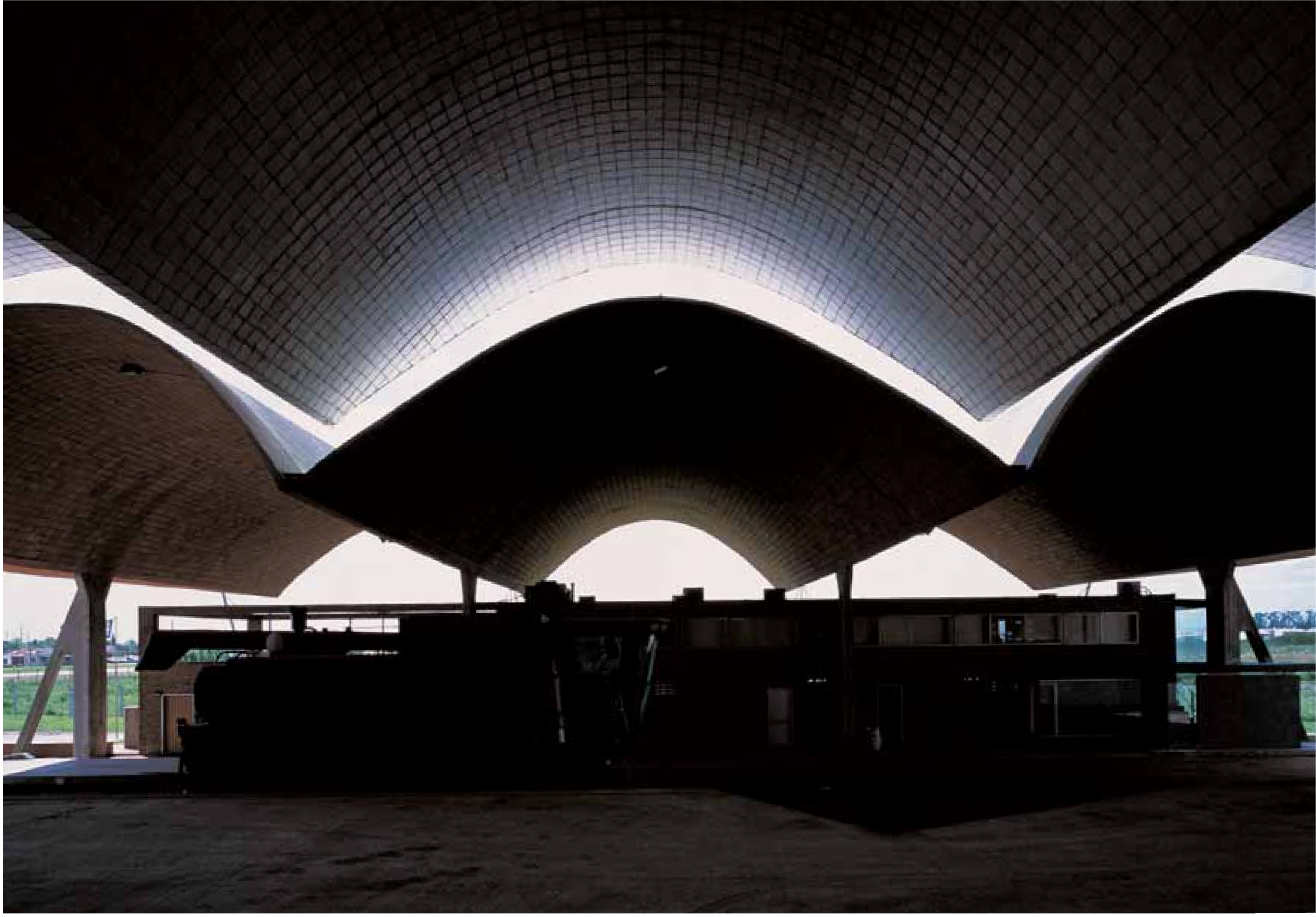


fig. 132


fig. 133


fig. 134

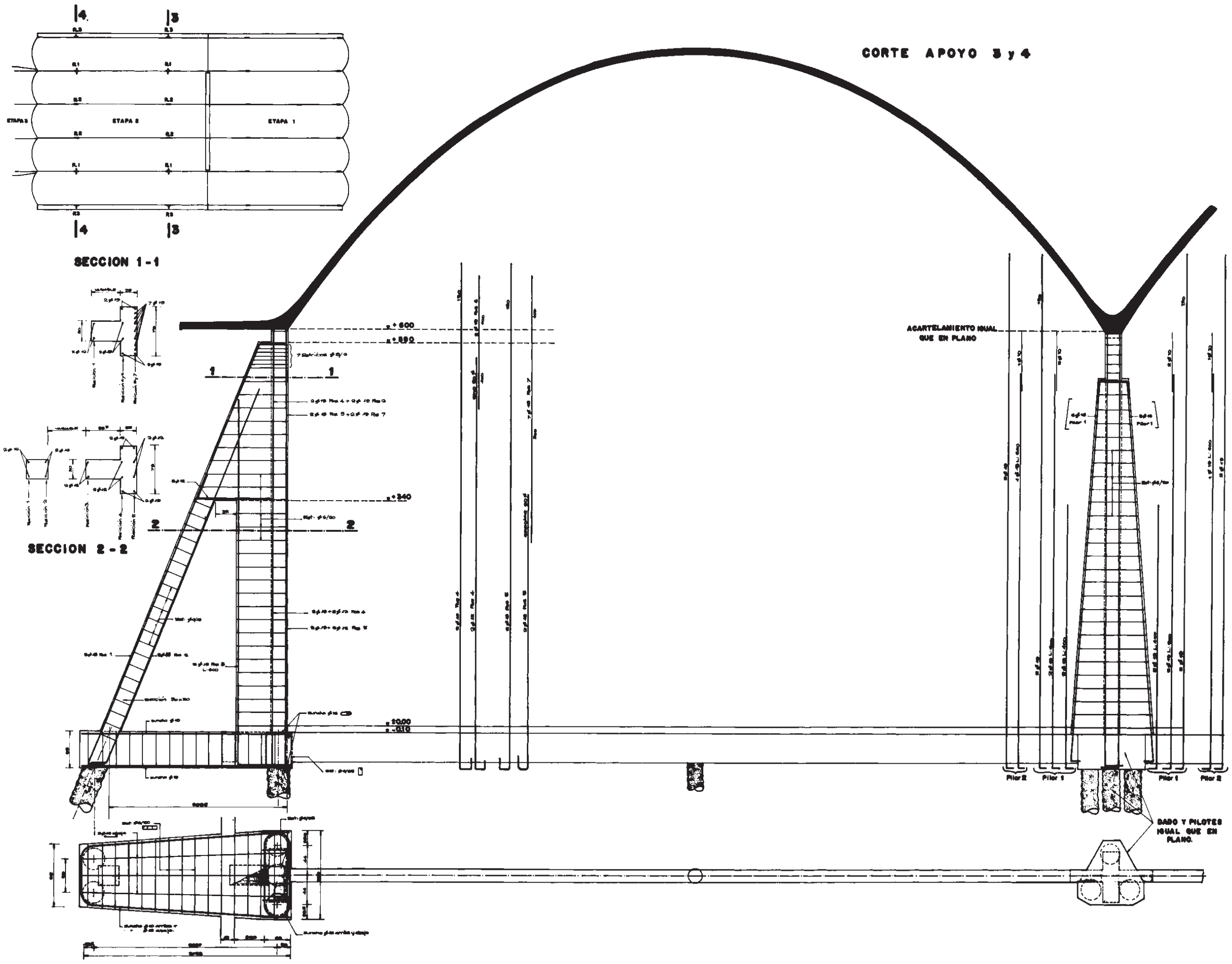



fig. 135

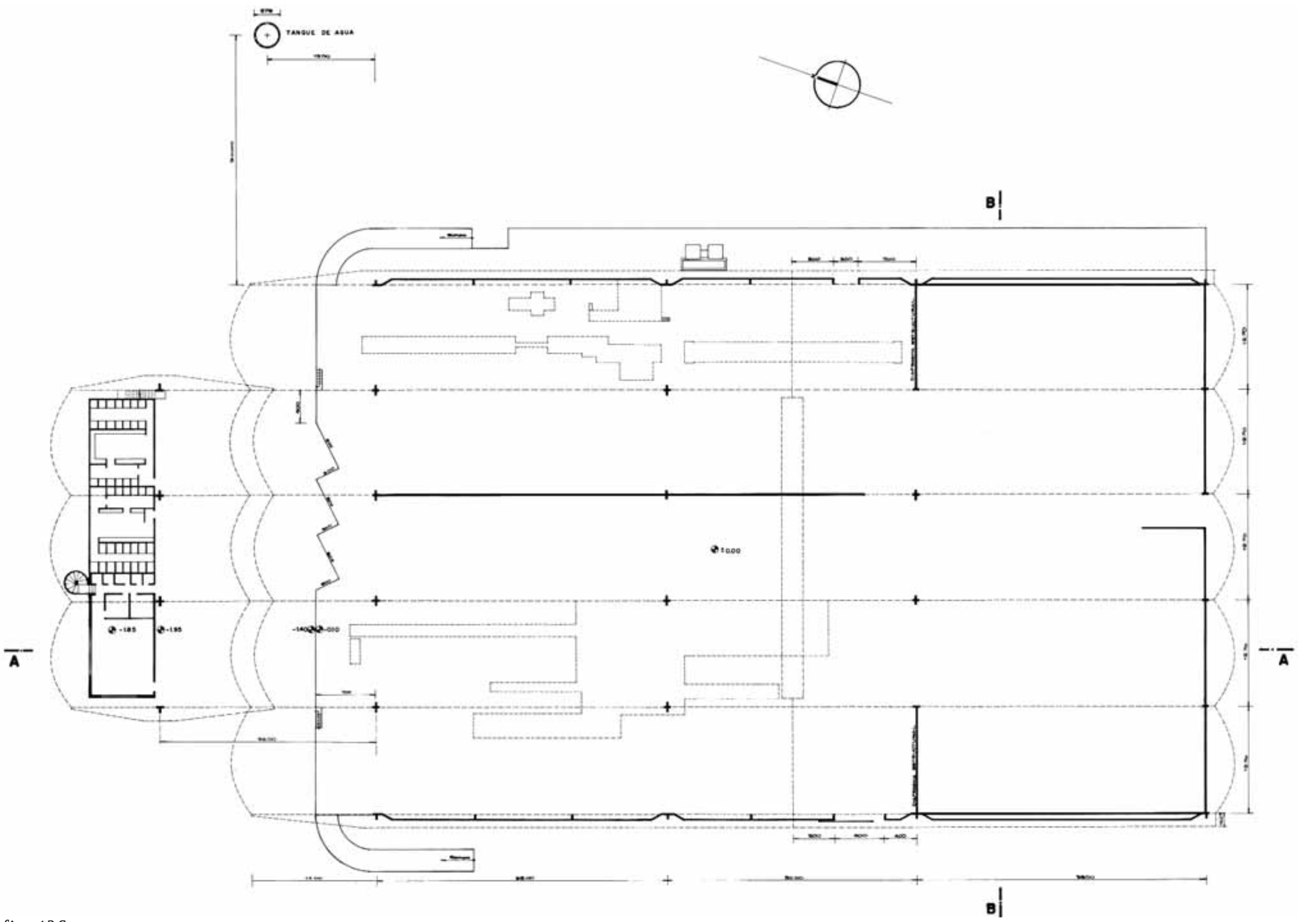



fig. 136

fig. 137

fig. 135: Transverse section of one of the extremely thin main vaults, with its outward lateral thrust restrained by an edge beam

fig. 136: Plan of the complex

fig. 137: View from under the cantilever of a main vault to the double-cantilever self-carrying vault with edge beam of the entry group

overleaf

fig. 138: Overlapping sets of vaults

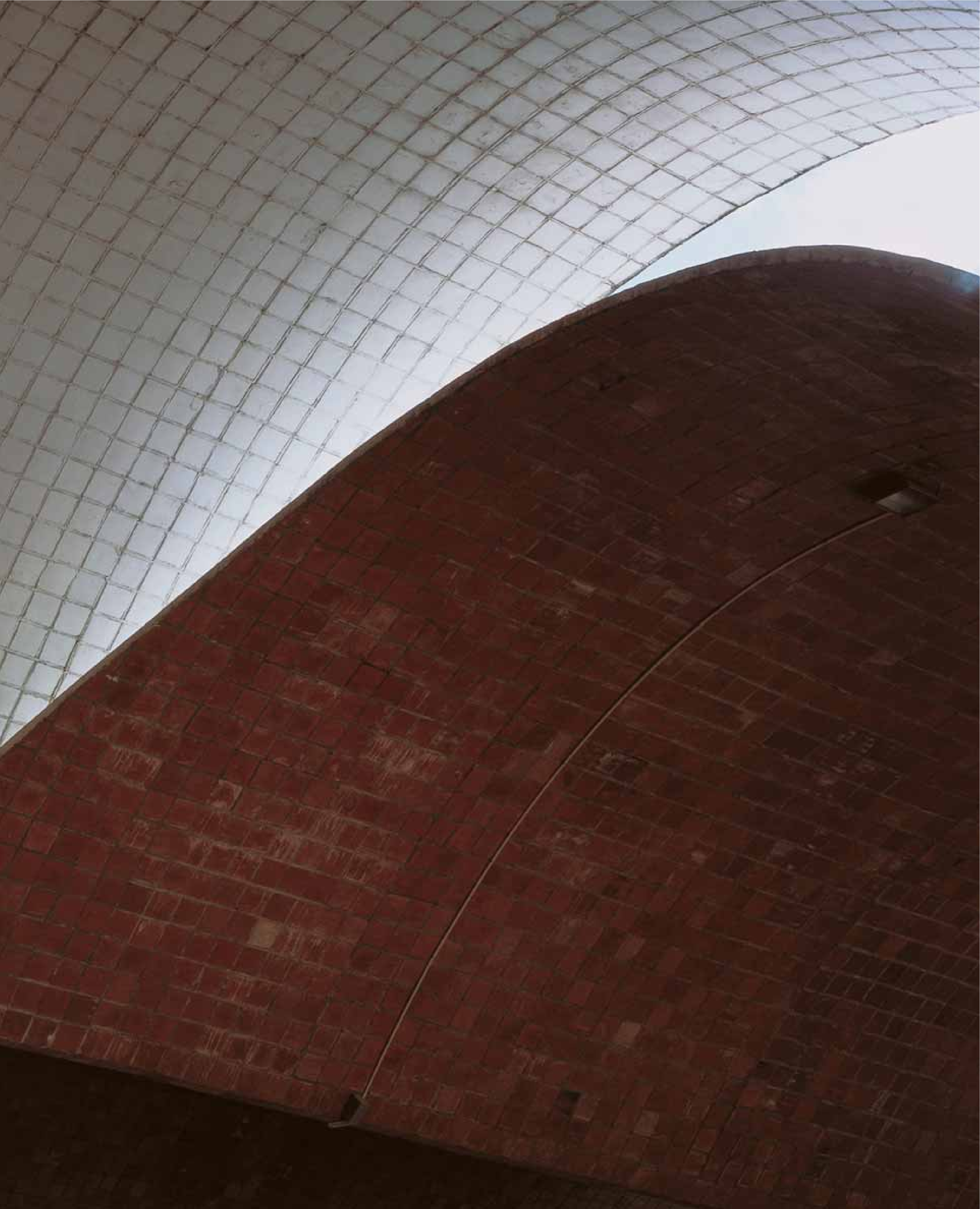


fig. 139

## REFRESCOS DEL NORTE

*Salto*, 1977–80

Like Massaro Agroindustries, Refrescos del Norte is another complex that employs self-carrying vaults, though it is much smaller and is enclosed. Originally a cola bottling plant, it incorporates more self-conscious architectural details, as it provides office facilities and was intended to receive the public as visitors. Most interesting is the entrance pavilion of double-cantilever self-carrying vaults supported on a row of three columns.

*Collaborator: Architect Nestor Minutti*

fig. 140

fig. 139: General view from the northwest

fig. 140: Entrance pavilion of double-cantilever self-carrying vaults with an edge beam

fig. 141: Cantilevered self-carrying vaults at a loading area outside the production facility

fig. 141


fig. 142

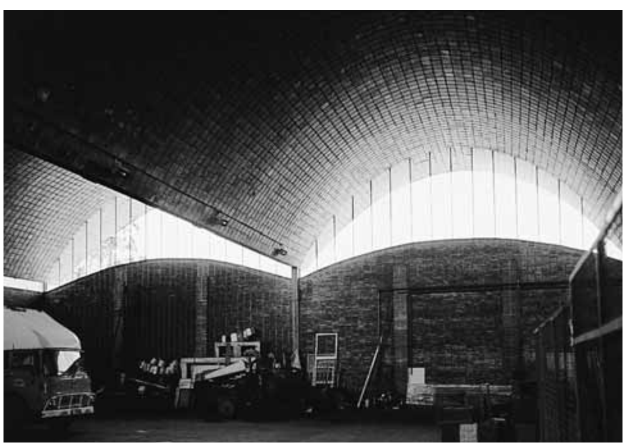


fig. 143

fig. 144

fig. 142: Office and reception area, with a view of the inclined columns and edge beam that absorb the lateral thrust of the vaults
fig. 143: Interior of the production area, looking away from the loading area
fig. 144: Public reception area on the upper floor, showing the independence of the walls from the vault

fig. 145

## SAN AGUSTÍN PARISH CENTER AND GYMNASIUM

*Montevideo*, 1978–80

Many of the works of Dieste y Montañez are of elemental construction and for simple programs, as with this work. The gymnasium for the parish of San Agustín is a single self-carrying vault with a span of 43 feet. Lateral thrusts are restrained by edge beams, one of which is extended into an entrance canopy. The minimal supports required by such vaults allow continuity of the windows, or of the space of a balcony at the two-story services construction.

fig. 146

fig. 145: View of the main front

fig. 146: Axial view of the interior, toward the front

fig. 147

# CARUGATTI GARAGE AND WORKSHOP

*Montevideo*, 1978–79

Like the San Agustín Parish Center gymnasium, the Carugatti garage and workshop are of simple program and construction. The structure, designed to repair construction equipment, is itself “rough and ready.” There is, nonetheless, an eloquence to the series of self-carrying vaults arranged at different heights to form the composition.

fig. 148

fig. 147: Views under the sheltering vaults
fig. 148: Exterior view of the group
fig. 149: Detail of overlapping vaults

fig. 149

fig. 150

## PORT WAREHOUSE

*Montevideo*, 1977–79

A warehouse at the Port of Montevideo was severely damaged by fire. The competition guidelines for designing a new warehouse assumed the demolition of what survived. Instead, Dieste worked with the remaining walls, using arguments that derived from aesthetics, conservation, and efficient use of resources.

The 164-foot span of this series of discontinuous double-curvature vaults that Dieste employed to enclose the warehouse is the greatest yet achieved by the engineer's method. With its wide span and low rise (only 21 feet maximum), there is great outward thrust on the side walls. This is taken up with substantial reinforced concrete edge beams atop the walls, to which tie rods are anchored. The beams cantilever inward from the wall to eliminate dimensional differences between the old walls, thus providing a uniform span for the new vaults and for the movable form upon which they were constructed. The old walls were reinforced and clad in new brick on the exterior, and brick buttresses were added at the end walls for wind loading.

Between the low and high edges of the successive s-shaped vaults, Dieste provides his characteristic glazing. The structural independence of the vaults and the end walls is underscored by the inclusion of windows, large and small, on the end wall. Balanced light pervades the space.

fig. 150: General view of the warehouse with discontinuous double-curvature vaults, from the south

fig. 151: View from the west wall through the warehouse

fig. 151

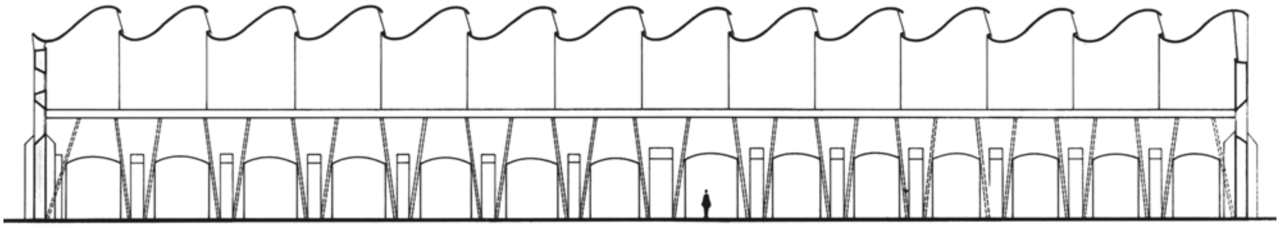
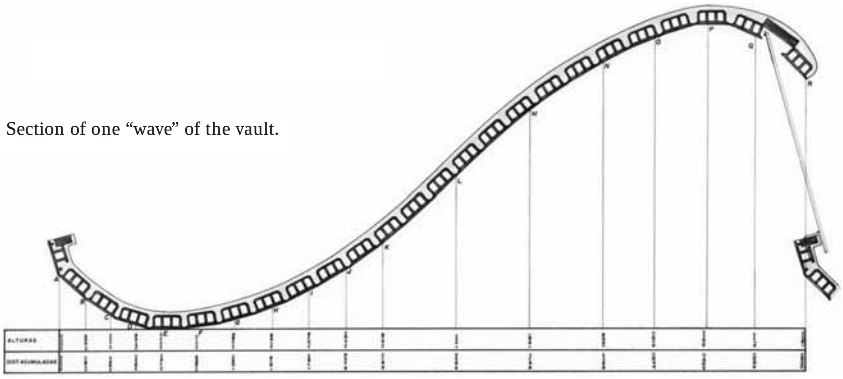
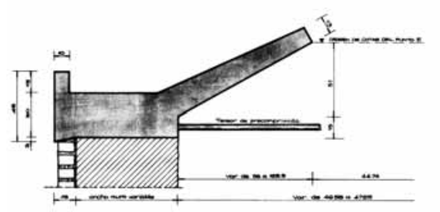


fig. 152

Section of one “wave” of the vault.





Detail of edge beam

fig. 153

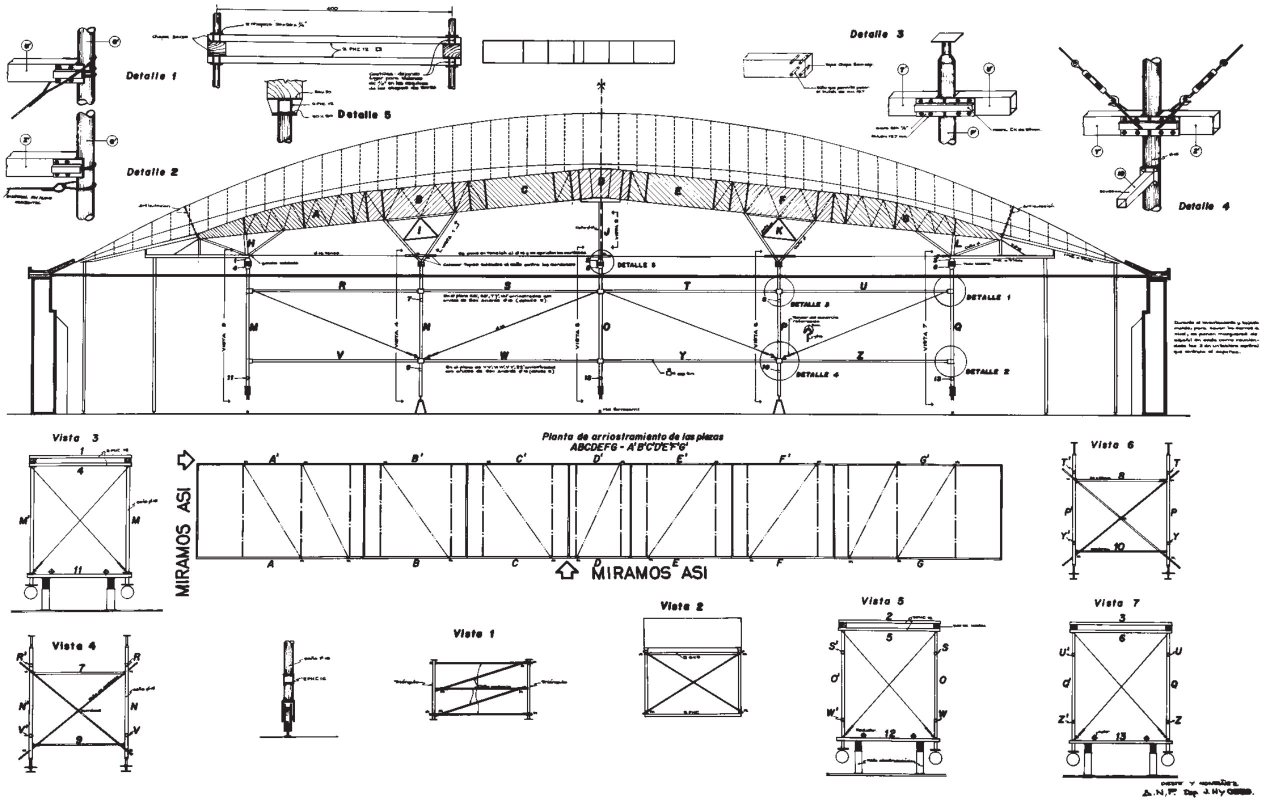



fig. 154

fig. 155

fig. 152: Longitudinal section at the center line

fig. 153: Geometry of the vault. The vault is 4.75 inches thick, of which 4 inches is the brick.

fig. 154: Design of the movable formwork

fig. 155: West end wall, with a thin line of glazing between the non-bearing wall and the lower side of the vault

fig. 156: Looking east

overleaf

fig. 157: Looking west, with the diffused light on the vaults

fig. 156

fig. 158

fig. 158: Interior of the west wall, showing the use of the existing brick walls

fig. 159: Interior of the east wall. Note difference of glazing at opposite ends of the building, as vaults are differentiated by their s-curves.

fig. 160: View eastward in the warehouse

fig. 159

fig. 160


fig. 161

## TURLIT BUS TERMINAL

*Salto,* 1980

In comparison to the Municipal bus terminal in Salto, the Turlit station occupies a much more constricted site. With a sharp change in level from the front of the site to the back, services are distributed on two levels. High vaults are still about one story above ground at the rear. Dieste once again designed double-cantilever self-carrying vaults on a single line of columns. With the high vaults rather detached from the pedestrian experience, Dieste was willing to use an economical edge beam, tapering from the center to the ends, following the magnitude of the lateral forces from the vault. That thrust is finally resolved, one story below the springing points, with a tie-rod in the slab of the mezzanine level connected to the shaped end columns.

Dieste sought to differentiate the vertical and horizontal load-bearing roles of the end columns by inserting a small steel box-beam between the concrete column and the concrete slab, but his design was not executed. The precise, lighter scale of the column was also overlooked and what was intended to be exposed concrete was covered in plaster. Because the two cantilevers are not balanced, steel-tensioned members were introduced at the rear. Despite these problems, the station serves its purpose very well and has a dramatic and compelling character.

*Collaborator: Architect Nestor Minutti*

fig. 162

fig. 161: General view from the northeast
fig. 162: Buses sheltered by the long cantilevers
fig. 163: End column and edge beam detail


fig. 163

## TECHNOLOGY AND INNOVATION IN THE WORK OF ELADIO DIESTE

*Remo Pedreschi and Gonzalo Larrambebere*

The work of Eladio Dieste is characterized by surprise. It is an architecture that seems to have been created in defiance of the pragmatic and rational process of building. At first the relation between light, space, and material is unaccountable—unusual places formed from structure and light. But Dieste was an engineer: the effect may be wondrous, but the science is sound. It was the very firmness of his understanding of the laws of physics that enabled him to invent these new places.

The role of technology and structures is essential to understanding Dieste's highly original work. In his development of structural form, use of materials, and construction techniques, Dieste was ahead of his time, surpassing his contemporaries in Europe and the United States. For this alone he deserves distinction. However, Dieste was driven by concerns broader than the strictly technological—concerns for architecture and humanity. These elements are bound together seamlessly, rather like the pieces of a beautiful and carefully crafted puzzle; he used technology as the key piece to hold the other parts in place. By dismantling and then reassembling this puzzle, Dieste's creative genius becomes apparent.

### The Nature of Structural Invention

In an essay entitled "Intuition and the Springs of Structural Invention," Rowland Mainstone, an authority on the history of structures, considered the nature of structural innovation. He identified three forms of intuition that conspire to produce and develop new structural forms:

> Intuitions of structural behavior: a spatial awareness of stability and the geometry of structures, and a feel for the nature of the forces in a structure; a muscular, physical sense of structure
>
> Intuitions of structural action: a more refined view of structural behavior, the basis of the mathematical analysis of structure; the description of behavior in the quantitative terms of forces and moments, stresses and strains Intuitions of structural adequacy: a quasi-empirical view of structures, based on experience and practice[1]

Mainstone used these concepts to discuss the development of historic structures, concluding that pre-scientific-era structures relied primarily on intuiting behavior and adequacy. The great developments in structural typologies and forms from the eighteenth century onward—as iron, steel, and reinforced concrete evolved—were made possible by advances in the understanding of structural actions, which led to the establishment of calculation as the dominant tool for structural design.

It is often said of engineers today that they become absorbed in the process of calculation and do not develop the intuitions of structural behavior. A reluctance to rely on structural intuition meant that the development of new forms of shell structures in concrete was hampered: engineers were unwilling to design structures for which there were not explicit mathematical calculations.[2] Dieste demonstrated all three forms of structural intuition in abundance, and they can be seen throughout his work. The catenary forms of Dieste's structures show an intuitive sense of behavior. Dieste's goal for structure is a purity of form based on structural principles —an architectural and technical ambition: "The resistant virtues of the structures that we are searching for depend on their form. It is because of their form that they are stable, not because of an awkward accumulation of matter. From an intellectual perspective, there is nothing more noble and elegant than resistance through form."[3] The roofs and walls of Dieste's buildings are folded where they need to be folded. The long cantilevers of his roofs project because their forms allow them to. Part of the joy of Dieste's work is in understanding the clarity of his structures.

The lightness in his buildings comes from a refinement of form achievable only by a rational mathematical analysis of behavior conditioned by evolution and experience. At the University of the Republic in Montevideo, Dieste developed an enthusiasm for the potential of mathematics as a tool for understanding the physical world: "I am very passionate about the possibilities of understanding reality by a physical-

mathematical language."[4] Throughout his career, he continued to study and research the behavior of his structures, refining the calculation methods used in designing them and developing his sense of structural action.[5]

Many of the buildings considered by Mainstone were monumental buildings constructed at great cost. The work of Dieste, on the other hand, was always constrained by limited resources. His concern was for both an economy of means and what he described as a search for "cosmic economy," by which he meant that things should be in accord with the profound order of the world. This search for economy led Dieste to create a unique repertoire of construction processes and technologies. In addition to a structural intuition, Dieste shows what could be described as a "constructive intuition"—an ability to perceive the evolution of a form through a clear understanding of its making.

### The Development of a Constructive Intuition

In most building projects there is a separation, a disjunction, between those who design and those who build. Mainstone's analysis focuses mostly on designers. Dieste, however, was both designer and builder. In his approach, he resisted the notion that the simplest way forward lies in finding and then adapting an existing solution to an ostensibly similar problem (a reliance on intuitions of structural adequacy). He felt that each problem should be studied in its own terms and with respect to its context: "I believe that we must contemplate each problem independently, keeping in mind the conditions of our circumstances and environment."[6]

Dieste acted in opposition to a persistent condition in the developing world, as it aspires to emulate the developed world, to import technology that is often costly and inappropriate to its needs. Such actions tend to increase the dependence of developing countries yet maintain the division between them and the developed world. Dieste was not convinced that economic progress at any cost was always beneficial. In his view, there was an important difference between economic and human development. Economic development is often driven by national statistics, such as the productive output per capita or the average standard of living, rather than by human fulfillment. As a young man touring northern Europe, Dieste observed the adverse effects of economic development in the impoverished, cramped, and unhealthy living conditions of factory workers in industrialized cities. The quality of life of these workers was worse than that of their superficially poorer rural counterparts in South America, who at least enjoyed access to clean air, fresh food, and open space. In Dieste's view, only Uruguay could deal with the sociological and technical challenges of its own development. Progress lay within its control.

1 Rowland Mainstone, *Intuition and the Springs of Structural Invention: An Essay in Structure in Architecture* (Aldershot: Ashgate, 1999), 17–26.

2 In the earlier part of the twentieth century, there was a great deal of debate over ways of developing and improving structures, particularly those utilizing reinforced concrete. This debate concerned the role of mathematical analysis in the design of structures. Should structures be designed that could not be analyzed, or should the limits of analysis guide the development of new structural forms? See David Billington, *The Tower and the Bridge* (Princeton, N.J.: Princeton University Press, 1983), 214–16.

3 Eladio Dieste, "Architecture and Construction," 187 of this volume. Originally published as "Arquitectura y construcción," in "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 84–93.

4 Juan Grompone, "Eladio Dieste, maestro de la ingenería" (unfinished draft of a thesis, University of the Republic, Montevideo, ca. 1994), 5. Translations from Grompone are by Manuel Figeroa, formerly of the Department of Architecture, University of Edinburgh. Here, the original reads, "me apasiona la posibilidad de comprender la realidad a través del lenguaje fisico-matemático."

5 These methods are explained in two of his books: Eladio Dieste, *Pandeo de láminas de doble curvatura* (Deflection in double-curvature vaults) (Montevideo: Ediciones de la Banda Oriental, 1978), and *Cáscaras autoportantes de directriz cateneria sin timpanos* (Freestanding vaults of catenary directrix without tympana) (Montevideo: Ediciones de la Banda Oriental, 1985).

6 Eladio Dieste, "Technology and Underdevelopment," in Antonio Jiménez Torrecillas, ed., *Eladio Dieste: 1943–1996*, trans. Michael Maloy and Harold David Kornegay (Seville: Consejería de Obras Públicas y

fig. 164

fig. 164: Berlingieri House, Punta Ballena, 1946–47
fig. 165: Types of barrel vaults: a) vault spanning between side walls, b) barrel vault spanning between end walls, and c) freestanding barrel vault without walls or tympana
fig. 166: Eladio Dieste, Municipal Bus Terminal, Salto, 1973–74

Dieste used his considerable intellect to find a solution that suited the limited economic resources of his country. In doing so he created a new and unique means of construction rooted in the conditions of Uruguay. It was based on a re-evaluation of brick construction. He saw a potential in brick to demonstrate all the characteristics assigned to modern building: accuracy, efficiency, prefabrication, consistency, and analytical rigor. "For architecture to be truly constructed," Dieste maintained, "the materials should not be used without a deep respect for their essence and consequently for their possibilities. This is the only way that what we build will have . . . cosmic economy."[7] Beyond this constructive intuition, Dieste's "cosmic economy" was also imbued with a serious regard for humanity and the consequences of development.

### Innovation in Structural Form and the Expression of Form: Freestanding Vaults

Dieste's first experience with brick shells came with the building of the Berlingieri house in Punta Ballena of 1946 (fig. 164). He was retained as structural consultant to the Spanish architect Antoní Bonet. Dieste proposed replacing the intended concrete shell roof with a thin brick vault spanning 20 feet. This application of brick was clearly new to Bonet, and at first he was skeptical, worried that Dieste was suggesting a traditional heavy masonry vault. Dieste later asserted his own innocence of earlier constructions in ceramics,[8] and indeed appears to have been thinking in purely structural terms of a simple thin shell in compression, of a substitution of brick for concrete.

The success of this project led Dieste to further explore the possibilities of thin brick vaults. There was sufficient commercial interest in these explorations for the engineer to form in 1956 Dieste y Montañez, S.A., with Eugenio Montañez (1916–2001), a friend from his student days. Through this firm, Dieste expanded the potential of brick beyond its use as a mere replacement for concrete in shell structures. He created a structural form that he described as a freestanding vault of catenary directrix without tympana. Dieste's forms distinguished themselves from traditional masonry vaults, which were heavy structures bounded by walls and buttresses. Dieste's vaults are lighter, free from buttresses and supporting walls, often simply roofs supported on the minimum possible support for stability.

Dieste's vault exploited the geometry of the arch for both architectural and structural purposes. The catenary geometry of the vault[9] allowed the thickness of the vault to be kept to a minimum, generally only one brick or clay unit in thickness with a thin covering of dense concrete mortar.[10] What distinguishes Dieste's innovations and serves to demonstrate his constructive intuition was the realization that brick masonry has significant practical advantages over concrete:

> Brickwork is around 20 percent lighter than concrete.[11] In arches, the greater part of the stresses are due to the dead weight. Lighter materials result in lower stresses, lighter formwork, and less steel reinforcement.
> When building in brick, most of the structure is already hardened when cast. Thus formwork can be stripped more quickly.[12]
> Brick vaults use less cement, a material imported to Uruguay and thus relatively expensive.
> The weathering characteristics of brick are such that it shows less degradation with age.
> The hygroscopic properties of brick help control environmental conditions inside buildings constructed primarily of this material.[13]

Transportes, 1996). Originally published as "Técnica y subdesarrollo," *CEDA: Revista del Centro de Estudiantes de Arquitectura* (Montevideo) 34 (Feb. 1973): 1–5.

7 Dieste, "Architecture and Construction," 187 of this volume.

8 "I had no idea if ceramics had been used in similar structures nor had I come into contact with the Catalan vault." Dieste, quoted in Grompone, "Eladio Dieste," 8.

9 A catenary is the natural sag into which a cable will deform under the action of its own weight. The stresses in the cable will be in uniform (axial) tension. This is the most efficient stress condition. By inverting the shape of the cable, the catenary geometry for an arch structure is obtained, in which case the stresses are in uniform axial compression. For further information, see Waclaw Zalewski and Edward Allen, *Shaping Structures* (New York: John Wiley, 1998).

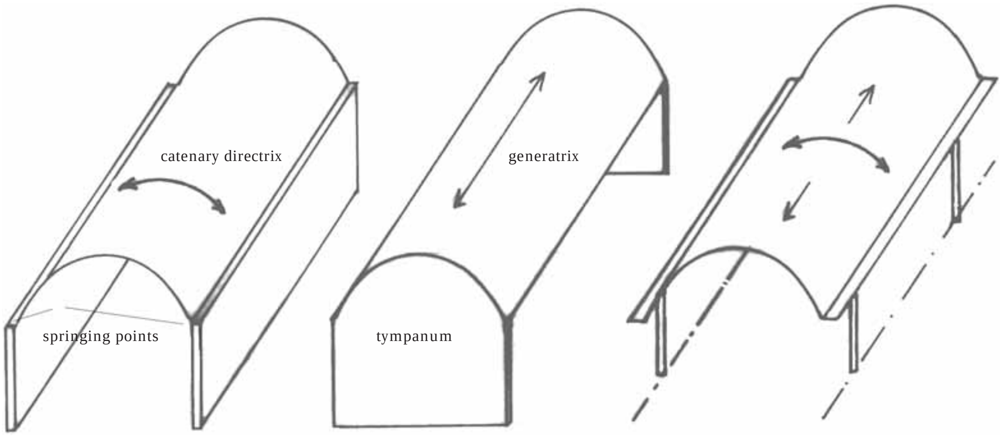



fig. 165 a) b) c)

fig. 166

All structural forms based on the arch require that the ends, or springing points, be braced to resist the horizontal thrust and thereby prevent horizontal movement. In traditional vaults, heavy walls and/or buttresses at the springing points or horizontal ties between the springing points are used to restrain this thrust. For aesthetic and structural reasons, neither solution was acceptable to Dieste. Using buttressed walls increases the mass of the construction and embeds the vault into the walls, anchoring it firmly to the ground. Buttresses can be avoided by using ties; however, the tie suggests a horizontal plane at the level of the springing points, which interferes visually with the expression of the underside of the vault. As Eduardo Torroja said, "The tie is always ugly."[14] Dieste avoided the use of walls, buttresses, or ties by manipulating the geometry of the vault, folding the surface of the vault to form thin but wide horizontal edge beams (fig. 165).[15] The edge beam cantilevers from the side of the vault, supported by steel reinforcement and transferring the thrust from the vault to reinforced concrete piers. Pre-stressed steel reinforcement is used to resist the tensile bending stresses that develop in the edge beam. The stiff edge beams allow the vault to become effectively freestanding, spanning, as a barrel vault, between discrete vertical buttresses.[16]

The shape of Dieste's vaults eliminates the need for either end walls or stiff arches and indeed celebrates their omission by allowing the vault to cantilever at its ends over the supports, further disassociating the roof from the side walls. It is these spectacular cantilevers that create such great excitement in Dieste's structures and lend a new structural expression to brick—one of lightness, in direct contrast to its traditional perception. Dieste was able to achieve this lightness primarily because of his choice of catenary geometry. Any other form of vault—for example, elliptical, parabolic, or circular—would try, under the load of its own weight, to deform into the catenary shape,[17] and thus require a tympanum or stiff arch to coerce the vault to maintain its shape.

Dieste exploits the structural capabilities of the barrel vault, allowing it to span as far as possible and thereby to minimize the vertical support structure (fig. 166). Although this leads to dramatic architectural expression, he is also making the structure work as hard as possible. In doing so, he reduces the resources used in the construction of foundations and vertical structure. The form produces an architecture that is simultaneously invigorating, structurally expressive, and frugal in materials and resources: the result of Dieste's search for cosmic economy. He has redefined the language of masonry construction from heaviness and mass to lightness and efficiency.

Barrel vaults exhibit two distinct forms of structural behavior. Across the directrix (the lateral direction), the vault

10 Catenary forms were developed in concrete by others such as Freysinett, Torroja, and Maillart. For further discussion, see John Ochsendorf's essay on pages 94–105 of this volume.

11 Many texts on structural engineering provide data on the weights of construction materials. For example, see D. L. Schodek, *Structures* (Englewood Cliffs, N.J.: Prentice Hall, 1980), 88.

12 The masonry unit absorbs moisture from the mortar used to fill the joints, causing it to harden more rapidly.

13 The full list of advantages appears in Antonio Jiménez Torrecillas, ed., *Eladio Dieste*, 34–36. Originally published as Eladio Dieste, "Acerca de la cerámica armada," *Summa* (Buenos Aires) 70 (Dec. 1973), 45. It is considered more fully here in John Ochsendorf's essay on page 103 of this volume.

14 Eduardo Torroja, *Philosophy of Structures* (Berkeley: University of California Press, 1967), 169.

15 The thickness of the edge beam is generally similar to that of the vault itself, namely one brick with a mortar topping. The "structural" depth, resisting the thrust of the vault, is the horizontal projection of the edge beam.

16 In many reinforced and pre-stressed concrete barrel vaults, additional support is required at the ends. According to Mario Salvadori, "barrels should be supported on end walls or stiff arches so as to avoid costly buttresses or interfering tie rods." *Why Buildings Stand Up: The Strength of Architecture* (New York: W. W. Norton, 1980), 191.

17 For relatively shallow vaults, the parabolic section is, however, relatively close to the catenary form.

fig. 167: Eladio Dieste, Massaro Agroindustries, Canelones, 1976–80, sections and elevations
fig. 168: Massaro Agroindustries, cantilever vaults
fig. 169: Massaro Agroindustries, part section through vault
fig. 170: Eladio Dieste, Refrescos Del Norte, Salto, 1977–80, vault and window detail

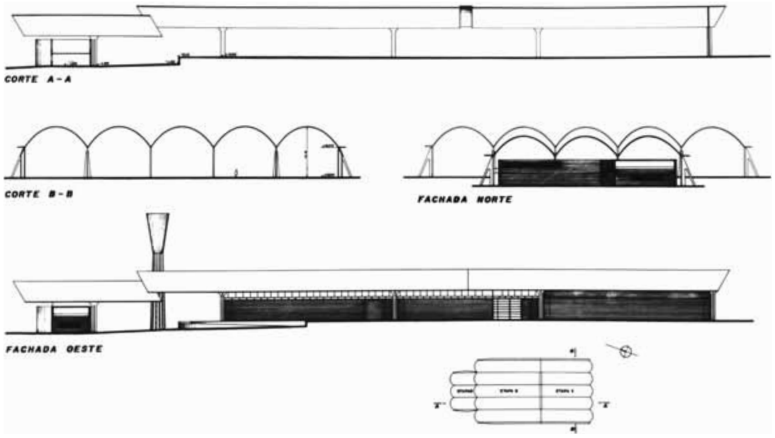



fig. 167

experiences axial compression. Along the generatrix (the longitudinal direction), the vault acts as a beam, and varying tensile and compressive bending stresses occur throughout the depth of the vault (fig. 167). Brick is a brittle material and will crack under tensile bending stresses; using pre-stressed steel reinforcement to pre-compress the vault counteracts the tensile stresses and thus prevents cracking. The position of the pre-stressing depends on the bending moments of the vault. Between the supports, tensile stresses will occur in the lower parts of the vault, while over the supports the tensile stresses will develop in the crown.

Perhaps the best example of the freestanding vault is the warehouse of Massaro Agroindustries, built in Canelones between 1976 and 1980 (fig. 168). The building is essentially a very large brick canopy supported on concrete columns over an open-sided storage area. The main part of the building consists of five parallel vaults, each 377 feet long and 42 feet wide. The roof spans 115 feet between columns and has a 54-foot cantilever at one end that projects over a lower vault covering the offices. The lower vault sits on a central row of concrete columns and cantilevers 43 feet on either side. The overlap of the two cantilevered vaults creates a powerful, dynamic juxtaposition.

The ground conditions were poor, requiring expensive piled foundations; the solution Dieste adopted minimized the number of columns and reduced the foundation costs.[18] The vaults were only 4 inches thick, consisting of 3-inch-thick hollow brick and 1-inch-thick reinforced sand and cement mortar (fig. 169). This very thin arch continues uninterrupted for the full length of the vaults and is clearly visible at the ends of the cantilever. The vault, unencumbered by any of the traditional accessories of barrel vaults—buttresses, tympana, or edge beams—expresses itself as a pure folded surface form, hovering above the ground.

Dieste used these freestanding vaults in many different applications: bus stations, warehouses, factories, and shopping centers. In most cases the form of the vault is clearly visible and separated from the support structure. Where a building is enclosed, the external walls stop short of the underside of the vault and glazing fills in the gap. The glazing is installed using a minimum of framing and usually no vertical mullions. The glass spans between the wall and a recess within the underside of the vault, deliberately avoiding any suggestion of support to the vault either by vertical mullions or by curved framing on the end walls that might suggest a stiffened edge. The vaults read as continuous through the enclosure (fig. 170). Therefore the elevation of the roof is also the cross section—a clear and unmistakable exposition of the structural form and its remarkable thinness.

Dieste's methods of pre-stressing the freestanding vaults were in themselves innovative. The lightness of the vault relies on practical and efficient construction methods. Pre-stressed concrete is generally perceived to be the more sophisticated brother of reinforced concrete.[19] Again, at first glance, the idea of applying a relatively complex technology to a crude, handmade material in a developing country that lacked the resources to buy the proper equipment would have been discounted by most "pragmatic" engineers almost immediately. Dieste saw the opportunity to exploit the cross section of the vault for great expression and economy of means, provided he could resolve the construction difficulties associated with the bending of the vault. He could deal with the problem of tension in a brittle material in either of two ways: by increasing the amount of steel reinforcement or by pre-stressing.

Reinforcement acts by strapping across the cracks caused by tensile stresses.[20] Adding more conventional reinforcement would have increased the thickness of the vaults considerably, in turn increasing the weight and the forces at the springing points, resulting in a heavier, less efficient, and less expressive form.

Pre-stressing works by inducing a state of compression that counteracts the tensile stresses. It creates a more comfortable stress condition, one that respects the nature of the material rather than repairing it. Therefore, the problem became one of finding a method of pre-stressing that did not use expensive proprietary equipment, maintained the overall thinness of the vaults, did not need expensive anchorages, and did not alter the construction of the vault significantly.

fig. 168

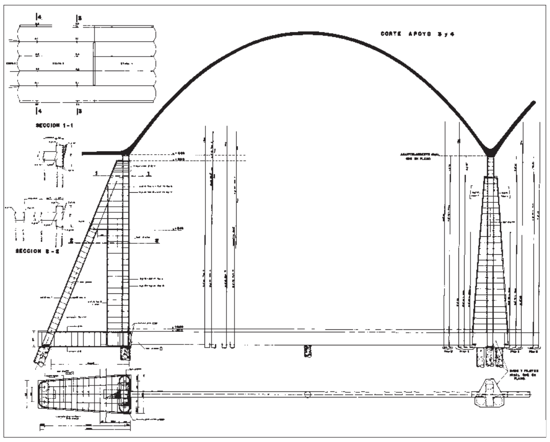


fig. 169

fig. 170

Conventional pre-stressing requires anchoring a steel cable at one end of a structure, stretching it by using a hydraulic ram at the other end, and then locking the tension in the cable against the hardened concrete structure. Pre-stressing has actually been used for thousands of years—for example, the heated iron bands placed around cart wheels, which contract as they cool, clamping the wooden parts together. Dieste developed various techniques of pre-stressing with the same inherent simplicity. To apply pre-stress force along the crown of the vault, loops of pre-stressing wire were placed on top of the hardened brickwork prior to the application of the final layer of concrete mortar. The ends of the loops were attached to steel reinforcement built into the vaults, forming a solid anchorage. Between the anchorage ends, the wires are free to move. Pre-stress force is applied by simply pinching the loops together at their midpoints, deforming the loop into a figure eight, then binding them together. The forces required to deform the wire and hence induce the pre-compression in the brickwork are less than those needed to stretch them axially. A simple, manually operated screw jack designed by Dieste is used to apply the force. The precise dimensions of the loop are critical. The degree of pre-stress is determined by the distance between the two sides of the steel loop at its midpoint. As the length of the loop increases, the distance between the sides of the loops also increases (fig. 171). This simple process allows the pre-stressing loops to be laid concentrically; the degree of pre-stress can be allowed to diminish as the distance from the support increases and the bending stresses decrease.

Although somewhat unorthodox, Dieste's technique has advantages over the more conventional methods of pre-stressing:

> The large radius at the ends of the loops allows an even distribution of pre-stress across the vault and eliminates expensive anchorages.[21]
>
> The pre-stressing equipment is very simple and can apply stress to a group of wires of differing lengths simultaneously.
>
> There is a simple relationship between the width and length of the loop, and therefore the required extension of the wire is easily checked.
>
> There is less loss of pre-stress due to mechanical slip and locking off than in conventional systems.

This system also ensures that the thickness of the vault does not have to increase to accommodate the anchorage details. In 1970, the renowned engineer Ove Arup, writing on the future of pre-stressed concrete, noted that "Anchorages could be eliminated by providing the pre-stress using looped steel and jacking across a hole left in the structure and subsequently filled." [22] He was cautious and went on to qualify the idea, saying, "The manufacture of such loops of accurate length and strength must be mastered and the loops made available before even the economic validity of the idea could be tried out." [23] Dieste had clearly succeeded in developing both the technology and economics of pre-stressing before Arup had even formulated the idea.

In the lower parts of the vault, between the supports, tensile bending stresses occur in the valleys between parallel vaults. Here a slightly different but nonetheless simple method of pre-stressing was developed by Dieste. Pairs of steel loops are anchored by attachment to reinforcement at each end of the vault. The ends of the loops overlap each other near the middle of the vault. A simple ram incorporating a modified truck jack is inserted into the overlap of the loops. The action of the ram pushes the ends of the loops apart, causing the wires to stretch. Once the gap between the ends of the

18 The firm of Dieste y Montañez also specialized in foundations; Dieste designed innovative piling equipment and foundation systems.

19 Pre-stressed concrete requires better quality concrete and steel, more careful design, and expensive hydraulic jacking equipment and anchorages, and it is most often carried out by specialist contractors.

20 In most reinforced concrete structures, cracking will occur in regions of tension at normal working loads. Correct sizing and placement of the steel reinforcement ensures that the width of the crack is minimal.

21 Using conventional anchorages creates points of high stress concentration that require thickening and heavy reinforcement.

22 Ove Arup, "The Potential of Pre-stressed Concrete," *Concrete* (June 1970): 256–57. Arup worked for contractors specializing in reinforced concrete early in his career, before going on to create one of the largest and most successful firms of consulting engineers in the world.

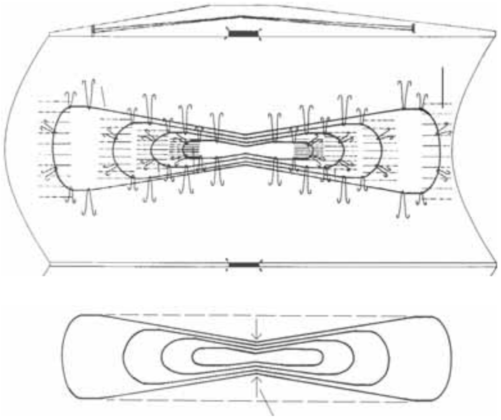


fig. 171

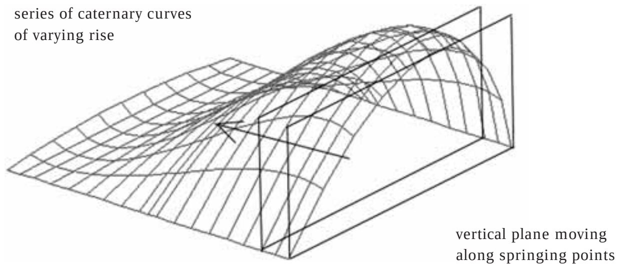



fig. 172

loops has reached the required extension, a steel block of predetermined length is inserted between the ends of the loops and the ram is removed. The block prevents the steel loops from contracting and hence locks in the pre-stress. In both pre-stressing methods, the vault is finished with the application of a concrete mortar topping over the pre-stressed steel.

### Further Developments in Structural Form: Gaussian Vaults

The freestanding barrel vaults developed by Dieste had their roots in the rediscovery and reinvention of a traditional structural form. What form of construction would evolve if it were based on first principles? In studying the barrel vault, Dieste had started on a journey that would lead to the purest expression of structural surface forms, of his desire to "resist through form": the Gaussian vault.

Barrel vaults have some disadvantages that limit the extent of their application. The rise is high—typically a quarter of the span. They have relatively short spans across the directrix—up to 50 feet in practice—and rely on pre-stressing to span longitudinally. This 4:1 ratio of span to rise ensures that the compressive stresses in the brickwork are very low. As the ratio between the span and the rise increases as the vault becomes shallower, the compressive stresses increase. Even at a ratio of span to rise of 10 (a typical ratio for Gaussian vaults), the stresses can be low. Theoretically, based on the catenary geometry, these low stresses imply that much larger spans are possible.[24] Because the vault is in compression, these large spans do not need to be pre-stressed. However, if the span increases without a corresponding increase in thickness, a second form of behavior dominates—namely, buckling. The vault will collapse in on itself due to buckling instability at much lower levels of stress than produced by its own weight.

Buckling instability can be prevented in a variety of ways. By increasing the thickness of the vault, the resistance to buckling increases but adds more weight to the structure and increases the thrust at the springing points. The actual stresses in the brickwork do not decrease.[25] An alternative method is to incorporate stiffening ribs. In this case, the vault acts as a curved slab, spanning between the ribs that in turn become heavier and concentrate the forces at the springing points. The surface form is lost in the process, and the vaults once again become heavier and more cumbersome.

For Dieste, neither of these approaches was satisfactory. His solution again lay in manipulating the surface of the vault. To resist buckling, it is necessary to increase the stiffness of the vault in areas where buckling will occur—at the middle sections. In Dieste's Gaussian vaults, the surface is warped with transverse undulations that deepen toward the middle of the vault and provide the necessary stiffness. The surface geometry changes continuously. To understand the form of the vault, it is useful to imagine a vertical plane between the springing points (fig. 172). Within this plane, a catenary curve is drawn. If the plane is allowed to move along the springing points, then the surface described by the motion of the curve is the same surface as a barrel vault. If, however, the rise of the catenary varies gradually as it moves, then an undulating surface is described. The undulations are most pronounced at midpoint, diminishing to become completely flat at the springing points. The undulation at midsection provides the necessary buckling resistance, while the flattening at the springing points allows a simple connection with the side walls.

The Gaussian vault can be thought of as a series of connected catenary arches with varying rises that share a common springing. At any longitudinal cross section the vault is subjected to axial compression, but the magnitude will vary between sections as the rise of the catenary changes. The variation in axial compression generates shear stresses between the segments, resisted by steel reinforcement placed between the brick units. Thus a highly refined structural geometry based on structural principles evolves that uses a minimum of material, distributed efficiently along the length of the vault and across its section.

In developing the Gaussian vault, Dieste avoided an empirical approach to design based on rules of thumb and precedents associated with traditional masonry vaults—advanced, as Mainstone described, through intuitions of structural adequacy. Indeed, these "rules" would have discouraged Dieste's ambitious forms. Rather, his approach led to the

fig. 171: Massaro Agroindustries, pre-stressing steel for cantilever vault
fig. 172: Development of Gaussian vault form
fig. 173: Eladio Dieste, Port Warehouse, Montevideo docks, 1977–79


fig. 173

discovery of a form with an uncontrived and natural beauty. The route took him logically—and almost inevitably—to the Gaussian vault. It was directed by a series of preconditions: the advantage of using bricks as an appropriate material in Uruguay, the understanding that catenary forms will produce the most efficient structure, and the belief that the most elegant structures come from surface forms.

Dieste employed Gaussian vaults "as the farmer uses the tractor,"[26] for heavy work, often in buildings constructed for agricultural purposes—low-cost buildings by any definition. In a typical Dieste building, the roof consists of a series of vaults creating a wavelike form of repeated undulations. This wavelike nature of the vaults provides the opportunity for top lighting, similar to that created by a sawtooth roof. In the areas of overlap between successive vaults, crescent-shaped slots along the span are glazed. The underside of the vault reflects and diffuses natural light into the building.

Each wavelike form is constructed using a single piece of formwork supported on a movable steel frame. Once the bricks have been set in place, the formwork can be removed after twenty-four hours and reassembled to support the construction of the adjacent vault. As formwork comprises a major part of the overall cost of constructing a building, its reuse rendered Dieste's method highly economical. Various other innovations in the construction process, such as the jacking system that allows rapid and accurate leveling and positioning of the formwork, increased the efficiency of this method as well.

To date, the largest Gaussian vault constructed according to Dieste's system forms the roof of the Port Warehouse at the Montevideo docks (1977–79) (fig. 173). Dieste y Montañez was awarded the contract by winning a competition to design a replacement for the original warehouse after it was badly damaged in a fire. Most entries were based on demolition and reconstruction; Dieste's proposal, by contrast, was to retain and repair the existing walls and construct a new roof using a Gaussian vault. The vault spans approximately 164 feet between the side walls, with a maximum rise of 21 feet. The roof consists of fourteen waves, each 18.6 feet in width (fig. 11). The overall thickness of the vault is 5.1 inches, 4 inches of which is formed of hollow clay block and the remaining 1.1 inches of sand/cement topping. The vault is supported on a projecting concrete edge beam. The depth of the edge beam varies to accommodate variations in the dimension between the side walls, thereby allowing the reuse of a single formwork for each section of the vault.

In this type of construction, the edge beam also contains the anchorage for the building's horizontal steel tie-rods (fig. 174). At the Port Warehouse, the ties were a necessary compromise, as the existing walls were not strong enough to support the thrust of the vaults, and the desire to retain the character of the walls precluded the addition of the extensive buttresses that would otherwise have been needed. The existing walls were reclad with a new skin of brick.

The walls at both ends of the warehouse were rebuilt to stop short of the underside of the vault. Dieste's characteristic minimal frame glazing was used as in-fill, allowing the thickness of the vault to be clearly expressed on the external elevations. By doing so, Dieste demonstrates that the walls do not provide any structural support to the vault; as with the freestanding barrel vault, he avoids the tympanum.

The windows at either end of the warehouse are quite different from each other, as they respond to different conditions. Here there is a hint of Dieste's feeling for the

23 Ibid.

24 For example, the stress will be approximately 435 lb/in2 in a catenary vault with a span of 330 feet and rise of 33 feet—well below the compressive strength of the brickwork.

25 The stresses in the vault are due to dead weight. The dead weight is distributed across the thickness of the vault. The weight of the vault is proportional to its thickness. Therefore, as the thickness increases, dead weight increases and the stress remains constant.

26 Remo Pedreschi, *Eladio Dieste*, The Engineer's Contribution to Contemporary Architecture (London: Thomas Telford), 46.

fig. 174: Port Warehouse:
a) longitudinal section at mid-span, and
b) vault sections
fig. 175: Port Warehouse, lateral view
fig. 176: Port Warehouse, high end wall window
fig. 177: Eladio Dieste, Church of Christ the Worker, Atlántida, 1958–60
fig. 178: Atlántida church, partial plan of edge beam and tie-rods within the troughs of the double-curvature vaults

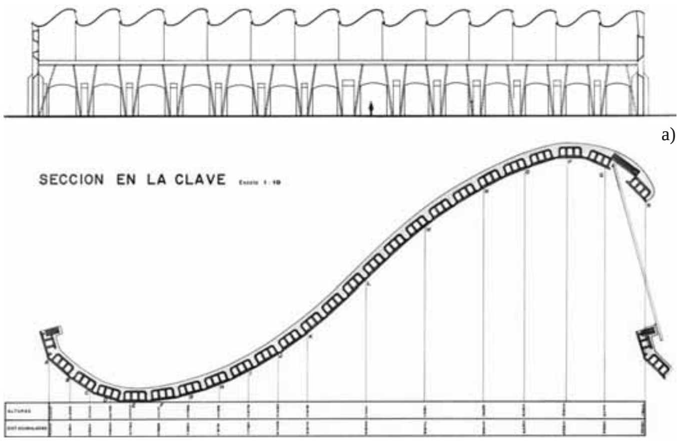


fig. 174


fig. 175


fig. 176


fig. 177

accuracy and precision of his "constructive intuition." The width of each wave is based on one-fourteenth of the span; thus the building starts and finishes on the leading and following edge of one wave. This is both pragmatic and expressive: pragmatic, in that this is the simplest and most effective way to use the formwork, avoiding its modification or the incorporation of special edge conditions; expressive, in that the windows allow the uppermost and lowest catenary curves of the vault to be seen in elevation, from both inside and outside the warehouse (fig. 175). From inside, by cross-referencing one end wall with the other, one can see the locus of the catenary curves used to generate the overall geometry of the vault. The walls themselves, instead of finishing at a horizontal line at the eaves, curve upward following the curve of the vaults, parodying the curved shape of the rooflights and heightening the dislocation between the roof and walls—the separation between traditional and modern construction (fig. 175).

The warehouse project was technically ambitious given the size of the building and the circumstances of its reconstruction. Fitting the roof onto the existing walls added complexity to the project, creating an interface between the prefabricated formwork and the traditionally constructed walls. This move underscores a recurrent theme in Dieste's work—the desire to respect the qualities he sees in the work of others.[27]

## Towers

Dieste's constructive intuition can also be seen in the design of towers. Like vaults, towers have an important historical significance, both pragmatic and symbolic. Traditional masonry towers relied on their mass for stability. The towers that Dieste designed have a language of their own, one in which the traditional associations of the material are again inverted, from bulk and heaviness to slenderness and lightness. The towers were most often used for industrial or agricultural purposes, such as storing water. Water is the lifeblood of an agricultural economy, giving the towers, constructed from the earth that the water feeds, additional symbolic presence. Throughout the twentieth century, many concrete towers were built; the challenge was in their construction—to produce economic

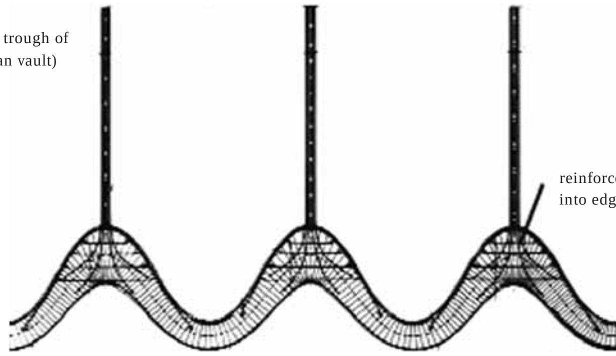


fig. 178

formwork and efficient techniques for pouring concrete at great height. Sophisticated techniques such as slip forming and climbing formwork were used, requiring a specialized construction plant and temporary support structures. Innovatively, the use of brick in Dieste's towers eliminated the need for formwork. In the same way that he developed pre-stressing techniques, Dieste developed construction methods for his brick towers that were profoundly elegant in their simplicity and ease of construction.

The tower shaft is a slender surface of revolution, forming gently tapering, truncated cones of reinforced brickwork typically 6 to 10.5 inches in thickness (see fig. 183). The gentle taper of the tower shaft eliminates the need for the temporary support of the brickwork. During construction the masons simply follow a series of wires used to describe the inclined surface of the tower. The shaft is constructed as a series of vertical ribs of bricks connected using staggered cross-ribs of reinforced brick. This arrangement creates a series of vertical slots in the shaft.

These slots are key to the design and construction of Dieste's towers. In a tower with a tapering solid shaft, the diameter of successive courses of brickwork becomes progressively smaller, requiring continual readjustment of the brick courses. In Dieste's works, the taper of the shaft is achieved by tapering the slots rather than the ribs. The width of the vertical ribs can therefore remain constant throughout the height of the shaft, avoiding the need to cut the bricks. Furthermore, the slots provide a simple device to support scaffolding beams, which in turn support the working platform for the bricklayers. Thus the working platform is supported simply and directly from the shaft, moving up in increments as the tower rises and eliminating the need for extensive scaffolding. The perforated nature of the shaft helps to reduce the wind load on the tower, and the staggered pattern of slots emphasizes the taper and the slenderness of the shaft.

### Accuracy and Precision

Brick evolved from a tradition of craft-based construction quite different from that of concrete and steel, which evolved from more engineering-based investigation. It seems that Dieste wanted to demonstrate that brick was not the poor relation of these "modern materials," that brick could speak for itself in the same terms of accuracy and precision. In Dieste's hands, brick is not only a material for factories and warehouses, where its beauty comes from the pure rationality of its use, but also one capable of conspicuous refinement. The churches at Atlántida and Durazno bear witness to this accuracy and precision.

The highly dynamic form of the Church of Christ the Worker at Atlántida of 1958–60 imbues visitors with wonder in the way that grand cathedrals do (fig. 176). Although approached as an engineer to assist with the construction of the church, Dieste used his skills to create a remarkable building. Through care, accuracy, and precision of construction, he elevated the process of building in simple brick—a material familiar to the poor agricultural workers who formed the congregation—to create an effect normally reserved for expensive stone and stucco. Consider only one detail: the connection between the wall and the roof of the nave. A Gaussian vault without glazing, the roof sits directly on top of the side walls. These two surfaces meet at the eaves, one undulating in a vertical plane and the other undulating in a horizontal plane. The wall and the roof work together, in effect forming a two-pinned portal frame. The structural action can be read in the section of the building and approximates to the shape of the bending moment diagram for the structure. The junction between the wall and the roof is a most lucid exposition of Dieste's desire to "resist through form." The crest of the undulation on the inside of the wall coincides with the trough of the Gaussian vault. A hidden horizontal tie runs within the trough, tying the side walls to each other. The ends of the tie connect to an edge beam on top of the walls. The edge beam follows the curve of the wall but widens at the junction of the tie. This detail, easily overlooked in the building, is revealed in a drawing of the structure (fig. 177). It has an unmistakable organic nature, like sinew growing around a bone. Again, the shape of the edge beam approximates the bending moments in the edge beam.

fig. 179: Atlántida church, roof during construction
fig. 180: Atlántida church, meeting of wall and roof on the interior
fig. 181: Eladio Dieste, Church of St. Peter, Durazno, 1969–71, interior
fig. 182: Durazno church, junction of nave, presbytery, and side aisle

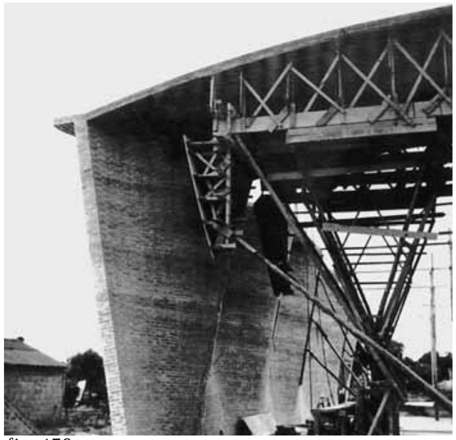


fig. 179

It would be wrong, however, to think this building's form is created solely through the representation of structural action. The juncture of the wall and roof not only deals with the complex collision of the two curved surfaces, but it also resolves the difficult interface between two different construction methods—one of traditionally laid brick and the other of shell construction using prefabricated formwork. The accuracy of the two side walls, each 23 feet high by 105 feet in length, in relation to one another is critical for the insertion of the formwork. In order to fit the formwork, these walls have to be constructed to an accuracy of one- or two-tenths inch in both the horizontal and vertical dimensions (fig. 178).[28] This level of accuracy is successfully maintained in the building. Nothing is hidden: the surfaces of the wall and roof simply meet. There is no compensating interface such as a shadow gap or cornice, habitually incorporated in buildings as a practical compromise that concedes the attainment of perfection before attempting it (fig. 179).

This precision is not the predilection of a pedantic technologist obsessed with the minutiae of construction. The ultimate success of the church at Atlántida consists precisely in the achievement of the necessary accuracy in its making. The underside of the vault presents a patterning of joints that is literally the three-dimensional manifestation of a wire-frame model. The pure expression of surface form, unencumbered by any framing or ribbing, creates a richness in the abstract quality of the constantly changing juxtaposition of surfaces. The organization of the construction using simple, familiar materials and indigenous skill, elevated in application almost to the limits of perfection, has a spiritual quality that speaks directly to the ordinary working people of the congregation.

The discussion of accuracy and precision in the work of Dieste naturally leads to consideration of arguably his most technically complex project: the reconstruction of the Church of St. Peter in the city of Durazno of 1969–71. In execution and resolution it is quite distinct from the Atlántida church, and in some ways it stands out as a unique piece in Dieste's portfolio. Nevertheless, there is a consistency in Dieste's philosophy of building that is easily and unmistakably read (fig. 181). As with Atlántida, the accuracy and precision in construction is breathtaking; in the church at Durazno, however, it is understated. To recognize it is to feel a sense of revelation.

The effort to create the unified quality of space by creating a continuity of surface is evident in the junction between the nave, side aisle, and presbytery. Four different surfaces meet at this point—the inclined nave wall, the wall of the presbytery, the roof over the side aisle, and the end wall of the side aisle—and none of these surfaces are at right angles to each other (fig. 182). There is no transitional node point to articulate the connection of these surfaces; neither cut bricks nor specially shaped bricks were used. Yet there is no break in the bonding pattern. The bricks are laid in stack bond arrangement with continuous vertical joints. The vertical joints in the nave wall align perfectly with those of the presbytery and also continue to run into the soffit of the aisle roof, then down the inclined walls of the side aisles. The bricks on the end wall of the side aisle are inclined at the same angle as those of the nave and presbytery wall to ensure that the corners between the presbytery wall and aisle walls are formed without cutting bricks. Thus, the vertical joints in the brickwork progress in an uninterrupted rhythm around the corner. As at Atlántida, this junction is also the critical interface between different constructional processes—between the more or less conventional brick walls, the reinforced brick slabs, and the heavy pre-stressed beam of the nave. Each of these elements requires different support conditions and construction methods, yet the resolution appears seamless. This juncture demonstrates Dieste's mastery of construction technique. It bespeaks the close relation he had with his workforce and their mutual respect. When complimented on the quality of this detail, Dieste's longstanding collaborator, Vittorio Vergalito, who was in charge of the construction, replied in a genuinely bemused manner, as if to say that these things are only as they should be: "What else can I do; if I make a mistake it is a mistake for one hundred years."[29]

The aspirations for both churches were architectural and sociological—the need to react against the pseudo-rationale of simplistic economics with the creation of meaningful

fig. 180

fig. 181

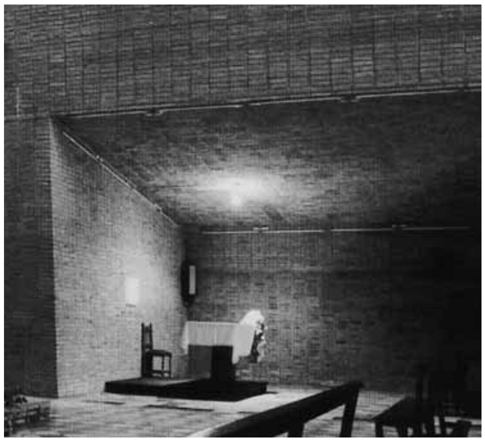


fig. 182

buildings. The resolution, via the rigorous logic of construction and the care and precision in their making, draws together all the layers of significance assigned to Dieste's work. As Dieste himself explained, "The rationalist who does not manage to produce architecture fails not because of an excess, but rather because of a lack, of true reason."[30]

## The Evolution and Development of Generic Structural Typologies

A defining characteristic of a successful technology is its continued evolution. New techniques must be able to exist past their initial novelty. Attempts by others to use reinforced and pre-stressed brickwork,[31] although technically successful, were rarely adopted because simpler techniques to do the same thing were available. Over the course of more than fifty years, Dieste y Montañez designed and constructed over 70 million square feet of building. Throughout this period, the firm became a traveling laboratory used by Dieste to test and develop masonry construction as a viable alternative to increasingly ubiquitous concrete and steel construction building practices.

The three main structural forms that Dieste created—the freestanding barrel vault, the Gaussian vault, and the perforated tower—developed incrementally through experience and practice to extend the limits of the technology and broaden its range of application. From the simple vaults at Punta Ballena of 1947, the freestanding vault evolved in a number of ways: for example, into the double cantilever vaults supported on a single row of columns, as seen at the Municipal bus terminal of 1973–74, and the highly improbable gas station canopy for Leggere and Barbieri of 1976, both in Salto.[32] In terms of scale, the 1,600,000-square-foot CEASA produce market in Rio de Janeiro of 1973 is notable. In the building for Fagar Cola of 1991–92, the vaults create an appropriately high-tech building in tune with the clean, highly automated operation of the plant.

The Gaussian vault has been similarly adapted and developed. External ties connected to extended vertical columns eliminated the need for internal ties or large vertical buttresses at the Don Bosco gymnasium of 1983–84, constructed on a particularly tight urban site in Montevideo. Another solution avoided the use of ties in the construction of the Growers' Pavilion at the CEASA market in Porto Alegre of 1971. Here the vaults incorporate a detail more typical in freestanding vaults: stiff cantilevered edge beams doubling as entrance canopies transfer the thrust of the vault directly to concrete buttresses. Perhaps the most dramatic evolution of the Gaussian vault is the horizontal silo, used to store bulk materials such as grain and salt. Its undulating geometry is developed using the same techniques; the only difference—critical nonetheless—is the extended height of the silos. The height may be more than half of the span, compared to one tenth of the span in other applications. The vaults curve to meet the ground and the thrusts transfer directly to the foundations of retaining walls. Here, form closely follows function: the geometry of the vault mimics the natural slope of bulk granular materials. The scale of these buildings is quite breathtaking. The most recent silo, at Nueva Palmira of 1996–97, has a cross section nearly 80 feet high and 148 feet wide. It consists of undulating vaults with an overall length of 465 feet.

The construction techniques used in towers took a great leap forward with the television mast in Maldonado of 1985–86. From agriculture to communications, the symbolism is obvious. Located close to the Atlantic coast, the tower is 197

27 This desire can also be seen in his work at the Church of St. Peter in Durazno.

28 A similar problem existed at the Port Warehouse at the Montevideo docks. The distance between the existing walls varies. The Gaussian vault spans onto a cast-in-place concrete edge beam, the width of which varies to provide a constant span for the vault.

29 Vittorio Vergalito, in conversation with the author, 19 September 1998.

30 Eladio Dieste, in his exposition on the Atlántida church, in Jiménez, ed., *Eladio Dieste*, 160.

31 See Remo Pedreschi and Braj Sinha's essay on pages 208–17 of this volume.

32 In structural terms this double cantilever is not a vault, as there is no arch behavior across its width. Its construction, however, relies almost entirely on the techniques used in vaults.

feet high with a 20-foot mast, yet is only 11.5 feet in diameter at its base—as slender as any concrete tower.

The large mall called Montevideo Shopping Center, constructed in 1984 and 1985, is effectively a catalog of construction techniques. Like projects of this type from the developed world, it demanded high-quality construction and strict attention to cost and program.[33] The project has free-standing and Gaussian vaults and pre-stressed undulating walls as well as some rather complicated foundations and an internal concrete frame. At its peak, Dieste y Montañez employed 350 workers on the site. The 106,000-square-foot building was completed in eighteen months.

Given the range of applications, the size of projects, and the scale of the structures used, Dieste's techniques have been tested extensively and proved to satisfy the criteria of modern construction—namely low cost, speed, repetitive procedures, high quality, and consistency.

In the United Kingdom and other parts of the developed world, reinforced masonry is still not used extensively. From the 1960s to the 1990s there was considerable interest in the use of reinforced and pre-stressed brickwork. Universities and some engineering practices began researching and designing brick structures. Progress, however, was slow. The eminent British engineer James Sutherland, in a paper delivered to the Institution of Civil Engineers, suggested that the potential application of reinforced brickwork was limited due to reluctance on the part of engineers: "One reason frequently given for the scarcity of examples of reinforced masonry in the U.K. is the lack of an adequate code of practice. If this is so it is a sad reflection on our independence of action as engineers."[34] Leading U.S. masonry consultant Clayford T. Grimm expressed similar views and considered there to be a number of constraints to innovation in reinforced brickwork.[35] He pointed particularly to the fragmentation of research and construction and the difficulties in introducing standards and codes of practice. Reinforced brickwork was trapped in the perception that it was a relatively poor substitute for reinforced concrete, and so it was only used in exceptional circumstances.

One particular form of construction in reinforced masonry that has had a limited degree of success is the post-tensioned diaphragm wall, pioneered by the British engineer Bill Curtin.[36] Tall, freestanding walls 26 to 30 feet in height, typically built in sports halls and assembly rooms, are stabilized against wind loads by vertical pre-stress. A series of steel rods anchored to the foundations runs through a cavity in the wall to a capping beam at the top of the wall. The wall is pre-compressed by stretching and anchoring the rod against the capping beam, usually using a calibrated torque wrench. The pre-compressions induced in the brickwork are comparatively low, and as a consequence the pre-stressing operations are much simpler than in conventional pre-stressed concrete. The post-tensioned diaphragm wall was hailed as a "breakthrough in brick design" by the British construction press and credited with having "revolutionized the structural qualities of brick work."[37]

In comparison with Dieste's work, Curtin's wall is considerably less ambitious. The pre-stress is used only to counter transient wind loads rather than the large bending stresses generated, for example, by a thin brick vault cantilevering more than 50 feet. The horizontal section of the wall is restricted to a simple rectangular box that remains constant through its height. Compare this with the stretched and distorted surface of the walls of the Church of San Juan

33 See Nadine Beddington, *Shopping Centres* (Oxford: Butterworth Architecture, 1991), 15–20.

34 Robert James Mackay Sutherland, "Brick and Block Masonry in Engineering," *Proceedings of the Institution of Civil Engineers* 70, part 1 (1981): 31–63.

35 Clayford Thomas Grimm, "Research and Innovation," *Masonry International* 2, no. 2 (1997): 36–37.

36 William George Curtin et al., *Structural Masonry Designers Manual* (London: Granada Publishing, 1984).

37 "Breakthrough in Brick Design," *Building Design* (May 23, 1986), headline.

38 The Church of San Juan de Ávila was based on a design for the Church of Our Lady of Lourdes, Malvín, Montevideo, designed by Dieste nearly thirty years earlier.

de Ávila in Alcalá of 1996.[38] At over 36 feet in height, they are taller than most post-tensioned diaphragm walls. There is a manifest difference in Dieste's innovations and those achieved elsewhere. This difference is a consequence of his habit of ignoring the restraints of accepted wisdom and of his readiness to discard conventional rules of thumb that, while intended to simplify, also serve to restrict one's field of vision.

The techniques developed by Dieste were used extensively in South America and more recently in Europe (particularly in Spain), where they were adopted for their economy, pragmatics, and beauty.[39] The engineer's construction methods have been successful because they have been applied, developed, and modified during a history of use that stretches over half a century and encompasses many varied applications. In Dieste's hands, brick is a material that meets all the requirements of a modern structural material; however, it also does more than that. His buildings remove the boundary between architecture and engineering; for Dieste, that boundary simply did not exist. Dieste could not divorce art and humanity from pragmatic engineering concerns; to have one without the other is to fail. His was a moral position, a position that considered architecture essential to a humane society: "Architecture is the shaping of space—something that is profoundly related to human life and deeply affects man's happiness."[40]

There is honesty in the work of Eladio Dieste. There, he brought all of his experiences—social, cultural, aesthetic, and spiritual—together. His innovations were not manipulations of technique for their own sake; instead, they were driven by a sense of honesty in materials and form, combined with a creative and moral responsibility. Dieste's life was a search for what he defined as "cosmic economy," to be in accordance with the profound order of the world. Through his work, he accomplished this.

39 In the early 1990s, Dieste was involved in a number of projects in Spain. See Pedreschi, *Eladio Dieste*, 122–40.

40 Eladio Dieste, interviewed by Damián Bayón and Paolo Gasparini, in Bayón and Gasparini, *The Changing Shape of Latin American Architecture: Conversations with Ten Leading Architects* (New York: John Wiley, 1979), 192.

fig. 183

# WATER TOWER

*Las Vegas Resort*, 1966

The 52-foot campanile of the church at Atlántida was Dieste's first tower, and was the progenitor of this, his first water tower, standing 89 feet. In both cases, the structure is a perforated cone in brick, though here, of course, the upper portion becomes solid to provide the 31,700-gallon tank. The simplicity of the form and the delicacy of the slight taper of the cone make these visually arresting objects. The penetrations yield a perceptual lightness but also serve in several practical ways: they diminish wind loads and provide support for minimal scaffolding during construction; the penetrations diminish in size as they ascend, so that the brick shafts can maintain constant size even as the diameter of the tower diminishes. Dieste staggered the perforations, as this gives the sense of a continuous surface rather than of individual bands.

fig. 183: General view
fig. 184: View inside the supporting cone

fig. 184

fig. 185

## WATER TOWER

*Refrescos del Norte, Salto,* 1979

Placed atop a supporting shaft similar to that at Las Vegas, the water tank of the Refrescos del Norte tower is an inverted cone, preserving an internal vertical passage. The walls of the 80-foot shaft are just 5.5 inches thick, and those of the tank, even thinner—a remarkable feat for this 13,200-gallon structure. The drawings of the tower show vertical and horizontal reinforcing throughout the shaft that allows the structure to act integrally in resisting both the vertical load and wind pressure.

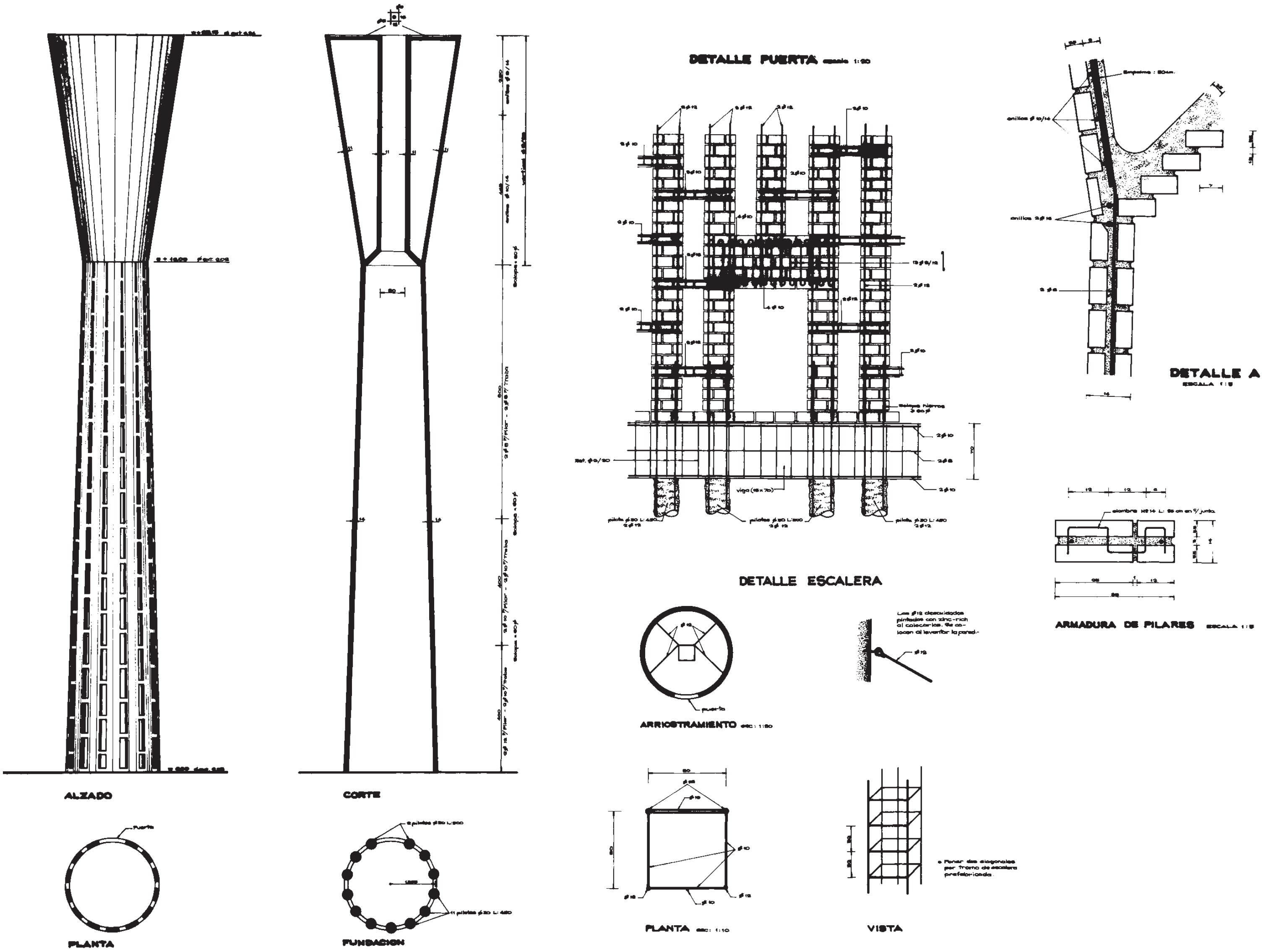



fig. 186

fig. 185: General view, with the Refrescos del Norte reception hall and production facility beyond

fig. 186: Plans, elevation, vertical section, reinforcing and door detail elevation, tank reinforcing detail. At the bottom of the door detail, in the center of the drawing, is the heavy steel-reinforced base to restrain outward pressure.

fig. 187: Photograph showing construction guide wires and the use of the penetrations to support scaffolding

fig. 187

fig. 188

## TV COMMUNICATIONS TOWER

*Maldonado*, 1985–86

Liberated from the heavy live loads created by the water tanks, the tower designed by Dieste for a television station is of notably slim proportions. The Maldonado tower, just 11.5 feet in diameter at its base, is stretched to a height of 197 feet, and is surmounted by an additional 20-foot concrete mast.

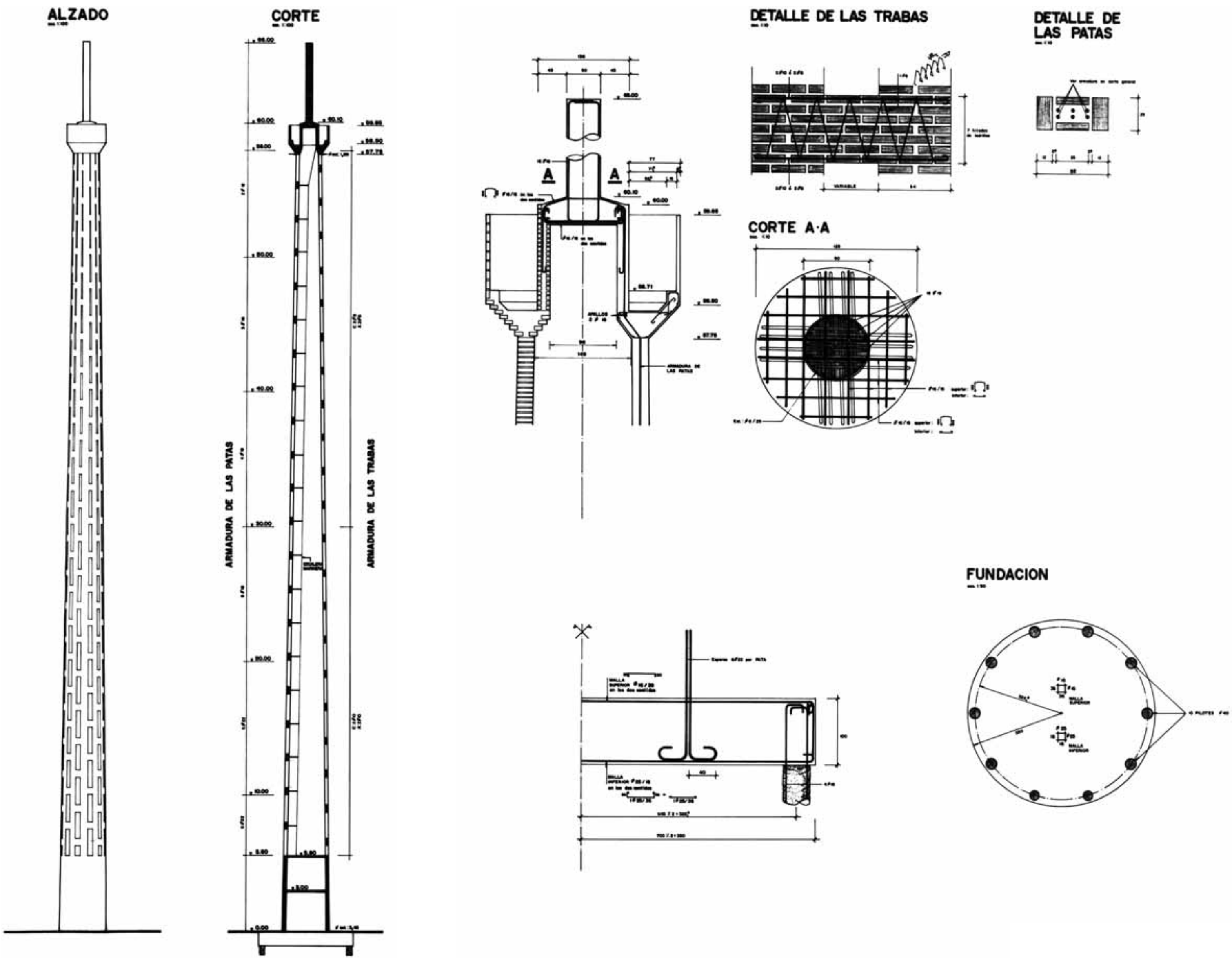



fig. 189

fig. 188: General view of the tower

fig. 189: Plan, elevation, vertical section, and details of the tower

fig. 190: Looking up through the shaft

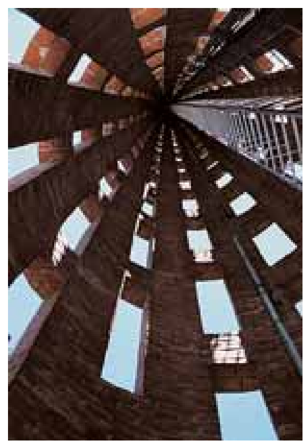


fig. 190

fig. 191

## DON BOSCO SCHOOL GYMNASIUM

*Montevideo*, 1983–84

To the great advantage of the gymnasium, this structure of discontinuous double-curvature vaults extends the internal columns of the building vertically in order to place the tie-rods above the roof, creating an unobstructed space. The strong façade facing a pleasant urban street, the lateral continuities of space, and the natural light from the skylights of the ceiling vaults provide a satisfying architectural experience.

*Collaborator: Esteban Dieste*

fig. 192

fig. 191: View of street façade

fig. 192: View from the balcony to the gymnasium

fig. 193: View from the playing floor to the adjoining spaces

fig. 193


fig. 194


fig. 195


fig. 196

fig. 194: View above the roof showing the extended columns and external tie-rods

fig. 195: View of vaults and skylight

fig. 196: View of the vaults and skylights. Note the tie-rods above.

fig. 197

# MONTEVIDEO SHOPPING CENTER

*Montevideo*, 1984–85, 1988

This 105,000-square-foot shopping center rests on a sloping site such that the entrances are located on the two levels within the building. The broad cross section is roofed by two 52-foot continuous barrel vaults at the sides and a 26-foot series of discontinuous double-curvature vaults at the center. The uncharacteristically high rise of these vaults gives them a distinctly warped appearance. Also uncharacteristic is the short span of the double-curvature vaults, but here they create a well-lit gallery through the center of the building. Additional light for the broader shopping areas is admitted through large lunettes at the ends of the barrel vaults.

The bottom half of the walls of the structure are built like those of the church at Atlántida; that form is then inverted and repeated for the upper story. This inversion of the ruled surface walls brings them back to straight lines at the top that are appropriate for the springing of the barrel vaults. Pre-compressing cables run from the ground floor to the vaults through the places where the walls form vertical lines. The outward lateral thrust of the vaults is resisted by tie-rods in the upper floor. The disproportionate thrust of the barrel vaults toward the center is taken up in curved stanchions located in the lower part of the central vaults.

*Architects: Gómez Platero-López Rey*

fig. 197: West façade, with entrances on either side elevation
fig. 198: Diagram of the wall structure
fig. 199: Transverse section
fig. 200: West façade and vaults

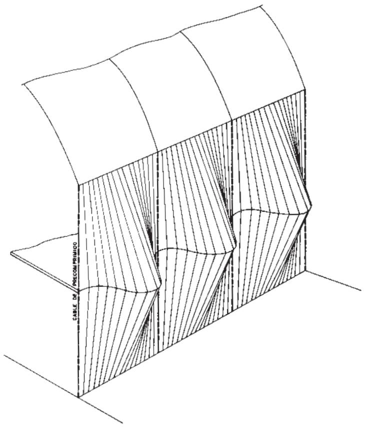


fig. 198

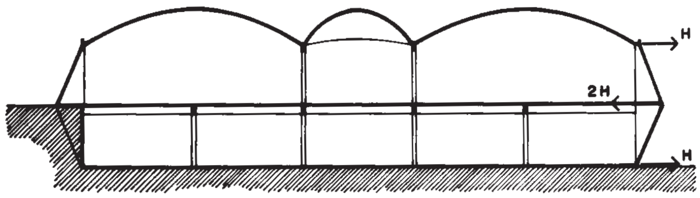



fig. 199

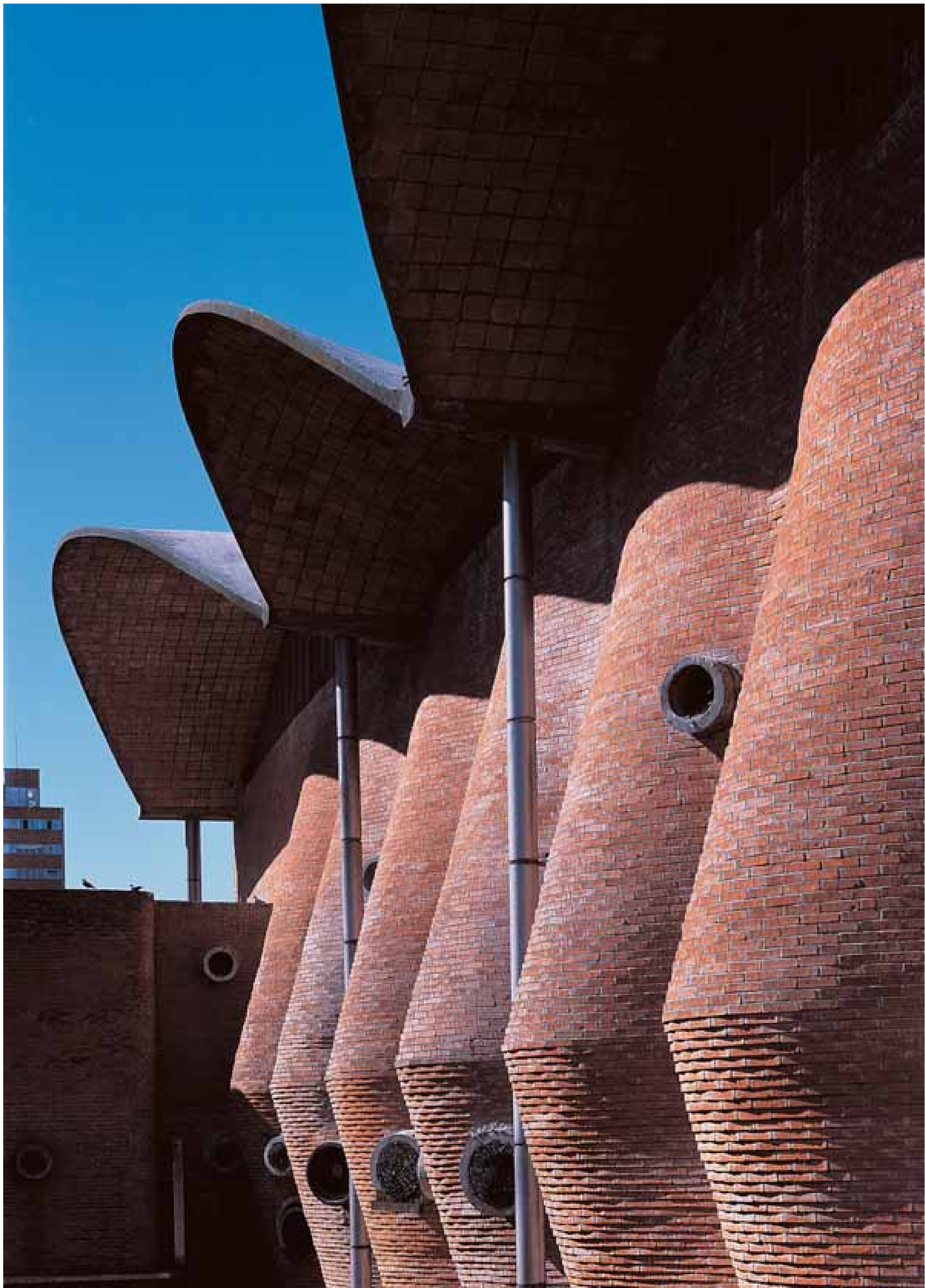


fig. 200

fig. 201

fig. 201: Upper level of the northern lateral wall
fig. 202: Central gallery
fig. 203: Northern wall and entrances
fig. 204: Vaults of the central gallery

fig. 202

fig. 203

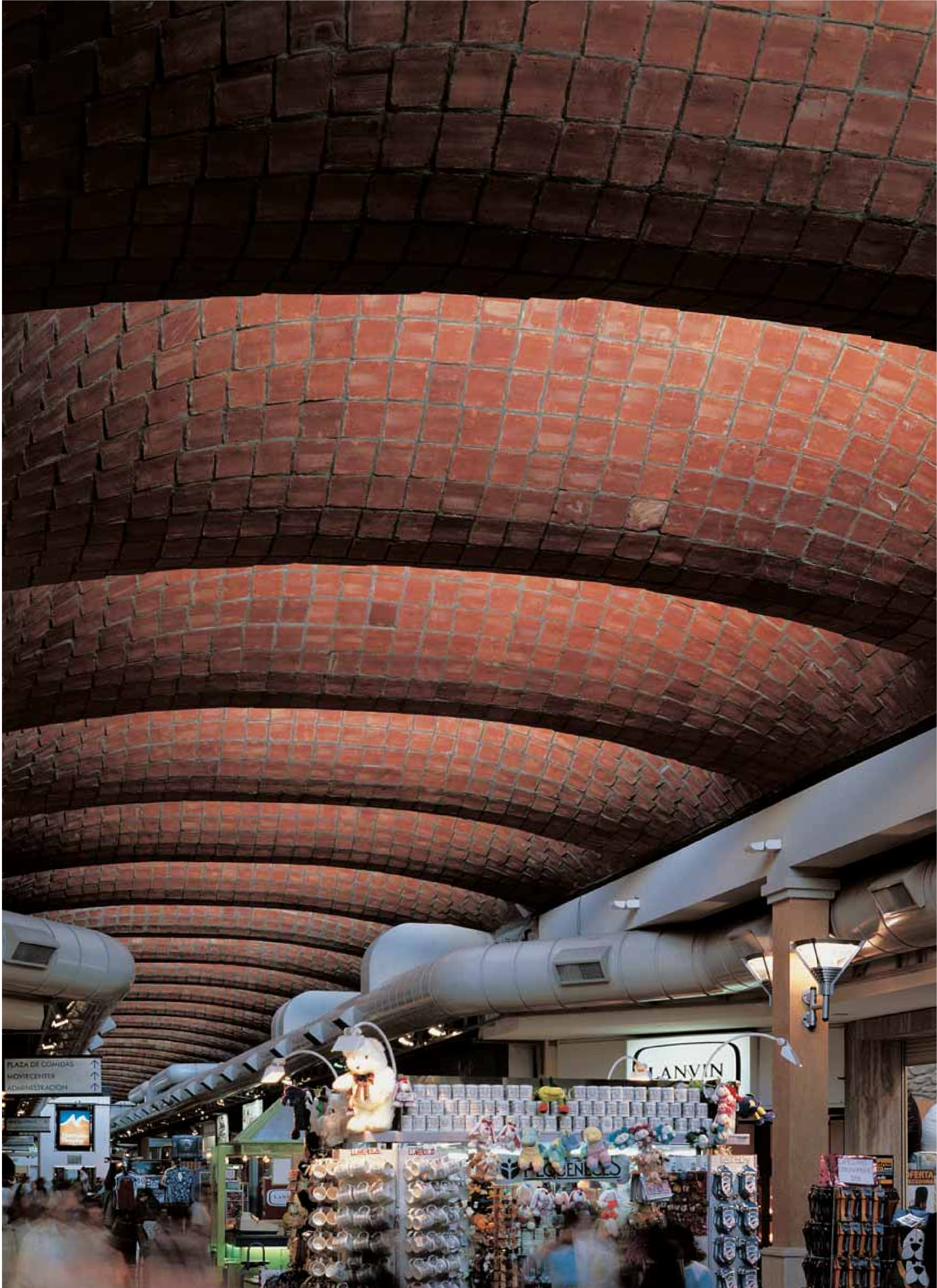



fig. 204

fig. 205

# FAGAR COLA BOTTLING PLANT

*Tarariras*, 1991–92, 1995–96

Four long freestanding vaults cover a warehouse/shipping area to the rear, an environmentally controlled production area to the front, and 42-foot-long sheltering cantilevers to the exterior of this bottling plant. As is typical with Dieste, windows are placed under the edge beams and where the tympana might be—both to admit daylight and to reveal the lightness of the vaults above.

Here the water tower is a solid cylindrical shaft, tapering ever so slightly from a 14-foot diameter to a little less than 12 feet over a height of 85 feet.

fig. 205: View from north
fig. 206: View from northwest with water tower

fig. 206

fig. 207

fig. 207: Cantilevered vaults
fig. 208: Interior of the production plant
fig. 209: Warehouse and shipping area

fig. 208

fig. 209

fig. 210

# ADF WOOL WAREHOUSE

*Juanicó, Canelones*, 1992–94

This facility is used solely for storage and shows the most economical use of the vaulting techniques developed by Dieste y Montañez over a generation of work.


fig. 211

fig. 210: General interior view
fig. 211: Exterior view
fig. 212: View of the vaults

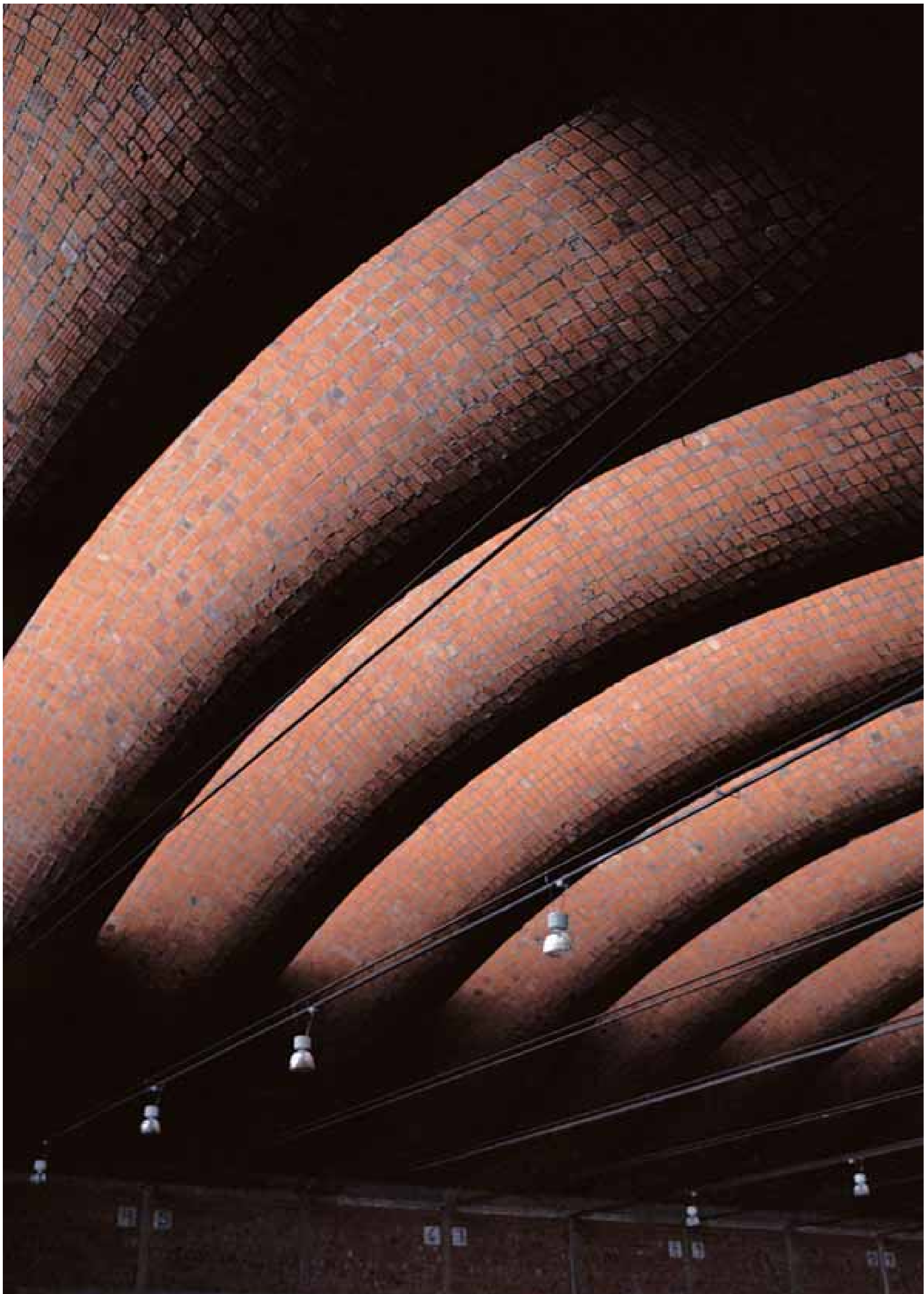


fig. 212

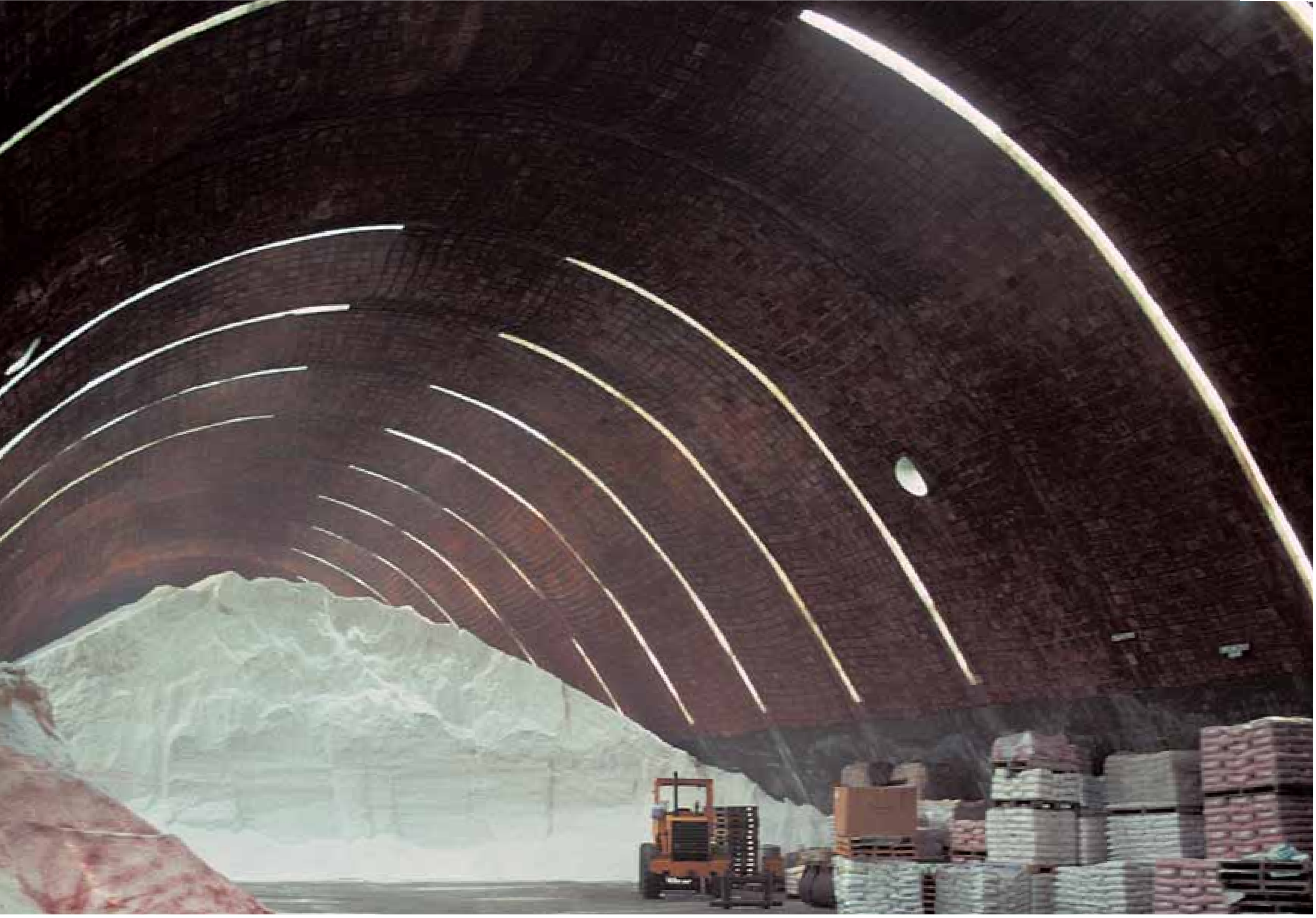


fig. 213

# SOLSIRE SALT SILO

*Montevideo*, 1992–94

The vaults of this silo are similar to those used in the grain silo at Young but for two notable differences: here the lateral thrust is taken up by tie-rods in the flat concrete floor; and, more importantly, illumination is provided by narrow skylights in the continuous double-curvature roof.

fig. 213: General interior view

fig. 214

# NAVIOS HORIZONTAL SILO

*Nueva Palmira, Colonia,* 1996–97

This large assembly of grain silos serves for trans-shipment from inland river transport to ocean freighters. From 1981 to 1990, Dieste y Montañez built three barrel-vaulted silos, 29,000 square feet each. This was followed by the construction of their largest silo to date, a continuous double-curvature vault of 148-foot span and a covered area of 75,300 square feet, with a capacity of 75,500 tons. The lateral thrusts are taken up by the foundation walls that are buried in heavy berms. The curved end walls are also of reinforced brick. Designed on the principles of Dieste, the calculations and construction supervision were by Gonzalo Larrambebere. Simple as the structural concept of this building is, its scale and the drama of its siting are simultaneously lyrical and of a melancholic strength.

fig. 214: Main silo from the north

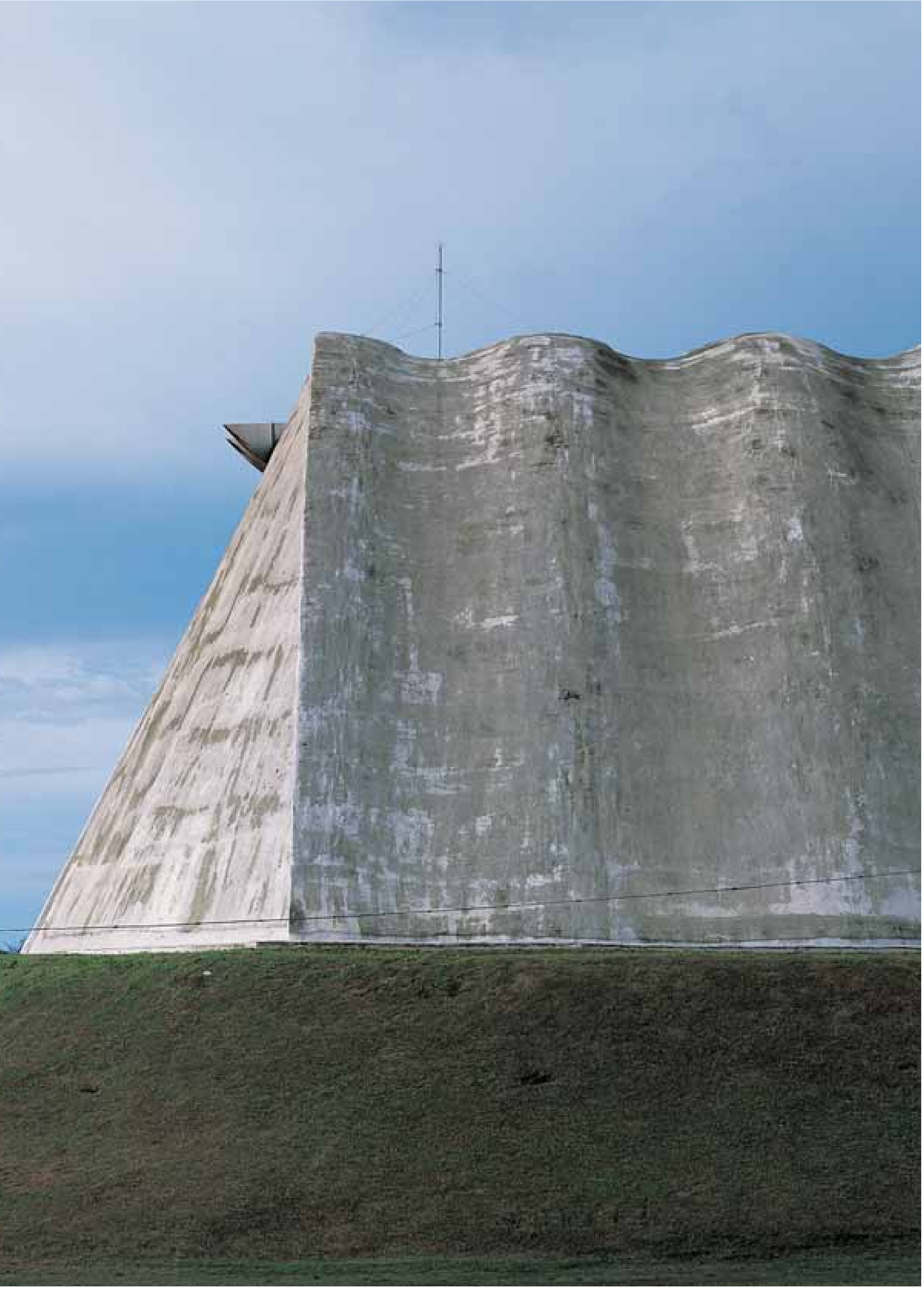


fig. 215

fig. 216

fig. 217

fig. 218

fig. 215: Landward end of the silo

fig. 216: Movable formwork used in building the vaults

fig. 217: Interior during construction

fig. 218: View from the northeast, illustrating three barrel-vaulted silos in the foreground and the continuous double-curvature silo beyond

fig. 219: Entrance, viewed from within

overleaf

fig. 220: Interior

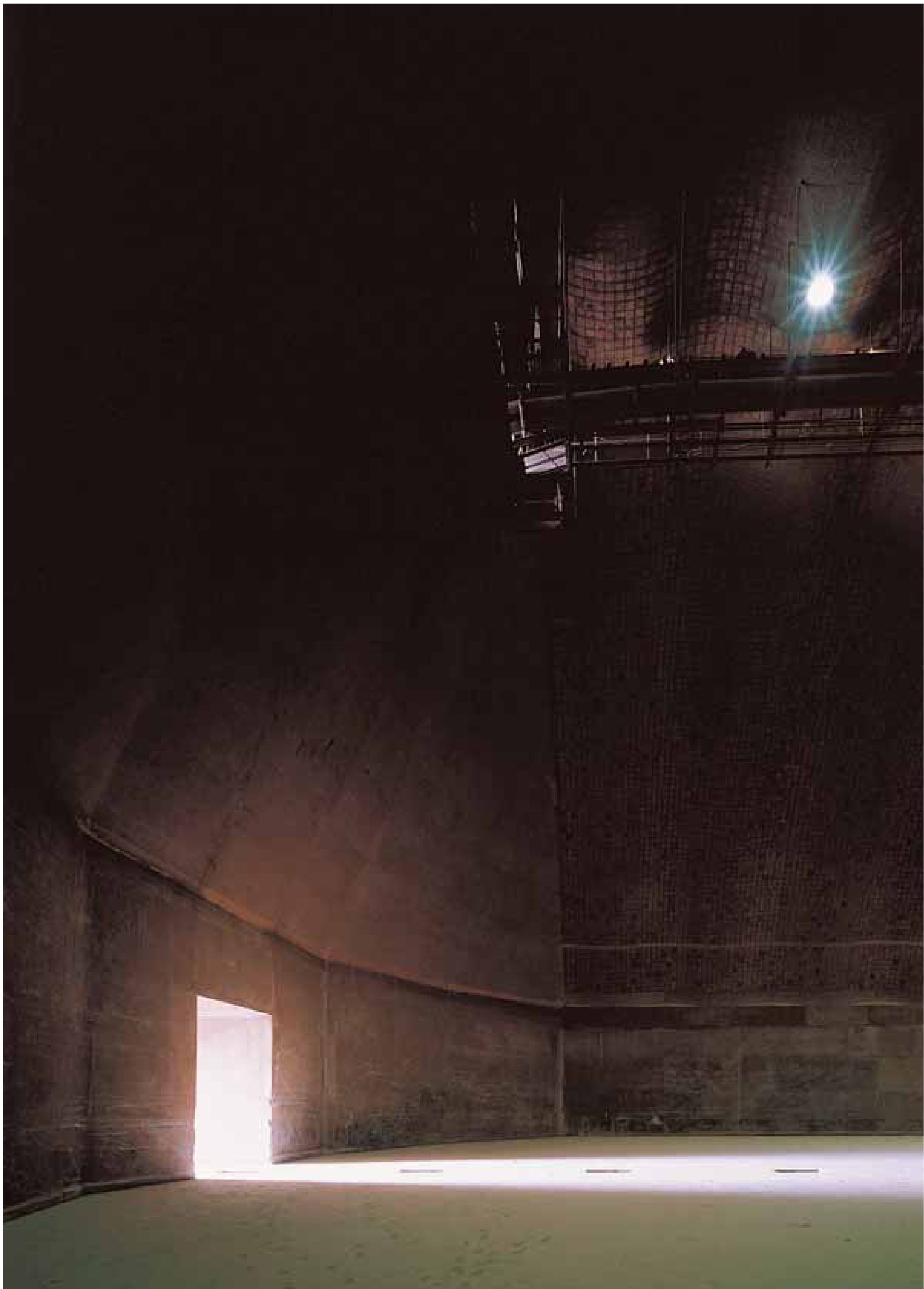
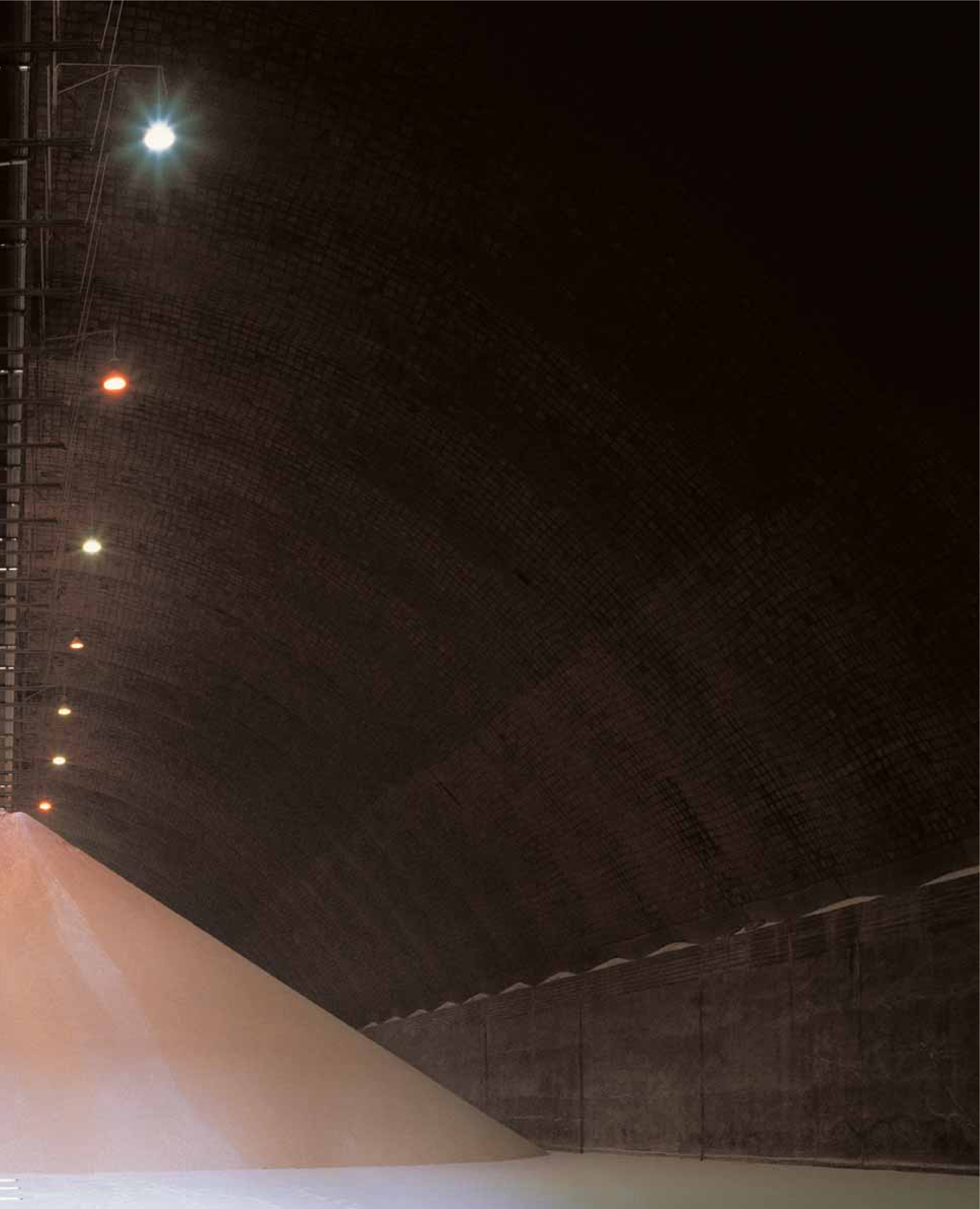


fig. 219



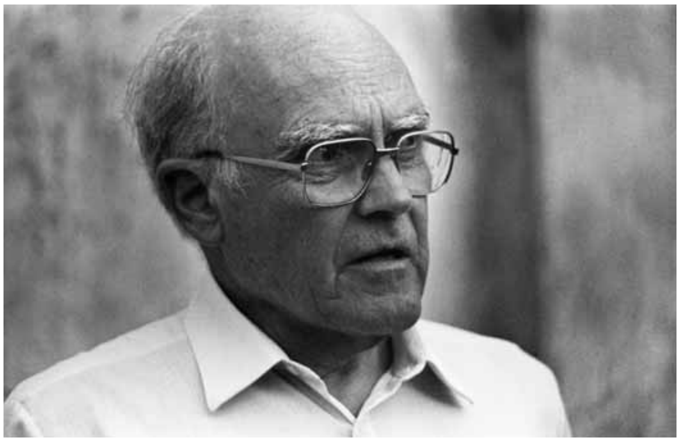

Julie Méndez Ezcurra

fig. 221

## DIMENSIONS OF A CREATOR: A TRIBUTE TO ELADIO DIESTE

*Lucio Cáceres*

Eladio Dieste was a man of essence. His life and work left no room for the anecdotal or the adjectival. He played an active role in a generation that exalted duty toward oneself and toward one's fellow man as a way to elevate the soul and to promote private and public virtues.

Raised in the modest home of immigrants, Dieste was enriched with the intellectual and spiritual fertility of a family that made knowledge and poetry, charm and religious faith, their most cherished patrimony. Under such circumstances it was natural for him to emerge as an ascetic, a personality that was admired (and sometimes endured) by those who shared his life, work, or classroom.

Destiny endowed him with an extraordinary intelligence, a noble face, and fine looks, maybe as proof of the saying that a man's mouth reflects the heart's wealth. His professional training and his gifts combined to provide him with an analytical capacity to envisage the problems of his trade with clarity and simplicity. His intuition and creative spirit gave rise to a "mechanism" that the artist feels as he works; he sees it operate in the immobile movement of architecture.

We were still too young to understand the significance of Dieste's recommendation that we read ***Razón y ser de los tipos estructurales*** ("Reason and being of the structural types"), by Eduardo Torroja.[1] In his manual on the philosophy of structures, Torroja wrote:

> Every material has its own distinct and specific personality, and every shape imposes a different stress phenomenon. The optimum natural solution to a problem—art with no artifice—vis à vis the set of previous impositions that caused it, impresses us with its message, concomitantly meeting the technician's and the artist's requirements.
>
> The birth of a structural whole, resulting from a creative process, implies the merging of art and technique, ingenuity and study, imagination and sensitivity. It escapes from the pure domain of logic to enter the secret frontiers of inspiration.

fig. 221: Eladio Dieste in Buenos Aires, 1987

> Before, and above all calculations, this is the idea, molding the material in a resistant manner in order to fulfill its mission.[2]

Creative work in architecture or engineering is the product of harmoniously considering the essence of functionality or utilitarian aims, a resistant function and a structural type, and economy and its constructive process, as well as the aesthetic qualities of the construction's shapes and dimensions. These basic considerations are present in the Gaussian shells of a warehouse or an industrial building, in the self-supporting shells of a bus terminal, in the ruled surfaces in Atlántida, in the folded plates of the aisles of Durazno.

The master's message becomes especially relevant in this technologically advanced era, when man, besieged by instruments, has available immediate solutions to his problems. Utilitarian concerns may be solved safely and inexpensively, but these solutions may occur at the expense of aesthetics. Dieste is a man prior to hypotheses. What I mean is that most men accept a series of hypotheses as truths that go beyond the basic axioms. One can accept Euclid or challenge him, put faith in the Ptolemaic system or discover Copernicus's, and open a new path of knowledge in each case. In twentieth-century architecture, structural typologies conditioned by the use of steel and concrete led builders to turn to flat surfaces. When Dieste conceived his solution of shells with double curvature and found brick to be the natural surrogate for concrete, he quit the accepted planar shapes and materials and placed himself prior to accepted hypotheses.

A wall is generally conceived as a vertical surface. However, for Dieste, as for Antoni Gaudí, it is possible for a wall to be a ruled surface, finding in its curves the inertia needed to prevent a thin structure from buckling. The paths exist; we only need pilgrims ready to take them to enhance knowledge.

Dieste rediscovered brick not out of nostalgia for the past but rather in light of its inherent virtues—it being resistant, elastic, inexpensive, and having acceptable thermal features. Its shapes give prestige to the material in its structural function. That function had been degraded since the introduction of steel, aluminum, and concrete—materials that, following the Industrial Revolution, seduced engineers and architects and led them to put aside the noblest materials in history, such as stone and wood. Rather than renounce technological developments, Dieste incorporated them in his work.

Dieste designed and built using materials and shapes of his own inspiration, making use of the old and the new, what was native to Uruguay and was taken from abroad. He mastered them all because he was a universal creator who achieved freedom through knowledge—sound, basic knowledge—through the rules of construction and physics, which he applied to the broadest range of aesthetic and structural problems.

The man, the master, the artist, Dieste was nourished by different sources that, when adequately combined, play that silent music that moves us when we contemplate or experience his work, enlightening our way when it is our time to design or construct, and bestowing upon us the personal freedom we need to face our future.

1 Eduardo Torroja, *Razón y ser de los tipos estructurales* (Madrid: Artes Gráficas, 1956).

2 Ibid., i. This prefatory statement, "the idea to which this book is dedicated," does not appear in the first English edition, *Philosophy of Structures* (Berkeley and Los Angeles: University of California Press, 1958). Translation by the author.

# APPENDICES

## THREE ESSAYS BY ELADIO DIESTE

The essays by Eladio Dieste published here were translated from the Spanish by Michael Maloy and Harold David Kornegay and published in *Eladio Dieste: 1943–1996*, ed. Antonio Jiménez Torrecillas (Seville: Consejería de Obras Públicas y Transportes, 1996). Mr. Maloy kindly gave the present editor permission both to use their translations and to revise them as he saw fit.

### ARCHITECTURE AND CONSTRUCTION

*Eladio Dieste*

*What follows is a somewhat vague meditation on the subjects that concern me. It is not a rigorous and comprehensive essay on the title's difficult subject. These are passing reflections that I have organized as best I could. They are reflections of an engineer who found in the process of building warehouses, he was creating architecture, even though that was not his object. He also found that he had an awareness of form and in confronting this awareness, he discovered that it helped him to solve problems that were strictly structural.*

I began to work on designing and building structures in 1942. Since then, I have thought about why we build things the way we do. I have thought not only about the source of the technologies that we apply but also about the philosophy, not evident to me at the time, that is the foundation of our activities.

In order to recount these reflections, it is necessary to summarize the evolution of construction methods since the industrial revolution. In analyzing this summary, the evident break in a thousand-year-old tradition that was concurrent with the industrial revolution has to surprise us. Until the end of the eighteenth century, the construction methods employed were a natural extension or evolution of the methods used in the late Middle Ages and the Renaissance. The great expressive traditions of the earlier periods (Romanesque, Gothic, etcetera) used fundamentally the same construction tools and, even more importantly, had the same concept of how construction was related to architecture. In passing from the eighteenth to the nineteenth century, the use of iron as a construction material became possible (first cast iron and later the different types of steel). With great speed, this new material began to be supplied in prismatic components that had to be assembled to form the structure of the building. It is quite common to emphasize the importance for the evolution of architecture of the fact that the structure of a building began to be thought of as a skeleton, partially independent of the walls, through which the function and space of architecture became free from the limitations of resistance in a way that was unknown until then.

Iron invaded and revolutionized construction technology very quickly. This rapid change was not due to economic reasons, since a new technology can be more expensive to use at the beginning, as it was in this case. Instead, the change can be attributed to the fact that, fortunately, man has the altruism to undertake endeavors that he feels are worthwhile. Structures were possible with steel that could not have been built with the previous technologies. These new technologies were well suited to the necessities of building programs in the large population centers of the industrial era: warehouses, large workshops, stations. The most typical architecture of the nineteenth century is the architecture of large iron structures.

However, there is an aspect of this revolution that I have not seen made explicit. Perhaps this is because it is strictly a structural consideration, but it seems to me every bit as important to the evolution of architecture as the liberation of the ground plan that structural independence permits.

#### Iron: The Technological and Theoretical Predominance of the Plane

The assembly process for iron components made it possible to break down a building into planar framework sections in a natural way and without neglecting to consider anything essential. What is more, these planar framework sections were calculable. The great advances in the science of construction were concurrent with this technological revolution. Even without the subtleties of the theory of elasticity and of superior stability, using only the great principles of statics (which are easily applied to planar systems) and the rudiments of the resistance of materials, the thrusts and sections of all the parts of a structure could be determined. This is why there was such a great effort to reduce everything to planar schemes, since engineers could work with only the planar structures with ease.

The technological dominance of the plane must have been of great importance to the later evolution of construction and consequently of architecture. Having rational security over a problem creates a confidence in oneself and, at the beginning, an interior elation. The most perceptive and daring minds set out enthusiastically to explore the new possibilities of the use of iron. The traditional technologies did not use this kind of analysis. Instead, their achievements were of a very different nature, and the perfection that was achieved is sometimes disconcerting. I remember seeing the analysis of one of the arch buttresses of Notre-Dame de Paris, in which the stress lines corresponding to the loads and the effects of wind, snow, and temperature were studied. These stress lines are transferred to the inside of the central nucleus in all cases, touching the edges of the nucleus and always staying inside it. Therefore, the buttress is always stressed without any extra section.

Those medieval masters seemed to know theories and working methods that were only formulated seven or eight centuries later. In order to contend with the always present forces of irrationality, it is advisable to note that this precision and accuracy of dimensions is not universal. The vaults, for example, are much heavier than is statically necessary. However, this example allows us to see the

points of refinement that this age-old process of adjustment achieved. As we said, all of a sudden engineers had at their disposal building methods that could be gauged with security, rather than by trial and error. These methods replaced long and imprecise processes with new forms of rapid analysis. Only the euphoria of such security can explain that an enormous amount of traditional wisdom of construction was abandoned.

This construction tradition had lost the vitality of its great creative movements, but as a sum of possibilities it was still intact. It was intact but resistant to the design methods of those who could have made use of it. This is the only way to understand how the minds that were capable of founding a whole new tradition were unable to make use of this older tradition—minds like Eiffel's, who was not only a brilliant engineer but also an artist, who built structures, and above all bridges, of great beauty.

The structures made from iron were planar. These are typical of the nineteenth century. Even today, the majority of buildings are designed with planar framework. These are the buildings that the science of construction analyzes, and they are almost the only ones that we have studied and continue to study in our engineering and architecture schools. The old structures, like Santa Sofia or a Gothic cathedral, are not planar. They are structural systems that have to be thought about in three dimensions and are much more difficult to conceive and analyze. In a Gothic cathedral, for example, the stresses of the ribbed vaults, which in the end are supported by each other, are concentrated on the central pillars. The thrusts are absorbed partially by the buttresses, and by the aisle vaults, and are finally transmitted to the ground by the walls and these same buttresses. It would be difficult even for an experienced engineer to imagine, much less calculate, the stresses of the different parts of such a building.

The rational clarity of planar framework must have had an enormous effect, even on the compositional aspects of architecture. Not only was it natural to build with the planes that construction technology provided, but its incipient rational clarity gave the plane a peculiar expressive force that one day would coincide with the formal investigations that were at the root of the Modern Movement. This plane that vibrates with a kind of religious fervor can be seen in the works of Le Corbusier, Gropius, and Mies van der Rohe.

Even today, architects are more at ease working with planes. Even though they may not always be the most appropriate forms, architects choose planes as a surface to limit a space in a natural way. We have all seen buildings in which the solution for the roof, for example, struggles structurally not to go beyond the plane. The fact that a building of this kind is much easier to express graphically has a great influence. I remember when I asked a friend about Gaudí's work, he told me that he wasn't at all interested. "His work has nothing to do with us," he told me. As a final argument, he added, "I wouldn't know how to draw one of Gaudí's buildings. How can we construct a building today without ground plans, facades and cross sections?" [1] This is something that was said without thinking. This friend was not interested in Gaudí as an artist. This is an example of a tacit mental outlook that thinks about the graphic means that we need to build structures, giving these means a disproportionate importance. The essential thing is the structure, not the plans. If the plans are not able to express something we have good reason to believe is valid, this is no reason to abandon the idea.

All of the great structures of the past were built with extremely simple plans. I am aware that the organization of work was very different. I also know by experience the difficulties involved in envisioning things that cannot be expressed well in drawings, but many times the results are worth this effort, worth it from the most utilitarian point of view. The double-curvature vaulted structures, for example, that cannot be easily represented in graphic documents, are very economical and easy to build. I believe it is evident (and serious because of how it impoverishes the process) that the first thing we do is draw plans. We think more about the plan than about the structure or, better said, we only think about the structure through the framework of the plans. Everything leads us to this; the way we build and even our training in which we learn (it is almost inevitable) to do projects, not build buildings. The natural tendency is to emphasize what we dominate. It is only with sustained effort that we can liberate ourselves from what José Luis Sert calls "the tyranny of the drawing board."

1 This was twenty-five years ago, when these brilliant works were still not appreciated. I did not know anything about Gaudí, but the great painter Torres Garcia had spoken enthusiastically about him to me.

Along with the new technologies, a new attitude toward the structure was formed. It was precisely the clarity, rationality, and speed of the design and construction process that did not allow the new technologies to gradually develop personalities of their own, as was the case in the past. It was very unlikely that we would suddenly be able to see in some corner something as alive as a human face (which happens so many times in older cities).[2]

One of the great advantages of planar framework is that it is so easy to analyze, but it also has great disadvantages from another point of view. The plane is structure's most elemental form. It produces structural solutions that are simplistic at times and does not make use of materials in any rational way. As in other cases, its primary clarity loses many of its most important elements along the way. The men who built the wooden roof trusses in the first basilica already knew its essence. All of the stone vaults and domes in medieval architecture came after this. Great technological refinement and penetrating analysis of the construction problem were necessary. There is a sensation of incompleteness that we still feel, at times, in front of good buildings that are structurally and compositionally created using linear structures. In the end, this sensation comes from the synthetic and intuitive perception that there is something incomplete in the analysis, something elemental that has been left unfinished.

### Concrete: Vaulted Structures, Calculations, Models, and Imagination

The technological revolution continued, and in the second half of the nineteenth century reinforced concrete was discovered.[3] From its modest beginnings, it very quickly became one of today's most vital technologies. With its discovery came a revolution in which the use of materials yielded structural forms that exploited surfaces and were both more rational and expressive.

In the beginning, reinforced concrete was used by breaking it down into planar systems: slabs, beams, arches, and pillars. This was not only the case when its use seemed logical and rational, as in a mezzanine, but also in other evidently absurd cases, such as putting beams in the ridge of a double-pitch roof or arches at the intersection of two cylindrical vaults. It was slowly realized that this was not the most rational way to use it. The ridge beam did not make sense, since one slab gives rigidity to the other and the arches channel their stresses along the intersection. The awareness of this problem is sufficiently new so that we have just begun to see its results. I remember how difficult it was to free myself from the traditional way of conceptualizing structures which was the consequence of all my previous training. Besides, when I did come up with other solutions, the analysis of the building process was consumed in a sea of doubts. I was continually on the threshold of knowing how to calculate something, and for an engineer to conceive of something was equivalent to knowing how to calculate it.

Sometimes when I speak to young people and explain that there is still not enough time dedicated to the study of the surfaces of structures, I see in their eyes the obvious question, why? The honest answer is that it is difficult to talk about vaulted structures without falling back on the list of solutions that are already known. Today, it is true that there is not a structure that cannot be analyzed in finite terms, and discussion about structural problems with an intelligent specialist is not difficult. However, we always find that the most magnificent forms are resistant to simple analysis, and we will have to do quite a bit of simple analysis before we can achieve the most sensible and responsible way to calculate these structures.

Almost all that has been written about this kind of structure—and certainly the most interesting—is the work of builders. These men devised a solution first and then, after the process that we spoke of before, completed the process by testing their ideas with trials at the site. Their analytical and building experience was systematized in theories that are valid for the structure used. The problem is that we can devise many more solutions, some logical, economical, and clearly stable, than those that we know how to calculate easily. We find ourselves in a situation that is symmetrically different than the situation at the beginning of the nineteenth century. We have a material that we have every reason to use and that is naturally very suitable for the surface forms of our work: slabs, diaphragms, polyhedron systems, vaults, and domes. However, we have to use inadequate and awkward

2 In this as in all things, there is no advancement or enrichment that does not imply risk. Let us take a contemporary example. Few things in our world are as marvelous as computer science. Many of the calculation difficulties that I refer to later have almost disappeared. This is because there is no system of differential equations, as complex as it might be, that can resist the capacity of a good machine to solve. However, a computer cannot respond on its own. It will never give us essentially more than we put into it. This is to say that the creation of forms will continue to be the result of work done by the human mind, that marvel that produced computers and transcends them infinitely.

There is, of course, an interaction between man and machine. He that knows how to and is able to solve equations acquires a great power. However, there are dangers when we let ourselves get carried away by a fascination for the instrument. Of course, I am speaking as someone who has acquired technologies but has not completely absorbed their uses due

analytical methods in our designs, and we have not succeeded in making them into efficient tools.

The study of models is possible, but in general it is necessary to understand that these models will give us a qualitative orientation. In order to make our efforts more quantitatively systematic, we will have to define and study the problem to achieve sufficient precision.

In addition, the model is slower and more expensive than computation. I see it as the final step in very complex structures. In my building experience, I have used the model very little. Whenever I thought about using it, I had, by that time, studied the problem so much that it wasn't necessary. What I can say is that I have proceeded bit by bit and that the smaller structures have been the models for the larger one.

Even with the help of all the modern methods, the design process for structures that are more rational and at the same time more expressive, will always be slow and require an enormous amount of work. I have come to think that the most rational thing to do would be to create a repertoire of forms—forms that have been thoroughly studied and in which we would perceive the interior solidity that is the fruit of an intense effort. Wouldn't the most sensible thing be to use these forms in the design process? Wouldn't this be a completely rational justification of what we could call by extension "style?" In ancient times, style was the creation of a repertory of studied forms and was part of a process that included building and the age-old perfection of proportions.

These richer and more complex forms cannot be made routinely. They require a love for the project and a taste for details—qualities that do not abound among businessmen. Anyone with experience knows that, in general, the construction engineer participates very little in the project (especially in the projects that are more typically architectural). He is limited to managing the efficiency or productivity and controlling the project financially and administratively. He does not participate actively in the construction process's daily routine. What I have described reaches, at times, scandalous extremes, and it is no exaggeration to say that in many cases it is the foreman that builds the project. I believe that this is the real cause of what is called low worker productivity. The worker feels that his superior does not contribute his share to the project, that he does not truly fulfill his duties and the part of the final benefits that he receives is not morally justified. This extremely immoral and all too common conduct is even more intolerable in the projects that we have discussed. We don't only have to design and calculate these structures, we also have to build them. This is not possible without a greater personal dedication on the part of the person that oversees the construction. This is why some building contractors are so resistant to these solutions. They say that they are expensive. This is not true. What is true is that these solutions require them to perform as they should, as builders, not just contractors or businessmen.

The builder is indispensable. In fact, the project for a building is not really complete if it does not consider how it will be built, and the ways in which a building can be built have a notable power of inspiration. All viable new structures are intimately related to construction methods, and these methods are visible in the finished building.

It is common that the legitimate and inspiring concern for the economic aspect of a project can be an obstacle. As soon as a new

to a generational problem. I cannot help but remember the dangers I saw in the attitude of a young man (director of a work group at MIT a long time ago). He believed that there was some dubious merit in not thinking, in "letting the machine do it," as he put it. Of the ten solutions he presented me, nine could be discarded just thinking about them for five minutes or, I would almost say, just understanding the problem.

The great danger of computers is this, that laziness and the tremendous mechanical labor that is required to make anything work is distancing us from the substance of reality. We tend to simplify and impoverish our concepts and thoughts so that they will fit into the mold that will "run on its own." For example, it is easy to program the calculation for the classic skeleton of an important building with columns. However, it is not so simple if we move to the solution, which could be more suitable, if we substitute for it diaphragms.

What precedes does not defend the reactionary or simple-minded position that we should not use these amazing instruments that technological progress has put in our hands. No modern day Luddism here. I only want to call attention to the dangers implicit in an attitude that leads me to believe that we could use this technological advancement in a way that will sterilize its force and, as a result, the capacities of man will not grow but instead shrink. I fear that what we will do, instead of being more fruitful and truly rational, will in the end be an impoverished simplification of what we have already done with more primitive methods.

3 What I say about reinforced concrete can be applied to reinforced brick.

solution is developed, cost calculations are made that are noticeably uncertain. The only costs that are known with any kind of certainty are those for structures that have been built many times. Cost estimates for really new solutions are not to be trusted. In this case, the only way to be certain is to break down the construction process into those parts in which the difficulty and price can be evaluated. In the last analysis, when the methods that are being considered are very new, it is the power of the imagination, the power to see the building process in its different stages, that will ensure its viability and efficiency. This ability to see the process using one's imagination is not something belonging to the highly gifted. I believe that human faculties are much more equally distributed than is imagined. This ability to imagine is learned. What we call difference of faculties or abilities is, more often than not, a difference in background or personal history. Lack of imagination is more likely an "ablation" of the mind that has turned its back on innovation and has chosen to remain with what is already known, like the boy that doesn't learn how to swim because he was frightened when he was a child.

We should note that when first we enter the process of thinking about structures, which is our everyday work and how we make our living, we do not do cost analysis. Analysis of the costs comes at a later stage and that permits adjustments and refinements in the details. We imagine the structures, sometimes all at the same time, with all their essential details: the tension patterns, the construction methods, the equipment. Later, reality almost always confirms what we have imagined. It is not appropriate for us to say that we have built these structures for crudely economic reasons, because they were less expensive. Even in the case of the more "artistic" projects, like the churches, the costs have been ridiculously low.

### Rationality and Expressiveness

After this first attempt to deal with the problems that we have set forth, it seems natural that we should consider once again something that seems evident to me. In many cases, once these structures are spatially conceived, designed, and built, we are moved by them. They move us not only because of their dimensions or their boldness but because they are mysteriously expressive. If we think about the reason for this, we will see that, in the first place, our emotion is due to the fact that we perceive in them our spirit, in a synthetic and intuitive way, a more exact adaptation to the laws that govern matter in equilibrium.

Keep in mind that this adaptation is not only rational in the sense that we normally give this word because we do not have perfect knowledge of the materials or of the loads that our structure must support, nor do we have calculation methods that permit us to determine the stresses of its different parts. This is also true in many common cases, like the mezzanine of an apartment building. We have become accustomed to and reassured by the secure results that we obtain. However, we forget how primary and approximate our analytical methods are and how much their results differ from reality. In other words, to give form to a structure, whether consciously or unconsciously, there is always something of a leap into the void. However, if we give ourselves to the problem seriously, we later acquire a different kind of security from all the analysis. It is then that we begin to live the structure from inside, and the leap we take is to fly rather than to fall. This is why it is more appropriate to talk about the art of construction rather than the science of construction. It is only with enormous rational effort that we will acquire the ability to take that leap.

### Financial Economy and Cosmic Economy

You might ask me if there is a reason for a line of inquiry that attempts to delve into the laws of equilibrium and into the many varied ways we can discover to adapt ourselves to them. Is it not enough if we try to build structures that are resistant, simple, and economical to construct? With what is normally understood as simplicity and economy, I do not hesitate in maintaining that this is not enough. What is called simplicity is usually unjustified simplification, and economy usually refers to money and its movements—economy in the financial sense. The things that we build must have something that we could call a cosmic economy, that is, to be in accord with the profound order of the world. Only then can our work have the authority that so surprises us in the great works of the past. This is what many of the practical gentlemen who control us have forgotten or do not want to hear. There are an enormous number of people in the world creating wealth, trying to adapt themselves to the world's profound order. It is this wealth that we later squander through carelessness, financial schemes, and speculation.

As an example of what I am trying to explain, I remember a passage from a novel by Knut Hamsun. The action takes place in a clinic for aristocrats in the north of Norway. Supplies arrive from the south every day by railroad. One day they run out of meat. The director of the establishment knows that a local peasant has a cow, and he wants to buy it. The peasant tells him that he cannot sell him the cow because it is not yet time for it to be butchered. The director says that he will pay him as if it were time for it to be butchered, but the peasant will not change his mind, which in the end shows that there is an order that is independent of money. The peasant asks the

director to return in the month of May when he will sell him the cow at its fair price and concludes by saying that it would be different if they had nothing else to eat. This conversation is significant because it brings face to face two ways of seeing reality: the apparently practical and the profoundly practical, which takes into account the existence of an order that permits disorder but also a squandering by those who do not serve the world and mankind but instead make use of them.

There are profound moral reasons (and practical ones, that in the end are the same) for our search. To attempt the search is to give form to our work. In other words, the form of the things that we build will make us able to adapt ourselves to the laws of matter. There is in this endeavor and exploration all the nobility and reverence that a dialogue with reality and its mystery implies. This struggle shows us that the world is not alien to us but is, instead, in essential communion with us.

The resistant virtues of the structures that we are searching for depend on their form. It is because of their form that they are stable, not because of an awkward accumulation of matter. From an intellectual perspective, there is nothing more noble and elegant than resistance through form. When this is achieved, there will be nothing else that imposes aesthetic responsibility.

### Architecture Is also Construction

The necessity to clarify other fundamental aspects of architecture has made it seem that we have forgotten something quite elemental—that architecture is also construction. It is not enough that we contemplate and resolve functional problems and their spatial expression. We should build architectural spaces, and their expression will be conditioned by how we build them. This is why the spatial conception and the form in which these spaces are built should be one and the same thing. They should be unified in the creative process only after they have actively and uncompromisingly interacted in the architect's head. Almost all of the buildings today seem assembled rather than built. We have the belief that we must enclose the spaces that we envision. The architecture that is a result of what we are talking about is like the very best of the construction process itself: if we proceed in this way we will find that the structures we build are rational and economical, much more so than if we had given more importance to primarily practical considerations.

This is why construction and its relationship with architecture are so important. There can be architecture without installations (electrical, plumbing, etcetera), but there cannot be architecture without construction.

Construction will always be indiscernible from architecture because it is like its flesh and bones. Furthermore, each art has its sphere, what we could call its limitations, if it were fitting to give this name to a process. This is why scenography is not architecture, or at least only a very special kind of architecture. There are great architectural works in which you sense this weakness. They are not constructed; they have something that makes them seem like scenography.

For architecture to be truly constructed, the materials should not be used without a deep respect for their essence and consequently for their possibilities. This is the only way that what we build will have the cosmic economy that we spoke of, and this cosmic economy is what sustains the world. When we use materials with this profound respect, we must be modest and be careful of our own aesthetic refinement. It is not enough to use brick because we like its texture and the fact that it is a material full of historical references. It is not that this is bad in and of itself, but we can take much better advantage of its possibilities. In this sense the current risks are much greater than before because modern technology apparently gives us the possibility of doing anything, of realizing any fantasy. It seems as if we can use construction materials as the set designer uses cardboard. The economic risks that this infers are not necessarily immediately visible, especially in the richer developed countries.

Up to now we have been looking for what should guide us in our structural conceptualization. We have also answered to simplistic objections that have come to our attention. However, there are other things to be said, although I would not necessarily say other things as much as the same things, phrased in a different way.

### Architecture Is an Art

Apart from its obvious functions, architecture is an art. Perhaps it is the most important art since it forms the spaces in which we move. It has in common with all the arts the ability to help us in the contemplation of the universe through its own infinite and therefore rationally incomprehensible definition.

If we could know the world in a perfect and infallible way, then we would not make art; we would simply contemplate the world. The moment of the final leap, like a lightning flash of vision, allows us to contemplate the harmony and intelligence of the world. This is the moment of art, but this does not mean that we can only contemplate through art. All of mankind's spiritual activity is the conscious or unconscious search for this contemplation. Once I told a friend, thinking about the ancient cities, cathedrals, and temples, that our era had not created anything similar.[4] It did not escape me that these works were the spatial expression of a culture, or rather, of a complete

vision of the world, man, and his destiny. In this sense, our era does not have a culture that informs the social body. My friend responded by saying that this depended on what we understood to be architecture. In his opinion, the Dutch highway system was as much architecture as Chartres Cathedral. It is like saying that there is no difference between a piece of good legal prose and a good sonnet by Quevedo.

What my friend said is partly true, but as a response to what I had said it shows a strange blindness. The two works were created for a purpose. It is through the full achievement of this purpose that we experience the pleasure that is the principle component of the happiness that art gives us. However, the two works are very different. In the second work, the artist or artists did something more. As a result of their attempt to interact with the world, they gave us a glimpse of the superior order that, through our struggles, we strive to contemplate. Without these glimpses that show us that the world has meaning, we would succumb to despair.

A building cannot be profound as a work of art unless it has an earnest and subtle fidelity to the laws of matter. Only the reverence that this fidelity requires can make our buildings serious, lasting, and worthy partners in our contemplative journey.

Not all the architecture that we create can aspire to be art in this last sense. There should be prose and poetry, popular dances and Bach cantatas. I believe that this final result cannot, nor should it, be directly sought after. When the final result is the product of a project that is earnest and humble, it will achieve art, but without having sought after it. The building or buildings in which we achieve difficult goals will have an exemplary power over the city. In these buildings men will see the true expression of mankind. They will recognize one another and their weariness will be overcome. Architecture that is understood and felt in this way is poetry. We are not all able to create it, but we all need it.

### Industrial Society and the Paths of Mankind

Once, I encountered the objection that the structures that we have been talking about would not be viable in the machine-driven society of the future, in which everything would be made by mass production in huge industrial complexes. Continuing to study forms that require skilled workers and an engineer's close supervision is a sentimental approach that is opposed to progress. First of all, we would have to define what we mean by progress, which would oblige us to define the goals of society or even the aspirations of man himself. If we do not specify these goals and principles, we cannot know if we are progressing toward them or if we are being consistent with them.

It is always the fundamentals that are left vague. Since this type of criticism is also levelled against things that are much more important than the ones we are talking about here and since it has the blind force of the imprecise, I think that it is important that we comment on it.

It is very probable that in the future we will have a civilization in which most, if not all, of what is produced will be produced by large organizations in which the use of the machine will be even greater than it is today. However, these organizations and machines will need to be built and maintained. Someone has to design the prototypes and processes. It seems to me that there is a great risk in taking for granted that the paths that dominate today will prevail in the future. If this were the case, the only reasonable thing to do would be to perfect what is already known. I do not believe this, because the failures of our admirable civilization are too evident for us not to believe that we find ourselves on the brink of changes as fundamental as those that brought us industrialized civilization. The kind of people that are captivated by a machine-driven society of the future and theorize about it are usually not people that *do* things. What they take as definitive and immutable is more like the past than the future. Their opinions are the result of a somewhat childish amazement when confronted with the power and efficiency of the world's powerful nations.

We are not confronted with a world in which the problems and solutions are clearly worked out. We are the eternal traveler who has or should have his compass and know his aims. I think that we would reach a wide consensus if we proposed as a common aim the fulfillment and happiness of mankind. This is an aim that would certainly produce different principles in accordance with each individual's philosophy of life and his religion.

From this sound point of view, focused on the aims of man, what we see around us is not acceptable. Today, the countries that are developed are those that initiated the revolution of the scientific interpretation of reality and later its application to technical knowledge. This is what we call the Industrial Revolution, and it had many positive aspects. It showed man part of his power to transform the world and truly make it his home. However, it took place with such great injustice that the repercussions from the fierce indignation that its inequities produced in mankind are the reason for the destructive madness that has spread throughout the world. In order to comprehend these injustices and inequities, I do not have to have read history books or novels by Dickens. It is enough for me to have worked one month in an industrial city in northeastern France. I cannot forget its miserable rows of squat houses, comfortable stables that housed the poor exploited wretches that are still not humanely treated even today.

These were, as I have said before, “houses with an animal comfort but without the slightest indication that they had been made for men who were destined to speak with the stars. The whole city was an insult to the destiny of man. I was there in spring and the only human things were the sky with swift clouds that cut across it and the lilies and cherry trees in bloom, which were not, of course, in the houses of the poor.” I will pose the same question again and again. Is development desirable at the price of this sordidness and misery? Does it make any sense to continue to make this or similar mistakes? For example, for years a paper manufacturing company dumped chemicals into a river in Porto Alegre that made the air unbreathable. Can we justify that this company comes to this poor area of the world to do what it cannot do in Sweden? Is there anyone who will defend such a thing? Is there not another way? I know that through our determination and persistence we will find other ways.

One of the clearest examples of this, even for someone who has little knowledge of architecture, is the modern city. Is what we see being done acceptable? Do we not see an iniquitous brutality that is destroying incredibly beautiful things and mercilessly ravaging the heroic dignity of the poor? There are few things more disheartening than the construction explosion in Europe that has not been aimed at correcting the deficiencies of the previous civilization but instead at crudely making money. Once again, I will refer to things that I have said on another occasion: “I remember Tours. From the war, two sections of the medieval city were saved, two marvels of ‘modern architecture.’ Then there was the boring, mechanical, unimaginative, and ungainly monstrosity that was the reconstructed zone. This, at a moment when technology would have permitted the creation of a city with a spatial abundance, with a harmonious approach to the space and the people in it. The Middle Ages could not have even dreamed of this approach. The difference is that in Tours, when the city was built in the Middle Ages they thought about eternal man: child, youth, adult, elder. When the parts of the city that were destroyed in the war were rebuilt, they thought about circulation problems, structures that would be solid, with good light and ventilation, good bathrooms, but they forgot the great number of things that we all have in our heads and hearts in our journey through life on this earth. The result is a truly ugly sight. The new city is not a city at all. It is a place built for the rapid and efficient circulation of automobiles. The people sleep and bathe comfortably, but they feel uneasy because at no time do they feel that the space expresses the mystery that they carry inside themselves.

“In the old part of the city you feel an intense happiness. This is due to the fact that the space, the thing that is so inexpensive, has been handled with wisdom and humanity. The music of space, which is architecture, is in accord with the music of the world and the music that we carry inside us. They thought about children chasing each other around in the streets, evoking this dormant memory that we all have of heroic deeds from other times. They thought about the young couples that discover the mystery of love, the old people that sit in the sun to reminisce. They thought about something dense, complex, profound, incomprehensible—like man. They did not use schematic concepts that are formulated in a quarter of an hour and leave everything that is important out.”

Let us return to the large organizations of which there is much more to be said and which we usually think of as if they were a means for us to sleep peacefully at night. In order for these organizations to serve mankind, they would have to be very different from the overwhelming majority of those with which I am familiar. They must not only be different in their aims and political and economic activity but also in their pure and brutal efficiency (true efficiency cannot be brutal.) Efficiency is the dark god to whom we sacrifice so many things. Its worshipers, in most cases, are ingenuous, irremediably sentimental, and dazzled by the prestige of the powerful. Having worked with them, I know what is behind many of these large organizations. I know about their scandalous inefficiency and stupidity and their very low technological level. I know about the unthinkable waste of human labor and the miserable, routine, and boring work. All of this is what they do. They do not deceive me. Their force is in the accumulation of capital that sustains them, not in their present level of efficiency.

4 I haven't done it, but I could do it, and I'm sure I will do it, and with a plenitude about which artists from other times could not have even dreamed. Concerning the lack of unity in our societies, comparing it with other “unities,” and summing everything up, pluralism is better. However, if this pluralism had a true fraternity, then nothing would impede the expression of man by spatial means.

The ingenuous South American (which we have all been) believes that behind this power there is always real efficiency. This is not true. What they do have is history. Surely there was efficiency, just as there was stealing, crime, and shameless exploitation (think about the slave trade and the opium war) and other equally iniquitous and sinister things. Today there is not even the barbarity that was at least audacious. The only thing left is an infernal machine that is mani festly senile yet always counts on our foolishness and complicity.

These large institutions that so many people admire do not deceive me. They do not deceive me because power for power's sake does not interest me. What interests me is the fulfillment and happiness of man. We have not found the way to make human fulfillment and happiness compatible with the great faceless monsters that dominate us (speaking of corporations, Chesterton called them "those institutions without souls to condemn and without bodies to kick senseless").[5] The great problem of industrial and post-industrial society is how to save mankind and even how to save this machine from self-destruction, the same machine that we have built and that has so many good and fascinating aspects.

Personally, what most terrifies me is not being able to find a way to prevent that the work of a large percentage of people will be boring and dangerous, even to a much greater extent than the strenuous work of other times. More than once, I have compared (during the same construction project) the workers from a highly developed country with our own countrymen. I have seen very well the poverty that they suffer and have felt the all-consuming desire to correct so much injustice. I would find myself in a serious predicament if I had to choose between the two destinies. In ninety-nine out of one hundred cases I would choose the destiny of the local laborer, even with his poverty. As a man, the worker in a developed society is much more alienated than the laborers from the River Plate area, and this is judging from men that I know from both groups. Another thing that I am sure of is that in a society in which such a large percentage of men live lives that are so unfulfilling, there will be a slow but general social disintegration.

In summary, I would like to say that I do not see "models" to imitate. I see something much more provocative: a task, a path, and I know that I have a compass.

It is obvious that what precedes is not intended to be an analysis or a judgement of industrialized society. These are things that I would not be able to do properly. I have a clear idea of the principle to which we should be faithful if we want to achieve the world that all of us, in some way, aspire to. I do not know very well what this world will be like. Who really knows that? What a great truth, the belief that "you find the path by walking!" What I would like is to try to destroy, using my years of experience as a builder, a false and paralyzing atmosphere (in our technology as well as our society) that seems to take for granted that all the paths are already inexorably plotted out. These already plotted paths are those that the powerful have marked out and those that have been marked out for us. It is not true that all the paths have already been inexorably plotted, nor is it true that the powerful are so powerful. They will not be powerful for very long if they ignore mankind, even if they can crush us momentarily.

The earliest version of this essay known to the editor is "Arquitectura y construcción," in "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 84–93. *Ed.*

[5] With expert assistance, the source of this quotation has, nevertheless, not been found. On Chesterton, see Dieste's essay "The Awareness of Form," on page 192, n. 5 of this volume. *Ed.*

## THE AWARENESS OF FORM

*Eladio Dieste*

When I have been asked to explain what has guided our projects, it is natural that I have always centered the explanation on what I had on my mind: the functional aspect. This is the most important consideration. Yet I understand this within the context of the richness of all aspects of human culture and its extremely complex necessities and desires, which are not easily put into words. When the function of something is schematized and simplified, the reality of what is being said or done is impoverished.[1]

I have explained, and supported with evidence, the concern for rationality in construction and economy understood in, I dared to say, a cosmic sense rather than a financial sense. However, this is not the only thing that has guided me. I have also been guided by a sharp, almost painful, awareness of form. Since I never had an academic education in architecture or in the visual arts, a certain modesty is natural (a modesty that I am trying to overcome with these words).[2] This modesty hinders me from talking about form since I have studied almost nothing of all that has been thought and written about the problems that it poses.

I believe that you can look at the different projects that are illustrated in this book[3] and compare the perception of the relationship between the form, the space that this form configures, and the functions that are realized in this space. At the Salto Municipal bus terminal, pedestrians pass along the west edge of the vaults, so it is natural that the space should accommodate and contain them.[4] For this reason, instead of cantilevering the horizontal slabs, which are necessary to resist the lateral thrust of the vault, the slabs were supported by the edge of the vault and a very slender pre-stressed beam. Using the beam as a structural strategy helped to define the space created by the vaults. I remember that I first resolved the structure by using slabs cantilevered from the edge of the vault, which is the simplest solution. After further reflection, the structure was built using a solution inspired by the visualization of the space. The roof is almost continuous, producing a sense of calm and stillness in accordance with being in the space. In contrast, at the main entries on each side of the terminal, one passes freely under cantilevered self-carrying vaults. No edge beam is required either structurally or for the definition of space.

At the Turlit bus station in Salto, the horizontal slabs are cantilevered from the edge of the vault, structurally the most economical solution. Taking another step, the best solution for these slabs that resist the thrust of the vault is to make them of variable width, growing narrower at the end of the cantilever. In the Turlit station, the vaults are twice as high as in the other Salto bus terminal, and what we might there call “spatial mending” is not necessary at Turlit. Here the edge beam is not required to define the space, and the roof can be dynamic without making us feel defenseless.

It is obvious that the form can either emphasize or betray a spatial sensation that one is trying to achieve. For the niche in the lateral chapel of the Atlántida church, the bricks were cut in such as way that they are thinner as they move away from the observer. This accentuates the sensation of depth that we were seeking. In reality, since the niche was filled with an effigy, the sensation of an indefinite depth is quite real. In the warehouse for the Port of Montevideo, the window openings and the pillars emphasize the form without disturbing the “Roman” solidity of the older masonry. Finally, in the Durazno church we attempted, with the architect Alberto Castro, to make the lateral and presbytery walls move away, ascending. With this we achieved a calm and at the same time dynamic space that has a visual dimension which is much greater than its real size. From inside, the church seems enormous, but its dimensions, “measured” from the exterior, are quite modest.

Coherence between the appearance of the form and the constructed reality is also important. Coherence makes the form intelligible to us. In the Maldonado television tower and the support structures for water tanks [at Las Vegas, for example], the horizontal elements were placed in a discontinuous manner. The alternative solution, which was the first that occurred to us, was much simpler. This solution would make a ring from each group of horizontal elements. I remember the first time we had to build a perforated tower

1 In another explanation, I used the example of the bell tower. Could one even compare what it can mean to climb the Chartres bell tower, the Strasbourg bell tower, or the towers of Gaudí’s Sagrada Familia with what is expressed, since we cannot climb it, in the pole that supports the bells in the Brasília Cathedral?

2 These lines are complemented by what I have said in other articles and essays, with examples that are more directly related to form.

3 Dieste here refers to the book edited by Antonio Jiménez Torrecillas in which this essay appeared. The reference is also applicable, however, to the present volume. *Ed.*

4 This paragraph and the next are effectively reconstructions by the editor. In the original, Dieste refers to specific features of his two bus terminals in Salto. Joining the sense of his argument with the features discussed allows for a formulation that is clearer and more compelling. I am also grateful for the consultation of John Ochsendorf. *Ed.*

of any importance, I was not convinced by the ring solution. I had come up with the idea shown in the finished works, but I could not find a conceptual justification that satisfied me. I shared my doubts with an architect friend for whom I had (and still have) the highest regard. After reviewing all the solutions he chose the rings because it seemed to him to be the simplest, the most "rational," as he often said. With much effort, I realized that the rings would divide the surface of the discontinuous shell that was the tower; they would not have been expressively appropriate to the structural unity of the surface.

The Turlit bus station provides an example of the serious expressive change that can occur because of elements that seem unimportant. Offices and a cafeteria were situated on the second floor of the station. The corresponding mezzanine was used as a tension tie in order to restrain, at the middle of the pillars, the thrust of the vaults. At the same time, these pillars could be used to support the mezzanine. This combination of uses could result in a lack of expressive clarity. This problem was to have been resolved by joining the mezzanine beam to the column with iron connections, which were made from two lengths of channel iron forming a box beam. These were the beginnings of the mezzanine's concrete beams, of which the outermost two were to support, in addition, the thrust of the vaults transmitted to them by the pillars. As a result, the concrete mezzanine appeared to be separated from the vaults' pillars. Due to negligence, the distance between the concrete facing of the mezzanine and the pillars was not respected and, in addition, the clear intention for formal precision was distorted when the mezzanine and pillars were covered with plaster (the concrete was to be left exposed). Furthermore, the pillars had a width of 25 centimeters where they joined the vaults, which was the result of the channel created by a band of two bricks. When the pillars were covered with plaster, this precision of form was lost. When the extreme pillar was covered with plaster, its expressive form was radically changed, and it became crude and heavy. The final result was a decrease in expressiveness and a quite distressing level of quality. I would like to point out that our contract was limited to the design for the structure and the construction of the vaults. The rest of the structure was built by a local businessman, and the errors that I have referred to are due to the fact the architect that oversaw the construction could not fulfill his obligations during the final phase of the project. To whoever thinks that the insistence on the precision of forms and dimensions is a kind of obsession and that these errors are not perceived by those who will use the structure, I would respond, as I did once a long time ago, that the difference between a long and short nose is only millimeters.

Form is a language, and this language should be intelligible to us. We are anxious for intelligibility and therefore for expressiveness. Part of modern anxiety is due to the absence of legitimate expressiveness. It is also due to the hermetic inexpressiveness of the things that surround us. This is the negation of the fraternity that we take for granted and should be naturally perceived in man's work in the space that surrounds him. The void of legitimate expressiveness is filled with refined or vulgar adornments that do not satisfy. In advertising, this void is filled with forms that fraudulently use studies in painting and sculpture from the last decades (someone with the necessary preparation will have to write about the use of cubism and surrealism in advertising). Furthermore, what we build will always be expressive. When our work does not communicate something to us because of inscrutability or carelessness, it expresses a deficiency that does not have the dignity of silence. Modern society is sick from the absence, savagery, and stupidity that occupy the place that our negligence has left empty.

There are many building projects that are important in themselves and because of what they will mean for the landscape. The only concern evident in these projects is what is technologically efficient. They do not show the slightest concern for how these structures might enrich our lives if they expressed the complex functions of what we do and if their principal function were legible.

For example, a microwave tower is something that is full of content. All of the richness of human life passes through it. Its membranes are like ears or mouths. Let us imagine that in our small cities, full of low houses and expressively neutral, we built, instead of the familiar metallic towers, brick towers similar to the Maldonado

5 The aphorism is actually from the American author and physician Oliver Wendell Holmes (1809–1894), in chapter VI of his *The Autocrat of the Breakfast Table* (Boston: Phillips, Sampson & Co., 1858). Holmes does not ascribe the paradox to any particular people or class. G. K. Chesterton, in the chapter "Dickens and Christmas" of his *Charles Dickens* [(London: Methuen, 1906), 127], only credits a "Boston paradox monger" and provides the text as follows:"'Give us the luxuries of life and we will dispense with the necessities.'" He introduces the paradox with an observation that the poor do not neglect special festivities but then says it applies to the entire human race. In the chapter "An Approach to Thomism" in Chesterton's *St. Thomas Aquinas* [(London: Hodder & Stoughton, 1933), 172], the quotation is identical and specifically ascribed to Holmes but now adduced simply as a good example of a paradox. The Spanish translations of these books render the saying differently; congruencies with Dieste's formulation suggest that Dieste's source was Chesterton's

television tower. The receiving (or "ear") membrane and the transmission (or "mouth") membrane could express their functions so that, with the same efficiency, the meaning of something that is so important in our lives could be perceived in space. I do not believe that the tower that I am proposing would be more expensive than the towers that are usually built. Perhaps with good guidance, the local bricklayer could build the tower, which would be another advantage. If the expressiveness of the density of human existence were embodied in everything that we see, our lives would be greatly enriched, and our quality of life would be incomparably better.

In order for expressiveness to be authentic, it cannot be gratuitous. The first principle is the consistency of what we build with the laws that govern matter in equilibrium. That is why it is logical that we build a structure to accommodate the stresses that it must resist. This is what nature does in its age-old and extremely subtle process of adapting the form to suit the function. However, when this process of adaptation is attempted by man, it does not always produce economies, at least not economies that are in line with a primal analysis.

In the pre-stressing equipment I designed and built, the lateral sides of the two U sections were reduced to adapt its form to the moments. Here, the intention was more instinctively expressive than a simple rational response to the need for resistance. I can affirm that when the equipment is assembled and in use, it has the quality of an abstract sculpture. Does this have any meaning or importance? I believe it does. I also believe that the person using this equipment unconsciously feels this just as I did when I built it.

When I speak of costs I am referring to the immediate costs, the construction costs. A more precise evaluation would measure the value of a structure in thirty or forty years. This evaluation would measure the benefits of seeing something that is elegant and expressive instead of something that can be equally efficient but less elegant, more mundane and less a source of inner strength, because it is less intelligible. When faced with incompetence and a false realism that believes that the only thing that matters is remorseless efficiency, we should remember the biting irony in the statement by G. K. Chesterton (1874–1936), "The people have always said, give us the superfluous and we will do without the necessities."[5] The superfluous, in this case, would be expressiveness and elegance, which respond to profound human aspirations that are full of meaning. In this sense, the superfluous will always find its way into our lives, even if it does so in a sordid or furtive manner.

Formal coherence and essential expressive adaptation are not valid in themselves, since they only comprise the ethical response to the problems that our work in space tries to resolve. They are like a preparatory school, and only with this school as a basis will a dynamic art be able to flourish. Without the revelation of the world's mystery, which gives us art, we will never be able to make anything really humane out of our lives.

The earliest version of this essay known to the editor is "La conciencia de la forma," in Galaor Carbonell, ed., *Eladio Dieste: La estructura cerámica*, Colección Somosur (Bogotá, Colombia: Escala, 1987), 185–92. *Ed.*

*Dickens*, as one might also expect from Dieste's ascription of the saying to "The people." Dieste also quoted Chesterton in his essay "Architecture and Construction" (see page 190, n. 5 of this volume).

G. K. Chesterton was a British poet, artist, playwright, essayist, and Catholic apologist in the first half of the twentieth century. At midcentury, Chesterton was very popular in Argentina, notably through the defense of his writings by Jorge Luis Borges. Ten of Chesterton's works were translated in a popular paperback series published in Buenos Aires. Chesterton was a friend and collaborator of the French-born, British Catholic poet and essayist Hilaire Belloc (1870–1953), whom Dieste references in his essay "Art, People, Technocracy" (see page 196 of this volume).

In personal communications, Antonio Dieste, a son of Eladio, confirms that numerous works of Chesterton and Belloc were in the Dieste library. Chesterton and Belloc invented a political philosophy they termed "Distributism," an anti-monopolist position that entertained various methods for the diffusion of capital. That Dieste, in these essays, cites only these two authors strongly suggests that he was sympathetic with their simultaneously Catholic and anti-capitalist position, which honored workers and those of limited means. (Dale Ahlquist, president of the American Chesterton Society, identified the possible sources for this quotation by Dieste. Arturo Villarrubia, a Chesterton expert in Madrid, provided information on the Hispanic appreciation of Chesterton. I am indebted to Carroll William Westfall and Ricardo Arosemena of the University of Notre Dame for checking the Spanish translations.) *Ed.*

ART, PEOPLE, TECHNOCRACY

*Eladio Dieste*

Some friends, whose opinions on the most important issues I share, differ with me when it comes to art. They talk as if art were just another luxury in a society sick with injustice and disorder. This is a misconception, but it is a congenial misconception. It is a reaction against the people who talk about art—people who believe art to be a less vulgar substitute for expensive perfumes and pedigree dogs.

Although art and good taste are very different things, for these people, art is the last and least important component of good taste. It is not easy, nor is it important, to define good taste. Nevertheless, permit me a definition that is valid for my particular limitations. I would say that it is the taste of that part of the upper class, sufficiently old and much better if it is already poor, that has done many different things in the course of its family history—the majority of which have been futile—and has developed a certain indifference toward almost all of these things. Certainly, this kind of good taste does not abound in the most familiar and visible aristocracy. Its formula in architecture could be Mies van der Rohe's creed, "Less is more." The definition that I have just given applies to one of the current styles of good taste, not to all styles nor to all time periods (remember the style at the end of the eighteenth century). At this point in time, this idea encourages a search for principles that have real value. One of these is the awareness of beauty in elemental and everyday things. Our world has acquired this awareness, I would hope definitively, through the influence of the modern architecture movement. For a tapestry to be more beautiful than a wool palliasse, the tapestry has to be very good. Many people prefer, and with good reason, a rough hospital cloth over almost all the elaborate fabric that is produced. It is difficult to make anything more surprisingly beautiful than a hammer, an axe, or a grafting knife. Their forms express with precision a given relationship with reality that is direct and decanted by time.

> Let us not make more out of good taste than it is. What really characterizes good taste is refinement combined with the desire to distinguish oneself, and for this purpose it often makes use of the human grace that gives life to the craftsman's hands.

Art is a different thing. It is the expression of man's awareness of his being and of the world. It is an awareness that, when it is intense, is always fleeting and is an expression that is mysterious even in the arbitrariness of the ways in which it manifests itself.[1] Bad taste can coexist with art. Quite often, the formidable artistic genius Gaudí did not have good taste. In his best works and in the essential moments of the others, a certain motley and cumulative heaviness disappears, and the light shines bright without shadows to obstruct it. The modest people that created the hammer and the grafting knife had good taste that transcended itself; they also had other qualities that are much more valuable, like innocence and a fresh appetite for the flavors of the world. From these qualities comes their baroque style, in the common sense of the word, not the architectural meaning. These qualities also foster their taste for adornment and decoration and the ease with which they are deceived by those that make commerce with their innocence and their respect for culture, using the prestige of long words to overwhelm them. For those of us who think it is important that good things reach everyone, it is important to know if modest people are indifferent to art. If this were irreparably the case, then it would not concern us so much anymore. I believe that they are indifferent to good taste that is nothing more than a passing fashion because they are not concerned about the game of those who want to distinguish themselves. They are concerned about tradition, a true and vivid tradition, rather than the one that the traditionalists talk about, which is an empty shell. What about art? If art were absent, would modest people be aware of its absence? Are they aware of its presence when so many signs seem to indicate the contrary?

In another place, I explain the conscious story, which is quite complex, of the things that guided me in the Atlántida church project. On the canvas that is this story, the soul embroiders obscure things for itself that almost always emerge painfully in the space, and because of this pain, have remained etched in the spirit. I also tell the story of how I was reassured by the comprehension shown by a very humble woman with her coarse shoes covered in mud. The itinerary that she followed, the places where she paused, the things that she said with complete simplicity and without accolades: these things made me realize that she really was seeing it. She did not see the complex, conscious intentions but rather the shape in which these had taken form. This was not, however, an isolated case.

I remember having attended, with very humble rural people, the moment when the scaffolding was removed from a very complex and audacious structure, audacious but serene. The structure was not important because of its size or cost but because you felt the tension of the effort that had made it possible. This is exactly what one of the men said, that it was not easy to build something like that. The audacity did not produce disbelief or surprise but rather happiness. This man distinguished very well the difference between what is important because of its size and cost and something that touches us in the most profound way because it expresses to us the force that produced it but without feeling that force.

I saw clearly, once again, that in order for something to truly reach modest people it must have a lightness, a mysterious ease, a concise simplicity, something like dance without effort or fatigue. It does not satisfy them, and they are right not to be satisfied, when a difficulty is resolved using blind force or money. They want the problem to be solved with the same effortlessness with which the sparrow hawk stays aloft and each flower in the field, when we really see them, is the center of a mysterious landscape and "not even Solomon, in all his glory, was dressed like one of them."[2] To perceive something in this way shows a penetration that is as delicate as the sweetness that the coarsest hands acquire when they caress the head of a child.

For those who are suspicious of anything that has an emotional charge, I want to clarify something. Like all human deeds that are dense with emotional force, what I have depicted above comes at the end of a rationally well-anchored chain of events. Behind the resolution of a problem that employs blind force and money, there is always the negligence, and behind the negligence there is the disdain or thoughtlessness and superficiality (which are other forms of disdain) of he who does not examine himself. This disdain is definitely contempt for human effort or for mankind itself; here, I think we have touched a common basis, something that we all agree on—the value of mankind. The grace that we demand from art is the flower of effort and energy, which is the opposite of negligence.

I use this example, as I do with those that follow, in an effort to investigate within my own experience whether or not art is important to modest people. For me, this is synonymous with whether or not art is important at all.

One of my childhood friends, Teófilo Ribeiro, was a good musician. He used to play the fugues of the *Well-Tempered Clavier* quite well on the guitar. We went together once to my father's small farm, and I remember how beautiful Bach's limpid music sounded beside the bonfire on those cold July nights. Within a week the farm workers had left their huts and were whistling very well these new songs that we had brought from the town. They whistled them because they liked them. They felt something of themselves expressed in them.

The most conclusive example of the creative capacity of modest people is the marvelous small villages that are something so perfect that there is almost no work of elite architecture that can be compared to them. It is conceivable that one or several geniuses could create something as beautiful as Chartres or the Parthenon again, but it is impossible that someone who is not a whole village of people could create something as marvelous as these villages. They are marvelous but at the same time fragile, precisely because of their innocence, so defenseless against the insolence of money or simply because that same innocence can be corrupted. Of these villages, I remember one in particular that was very close to my father's village and only a little bigger.[3]

The first time that I was there it was the end of summer, but because of the cool and misty climate, the vines that covered the path that lead into the village were still a transparent and tender green, as if it were springtime. The road came out onto a space that was a square and courtyard at the same time; or, in other words, the private space was public. It was surrounded by very old stone houses with windows that seemed as if they had been built from the inside, as we would make our eyes, if we could make them. (Haven't we really made them in the course of many thousands of years in which we attained, until the ages of stone and fire, an ever-increasing reverence for the mysterious center that spiritualizes the world?) From this square-courtyard with its flagstone surface, another street, which was lined with the same kind of houses, connected to another square-patio with a stone cross and a small tavern. In these squares there were several old women, as old as time, spinning wool as they did a thousand years ago. There was not even one tree; only stone, sky, and clouds. It was a landscape totally recreated by architecture with an unforgettable beauty and extremely modern. Everything that modern architecture was searching for was realized there. I thought with horror about the fact that the desire to correct the deficiencies, such as the sanitary system, of a village like this one would ruin this amazing masterpiece of architecture.[4]

Here, I would like to bring up another idea. Modest people have historically placed more importance on beauty than on the primary

1 I believe that this is what Aristotle wanted to express when he said that "the form is the soul of things."

2 Matthew 6:28, 29. *Ed.*

3 Antonio Dieste explains that Eladio Dieste's father was born in Uruguay but lived several years in Rianko, a small village near Santiago de Compostela in northwestern Spain. *Ed.*

4 Years after writing this, I visited the town again and found that this marvelous place had been destroyed "by the defenseless innocence of the people against the power of money" and by the very human aspiration to liberate oneself from "corporal servitude."

5 For more information on Belloc, see page 192, n. 5 of this volume. *Ed.*

6 Matthew 6:33. *Ed.*

commodities that so obsess the modern world. The sanitary deficiencies that are referred to are obvious. I am not opposed to overcoming them. On the contrary, I believe that the modern aspiration to liberate man from corporal servitude is very noble and humane. I would simply like to point out that the focus of popular concern has always been directed at the most noble things. They are more concerned with proportions than bathrooms. In a way, this does make good sense. We always have proportions present in our lives, but we only spend a few short minutes in the bathroom.

We also have unexpected examples of this in the city, among us. Many years ago, during a project I directed, there was the risk that some old and poorly constructed houses would be adversely affected by the work that we were doing. The houses were rented by the room—one of our old tenement houses. I went to speak with the tenants to propose that they go to a hotel for a few days until the dangerous part of the work was finished and we had repaired the damages that had already been caused. Many of the rooms were quite cozy, but there was one in particular in which an extremely gracious little old lady lived. It was a marvel of spatial organization or, we could say, architecture. The shelves, the tables, the rocking chair, all seemed to extend her already trembling arms and knotted and wrinkled hands. She had the touching beauty that a life of work gives human beings. The room and everything in it had taken shape around and through her. As a consequence, the space was ordered in a very humane and beautiful way.

Knowing how to look beyond deceptive appearances, I would say that all of my experience tells me that people make art if you let them. They are sensitive to art and would surely be much happier if our cities, villages, and even our countryside were more humane, more like the little old lady's room. When we say "countryside" or "nature," we should know that it is man that permits us to see, contemplate, and understand these spaces. In the almost lunar plains between Cuzco and La Paz (as a whole, this is probably the most spectacularly beautiful thing that I have seen on earth), there is the vibrant presence of the Indians. On the train, from far away, they look like little ants. Then suddenly, they straighten up and look at the train that is carrying us and passes by. The Indians are like a flash of lightning that illuminates your soul. Only then, the vision, like an arrow, penetrates into the abyss of contemplation, and we see as never before. We see the yellow plain, the mountain peaks covered with snow, and the motherly affection that pulsates for us in the earth.

Let us leave the modest people and move on to those that control the world. It has been an unexpressed but vaguely felt desire of all aristocrats that there should be human archetypes of behavior and lifestyle, and they designate themselves to embody them (except for great men like Ortega in deplorable moments of weakness that it is better to forget). The payment for this is to eat better and to receive better treatment. In great moments of innocence or of great tension, like revolutions, these archetypes are produced. They are archetypes because they are created by the weight of the community, encouraging them and making them into their voice and their expression. When complexity and the lack of essential well-being in human relations cause these archetypes to become weak and nebulous, it is more difficult for them to be exemplary virtues and those that really have some force. It is most likely—we see this all the time—that a base shrewdness will take its place. Now, it is almost exclusively among the poor that magnificent, noble, and exemplary expressions take refuge. These are expressions of an aristocracy but in the etymological meaning of the word—more authentic than the aristocracy of sauces and perfumes. It is not, however, in the hands of the people but rather in the hands of the bourgeois elite that is spawned what we usually call aristocracy (Belloc said that the aristocracy is old wealth[5]) and the manipulation of art that we find among us. The result is as radically miserable and inhumane as the society that adopts it. It is these pseudo-aristocrats of today that have made our cities so ugly with museums full of beautiful paintings, our jarring streets, and our concert halls. This concern for art would be more logical and humane if it had a more general, less specialized character. Our societies are less and less popular and democratic. They are more and more controlled by technocrats, those gentlemen who think about everything except what is important. They make big decisions that have nothing to do with the final objectives of mankind. They do not consider these objectives because, in most cases, they are extremely cynical or politically pessimistic and, in general, are being paid by those who have no interest in considering these issues. The worst kind of aristocracy is the elite that believes that its preeminence is justified and is based on something serious like science rather than on trifles like sauces and perfumes. I have found among them a curious aberration: a certain horror at the idea that beauty is present in our lives. For them, the only option is for the world to be ugly and sordid because that is what is efficient, that is what works, and from this sordidness we can make a lot of money to buy paintings for the museums and music for the concert halls. What I am saying could seem a bit exaggerated, but, unfortunately, I have examples. Two years ago, I had an argument with a colleague who had decision-making power in the choice between two alternative proposals for a bridge. The project that he insisted on defending was more expensive without being any safer, but since it was uglier and unwieldy he supposed that it had to be

more efficient. On another occasion, I proposed a structure for a steelworks. It took all the patience I had to counter the objections that were made until we reached the heart of the antagonism. In some way, they thought that it was immoral to build something that they felt was “not ugly” for a steelworks. They were suspicious of a concern for beauty. They felt something that was inexpressive, cold, and, as a consequence, ugly would be the safest. Without meaning to, they had created a new Moloch, which was no less sinister than the original. This new Moloch was meant to efficiently crush the people for their own good, and later they would receive good dividends.

Another time, when I was finishing a factory building with sawtooth vaults, I tried to convince the decisionmakers to put clear glass in the skylights. It was beautiful to watch the clouds go by and even a few seagulls, as we were not far away from the ocean. I was not successful. There were various objections, but the essence of them all was a dark fear that the beauty and grace of the world would become part of our lives. Even though they were shocked by this idea and complained that this was not at all what they were suggesting, everything that they had said suggested that life's grace and beauty should be isolated and stratified into levels of quality that become lower and lower as we get closer to the poorest classes. Does this have any justification, or for that matter, is it even efficient (although this kind of efficiency, if it existed, could not be justified)? Of course it does not. The worker who lifts his head from what he is doing and sees the clouds pass by or the marvelous security and grace of a bird in the air will not be as tired and will acquire in this contemplation new energy. In the end, he will produce more. In a hierarchy with appropriate intentions, all of this should be a reality, not intention. (“Seek first the kingdom of God and his justice and all these things shall be added unto you.”[6]) They should make sure that everything is noble, appropriate, and elegant because this is what sustains man, what makes him. However, since their hierarchy of values is erroneous, they never seem to get it right.

In summary, the experience that I have had in my contact with modest people has shown me that they have a desire for contemplation (as all men do, because they are men). This desire is satisfied and nourished by the works of society and its individuals in the space that surrounds us. In the same way, my experience with the elite that governs us has shown me, in general, a mitigation of this noble desire, a lack of understanding for the importance of art for human happiness and, as a consequence, for its practical value. I have given examples that might be a bit extreme, but in order to see that what I am saying is essentially true, all we have to do is to look at our city or any other city. The spirit only rests in old things, in things that have been abandoned by “living forces,” that seem to have become more human with the passing of time. However, this is not the vital and abundant expression of the mystery of the world in space, which is so important to a really humane existence.

> Nobody denies a kind of beauty to today's big cities. New York is beautiful; Buenos Aires is also beautiful. Everything human has an indestructible beauty. Mankind is expressed in these enormous urban areas. Nevertheless, what a difference there is between what they are and what they could be! What a contrast between their broken and frustrated appearance (redeemed only by the evening's sweetness, the sky's limitless depth, the tree's strength, the dove's grace) and what they should be—the home of mankind!

These lines do not suggest mistrust in the future of our civilization. On the contrary, there is nothing essentially inhuman. There is humanity in large urban centers and even in industrialization. These are paths that we have to follow to the end, but we should not take a single step that we can avoid, that is not guided by the principle that we all say we believe and yet betray all too often. We should be guided by an awareness of the dignity and value of mankind and its mission to make the earth a more humane place, to make the earth man's true home.

It is not easy to have a clear image of the goal. On the other hand, it is much easier to have a clear image of the foundations and principles that will shape that goal. This is why the idea that “the ends justify the means” is a drastic mistake. We do not know what the end will be. We have an image of our goals, but these will never be realized if in our actions we betray the principles that will shape and form these goals. We cannot postpone for the future city the beauty and dignity that we need so badly to endure the severities of life. We cannot postpone them as principles even though we might have to compromise in practice. When we have no other choice, we will have to compromise, but we should always continue to try to achieve the principles that will shape the goal, our future.

In this battle, as in all battles, we are sure that, through errors and ignorance that are certainly no greater than the mistakes and ignorance of the ruling elite, modest people will always come out on the winning side.

The earliest version of this essay known to the editor is “Arte, pueblo, tecnocracía,” in Galaor Carbonell, ed., *Eladio Dieste: La estructura cerámica*, Colección Somosur (Bogotá, Colombia: Escala, 1987), 195–200. *Ed.*

# A GRAPHIC PRIMER ON DIESTE'S CONSTRUCTION METHODS

*Gonzalo Larrambebere*

Self-carrying vaults (also called freestanding vaults)
A series of photographs illustrate the construction of small, simple vaults at the CEASA markets in Porto Alegre, Brazil, 1969–72.

fig. 222: Small self-carrying vaults. In the foreground, the reinforced masonry “valleys” of what will be the laterally adjoining vaults can be seen; beyond, the wooden formwork for a series of barrel vaults.

fig. 225: Small wood strips, nailed to the formwork to position the bricks. This stage is followed by the placement of reinforcing bars between the bricks and filling the joints with mortar.

fig. 223: Timber trusses for the formwork in figure 222. The formwork moves on rails set on the timber platform.

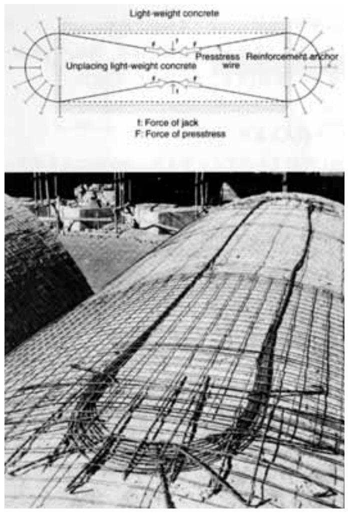



fig. 226: Looped pre-stressing steel, which absorbs negative bending moments. The brick vault, still supported by formwork, is shown prior to spreading the mortar that will cover most of the vault, including the fixed ends of the steel loops.

fig. 224: Detail of the simple displacement devices. Metal wheels and rails are used for horizontal movement; metal screws, for vertical displacement.

fig. 227: Pre-stressing the looped steel rods with a mechanical jack. The light steel welded mesh will be bent back and cemented to complete the roof.

Double-curvature vaults (also called Gaussian vaults)
A second series of photographs, illustrating a variety of projects, shows the construction sequence for moderately large, discontinuous double-curvature vaults.

fig. 228: Metal framework and timber superstructure (ribs and planking) of formwork for a vault of 98.5-foot (30-meter) span. Rails are placed just under the outermost steel pipe columns. During horizontal displacement of the form, the central columns do not play a structural role. (Lanas Trinidad wool warehouse, Durazno, ca. 1988)

fig. 229: Detail of a device to allow movement of the formwork past the tie-rods. Two parallel metal beams, separated by wood blocks, are placed in the direction of the horizontal movement, between the pipe column and the upper lattice truss.

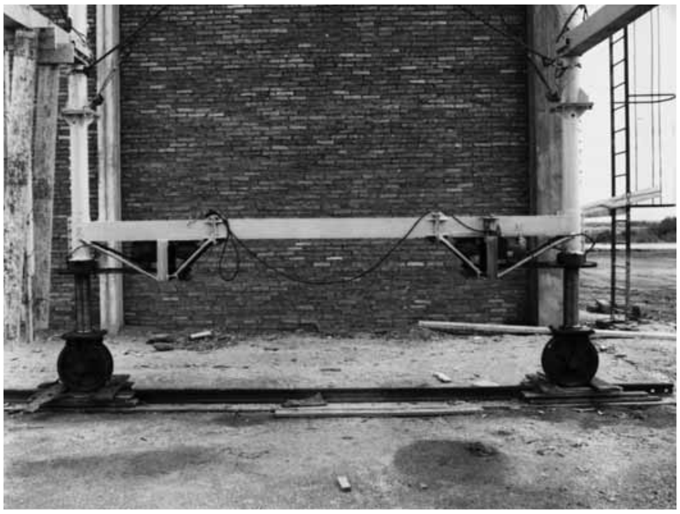


fig. 230: Wheels on rails, used for horizontal movement, and electromechanical jacks, used for vertical displacement

fig. 231: Timber ribs of the formwork, just before laying the surface planking

fig. 233: Detail of an expansion joint between two Gaussian vaults. To the left is the beginning of the groove to lodge the upper edge of the skylight. (CEASA markets)

fig. 232: Discontinuous vaults with skylights. In the left foreground, wood strips on the planking control the location of the bricks. Reading into the center distance and back on the right side of the photograph, successive stages of the placement of brick, reinforcing, filling joints with mortar, and covering the bricks with a thin coating of cement are visible. The holes at the upper edge of the vault at the right allow the fixing of the vertical frames of the skylight. (TEM factory, Montevideo, 1960)

fig. 234: Interior view of discontinuous vaults. The vault at the left is newly finished; the formwork is positioned for the next vault. (CEASA markets)

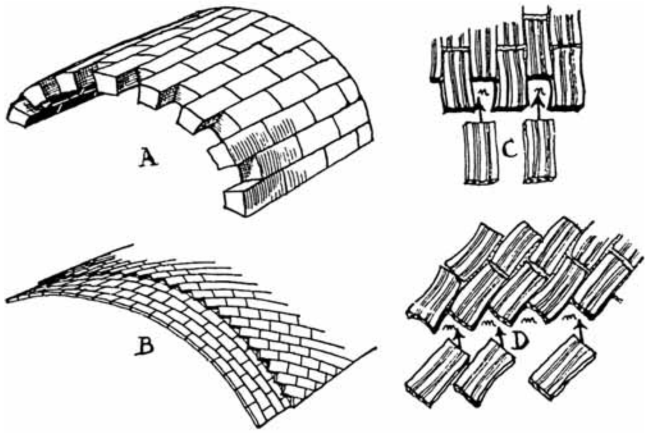



fig. 235

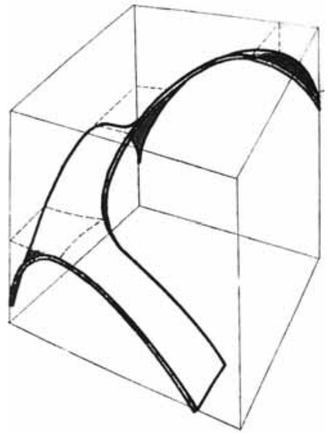


fig. 236

BUILDING CATALAN THIN-TILE VAULTS IN SPAIN:
A FIELD JOURNAL

*Timothy P. Becker and Kent Anderson*

The origins of thin-tile vaulting are ancient, but the building method used to produce these elegant and expressive structures was not perfected until the early nineteenth century, in Spanish Catalonia. “Catalan vaulting,” as it is called in Spain, is a system for constructing thin masonry vaults of broad, thin, terra-cotta tiles laid flat, usually in two or more layers, to form a pure masonry structure requiring no steel reinforcement. In contrast to standard stone or masonry vaults, Catalan vaults achieve a remarkable strength through the use of a highly cohesive mortar and the sandwiching of tiles to form a thin laminated surface. This sandwich construction, combined with the funicular shape of the vault, enables masons to build these vaults without falsework or supports (fig. 235).[1] This vaulting method allows experienced builders to create with ease, using a series of straight lines, the curved or warped surfaces known as “quadric ruled surfaces.”

In 1981 and 1982, the primary author of this essay, Tim Becker, initiated his research on Catalan vaulting. In 1988, he returned to Spain to study Antoni Gaudí’s use of Catalan vaults and to document their construction procedures.[2] At this time, Becker met coauthor Kent Anderson, a Canadian sculptor interested in ceramic sculpture, who was in Spain to explore the sculptural potential of Catalan vaulting. Both were invited to conduct research at the Catedra Gaudí (Gaudí archives) in Barcelona. Between 1988 and 1989, the authors constructed six Catalan thin-tile vaults, documenting the process of construction. In this essay, we demonstrate how three of those vaults are laid out and built.

Bóveda de escalera (stair vault)

Tournabous, Llerida, Spain, March 1989
Supervising builder: Pere Camats
Head mason: Demetri Camats
Builders: Demetri Camats and Tim Becker

Becker began his investigation of traditional vaulting in consultation with the architect Puig Boada, a former student of Gaudí. Boada was director of the Sagrada Familia project during a period of growth in the 1950s and 1960s and was the designer of several churches in Catalonia. For instruction in classic Catalan building techniques, Boada recommended study with Pere Camats, a highly regarded builder in the Llerida region west of Barcelona. In the spring of 1982, the Camats family showed Becker how to build a thin-tile stair vault called an *arco de caballo* (horse arch). Upon his return to Spain in 1988, the author reestablished contact with Camats and arranged to build and document a *bóveda de escalera* (stair vault).[3]

The *bóveda de escalera* is commonly found in square or rectangular stairwells of older buildings. It is comprised of a series of horse arches built against each wall face, with each successive vault springing from the top of the preceding one (fig. 236). A landing is formed at each corner.

Work began by clearing a space in a corner of a high-walled yard. Pere Camats emphasized the importance of accurately laying out the stairs before starting to build. Treads and risers were marked on the walls. After their locations were established, the center point of the stair was located, and a vertical guide pole was driven into the ground at that point. From the wall, the point at the bottom of each riser was transferred over to the guide pole using a straightedge and level (fig. 237).

The actual vault layout began with marking the line of the arc of the stair vault using a strip of thin, flexible wood veneer (fig. 238). Determining the proper shape is very important: if it is too sharp, the vault will be too steep; if it is too shallow, the vault will buckle and fail. The correct shape will transfer the loads down to the ground within its thin structure. Although there is a formula given in some masonry manuals, Pere Camats, like most experienced Catalan masons, formed the shape by eye.[4]

The veneer strip was bent to the proper shape against the wall and pinned with concrete nails. Pere Camats did the initial layout, with his son Demetri assisting. They mixed small batches of *hueso para lucir paretes* (a quick-setting plaster) used to glue the edges of the tiles together temporarily. Had this been a permanent exterior stair, *cemento rapido* (a rapid-setting, water-resistant mortar) would have been used instead of the plaster.

The first batches were slapped up against the underside of the guide strip and allowed to set. The strip was then removed, leaving a thin ledge of plaster that would serve as a guide for the tile assembly and as a temporary structural support to attach the tiles to the wall.

In the next phase of layout, a string was stretched between the lower riser points on the wall and level with the riser marks on the guide pole (fig. 239). Strings forming a series of straight lines generated a curved surface—technically, a ruled surface. These strings served as building guides and took the place of wood centering. This was one of Gaudí’s principal methods for generating complex forms.

After the line of the arc was bent, a foundation, or “kicker block,” was built to deflect and transfer lateral forces down into the ground (fig. 240). The location of the base of the arc was slightly below the first tread. The masons used *jeros*—light, extruded terra-cotta bricks with air cavities—for this part of the construction. The *jeros*

fig. 235: Illustration comparing a) a traditional brick or stone vault, which relies solely on compressive forces to transfer gravity loads, and b) a thin-tile vault, which allows for some tensile forces to be resisted by the "cohesive" laminar construction where joints do not align one on top of the other. Two methods of assembly are also shown: c) tiles laid orthogonally, with joints parallel and perpendicular to the axis of the vault, as at the lower course in b); and d) an alternative assembly of tiles laid diagonally, with joints at 45° to the axis, as at the upper course in b).

Bóveda de escalera (stair vault).

fig. 236: Illustration showing parabolic arcs of vaults as they climb each wall. This version incorporates pendentive corners.

fig. 237: Masons lay out the center of the stair and transfer of the stair riser points with a straightedge and level.

fig. 238: The parabolic arc that will be used by the masons as a guide to form the vault is constructed using a strip of thin, flexible wood veneer.

fig. 239: Stair center guide pole and strings are set up to guide masons in the formation of the helicoid shape of the inside edge of the vault. The strings generate a quadric ruled surface.

fig. 240: Construction of the foundation, or "kicker block," of the stair vault involves a quick-setting plaster, used to "glue" the tiles together edge to edge.

fig. 241: Tiles are assembled along the interior edge of the vault.

fig. 242: The completed vault was able to support a concentrated load about four hours after the last tile was set in place.


fig. 237


fig. 240


fig. 238


fig. 241


fig. 239


fig. 242

were approximately 11 inches long, 5 inches wide, and 4 inches thick. To this point, the layout was similar to that of a standard masonry or stone vault except for the curve of the arc.

The Camats demonstrated how to cut the tiles and mix plaster with the traditional Catalan masonry trowel called a *paleta. Mahones* —extruded terra-cotta tiles with air cavities that measure roughly 11 inches long, 5 inches wide, and 1 inch thick—were used for the vault construction.

During the construction of the first course, compression of the plaster between each tile is key. After the mason knifed a generous portion of plaster onto the tile's edge, he set it in place with a few taps of his trowel handle. This produced a slight suction that locked the tile firmly in place and created a compressed joint.

The Camats began laying the tiles using a quick-setting plaster. They cut and glued the tiles together at the edges, starting at the wall and following the line of the arc. After the first line was partially built, the second, third, and fourth lines were started, the mason making sure to stagger or break the joints. The bottom of the tiles just grazed the top of the string lines.

At this point, the building of the vault entered fully into the world of cohesive construction. The masons mixed up a small amount of plaster—enough for one or two tiles—and tiles were cut, plastered, and fitted quickly. The mason held the tile in place until he felt the plaster set up—usually about 45 seconds—then let go and set the next tile. The end tiles, in a line, appeared to float or be suspended in air (fig. 241).

As the vault turned the corner at the first landing, the interior edge, which curved around to begin the second arc, contrasted with

1 Luis Moya Blanco, *Bóvedas tabicadas* (Madrid: Dirección General de Arquitectura, 1947).

2 This study was funded by a Fulbright/Hays Spanish Government grant.

3 This type of stair is also referred to in some masonry manuals as a *zanca a montacaballo* (horseneck vault).

4 A formula determining the proper shape of the parabolic arc can be found in an interesting Spanish masonry manual that features two chapters on thin-tile vaults: Fernando Cassinello, *Bóvedas y cúpulas de ladrillo* (Madrid: CIDE, 1969), 122.

the wall edge that followed the line of the scribed arc and dead-ended into the opposing wall. All tiles followed the guide strings to form a warped surface (fig. 241). Making a smooth transition on the interior edge was difficult work, requiring a good eye and proper cutting and placing of tiles. If the underside of the stair is visible, masons will often use a higher quality glazed polychrome tile and fit the pieces tightly with a very thin grout line.

Once the first layer had advanced a little more than half way up the wall, a second layer was started. A high-strength mortar was spread over the top surface of the first layer, and tiles were set into the wet bed of mortar with edges snug and all seams staggered. The mortar consisted of Portland cement and sand, mixed in a ratio of 1:3.[5]

Once the mortar or plaster has cured, the entire vault behaves as a single piece of material with remarkable tensile resistance for a masonry product. This is what gives thin-tile vaults their strength. When cured, the vault is so taut that it resounds like a drum when tapped; for this reason the vaults are sometimes referred to as *timbrel* (tambourine) vaults.[6] This single layer test vault was able to support a concentrated load about four hours after the last tile was placed (fig. 242).

Bóveda de quatro puntos (four-pointed vault)

Montmelo, Spain, May 1989

Supervising builder: Sr. Castells

Head mason: Francesc Marin

Builders: Francesc Marin and assistant

To begin the *bóvedas de quatro puntos*, barrels and boards were set up to simulate walls. The masons used *jeros* and built above each wall with *cemento rapido* to form four arcs (fig. 243). Construction of the vault started in the corners with thin-tiles—in this case, extruded solid *rasilla* tiles about 8 inches long, 4 inches wide, and 1/2 inch thick. The tiles were cut and fitted in a zigzag pattern. The first line of tiles ran up along the edge of the arc (fig. 244).

The masons worked carefully in the beginning because the placement of the early tiles determines the final shape of the vault. All corners were worked up together, and subtle adjustments were made to each new tile as it was held in place and the *cemento rapido* was setting up. The masons added bit by bit to the whole vault, making repeated passes as they built (fig. 245).

Had this been a permanent vault, a second layer of tiles would have been started when three full lengths of tile sprang from each corner. A thicker layer of high-strength mortar was used at each corner to add ballast and to strengthen those points (fig. 246). The arched ends of the vault are not structurally necessary; they are often left open or filled in with a thin-tile lattice to screen out the sun. All the weight of the vault is transferred through the four points at the wall corners (fig. 247). These vaults were commonly used in storage buildings in the Catalan countryside. When viewed from a passing car or train, they look like inflatable membranes, billowing and tent-like.

5 The ratio of Portland cement to sand varies between 1:3 and 1:4, depending on the amount of moisture in the building materials. This formula was identified by Pere Camats as a common recipe used by local masons.

6 See George R. Collins, "The Transfer of Thin Masonry Vaulting from Spain to America," *Journal of the Society of Architectural Historians* 27, no. 3 (October 1968): 179, fig. 6, for a description of timbrel vaults.

Bóveda de quatro puntos (four-pointed vault)

fig. 243: Masons mock up walls with arched tops in preparation for building a vault.

fig. 244: Tile assembly begins at each corner and the masons gradually work up each portion.

fig. 245: The vault is constructed purely by eye, with no formwork or guidelines apart from the four arched wall tops.

fig. 246: A final touch-up using quick-setting plaster. Note that the vault corners are built up with a cement-based mortar to help transfer the load to the walls.

fig. 247: An interior view of the completed vault shows the oculus

fig. 243

fig. 245

fig. 244

fig. 246

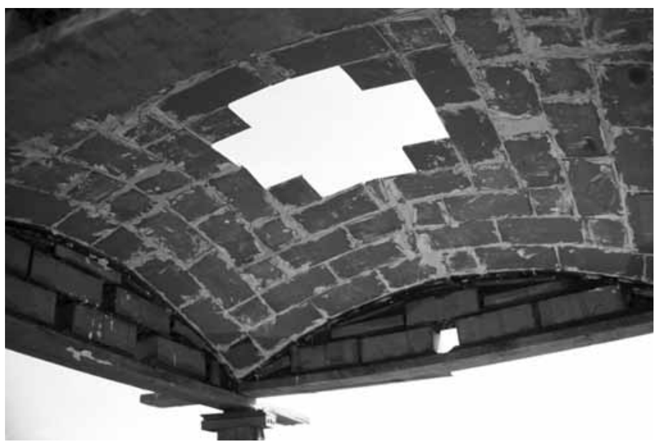


fig. 247

Bóveda de caracol (snail vault)

La Bisbal d'Emporda, Gerona, Spain, June 1989

Supervising builder and mason: Joan Rasos

Builders: Tim Becker and Francesc Font

Joan Rasos, a traditional builder from the Gerona region, provided instruction on constructing a *bóveda de caracol* while working on a country house north of Barcelona. The vault took six days to build and document.

Rasos began by laying out the wheel and spoke plan of a circular stair, marking risers and treads directly on the concrete floor (fig. 248). Next he began an exterior supporting wall using *mahones*. Tiles were joined with quick-setting plaster, and the wall was built to a height of 7 risers. (In a permanent stair, the builder would start with a cylindrical stairwell.) Tread and riser lines were then transferred vertically from a central point on the floor plan and horizontally from a central column to the supporting wall with the aid of a level. Using straightforward building techniques, Rasos began transforming the plan into the three-dimensional stair.

He scribed construction lines onto thin beds of wet mortar to guide the mason in forming the helicoid vault (fig. 249). A temporary central column was built to form the inside curl of the stair, and the mason translated the riser lines from the floor plan to the column (fig. 250). The shape of the spiral stair vault was generated by a series of straight lines that were rotated in an ascending pattern. The vault was built following the lines brought up from the original floor plan. Lengths of bamboo provided the three-dimensional representations of the riser spokes in the floor plan and served as guides in the construction of the vault (fig. 251).

When the vault was completed, the column support was removed. The riser and tread lines scribed on the inside of the supporting wall represented the profile of the future stair, which would be built on top of the vault. The structural load was carried through the vault and the supporting wall to the floor (fig. 252).

The authors' investigation into traditional Catalan construction techniques provided special insight into the originality of this fluid style of vaulting. While the mechanics of each vaulting type varied, all shared a common reliance on a remarkably simple construction process. The lack of formwork allows masons to proceed without a rigid *a priori* shape for determining form. With faceted or tessellated assembly, the small bricks are joined together quickly, mosaic fashion, allowing for subtle alterations by the builder and designer during the process of construction. Gaudí in particular understood that, in the hands of a talented mason, this system could provide an unlimited vocabulary of form. In our opinion, such extreme economy and direct exposition gave architects like Gaudí greater freedom to experiment.

The compelling qualities of Catalan vaulting are both practical and poetic. On the practical side, the lack of formwork means that a construction company requires one less layer of skilled workers (i.e., formworkers); the transportation and storage of the formwork material are also eliminated. To this day, modern Catalan masons use small trucks, which carry only the bricks and mortar needed for the job at hand. The independence of the process from a more elaborate infrastructure encouraged a true vernacular building tradition, resulting in subtle variations from village to village. Another important implication of the lack of formwork is that masons must employ ruled surfaces; this not only imbues the vaults with grace but also creates forms on demand and with ease, with sound structural properties like those found in nature.

The poetic analogies are numerous. All masonry structures have a cave-like permanence that resounds deep in our past, but these thin-tile vaults go further to become a kind of miraculous hybrid of caves and tents. Upon finishing a vault, one has the feeling of a rightness of form, like a sail filled with air or a freshly thrown pot on the potter's wheel. The vaults, whether part of Gaudí's Colonia Güell crypt or a lowly carpenter's shop in a small village, have a magical quality that cannot be captured in words. When you are in these curved, textured spaces and you rap your knuckle on the taut surface, you truly appreciate the beauty of a Catalan vault.

The authors wish to thank Edward Allen of the School of Architecture, MIT; Juan Bassegoda i Nonell of the Gaudí Archives, Barcelona; and Dolores Ros of La Escuela de Cerámica de La Bisbal. We would also like to acknowledge the assistance of our editors and friends Carrie Allen; Bruce Hevly of the Department of History, University of Washington; Arnie Katz; James Thomas; and especially, Mary Lane. Special thanks go to the late George Collins of Columbia University for his early help and encouragement in 1981.

Bóveda de caracol (snail vault)

fig. 248: Lines of risers and treads of the spiral stair are laid out in plan on the floor.

fig. 249: A thin wall of hollow core tiles is built up to simulate part of a cylindrical stairwell, and the working lines are scribed into a bed of wet mortar.

fig. 250: A temporary central column is built out of a plastic pipe sheathed with cut tiles and coated with plaster.

fig. 251: The helicoid vault is built over a minimal ruled surface guide formed with bamboo sticks.

fig. 252: When the partial vault is complete, center column is removed.


fig. 248


fig. 250


fig. 249


fig. 251


fig. 252

## RESEARCH AND PRACTICE IN REINFORCED AND PRE-STRESSED BRICKWORK AND THE PLACE OF DIESTE WITHIN IT

*Remo Pedreschi and Braj Sinha*

Eladio Dieste's work suggests a new paradigm for the use of traditional materials, a change in perception, and an expansion of possibilities. His work is exceptional in the history of structural brickwork. Overlapping with the period when Dieste was building, between 1943 and 1996, there was a general re-examination of the potential applications of structural masonry, mostly in Europe and the United States but ultimately worldwide. A sizable community of academics and engineers conducted research and developed many aspects of structural masonry. By and large, this community was unaware of the remarkable accomplishments of Dieste in South America. A review of the research and practice in reinforced and pre-stressed brickwork during the twentieth century may provide a further perspective on the work of Dieste and the nature of his innovations.

Although research on reinforced brickwork was in evidence for most of the twentieth century, various publications suggest that the major resurgence of interest in brickwork as a contemporary structural material started in the late 1950s in Switzerland.[1] Innovative tall load-bearing unreinforced brick structures were constructed using thin, engineered brick walls. Apartment buildings up to eighteen stories were being constructed with walls between 5 and 10 inches in thickness. The thinness of the walls was determined by rational structural analysis and substantive material tests. (Prior to this, load-bearing walls were designed largely by empirical methods; brickwork buildings taller than four or five stories were uneconomical and, by this time, had been superseded by steel or concrete frames.) A research community was stimulated. Many programs were initiated to develop the use of masonry in multi-story applications and to provide the necessary input into national building codes. These structures used the high compressive strength of masonry in an appropriate manner.

As the structural properties of brickwork became quantifiable, further applications were considered. Brickwork shares characteristics with concrete: it is brittle, but strong in compression. Could brickwork be used in beams, where tension occurs? Concrete deals with tension by either reinforcing or pre-stressing. Thus there was a progression in the interest of researchers and engineers toward the use of these techniques in brickwork. This appendix concentrates on the application of reinforcing and pre-stressing to primary structural elements rather than the use of reinforcement to improve earthquake resistance of masonry buildings or in secondary elements such as lintels. Developments in reinforced and pre-stressed brickwork are considered separately.

### The Development of Reinforced Brickwork

The earliest recorded application of reinforced brickwork is attributed to Marc Isambard Brunel (1769–1849) (Beamish 1862). In 1825, during the construction of the Thames Tunnel, Brunel used wrought iron rods and hoops to strengthen two large brick shafts. The shafts, 49 feet in diameter and 43 feet in height, were sunk into the ground by excavating from inside the shaft. The reinforcement proved effective. Despite uneven settlement there was no cracking in the shaft during the lowering operation.

In 1837, Pasley (Marchant 1965) carried out experiments on unreinforced and reinforced brickwork beams. His results showed that the flexural strength of brickwork was increased many times in beams with reinforcement. Pasley used his results to develop an empirical procedure for structural design.

In the early part of the twentieth century, there were a few notable and substantial experimental studies in reinforced brickwork, by Brebner in 1919 in India and later Fillipi in the U.S. and Kanamouri in Japan. In 1923 the Public Works Department of India published the results of 282 tests on beams and slabs carried out by Brebner (1923). The tests confirmed that the behavior of reinforced brickwork was similar to that of reinforced concrete. He also tested brick columns with lateral and longitudinal reinforcement—columns with square, circular, and fluted cross sections, with longitudinal reinforcement varying from 0 to 1 percent of the cross-sectional area of the column and up to 6 percent lateral reinforcement. The longitudinal reinforcement did not significantly increase the strength of the column but the confining effect of the lateral reinforcement increased the strength by up to 36 percent and 62 percent for the circular and square columns, respectively. The results of the research were applied in a large building program in the state of Bihar in India: 279,000 square meters of building were constructed.

In Japan, Kanamouri's researches into the structural behavior of reinforced brickwork led him also to conclude that reinforced brickwork behaved in a manner similar to reinforced concrete. However, he also found differences: the modular ratio[2] was higher: 25 for reinforced brickwork compared with 15 for concrete. His work also demonstrated the increase in strength that the addition of steel reinforcement provided. The strength of a reinforced brick structure could be increased fourfold by incorporating up to 0.3 percent by volume steel reinforcement. This work supported the use of reinforced brickwork in retaining walls.

In the U.S., Fillipi (1933) published the results of tests on reinforced brick slabs and beams. He compared the results with the requirements of the Chicago building codes of the time, demonstrating that the deflections of reinforced brick structures were less than the maximum allowable, and further, that even when loaded to 1.5 times the design load, the recovery of deflection was around 80 percent.

During the period 1922 to 1935, a number of academic institutes in the U.S. became interested in reinforced brickwork. Whittemore and Dear (1932 and 1933), of Virginia Polytechnic, reported tests on thirty reinforced brick slabs, each 95 mm thick and using a 1:1:6 (cement, lime, sand) mortar. They compared the results with tests on similar reinforced concrete slabs. The reinforced brick slabs exhibited considerable ductility, had an adequate reserve of strength over the working load, and could be designed using principles similar to those for reinforced concrete.

Parsons, Stang, and McBurney (1932) studied the shear strength of reinforced brickwork, an area that a number of researchers would consider later. They tested eighteen beams, using two different formats of brick with steel reinforcement equivalent to 1 percent of the cross-sectional area. The shear strength obtained from these tests varied from 65 to 159 lb/in$^2$. They also studied more detailed aspects of behavior of reinforced brick beams, such as the strength of the brick/mortar interface and the bond strength between brickwork and steel reinforcement.

Withey (1933) presented the results of tests on twenty-five beams, with percentages of steel reinforcement varying between 0.5 and 2.5 percent. Shear reinforcement was incorporated in all of the beams. The research identified different modes of failure in the beams depending on the quantity of reinforcement, both over-reinforced and under-reinforced.[3] Three beams with a high percentage of steel were over-reinforced and failed by crushing of the brickwork rather than yielding of the steel. As with earlier researchers, Withey's results showed that calculation methods similar to those for reinforced concrete could be applied to reinforced brickwork.

Lyse (1933) tested thirty-three reinforced brick columns. The reinforcement was incorporated into a central core filled with concrete grout. The percentage of steel used varied from 0 to 2 percent for columns with mild steel and 0 to 0.675 percent for columns with high-yield steel reinforcement. Varying percentages of lateral steel reinforcement were placed in the bedding courses of the columns. Withey (1935) carried out a similar program of tests on thirty-two reinforced brick columns, varying the percentage of longitudinal and lateral reinforcement. The results of both researchers showed that reinforced brick columns behaved quite differently from unreinforced columns. Unreinforced columns failed in a brittle manner, while the failure of reinforced columns was initiated by vertical cracking followed by spalling[4] of the brickwork. The incorporation of lateral reinforcement helped to confine the longitudinal reinforcement, improving the structural behavior.

These early investigations demonstrated the ductility of reinforced brickwork. In the area around San Francisco, many buildings built in the 1930s used reinforced brickwork to improve resistance to earthquakes.

Hamman and Burridge (1939) conducted experiments on over-reinforced brickwork beams with substantial amounts of shear reinforcement. However, even with high levels of shear reinforcement most beams failed in shear rather than flexure.

In the United Kingdom, Thomas and Simms (1939) of the Building Research Station U.K. conducted a series of comparative tests on reinforced brickwork and reinforced concrete beams. Both sets of beams had the same cross-sectional areas and the same percentage of steel reinforcement. Tests were also conducted on beams with higher percentages of steel, with and without shear reinforcement. Both brick and concrete beams with low percentages of reinforcement demonstrated almost identical behavior with similar deformations and strengths. This was not surprising, as failure was determined by the steel yielding rather than by the strength of the brickwork or concrete. In more heavily reinforced beams, the failure mode changed from steel yielding to shear, indicating the weaker shear strength of brickwork.

To economize in the use of steel during World War II, reinforced brick columns were used in the construction of single-story

1 See A. W. Hendry, *Structural Masonry* (Basingstoke, England: Macmillan Education, Ltd., 1990); Brick Industry Association, *The Contemporary Bearing Wall*, technical note no. 24 (Reston, Va.: The Brick Industry Association, 2002); and H. W. H. West, "The Development of Masonry," opening address to the Eleventh International Brick Masonry Conference, Shanghai, 1997, published in *Masonry International* 11, no. 3 (1998): 65–67.

2 The modular ratio is the ratio of the elastic modulus of steel to the elastic modulus of concrete or brickwork. It is a measure of the relative compressibility of the material. The greater the modular ratio, the more easily compressed the material compared with steel.

3 Under-reinforced beams fail by yielding of the steel and are characterized by large deflections and cracking. Over-reinforced beams fail by crushing of the brickwork or concrete *prior* to yielding of the steel. This type of failure is sudden, sometimes explosive, and thus considered undesirable.

sheds. Davey and Thomas (1950) reported on tests of eccentrically loaded columns. The columns were subject to both axial compression and bending. High stresses in both steel and concrete were reported.

Chambers and Schneider (1951) considered the effect of workmanship and other factors on the strength and behavior of reinforced brickwork. The research showed that the strength and behavior of reinforced brick structures are considerably influenced by workmanship in construction. Beams with careful construction, even with weaker mortar, were stiffer and stronger than comparable beams with stronger mortars but less care in construction. The strength reduced on average by 30 percent due to the effects of workmanship. Their research also demonstrated that the incorporation of shear reinforcement increased the shear strength of reinforced brick beams.

In the U.K., Bradshaw (1963) constructed a series of demonstration structures. Simply supported beams and slabs, cantilever beams, and stair treads were designed in accordance with the relatively limited guidance of the then current British Standard (BSI, 1948). Some of these structures sustained loads twenty times greater than the calculated working load. The research demonstrated very clearly that reinforced brick structures could be designed safely; however, it also showed the inadequacy of the simple elastic methods used in the British code to predict the load-carrying capacity.

Johnson and Thomson (1969) studied the effect of beam shape and the use of high-bond-strength mortars on the shear strength of reinforced brickwork. A total of twenty-two beams were tested. The high-bond-strength mortar produced much better results, with higher shear strengths than beams using normal type M mortar.[5] The tests also demonstrated the influence of the ratio of shear span to effective depth on the shear strength of the beams.[6] As the shear span to effective depth ratio increases, the shear strength decreases.

Anderson and Hoffman (1969) considered whether the method of calculating the ultimate load of reinforced concrete columns proposed by the American Concrete Institute (ACI) could be applied to reinforced brick columns. A series of load tests were conducted on rectangular brick columns 12 by 16 inches in cross section. The reinforcement was placed within a central cavity filled with concrete grout. Horizontal stirrups were incorporated in every third course of brickwork. The columns were subjected to axial and eccentric loads. The project confirmed that the ACI method of design is applicable to reinforced brickwork. They also suggested that further research was needed to take more accurate account of the stress-strain characteristics of brickwork and the effect of varying percentages of steel on strength.

In summary, most of these early studies were concerned with three issues:

To demonstrate that reinforced brickwork was similar in behavior to reinforced concrete; namely, that the reinforcement adds ductility to brickwork

To develop empirical design procedures

To develop design procedures based on elastic methods of analysis

From the 1970s onward, research was directed toward a more detailed study of shear strength and the development of ultimate load analysis techniques, mirroring the shift in design philosophy taking place in reinforced concrete from an allowable stress approach to ultimate load methods.

Suter and Hendry (1975 a and b) studied shear strength by testing twelve reinforced brick beams. The shear span to effective depth ratio varied from 1 to 7. Two different percentages of steel reinforcement were used: 0.24 and 1.46 percent. Based on their results and the work of other researchers, Suter and Hendry proposed that the characteristic design shear strength of brickwork should be 0.35 $N/mm^2$ (51 $lb/in^2$), applicable for beams with a shear span to effective depth ratio of 2 and greater. In contrast to the design of reinforced concrete, they further proposed that there should be no increase in characteristic shear strength for increased areas of primary tensile steel.

Suter and Keller (1976) compared the shear strength of reinforced brick beams using different methods of construction. Beams were constructed using grouted cavity construction; reinforcement was placed in a cavity created between two skins of brick that was subsequently filled with concrete. These beams are in effect a hybrid brick-concrete construction. The other form of beam incorporated the reinforcement within thickened bed joints. Their results showed that the shear strength of the grouted cavity beams was greater than beams with bed-joint reinforcement but less than similar reinforced concrete beams. They compared the results with tests on reinforced concrete beams (Kani 1966) and suggested that the shear strength of grouted cavity beams could be calculated by adding the separate shear strength components of the brickwork and concrete core, taking due account of the relative thickness of each section.

In addition to a concern for shear, researchers were interested in the prediction of the ultimate flexural strength of reinforced brick structures and, consequently, the correct assessment of the compressive strength of brickwork in flexural compression. It was known that the compressive strength of brickwork is quite different from the compressive strength of either the brick or the mortar that constitute the brickwork (Hendry 1990). Brickwork is anisotropic in nature—the

strength is influenced by the direction of the applied force in relation to the bed joint. Therefore, in flexural applications the compressive strength within the beam is different from the compressive strength in a conventional axially loaded wall.

Maurenbrecher et al. (1976) conducted tests on a series of reinforced brick retaining walls. The walls were constructed in both grouted cavity and Quetta bond formats. These tests were used to study different methods of calculating the ultimate load. The percentage of steel reinforcement varied between 0.33 and 1.78 percent. With low percentages of steel, failure of the walls occurred by steel yielding. Increasing the percentage of steel (from 0.33 to 1.78 percent) increased the strength fourfold. The experimental results were compared with the recommendations of the then current British building code for structural masonry, CP111: 1970, based on elastic methods. On this basis, using the recommended allowable stresses indicated that the factors of safety varied from 3.4 to 8.4. Replacing the allowable stresses of the code with allowable stresses obtained directly from small-scale tests on the actual brickwork used in the construction of the walls resulted in more uniform and acceptable factors of safety, from 2.8 to 3.2.

Research by Sinha (1979a) confirmed the inadequacy of the British structural brickwork code CP111. He tested a series of twelve grouted cavity brick slabs. Various methods of analysis were used to predict the ultimate strength. The current code was again found to considerably underestimate the ultimate strength of reinforced brickwork. A method following Zegler (1970) was proposed, which predicted the shear strength of the slabs accurately.

Sinha (1981) later proposed a method of predicting the flexural strength of brickwork, based on the stress-strain characteristics obtained directly from tests on brickwork prisms. A mathematical model was developed, assuming either a cubic polynomial or a curvilinear shape for the stress-strain relationship. Both models accurately predicted the strengths obtained from tests on brickwork beams.

Sinha (1982) presented the results of a further series of tests on the shear strength of grouted cavity beams and slabs. A comprehensive program was reported that considered the following variables: shear span–effective depth ratio; percentage of reinforcing steel; brick strength; mortar grade; and the effect of shear reinforcement. The results showed that thin wall sections have greater shear strengths than beams, that increasing the percentage of tensile steel increased the shear strength, and that shear strength is unaffected by brick strength and affected only to a minor degree by mortar grade.

Edgell et al. (1982) reported tests on four reinforced pocket-type retaining walls.[7] The percentage area of steel varied from 0.28 to 0.92 percent. Failure of the walls was due to steel yielding. The results were compared with the recommendations of the draft code of practice (BSI 1985).

In the same year, Appleton and Southcombe (1982) and Garwood and Tomlinson (1982) reported on separate experimental projects on reinforced grouted cavity beams. The aim of both studies appears to be a comparison of the provisions of the draft code of practice for reinforced and pre-stressed brickwork (BSI 1985). Both groups of researchers reported anomalies with the draft code. The working load and ultimate moments were underestimated by the draft. Appleton and Southcombe also found differences in the actual measurements of compressive zones and those suggested by the code. Garwood and Tomlinson suggested the use of lower partial safety factors to obtain more realistic design moments for the test results. Such calibrations with draft codes are inevitable, however; the most accurate predictions could have been obtained using the actual physical properties of the brickwork from small-scale tests on brick prisms, a procedure also allowed in the draft code.

Tests by Tellet and Edgell (1983) on a series of reinforced pocket type retaining walls showed that these types of wall conform to the same effect of increasing shear strength with decreasing shear span-to-depth ratio.

Hendry (1984) reviewed the research on shear in reinforced brickwork beams and found differences in behavior between beams where the reinforcement was surrounded with mortar—in the bed joints, for example—and where the reinforcement was surrounded by concrete, in grouted cavity construction. His analysis helped to explain the differences in the results from different researchers. In

4 Spalling happens when the outer surfaces of the column break away from the core of the column.

5 Type M mortar has the following mix proportions: 1 part cement, 1/4 part lime and 3 parts sand, with a minimum compressive strength of 2,500 lb/in$^2$ at twenty-eight days.

6 The shear span is the section of a beam span where shear dominates over bending stress. For a uniformly distributed load on a simply supported beam, the shear span is the first quarter of the span measured from each end. The effective depth is measured from the uppermost compression fiber to the center of the primary steel reinforcement. The section of the beam below the reinforcement is not considered to contribute to the flexural strength of the structure.

7 In pocket-type walls, the reinforcement is placed in a “pocket” in an otherwise solid brick wall. Once the reinforcement is in place, the pocket is filled with a concrete grout.

fig. 253: Examples of reinforced brick beams:
a) grouted cavity construction,
b) pocket-type construction
c) pocket type, Quetta bond, and
d) bed-joint reinforcement
fig. 254: A typical post-tensioned wall
fig. 255: Examples of pre-stressed brickwork beams (in cross section):
a) unbonded tendon, and
b) bonded tendon

grouted cavity beams, the shear strength is greater due to the additional contribution of the concrete and the more effective contribution of the primary tensile steel. Examples of reinforced brickwork beams are illustrated in figure 253.

Schneider and Dickey (1980) published a comprehensive text on reinforced masonry design covering most aspects of structural behavior and construction. The design of flexural elements is based on elastic methods. The text concludes with a chapter reviewing research on reinforced masonry.

Davies and El Traify (1982 and 1984) studied behavior of reinforced brick columns subjected to bi-axial bending. They produced design charts to determine the ultimate load, taking account of the interaction between bi-axial bending moment and axial force.

Some studies have been carried out on the long-term behavior of reinforced brickwork. Sinha (1979b) and Maurenbrecher et al. (1976) monitored the movements of reinforced brick retaining walls. These tests tended to confirm an earlier study by Disch (1949) that the long-term movements of reinforced brickwork beams were generally less than those of comparable concrete beams. In both the U.S. (BIA 1988) and the U.K. (Curtin 1982), there were some notable applications of reinforced brickwork. In 1957, two 65-foot beams were used to support the roof of St. Hedwig's Church in St. Louis. At just over 10 feet deep and 17 inches wide, the beams were quite conservative in design. Compared to alternative constructions, the reinforced brick beam was considered to be cheaper when the cost of cladding either a concrete beam or steel truss was taken into account. Bradshaw and Drinkwater (1982) described the application of reinforced brickwork in the corporate offices of a major U.K. brick manufacturer, George Armitage and Sons, Ltd. A two-story-high reinforced brickwork frame comprising columns and cantilever beams was built. The frame supported a reinforced concrete roof and floor slabs. The project was intended to demonstrate the application of reinforced brickwork.

This latter period of research concentrated on a rational and comprehensive understanding of the structural behavior of reinforced brickwork, but was nevertheless still concerned with the comparison between and substitution of brickwork for reinforced concrete frames, beams, and columns. The development of brickwork building codes tended to follow concrete building codes. The strength of reinforced brickwork is very similar to that of reinforced concrete when ultimate failure is due to either steel yielding or brick crushing in flexure. However, the shear strength of reinforced brick is less than that of reinforced concrete and is influenced by factors not apparent in concrete, such as the position of the reinforcement in either a cavity or bed joint. The nature of construction makes it more difficult to incorporate shear reinforcement in brickwork.

### Development of Pre-stressed Brickwork

The most comfortable stress condition for a brittle material such as brickwork or concrete is compression, where it is strongest. Reinforcing is essentially a repair that allows a brittle material to crack without collapsing. Reinforcement does not become effective until the brickwork (or concrete) cracks. Pre-stressing induces a more agreeable state of stress, a vaccination that prevents cracking. Although engineers like Eugène Freyssinet developed pre-stressing techniques for concrete early in the twentieth century, the techniques were not applied to brickwork until the second half of the century.

In 1952, Samuely used pre-stressing to stabilize 33-foot-high slender brick piers (Sutherland 1982). There seems to have been little further work until 1963, when Thomas (1969) described tests on two pre-stressed brickwork beams. High pre-stress forces of up to 1,600 lb/in$^2$ were applied. Plowman (Thomas 1963) followed this work with a program of tests on thirteen beams. In both programs, pre-stressing wires were threaded through small cavities formed by aligning the perforations in extruded bricks. Although there were construction difficulties, the results demonstrated a considerable reserve of strength past the decompression moment, and that the failure mode was flexure rather than shear, which occurred more typically in reinforced beams.

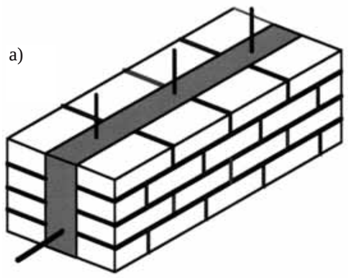
Around this time there was some research (Thomas 1963; Wass and Turner 1969) on the development of pre-stressed masonry floor systems. These systems used extruded clay units. Although these systems were patented, they appear to have had limited commercial application.

During this period there were some interesting applications of pre-stressed brickwork. In 1966 (Sutherland 1982), a 23-foot-high brick wall was stabilized using pre-stressing to increase its resistance to wind loads. The wall was only 10.9 inches in thickness. Pre-stressing avoided the need for piers or buttresses. Foster (1971) designed a 39-foot-diameter, 16.4-foot-high circular water tank. Both vertical and hoop pre-stressing were used. Pre-stressing was also used in the construction of a one-story-high box beam that used concrete floor slabs as flanges and brick walls as webs. The walls were pre-stressed to increase their resistance to diagonal cracking.

From 1979 onward there was a marked rise in both the research and application of reinforced brickwork. Two different areas can be identified: pre-stressed walls, and pre-stressed beams.

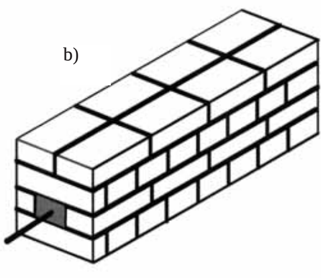
The most common application of pre-stressing to brickwork is in conjunction with diaphragm walls. Vertical pre-stressing is used to

a)



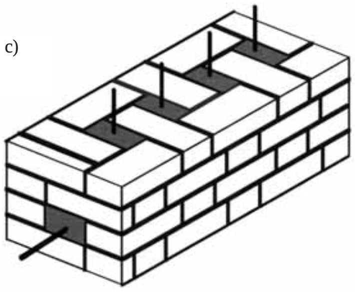
grouted cavity construction

b)



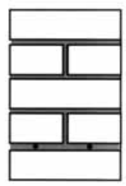
pocket-type construction

c)



Quetta bond:
horizontal and vertical pockets

d)



reinforcement in bed joints

fig. 253

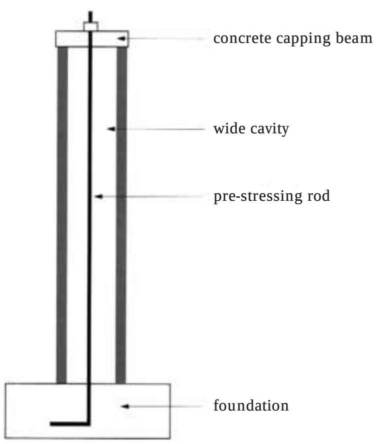
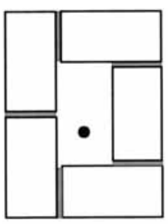
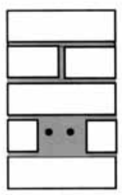



fig. 254



Unbounded tendon
(after Williams and Phipps, 1982)



Bounded tendon
(after Pedreschi and Sinha, 1982)

fig. 255

stabilize tall, single-story walls used in shed-type buildings or as retaining walls. Typically, such walls consist of two wythes of brickwork separated by brick diaphragms (fig. 254). The walls are usually between 17 to 28 inches in overall thickness. Pre-stressing tendons are attached to the foundations and run through the cavity in the walls to a concrete capping beam at the top of the wall. The wall is pre-stressed by tensioning the tendon against the capping beam, using either hydraulic rams or calibrated torque wrenches.

Williams and Phipps (1982) tested a series of six post-tensioned diaphragm walls. The tendons passed through the center of the walls and were unbonded and therefore free to move within the cavity as the walls deflect. By incorporating cross ribs within the walls to restrict the relative movement of the tendon, the strength of the wall was increased.

Curtin and Phipps (1982) tested two full-scale diaphragm walls 24 feet high. They studied the influence of pre-stress on the load to cause cracking in the wall. The pre-stress applied varied from 0–261lb/in$^2$. Not surprisingly, increasing the pre-stress increased the lateral load that the walls could sustain.

Roumani and Phipps (1985) tested fifteen beams, modeling typical sections of a diaphragm wall. They studied the influence of shear span-to-depth ratio and degree of pre-stress on the strength of the walls. They proposed a relationship between shear span-to-depth ratio and shear strength.

Montague and Phipps (1984) extended the earlier study of Williams and Phipps with a series of tests on twelve concrete block walls. Their study considered the influence of construction details such as the incorporation of a vertical damp-proof course between the diaphragm and outer leaf.[8] The damp-proof course was found to reduce the strength by between 20 and 30 percent. Thus, incorporation of practical construction details necessary for environmental performance can compromise structural efficiency.

An appropriate application of diaphragm walls is in retaining structures for soil or bulk solids. The loads from retained materials are applied in one direction only.[9] A series of research projects by Hobbs and Dahou (1988), Curtin and Howard (1988), Ambrose et al. (1988), and Sinha (1990) reflected this application. All of these projects studied the behavior of walls with eccentric pre-stress force. In most cases the pre-stressing cable was left unbonded. Filling the cavity with concrete grout—bonding the steel to the wall—increases the strength of the walls (Sinha 1990).

Generally speaking, the post-tensioned wall has been shown to be a practical form of construction. Quite a number have been built, either as retaining walls (Shaw 1980; Bradshaw et al. 1982;

Drinkwater and Bradshaw 1982), as tall walls of single-story buildings subject to wind-loading (Curtin et al. 1982; Shaw 1982), or to brace tall walls from the thrust from roofs (Allen 1986).[10] In most cases the level of skill required by the bricklayers was not much different from that needed for conventional building. Indeed, in some of the reported projects, the builders had not used post-tensioning before. Bradshaw et al. (1982) demonstrated that even farmers using agricultural laborers as builders could apply the techniques successfully. Other practical applications include:

> The use of post-tensioned diaphragm walls to support foundations in areas subject to mining subsidence to minimize subsequent damage as the building settled (Shaw 1982)
>
> The construction of channel-shaped walls (Othick and Priestley 1986)
>
> The stabilization of tall brick piers (Shaw 1980)

Some studies have been undertaken to consider the potential use of the technology in developing countries (Pedreschi 1994) and in Brazil (Parsekian and Franco 2000).

## Pre-stressed Brickwork Beams

The use of pre-stressing in brickwork beams evolved largely from the experience of reinforced brickwork in an effort to improve the shear resistance and reduce or eliminate flexural cracking under working loads. A major difference between pre-stressed beams and post-tensioned diaphragm walls is the level of pre-stress applied to the brickwork. In walls the stresses are generally low, used to counter the effects of wind or retained materials. Pre-stressed beams, on the other hand, are much closer in concept to concrete beams acting as primarily flexural elements with consequently much higher levels of pre-stress. What distinguishes this latter period of research is the depth and scope of the investigations. In a series of publications, Pedreschi and Sinha reported the results of an extensive study of pre-stressed brickwork beams (Pedreschi 1983; Pedreschi and Sinha 1982, 1985, 1992). A total of sixty full-scale tests were carried out dealing with level of pre-stress force, brick and mortar strength, percentage of steel, type of brick, and shear span-to-depth ratio (fig.255).

Beams spanning up to 21 feet and pre-stressed up to 1,087 lb/in$^2$ were tested. A detailed study of the load/deformation behavior of brickwork using a large number of small-scale tests was carried out (Sinha and Pedreschi 1983) and used to develop a theoretical model of post-tensioned brickwork beams. The model took into account the non-linear material behavior of brickwork and cracking once the initial pre-stress had been neutralized. The model was shown to provide excellent agreement with the experimental results (Pedreschi and Sinha 1985).

In a subsequent study, Walker and Sinha (Walker 1987; Walker and Sinha 1985, 1986) considered the use of partially pre-stressed brickwork beams. These beams included both pre-stressed and conventional non-stressed steel reinforcement. The study recognized that partial pre-stressing may offer a useful intermediate alternative to fully pre-stressed brickwork, retaining the improvements in shear and flexural behavior of pre-stressed beams while reducing the camber and anchorage stresses. A program similar to the earlier project of experimental tests on full-scale beams, with beams using various combinations of stressed and non-stressed steel, was conducted. The analysis techniques were refined further, and a computer program for the design and analysis of reinforced and pre-stressed brickwork beams was developed. It was found that the use of partial pre-stressing improved the post-cracking behavior of the beams, thereby allowing limited and controlled cracking at working loads.

These two projects demonstrate clearly that pre-stressed brickwork, if properly designed and constructed, has repeatable and predictable structural behavior and can be modeled accurately, provided the appropriate physical characteristics are obtained from suitable small-scale tests.

Robson et al. (1983) reported on a series of tests on eighteen pre-stressed beams, all with unbonded tendons. The results were compared with the recommendations of the British Standard, which was found to underestimate the strength of the beams substantially, and to overestimate the deflections.

Garwood (1986) reported on the results of nine tests on pre-stressed beams having varying degrees of pre-stress. The beams with lower pre-stress forces tended to fail in shear while those with higher pre-stress failed in flexure.

Uduehi (1989) compared the behavior of pre-stressed brickwork beams with pre-stressed concrete beams. The beams had the same cross-sectional dimensions, pre-stress forces, and compressive strengths. The results showed that the cracking moment was slightly higher for the concrete beams, but the moment-curvature relationship, load-deflection response, and strengths were similar.

Lenczner (1983; and Lenczner and Davies 1984) studied the long-term behavior of pre-stressed walls and developed a method to predict the long-term loss of pre-stress. Since brickwork does not undergo the same shrinkage as concrete, the long-term loss of pre-stress is generally less than in pre-stressed concrete structures.

Shaw and Baldwin (1995) claimed to "progress the application of structural masonry into a new era" with the construction of two post-tensioned brickwork footbridges, one using Parafil[11] pre-stressing cables and the other using steel rods. The span of the footbridges was

just under 20 feet. The bridges were constructed vertically, in the same manner as a diaphragm wall. The pre-stressing cable passed through the central cavity of the section. The sections were cambered to allow for rainwater drainage. The sections were pre-stressed in their vertical position and then lowered onto abutments. The sections were similar in principle to those tested previously by Roumani and Phipps (1985). The major benefit claimed by this construction method was the construction of horizontally spanning brick elements without the use of formwork.

Baqi et al. (1999) carried out tests on twenty pre-stressed, rectangular brickwork beams. Their conclusions verified the work of earlier researchers.

Capozucca and Minnetti (1999) studied the behavior of pre-stressed brickwork beams subjected to cyclic loads. They used beams similar to those tested by Pedreschi and Sinha. A load of 60 percent of the ultimate strength of the beams was applied cyclically 180 times. Following the cyclic loading, the beams were tested to destruction. The effect of the cyclic load had only a minor influence on the strength of the beams.

## Research and Practice in Relation to the Work of Eladio Dieste

As the previous sections have shown, during the twentieth century there has been a substantial body of research into the structural behavior of reinforced and pre-stressed brickwork, and there are now relevant building codes in many countries. Yet it is true to say that the use of reinforced or pre-stressed structural masonry is not extensive, certainly not in comparison with the other primary structural materials, steel and concrete. A great deal of the research was predicated on comparing reinforced and pre-stressed brickwork with reinforced concrete structures. The research has demonstrated that reinforced pre-stressed brickwork does behave in a manner similar to reinforced concrete structures, provided the physical properties of the brickwork are properly determined and used in the analysis. Being comparable, however, is not enough; there are inherent difficulties in the substitution of reinforced brickwork for concrete in framed structures:

Brickwork is more difficult to reinforce using conventional brickwork bonding.

Brickwork is weaker in shear and more complex in behavior.

The physical properties of brickwork are anisotropic in nature.

The specimens used to determine the physical properties of brickwork are dependent on the size, shape, and orientation of the bed joints, whereas standard, universal test specimens, such as the cube or the cylinder, have long been established for concrete.

Relative to concrete, brickwork is more sensitive to workmanship, which may become critical in highly stressed reinforced brick structures or in conditions where shear is significant.

Some of these weaknesses can be overcome by pre-stressing. Pre-stressing increases the shear strength of beams, and the behavior is perhaps more predictable than that of reinforced brickwork, as the compression characteristics of brickwork are more reliable than its limited tensile properties. Again, direct substitution for pre-stressed concrete is possible, but the same conditions apply. The use of post-tensioning in diaphragm walls is, however, an advance that at a construction level succeeds over alternatives in concrete. Vertical walls are simpler to construct in brickwork than in in-situ concrete and, coupled with a simple method of pre-stressing, prove to be a practical system. The wall is both structure and enclosure in the same way that the multi-story load-bearing–wall building combined structure and enclosure, eliminating the steel or concrete frame. The post-tensioned diaphragm wall can save the cost of a portal frame in the construction of large single-story buildings. Thus, there is direct and tangible benefit that has a positive impact on the building as a whole.

Research has tended to focus on structure rather than construction. The nature of academic research is too often to focus inward, to refine analytical techniques, to dissect existing practice, or to probe weaknesses in building codes and develop new ones. Thus, the research tends to follow work on reinforced and pre-stressed concrete. The research community tends to be inward looking, with praise or success being measured by the esteem of peers within the community. West (1994), in his address to the Tenth International Brick Masonry Conference, spoke of an International Masonry Community. On this occasion he analyzed the proceedings of the ten

8 The damp-proof course was a continuous bituminous vertical layer that separated the outer leaf from the internal diaphragm, separating the two layers.

9 In the use of diaphragm walls in buildings where the predominant lateral load is wind, it must be assumed that the load can be applied in either direction perpendicular to the surface of the wall.

10 Eladio Dieste used vertical pre-stressing to brace the walls of the Montevideo Shopping Center in order to carry the thrust from the roof vault. Remo Pedreschi, *Eladio Dieste*, The Engineer's Contribution to Contemporary Architecture (London: Thomas Telford, 2000).

11 Parafil is the trade name of a high-strength rope, made from high-strength synthetic fibers, enclosed in a polymeric sheath.

conferences, starting with the first in Austin, Texas, twenty-seven years earlier. Over the ten events, a total of 1,299 technical papers were presented. He broke these down according to countries. It is not surprising that the bulk of the papers came from North America and Europe.[12]

Out of this total, only two papers originated in Uruguay, one of which was written by Eladio Dieste (1991) and presented at the Ninth International Brick Masonry Conference in Berlin. The other was about Dieste and brick structures in South America (Diehl 1991). At the same time as the 1991 conference, the first exhibition of Dieste's work in Europe took place at the Hochschule der Künste in Berlin.[13] As far as the authors can determine, few of the delegates at the conference visited the exhibition. From the perspective of this community, Dieste was evidently on the margin. Although Dieste's paper presented some of his innovations in reinforced and pre-stressed brickwork that were altogether more ambitious than many of the technical papers presented at the conference, it was placed in the "architectural" section of the conference. The recognition that his work received tended to be by the architectural press, for its obvious architectural qualities.

Dieste's work was not reported in the scientific or engineering press. (Most papers in this area are actually written by researchers describing their own research rather than the work of others.) There is not the same tradition of journalistic review in engineering journals as compared to architectural journals. Dieste's work provided the most extensive and consistent application of reinforced and pre-stressed brickwork to date, yet it was largely unknown within the research community.

What then can be learned about the work of Eladio Dieste in relation to this considerable research field? The research certainly validates and supports Dieste's innovations in terms of his interpretation of structural behavior. It has shown that brickwork is a material that is capable of development and refinement and can be understood, predicted, and designed with the same level of accuracy as concrete. It does not, however, anticipate the spectacular forms shown to be possible by Dieste's work.

The difference between Dieste and the others is that Dieste sought to create new forms that were appropriate to the character and nature of brick, rather than replace concrete in linear, framed structures. Dieste saw these new forms and adopted them partly out of necessity and partly from a vision of the forms themselves. A comparison with St. Hedwig's Church is informative. Here, reinforced brickwork was used to create large rectangular beams to carry flat concrete roof slabs—a direct substitution for concrete with brick. Dieste, on the other hand, combined both roof and structure in one element, producing a surface form that acted both as cladding and structure. The most successful applications of contemporary structural masonry are those in which synergistic combinations of structure and enclosure were developed, such as in the diaphragm wall and the multi-story load-bearing brick building. Much of the research of others concerned the exploration of the structural—rather than the constructive—potential of the material. Academic rigor is often held to be synonymous with accuracy in prediction and analysis. Research and innovation are often used together, although success in one area does not always lead to success in the other. The research community itself has noted the lack of innovation in masonry by the construction industry. The British engineer James Sutherland (1981) considered this problem to be due to a lack of codes of practice, which engineers come to rely on and without which they are reluctant to innovate.

The Brick Institute of America, now called the Brick Industry Association (BIA 1988), is also reticent in its promotion of reinforced brick and suggests that its use is most appropriate when the structural medium is brick, the surrounding area is brick, or the appearance of brick is required. In an article entitled "Research and Innovation," the U.S. consultant Clayford Grimm (1997) considered the constraints on innovation in brickwork, among which were the fragmentation of both the research and construction sectors, and the lengthy and bureaucratic procedures for the introduction of building codes and standards.

The root of the problem lies, then, in two areas: the lack of codes, which in itself says much about the education and practice of engineers; and, perhaps more fundamentally, a perception that reinforced brickwork is not an entirely practical alternative to reinforced concrete beams and columns. West (1998), in a later address, reflected on innovation in structural brickwork. He concluded that reinforced masonry would not replace concrete in framed structure and that innovation in reinforced brickwork would be limited to a few selected applications. In other words, the developed economies, with relatively efficient and well-established construction methods and an engineering profession well-versed in their use and codes, do not really need a slightly more complicated and less understood alternative.

What then can the masonry community learn from Dieste? He was a designer, theoretical analyst, and builder. All of his innovations were driven by a need to find an effective and contemporary structural material that responded to the resources and skills of Uruguay. He had a clear vision that his material was not a substitute for concrete: "It is possible to find rational uses for bricks when combined with an adequate structure and suitable techniques which

are not an imitation of what is done in concrete."[14] The construction methods he developed respected contemporary concerns for speed, prefabrication, and repetition: he pushed the technology to maximum advantage. His use of surface forms based on catenary shapes (especially the Gaussian vault) meant that the predominant stresses were in compression, and reinforcement was needed only to deal with secondary effects. In barrel vaults the surface form allowed the simple placement of reinforcement and pre-stressing steel. The pre-stressing techniques he invented distributed the pre-stress forces over the large cross section of the vault, avoiding highly stressed areas. The problem of shear was also minimized by similarly spreading the shear force over the large cross section of the vault and by using pre-stressing to eliminate tensile stresses. The additional payback was the reduction in the vertical structure and foundations, due to the relatively low self-weight and the large spans of the vaults.

Clearly, Dieste needed neither the output nor the support of the international research community to make progress through his innovations. He had a profound sense of, and confidence in, the application of the laws of physics, rather than codes, and used these to develop structural forms. He combined this with a social and artistic sensitivity that justified his endeavors across a much broader platform of ideas, thereby providing the backbone to support and sustain his work throughout his long and highly productive career.

References

Allen, L. N. (1986). "Post-tensioned Brickwork at Rushden Fire Station," *Engineers File Note No.1.* Winkfield, England: Brick Development Association.

12 Two hundred and thirty papers originated from the U.K.; 221, from Germany; 202, from the U.S.; 172, from Italy; 84, from Australia; 66, from Canada; and 6, from South America (including 2 from Uruguay). It should be noted that contributors from the developing countries often cannot afford to attend international conferences: the fees are high, and papers are generally not accepted without payment of the fee.

13 Dieste was a special delegate to the conference, his attendance paid for by German sponsors.

14 Damián Bayón and Paolo Gasparini, *The Changing Shape of Latin American Architecture: Conversations with Ten Leading Architects* (New York: John Wiley and Sons, 1979), 205.

Ambrose, R. J., R. Hulse, and S. Mohajery (1988). "Cantilevered Pre-stressed Diaphragm Walling Subjected to Lateral Loading," in J. W. de Courcey, ed., *Brick and Block Masonry*. London: Elsevier Applied Science, 583–94.

Anderson, D. E., and E. S. Hoffman (1969). "Design of Brick Masonry Columns," in F. B. Johnson, ed., *Designing Engineering and Constructing with Masonry Products*. Houston, Tex.: Gulf Publishing, 94–100.

Appleton, C., and C. Southcombe (1982). "Forces Acting within a Reinforced Brickwork Beam in Determining the Serviceability Limit State," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 471–80.

Baqi, A., N. M. Bhandari, and D. N. Trikha (1999). "Experimental Study of Pre-stressed Masonry Flexural Elements," *Journal of Structural Engineering* (March): 245–54.

Beamish, R. (1862). *Memoirs of the Life of Sir Marc Isambard Brunel*. London: Longmans.

Bradshaw, R. E. (1963). *An Example of Reinforced Brickwork Design*, special pub. no.38. Stoke-on-Trent: British Ceramic Research Association.

Bradshaw, R. E., and J. P. Drinkwater (1982). "Reinforced Brickwork in George Armitage Office Block, Robin Hoood, Wakefield," in Curtin (1982), 13–22.

Brebner, A. (1923). *Notes on Reinforced Brickwork Tests: Theory and Actual Construction of Reinforced Brickwork in India*, technical paper 38. London: Government Public Works Department.

Brick Industry Association (1988). *Reinforced Brick Masonry Girders—Examples*, technical note no. 17m. Reston, Va.: The Brick Industry Association.

——— (2002). *The Contemporary Bearing Wall*, technical note no. 24. Reston, Va.: The Brick Industry Association.

British Standards Institution (1948). *Structural Recommendation for Load Bearing Walls*, Code of Practice 11. London: The British Standards Institution.

——— (1985) *Use of Reinforced and Pre-stressed Brickwork*, Code of Practice 5628. London: The British Standards Institution.

Capozucca, R., and R. Minnetti (1999). "Influence of Cyclic Loads on Brickwork Pre-stressed Beams," *Masonry International* 12, no. 3: 104–10.

Chambers, C. A., and R. R. Schneider (1951). "Conditions and Objectives of the Grouted Brick Masonry Tests," *Southwest Builder and Contractor* (28 December): 35–52.

Curtin, W. G., ed. (1982). *Reinforced and Pre-stressed Masonry*. London: Thomas Telford.

Curtin, W. G., J. K. Beck, G. Shaw, and L. S. Pope (1982). "Post-tensioned Free Cantilever Diaphragm Wall Project," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 1645–56.

Curtin, W. G., and J. Howard (1988). "Lateral Loading Tests on Tall, Post-tensioned Diaphragm Walls," in J. W. de Courcey, ed., *Brick and Block Masonry*. London: Elsevier Applied Science, 595–605.

Curtin, W. G., and M. O. Phipps (1982). "Prestressed Masonry Diapragm Walls," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 971–80.

Davey, N., and G. T. Thomas (1950). "The Structural Use of Brickwork," *Structural and Building Paper 24*. London: The Institution of Civil Engineers.

Davies, S. R., and E. A. El Traify (1982). "Uni-axial and Bi-axial Bending of Reinforced Brickwork Columns," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 843–54.

——— (1984). "Influence of Bi-axial Bending on Short Columns of Reinforced Masonry," in B. P. Sinha, ed., *International Symposium on Reinforced and Pre-stressed Masonry*. Edinburgh: University of Edinburgh, 234–47.

Diehl, K. L. (1991). "Latin American Architecture in Brickwork as the Expression of an Independent Movement and an Attempt to Distinguish it from the Architecture of the Highly Industrialized Countries," in *Proceedings of the Ninth International Brick/Block Masonry Conference*. Berlin: DGfM, 1659–69.

Dieste, E. (1991). "Reinforced Brick Structures," in *Proceedings of the Ninth International Brick/Block Masonry Conference*. Berlin: DGfM, 1670–77.

Disch, A. G. (1949). "Plastic Flow of Plain and Reinforced Masonry," M.Sc. thesis, University of Wisconsin.

Drinkwater, J. P., and R. E. Bradshaw (1982). "Reinforced and Pre-stressed Brickwork in Agriculture," in Curtin (1982), 89–96.

Edgell, G., J. Tellet, and H. W. H. West (1982). "Research into the Behavior of Pocket-type Retaining Walls," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 805–16.

Fillipi, H. (1933). "Reinforced Masonry Principles of Design and Construction," *Brick Engineering*, vol. 3. Cleveland, Ohio: Brick Manufacturing Association of America.

Foster, D. (1971). "Design and Construction of a Pre-stressed Brickwork Water Tank," in H. W. H. West and K. Speed, eds., *Proceedings of the Second International Brick Masonry Conference*. Stoke-on-Trent: British Ceramic Research Association, 287–94.

Garwood, T. G. (1986). "A Comparison of the Behaviour of Reinforced, Pre-stressed and Partially Pre-stressed Brickwork Beams," *Proceedings of the First International Masonry Conference*. London: British Masonry Society.

Garwood, T. G., and A. Tomlinson (1982). "The Cracking, Deflection and Collapse Behaviour of a Series of Reinforced Brickwork Beams," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 481–92.

Grimm, C. T. (1997). "Research and Innovation," *Masonry International*, vol. 2, no. 2: 33–37.

Hamman, C. W., and L. W. Burridge (1939). "Reinforced Brickwork," *The Structural Engineer* (London) 17 (April): 198–250.

Hendry, A. W. (1984). "The Shear Strength of Reinforced Brickwork," in B. P. Sinha, ed., *Proceedings of the International Symposium on Reinforced and Pre-stressed Masonry*. Edinburgh: University of Edinburgh, 104–22.

——— (1990). *Structural Masonry*. Basingstoke, England: Macmillan Education, Ltd.

Hobbs, B., and Y. Dahou (1988). "Post-tensioned T-section Brickwork Retaining Walls," in J. W. de Courcey, ed., *Brick and Block Masonry*. London: Elsevier Applied Science, 665–75.

Johnson, F. B., and J. N. Thomson (1969). "Correlation of Tests of Masonry Assemblages with Strength Characteristics of Reinforced Masonry Beams," in F. B. Johnson, ed., *Designing, Engineering, and Constructing with Masonry Products.* Houston, Tex.: Gulf Publishing, 150–60.

Kanamouri, S. (1930). "Reinforced Brickwork Opens Great Possibilities," *Brick and Clay Record* 72 (July 15): 96–100.

Kani, G. N. J. (1966). "Basic Facts Concerning Shear Failure," *Journal of the American Concrete Institute* 63, no. 6 (June): 675–92.

Lenczner, D. (1983). "Loss of Pre-stress in Post-tensioned Brick Walls and Columns," *Proceedings of the Eighth International Symposium on Load-bearing Brickwork*. London [unpaginated].

Lenczner, D., and D. Davies (1984). "Loss of Pre-stress in Post-tensioned Brick Walls and Columns," in B. P. Sinha, ed., *Proceedings of the International Symposium on Reinforced and Pre-stressed Masonry*. Edinburgh: University of Edinburgh, 76–89.

Lyse, I. (1933). "Tests of Reinforced Brick Masonry Columns," *Journal of the American Ceramic Society* 19: 583–97.

Marchant, E. (1965). "Reinforced Brickwork," M.Sc. thesis, University of Liverpool.

Maurenbrecher, A. H. P. (1972). *Reinforced Brickwork: Pocket Type Retaining Walls*, special report 13. Hertford, U.K.: Structural Clay Products Ltd.

Maurenbrecher, A. H. P., A. B. Bird, R. J. M. Sutherland, and D. Foster (1976). *Reinforced Brickwork: Vertical Cantilevers*, special reports 10–11. Hertford, U.K.: Structural Clay Products Ltd.

Mehta, K. C., and D. Fincer (1970). "Structural Behaviour of Pre-tensioned, Pre-stressed Masonry Beams," in H. W. H. West and K. Speed, eds., *Proceedings of the Second International Brick Masonry Conference*. Stoke-on-Trent: British Ceramic Research Association, 215–19.

Montague, T. J., and M. Phipps (1984). "The Behaviour of Post-tensioned Blockwork Masonry in Flexure and Shear," in B. P. Sinha, ed., *Proceedings of International Symposium on Reinforced and Pre-stressed Masonry*. Edinburgh: University of Edinburgh, 427–47.

Othick, G. J., and C. L. Priestley (1986). "The Orsborn Memorial Hall Channel Section Wall," paper 18, *Practical Design of Masonry Structures*. London: Thomas Telford.

Parsekian , G. A., and L. S. Franco (2000). "Cost Comparative Analysis of the Use of Pre-stressed Masonry in Brazil," in B. V. Reddy and B. P. Sinha, eds., *Sixth International Seminar on Structural Masonry for the Developing Countries*. Bangalore: Indian Institute of Technology, 203–14.

Parsons, D. E., A. H. Stang, and J. W. McBurney (1932). "Shear Tests on Reinforced Brick Masonry Beams," *U.S. Bureau of Standards Journal of Research* (Washington) 9: 749–68.

Pedreschi, R. F. (1983). "A Study of the Behaviour of Post-tensioned Brickwork Beams." Ph.D. diss., University of Edinburgh.

——— (1994). "The Potential of Post-tensioned Brickwork in Developing Countries," in H. Roman and B. P. Sinha, eds., *Fifth International Seminar on Structural Masonry for Developing Countries*. Florianopolis, Brazil: University of Santa Caterina, 660–69.

Pedreschi, R. F., and B. P. Sinha (1982). "Development and Investigation into the Ultimate Load Behaviour of Post-tensioned Brickwork Beams," *The Structural Engineer* 60b, no. 3: 63–67.

——— (1985). "Deformation and Cracking of Post-tensioned Brickwork Beams," *The Structural Engineer* 63b, no. 4: 93–99.

——— (1992). "Predicting the Flexural Strength of Pre-stressed Brickwork Beams," *The Structural Engineering Review* 4, no. 3: 211–21.

Plowman, J. M., R. J. M. Sutherland, and M. L. Couzens (1967). "The Testing of Reinforced Brickwork and Concrete Slabs Forming Box Beams," *The Structural Engineer* 45, no. 2: 379–94.

Plummer, H. C., and J. A. Blume (1953). *Reinforced Brick Masonry and Lateral Force Design*. Washington, D.C.: Structural Clay Products Institute.

Robson, T. I., R. J. Ambrose, R. Hulse, and J. Morton (1983). "Post-tensioned, Pre-stressed Brickwork Beams," in H. W. H. West, ed., *Proceedings of the British Masonry Society*, 1. Stoke-on-Trent: British Ceramic Research Association, 100–05.

Roumani, N., and M. Phipps (1985). "The Shear Strength of Pre-stressed Brickwork I and T Sections," in T. McNeilly and J. C. Scrivener, eds., *Proceedings of the Seventh International Brick Masonry Conference*. Melbourne: Brick Research Development Institute, 1001–14.

Schneider, R. R., and W. L. Dickey (1980). *Reinforced Masonry Design*. Englewood Cliffs, N.J.: Prentice-Hall.

Shaw, G. (1980). "Practical Applications of Post-tensioned and Reinforced Masonry," paper 14, *Practical Design of Masonry Structures*. London: Thomas Telford.

——— (1982). "Post-tensioned Brickwork Diaphragm Wall Subject to Severe Mining Settlement," in W. G. Curtin and R. E. Bradshaw, eds., *Reinforced and Pre-stressed Masonry*. London: Thomas Telford, 103–14.

Shaw, G., and R. J. Baldwin (1995). "The Construction of End-built Pre-stressed Masonry Flat Arch Bow Girder Footbridges," *Masonry International* 9, no. 1: 1–5.

Sinha, B. P. (1979a). *Reinforced Brickwork: Grouted Cavity Shear Tests*, special report 16. Hertford, U.K.: Structural Clay Products Ltd.

——— (1979b). *Reinforced Brickwork: Retaining Walls, Long Term Tests*, special report 14. Hertford, U.K.: Structural Clay Products Ltd.

——— (1981). "An Ultimate Load Analysis of Reinforced Brickwork Flexural Members," *International Journal of Masonry Construction* 1, no. 4 151–56.

——— (1990). "Behaviour of Pre-stressed Brickwork Pocket Type Walls under Lateral Loading," in B. P. Sinha and G. T. G. Mohamedbai, eds., *Third International Symposium on Masonry for the Developing Countries* (Mauritius). Edinburgh: International Council of Masonry Engineering for the Developing Countries and University of Edinburgh, 223–30.

Sinha, B. P., and R. C. De Vekey (1982). "Factors Affecting the Shear Strength of Reinforced Grouted Cavity Brickwork Beams and Slabs," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 831–42

Sinha, B. P., and R. F. Pedreschi (1983). "Compressive Strength and Some Elastic Properties of Brickwork," *International Journal of Masonry Construction* no. 3: 19–35.

Suter, G. T., and A. W. Hendry (1975a). "Shear Strength of Reinforced Brickwork Beams: Influence of Shear Arm/Effective Depth Ratio and Amount of Tensile Reinforcement," *The Structural Engineer* 53, no. 6: 249–53.

——— (1975b). "Design of Reinforced Brickwork Beams," *Proceedings of the British Ceramic Society* 24: 191–96.

Suter, G. T., and G. Keller (1976). "Shear Strength of Grouted Reinforced Masonry Beams," in *Proceedings of the Fourth International Brick Masonry Conference*, Bruges, Belgium: unpaginated.

Sutherland, R. J. M. (1981). "Brick and Block Masonry in Engineering," *Proceedings of the Institute of Civil Engineers* 70, pt. 1: 31–63.

——— (1982). "The Future of Pre-stressed Masonry," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 582–93.

Tellet, J., and G. Edgell (1983). "The Shear Strength of Reinforced Brickwork Pocket-type Sections," in H. W. H. West, ed., *Proceedings of the British Masonry Society*, 1. Stoke-on-Trent: British Ceramic Research Association, 91–95.

Thomas, F. G., and G. T. Simms (1939). "The Strength of Some Reinforced Brick Masonry Beams in Bending and Shear," *The Structural Engineer* 7 (July 27): 334–49.

Thomas, K. (1969). "Current Post-tensioned and Pre-stressed Brickwork and Ceramics in Great Britain," in F. B. Johnson, ed., *Designing, Engineering and Constructing with Masonry Products*. Houston, Tex.: Gulf Publishing, 94–100.

Uduehi, J. (1989). "A Comparative Study of the Structural Behaviour of Pre-stressed Beams of Brickwork and Concrete, and a Study of the Shear Strength of Brickwork," Ph.D. diss., University of Edinburgh.

Walker, P. (1987). "A Study of the Behaviour of Partially Pre-stressed Brickwork Beams," Ph.D. diss., University of Edinburgh.

Walker, P., and B. P. Sinha (1985). "Behaviour of Partially Pre-stressed Brickwork Beams," in T. McNeilly and J. C. Scrivener, eds., *Proceedings of the Seventh International Brick Masonry Conference*. Melbourne: Brick Research and Development Institute, 1015–30.

——— (1986). "A Comparative Study of Reinforced, Fully and Partially Pre-stressed Brickwork Beams," CIB 86, *Proceedings of the Tenth Triennial Congress of the International Council for Building Research Studies and Documentation* (Washington, D.C.) 6: 2661–71.

Wass, R. J., and D. J. Turner (1969). "A Pre-stressed Clay Masonry Floor," in F. B. Johnson, ed., *Engineering and Constructing with Masonry Products*. Houston, Tex.: Gulf Publishing, 200–09.

West, H. W. H. (1994)."The International Masonry Community," closing address to the Tenth International Brick Masonry Conference, Calgary, Canada, 1994, published in *Masonry International* 8, no. 1: 1–4.

——— (1998)."The Development of Masonry," opening address to the Eleventh International Brick Masonry Conference, Shanghai, 1997, published in *Masonry International* 11, no. 3: 65–67.

Whittemore, J. W., and P. S. Dear (1932). *An Investigation of the Performance Characteristics of Reinforced Brick Masonry Slabs*, bulletin no. 9. Blacksburg: Virginia Polytechnic Institute Engineering Experimental Station.

——— (1933). *A Comparison of the Performance Characteristics of Reinforced Brick Masonry Slabs and Reinforced Concrete Slabs*, bulletin no.15. Blacksburg: Virginia Polytechnic Institute Engineering Experimental Station.

Williams, E. O. L., and M. Phipps (1982). "Pre-stressed Masonry Diaphragm Walls," in *Proceedings of the Sixth International Brick Masonry Conference*. Rome: ANDIL, 971–80.

Withey, M. O. (1933). "Tests on Reinforced Brick Masonry Columns," *Proceedings of American Society of Testing and Materials* 34, pt. 2: 651–65.

Zegler, G. P. (1970). "Shear Design of Brick Lintels," in H. W. H. West and K. Speed, eds., *Proceedings of the Second International Brick Masonry Conference*. Stoke-on-Trent: British Ceramic Research Association, 161–64.

## A PROSPECT FOR STRUCTURAL CERAMICS

*Antonio Dieste*

Dedicated to Elizabeth Friedheim de Dieste, my mother

In considering the work of Eladio Dieste, I propose to separate the analysis of technical and economic issues from architectural considerations. My father's architectural work cannot be continued. As with any other artistic expression, his formal creativity is personal and non-transferable. This is not to imply that his works, writings, and teaching are to be forgotten. Quite the opposite, it is possible to continue using the technologies that he created. This continuity of use, however, will only be fruitful if those technologies are adapted and developed. It is not enough to repeat what has been done before. In Dieste's words, "it is necessary to think everything anew."

But to rethink everything does not mean to walk again down the same path, adjusting details. It is necessary to encounter new paths, which is difficult because it requires inspiration. Nonetheless, inspiration is not enough. The leap of intuition that is required can only be recognized when we are truly immersed in the problem. We need rigor, dedication, and effort. Dieste conceived structures, developed the corresponding construction and calculus procedures, and designed the mechanical and hydraulic jacks that he needed and made them economically feasible. With this working method he made good architecture.

With a modesty that I deliberately will not qualify, Dieste said that every building belongs to society as a whole. Certainly, all that he did was not done by him alone, as many collaborated with him at different stages in his life. In order not to offend by omission, I forego naming them all. Nevertheless, there is no doubt that he was the motor (fig. 256).

When considering Dieste's production, we must take into account that the vast majority of the works were completed successfully in economic competition with alternative solutions. It is not surprising that these roofs whose forms derive from technical considerations have an architectonic quality that largely transcends them. Rafael Dieste (1899–1981), Eladio's beloved uncle, wrote a poem, "Sorpresa del Molinero," that evokes such transcendence:

> Hiciste un molino
> creyendo que sólo
> para moler trigo.
>
> El agua encauzaste
> creyendo que sólo
> para que trabaje.
>
> Pero el agua dice
> sentencias y coplas
> que no le pediste.
>
> Y al agua responde
> pensativo y lírico
> el molino dócil.
>
> Haciendo un molino
> y encauzando el agua
> dibujaste un signo.
>
> Y absorto investigas
> viendo la molienda
> lo que significa. [1]

The technical and economic features of Dieste's production may permit its continuation, though not without innovation. Why is a technique that developed successfully in Uruguay and then vigorously expanded into the neighboring countries of Argentina and Brazil now falling behind?[2] In Uruguay, during the last twenty-five years, the cost of labor increased more than the cost of basic construction materials: two to three times more than cement, for example, and four times more than steel. The reinforced concrete industry's response was technological; different structural designs emphasizing simple construction and improved equipment, formwork, production machines, and transportation of mixed cement were all introduced. By comparison, reinforced ceramics became cost ineffective, and the economic need to innovate emerged.

The technique for building in reinforced ceramics will need to develop in all of the following ways if it is to remain economically viable:

Moveable Formwork or Molds—It is enough to compare the early, heavy wood molds to the metal ones used today to realize what a long way we have come. However, the jacks for lifting formwork could be improved, as well as the maneuvering system that allows the tie-rods to pass through the structure that supports the formwork as it advances from one modular position to the next.

Materials—It will be necessary to involve the manufacturers in order to obtain special pieces of ceramic materials at a standard price. We have, in particular, thought about a piece that we call "the ravioli" for its formal likeness to the homonymous pasta.

fig. 256: Eladio Dieste, Church of Christ the Worker, Atlántida, 1958. The photograph of mason Vittorio Vergalito building a wall of the Atlántida church embodies my gratitude to all the workmen involved in Dieste's constructions.

fig. 256

A component with that shape would enable mortar to be placed in a single layer while leaving the necessary space to guarantee adequate coverage of the reinforcing steel. We also envisage the use of alternative materials in combination with ceramics. Glass bricks, for instance, could be used in order to obtain natural lighting without losing the continuity of the vault.

Rapid Form Removal—There are no high-initial-resistance cements in Uruguay. To date, setting accelerators have not been widely employed because their chlorine content is potentially harmful to the durability of the reinforcing steel. The use of steam to achieve a faster setting of the cement, together with an adequate initial cure, may prove very efficient, enabling the completion of one module per mold per day in any climate. The necessary equipment is not excessively costly. In Uruguay, a more precarious system of electric heating has been successfully applied in winter.

Lifting of Material—For the lifting of ceramic pieces and the bars or reinforcing grids, a mid-size crane with a small load capacity is adequate. In terms of mortar, the existing pumping equipment is not fully adaptable; it is evident that a low-output mortar pump is required, even more so if the ceramic units employed allow a single application of mortar.

Prefabrication—It is obvious that prefabrication can play a leading role in the construction of movable formwork, as this type of structure is always modulated and the necessary crane for the setup of the pieces (posts and beams) is self-propelled and available practically anywhere. The possibility of premanufacturing part of the vaults themselves is not as evident; however, with the work of Martin Speth in Germany, a promising panorama on this field has opened.[3]

Durability—Even if today it is an unbelievable absurdity for us (the "university scum,"[4] in the words of Gabriel Zaid), it was believed, in Uruguay at least, that "concrete is eternal." Only recently have we begun to realize our error. Studies on the durability of concrete obviously existed earlier, but most of us had not looked closely at their implications.

The reinforcing bars in structures of reinforced ceramics have problems similar to those of reinforced concrete, with the added disadvantage that an adequate coverage (depending on the type of ceramic unit used) would entail very wide joints. Furthermore, the inevitable repairs are difficult to carry out without spoiling the aesthetic quality of the structure.

Even if it is true that many structures of reinforced ceramics have responded well to the passage of time, in some cases of particularly high exposure (a marine environment, or places where permanent condensation forms on the interior surface of a vault), problems of corrosion in the reinforcement have occurred. In one case—the only case of which I know—the chemistry of the ceramic material was the cause of the problem.

The geometry of the ceramic units is a determining factor in the thickness of the reinforcement coverage that can be guaranteed. Physical properties of the units, such as resistance and porosity (intimately linked to one another) are of tremendous importance. Consequently, the future development of the technique of reinforced masonry construction implies an advance in standards of specification and testing. Alternative reinforcing materials should be evaluated:

> Stainless steel, or galvanized and/or epoxy-covered steel—Although expensive to date, the relative cost of the material will likely go down. Structures employing these products may require very moderate amounts of steel (less than 3/4 pound per square foot in single or double vaults), creating additional cost savings.
>
> Polymer bars reinforced with fibers—Carbon fibers, though still very expensive, have very promising properties.

1 Rafael Dieste, *Obras completas* (Sada/A Coruña: Ediciós do Castro, 1995), 1: 484. An English translation of this poem by Ann Pendleton-Jullian appears on page 11 of this volume.

2 I exclude here works built in the last few years in Spain because they belong to the universe of special constructions to which my economic analysis does not apply. I also leave aside some special works like the churches of Durazno and Atlántida. Of Atlántida Dieste said, and honestly believed, "it cost the same as a shed," which is strictly untrue. But in order to complete this work he had to deceive himself and, with his enormous charm, bring others—in good faith—along in this deception.

3 See Martin Speth's essay on pages 223–30 of this volume.

4 Gabriel Zaid, *Obras*, vol. 3, *Crítica del mundo cultural* (Mexico City: El Colegio Nacional, 1999), 429–35.

Cathodic protection—In the bridge at Maracaibo, Venezuela, cathodic protection was used successfully in protecting the most critical zone of the pylons—their juncture with the spanning structure. I do not know of the use of such protection in laminar structures, but it is another open possibility for research.

Fire- and vandalism-resistant tie-rods—Structures with exposed tie-rods are very sensitive. At the Port Warehouse in Montevideo, a fire cut one of the tie-rods. The double-curved vault, which has a 164-foot span, fortunately did not suffer any considerable damage, but the replacement of the damaged tie-rod was very dangerous. The design of future projects must take this into account.

Joints—Modern standards discourage the design of structures in which the failure of one module or element would trigger a chain of failures. Self-supporting vaults clearly belong in this category. The solution is to include joints in the project. The corresponding additional cost is negligible.

The preceding list is hardly a complete record of the conditions that frame the possible development of shell structures of reinforced brick. The problem has many dimensions and, happily, perhaps multiple solutions.

## UNREINFORCED SHELL STRUCTURES IN TRADITIONAL MASONRY: A CONTEMPORARY APPROACH TO DESIGN AND CONSTRUCTION

*Martin Speth*

Is it possible to build shell structures in traditional masonry? What effect does the material have on design and construction? Are there morphological groups that are particularly suitable for this choice of material?

Inspired by the buildings of Eladio Dieste, a team of scientists and architectural students formed at the Institute for Structural Design and Research at the University of Hannover in 1996 with the intention of building shell structures.[1] Dieste developed his technique of reinforced masonry construction under particular circumstances determined by the availability of raw materials, economic conditions, climate, the manual skills of his workmen, labor costs, and structural considerations.[2] Discussion about the transferability of Dieste's technique soon revealed that simple copying and adaptation would be fruitless. Under the local circumstances of northern Europe in the 1990s—circumstances different from those of Uruguay in the mid-twentieth century—the idea of Dieste's work would need to evolve into a new technique for constructing shell structures in brick masonry. Questions about climate and appropriate corrosion protection of the reinforcement would have to be addressed. The increasing ratio of labor costs to material costs would also need to be adjusted. But encouraging further investigation was the fact that, to avoid frost damage, brick building material for external use in Germany is usually fired at high temperatures; the resulting high strength of the material was seen as a valuable byproduct that was not being exploited by existing masonry construction techniques. Furthermore, although curved forms could be easily produced in hand-worked masonry just by varying the dimensions of the joints, this morphology had not been widely explored. So the question arose as to whether it was possible to build shell structures out of plain masonry, making use of the full structural and formal potential intrinsic to this traditional material. Could the use of both reinforcement and surface formwork be avoided?

### Positioning Traditional Masonry

The form of Dieste's shells seems magically to suggest an inseparable unity of construction and architecture. In contrast to the concrete of conventional modern shells, the material of Dieste's shells—brick, which has been layed on curved surface formwork, its joints filled with steel reinforcement and concrete—lends scale to the surface. The structure appears comprehensible and engaging when viewed from both near and far (fig. 257). The square grid of joints traces how the structure works. A square net of reinforced steel together with the concrete and hat-like bricks form a powerful construction. A basic rule in structural design dictates that "force follows stiffness"; the grid of reinforced steel and concrete concentrates forces within the cross section of the shell as a result of its increased stiffness, as compared with bricks. Yet it would be wrong to understand Dieste's shells as grid structures of reinforced concrete. The efficiency of his technique results from the combined use of steel, concrete, and brick, where the brick not only constitutes shear bracing but also provides a load-bearing medium for an economical level of self-weight. According to the model of stiffness, there is a structural analogy to the steel-grid shells of the noted German engineer Jörg Schlaich. In his filigreed steel grid structures, the shell forces act in discrete straight members (fig. 258).[3] The bracing of the quadrilateral grid is achieved by way of diagonal cables. Dieste's and Schlaich's structures exhibit basically the same behavior but are made of different materials. Developed under different requirements, they produce different types of architecture.

Considering unreinforced solutions, Catalan vaulting is a unique technique for building in plain masonry that has produced a rich variety of shell structures.[4] The Vapor Aymerich Textile Factory outside of Barcelona (now the Museum of Technical Sciences of Catalonia) was built in 1908 by Lluís Muncunill i Parellada (1868–1931) (fig. 259).[5] Constructed with Catalan vaults, it provides a remarkable example of the efficiency of unreinforced structural solutions. The shape of this building recognizes to a great degree the characteristics of both brick and steel. The inclined shell arch is principally under compressive stress acting parallel to its span. The placement of

1 The work of Eladio Dieste, known through an exhibition in 1991 at the Hochschule für Künste in Berlin, led to the research activity presented here.

2 Eladio Dieste, in *Eladio Dieste: La estructura cerámica*, Galaor Carbonell, ed., Colección Somosur (Bogotá, Colombia: Escala, 1987), 31–145.

3 Jörg Schlaich and Hans Schober, "Verglaste Netzkuppeln," *Bautechnik* 69 (1992): 3–10.

4 Luis Moya Blanco, *Bóvedas tabicadas* (Madrid: Ministerio de la Gobernacion, Dirección General de Arquitectura, 1947). See also Edward Allen's essay on pages 66–75 and Timothy P. Becker and Kent Anderson's essay on pages 202–07 of this volume.

5 Mireia Freixa and Teresa Llordés, *Lluís Muncunill* (Barcelona: Lunwerg, 1996).

the curvature perpendicular to the span, which from an aesthetic point of view allows the surface to appear smooth, is, from a structural point of view, an effective means of increasing stiffness and thus avoiding buckling. The logic of the structure follows the conditions of its materials: the vertical support of the shell is shared equally by a row of brick arches that are fixed to slender steel columns. All horizontal thrust is taken up by steel tension members. Steel, more than one hundred times stronger (and also more expensive) than ceramics, needs just a very small cross section to maintain the shell's equilibrium.

In the Catalan technique, the shell consists of a number of layers of ceramic tile. The first layer is built with a quick-setting mortar or gypsum, sometimes cantilevering outward. This layer becomes formwork for the next layer of tile. Subsequent layers are laid with an overlap, resulting in a geometrically interlinked composite material of brick and mortar that is structurally efficient (fig. 260). In addition to good resistance to compressive stress, tensile stress may also be accommodated due to the bond between the bricks and the high-adhesion mortar. Thus, the laminated tile section approximates the compressive and tensile strength of a laminated timber beam in its principal structural behavior.

This brilliant technique was transferred by Rafael Guastavino (1842–1908) to America by 1900.[6] His work can be found in more than one thousand buildings in the northeastern United States, particularly in New York City and Boston. Contemporary architecture, however, no longer makes use of this construction method. One of the reasons for this is a lack of skilled workmen. (This is a general predicament regarding vault construction in industrialized countries, which is true irrespective of economic conditions.) Consequently, a contemporary approach to building shells of masonry would need to employ current standard techniques that are within the capabilities of the local workforce.

Traditional masonry vaulting has an important advantage over Catalan vaulting—the advantage of reliable knowledge, most of which is laid down in local codes, thus simplifying the necessary procedures with building authorities. As with the Catalan technique, traditional masonry uses the principle of overlap (fig. 261): the masonry bond can be seen as a typical detail, from the point of view of both design and structural behavior.

Owing to this important principle, concentrated loads at the top of a wall are distributed over the whole area. Also, shear stress and even tensile stress parallel to the bed joints are easily absorbed. Similar to the interlinked composite that characterizes the Catalan technique, the bond brings mortar and brick together to make a


fig. 257


fig. 258


fig. 259

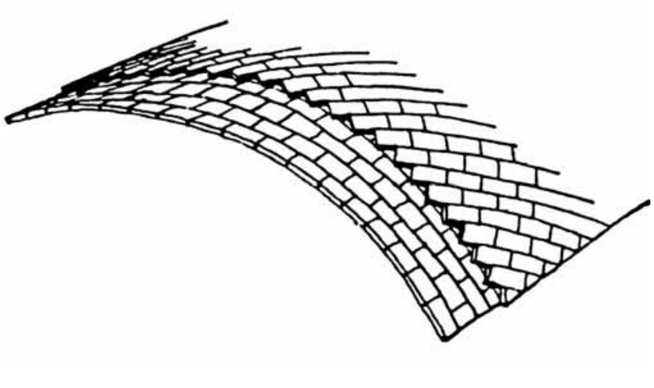


fig. 260

fig. 257: Eladio Dieste, Port Warehouse, Montevideo, 1977–79
fig. 258: Jörg Schlaich, double-curved steel grid structure, 1998. Shell structures of reinforced masonry and filigreed steel grid structures share structural principles.
fig. 259: Lluís Muncunill i Parellada, Vapor Aymerich Textile Factory, Terrassa, Spain, 1908 (now the Museum of Technical Sciences of Catalonia)
fig. 260: Principle of overlap in Catalan vaulting
fig. 261: Principle of overlap in masonry bond
fig. 262: Principle of overlap in friction grip of two steel plates
fig. 263: Principle of overlap in lap joint of reinforcing bars
fig. 264: Funicular curves of the arch and varying changing loads: *g*=evenly distributed dead load, and *s*=snow load in varying distributions

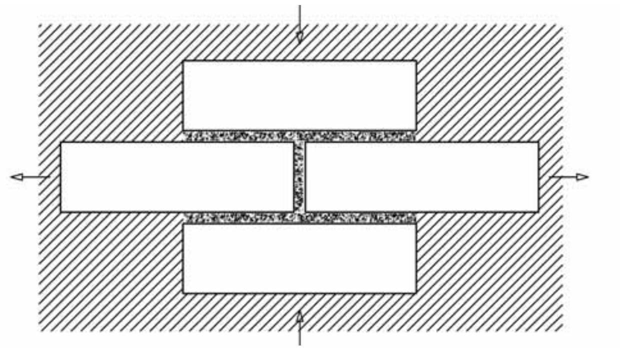


fig. 261

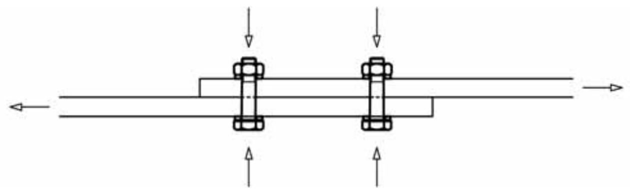


fig. 262

powerful team. Due to the direction of the bed joints, the effectiveness of the bond in traditional masonry is affected by the adhesion of mortar and brick as well as friction caused by axial loads. Different geometric patterns of masonry bond also influence a wall's structural behavior. Owing to experience in practical use, German codes do not allow tensile stresses perpendicular to the bed joints. The principle of transferring forces by overlapping members is common in numerous building methods and materials—for instance, the friction grip joint of two steel plates, or the common lap joint of reinforcing bars in all reinforced concrete structures (figs. 262, 263). In these examples, the amount of transferable force is being controlled by usual methods of design. Construction in masonry, on the other hand, has the property that the lateral resistance of the masonry increases with the weight of the axial loads. No other building material shares the property that its structural performance grows with increasing levels of compressive stress! This is why conceptual design and construction of masonry structures is exciting work. Provided that it is used in the appropriate form, traditional masonry easily fulfills the requirements of steel structures.

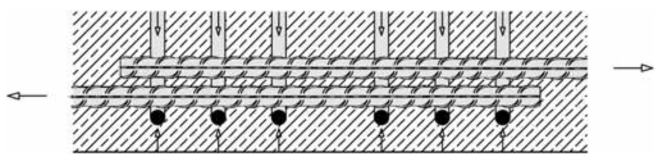


fig. 263

## Shaping

In linear spanning structures, the type of member that carries distributed loads in compression to the ground is the arch. The high dead load produced by massive solid materials adds to the funicular curve of the arch, thus developing its shape (fig. 264). A structure that follows this curve carries loads to its supports under axial compression and without bending. The shape of this curve changes with different types and distributions of loads. So, besides a symmetrical

6 George R. Collins, "The Transfer of Thin Masonry Vaulting from Spain to America," *Journal of the Society of Architectural Historians* 27, no. 3 (October 1968): 176–201. For more detail on Guastavino, see Edward Allen's essay on pages 66–75 of this volume.

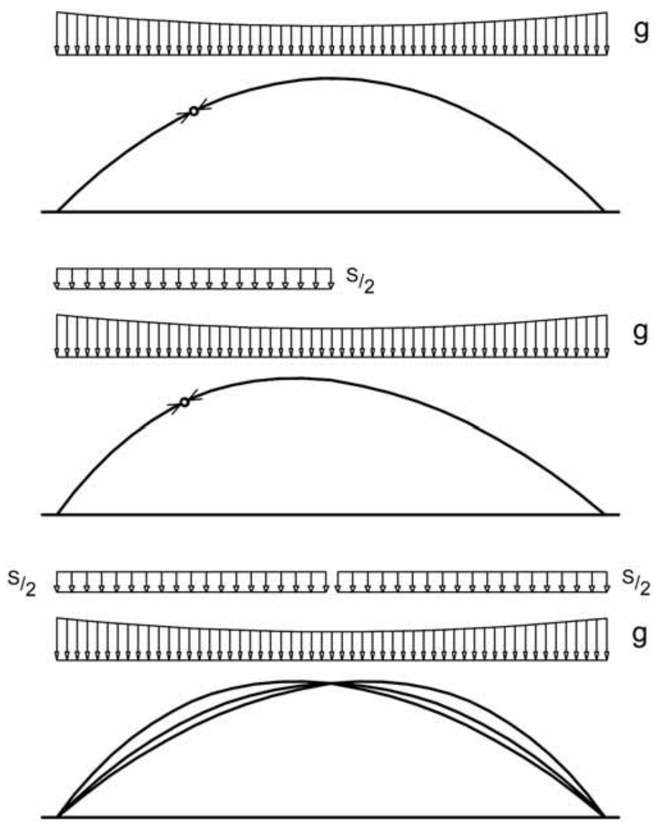


fig. 264

curve that results from the evenly distributed dead load, there are numerous other curves that appear with the different loads the structure must resist. Because plain masonry has no tensile strength perpendicular to its bed joints, a simple rule must be followed: a masonry vault has to envelop this range of curves within the core of its cross section. This may happen in two different ways: one way is to enlarge the area of the cross section, thus increasing material and load; the other way is to change the shape of the cross section appropriately, while keeping its area constant, thus following the principles of lightweight structures (fig. 265). In this case, stiffness is produced by shaping rather than by adding material and mass. A slender masonry arch that is also curved perpendicular to its span would easily fulfill the structural requirements of a shell arch, provided its shape has been developed correctly.

In circular plans, domes look almost like a three-dimensional arch structure. The question arises as to whether or not for a given load there also exists a best shape, analogous to the funicular curve of the arch. It follows that we can ask for more than the absence of bending; we can try to identify a shape of shell within which the stress is of the same magnitude at every point and in every direction. This leads to a dome of constant strength.[7] Another significant shape is that of the shell of revolution that has no stress in the ring direction (fig. 266).[8] Although these dome shapes were developed from a theoretical point of view and practical aspects have not been fully considered, a knowledge of them is helpful in understanding the structural behavior of differently shaped structures. Various other shells of revolution are suitable for masonry building material. The conical shell, for instance, causes compression in both the annular and meridian directions—a fundamentally sound condition for stone construction.

To find the appropriate shape for a masonry structure, both numerical and experimental methods are suitable. Many historic structures have been developed using hanging models. Tower Bridge in London shows explicitly that a tension structure follows the laws of compression, but the other way around (fig. 267). The bridge was completed by the engineer Barry Wolfe in 1896 and uses the “strong” material steel. The available methods of calculation probably did not allow a safe assessment of the effect of the slender stiffening girder, so the engineer designed the suspension girders in a shape that envelops the curves that would be taken up by a freehanging cable under moving loads. Depending upon the position of a moving load, either the upper or lower chord of the suspension girder is stressed. The high strength of steel results in small cross-sectional areas and thus a comparatively low level of dead load in the structure. Before the bridge

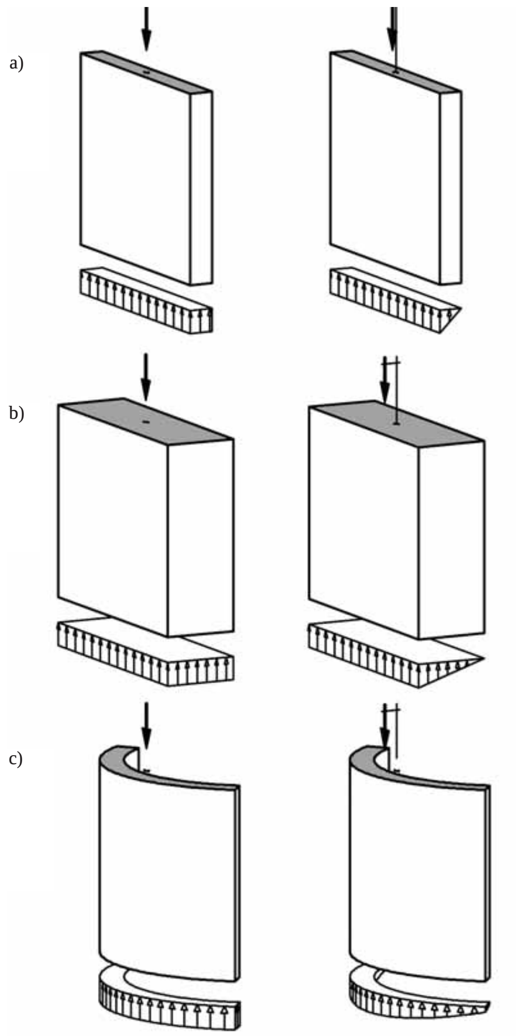


fig. 265


fig. 266 a) b)


fig. 267

fig. 265: Eccentric load in
a) thin masonry,
b) thick masonry, and
c) shaped masonry

fig. 266: Significant shells of revolution:
a) dome of constant strength, and
b) shape with no stress in ring direction

fig. 267: Barry Wolfe, Tower Bridge, London, 1896. Suspension girders approximate a three-hinged, statically determinate system.

was completed, the medievalizing facing brickwork of the towers was publicly criticized. The engineer, who probably would have liked to show more of this interesting steel structure, kept a low profile during this discussion. The weight of the brickwork was a welcome ballast to stabilize the structure when one-sided loads were on the bridge.

What is to be learned from this for the design and construction of shell structures made of plain masonry? The shape may be found by inverting a hanging model. The structure should be planned in such a way that tensile stress perpendicular to the bed joints is avoided. Taking the catenary as the funicular curve of the arch, an additional curvature perpendicular to the span envelops the range of funicular lines that match the numerous moving loads. A shape that is developed in this way acts structurally like a thin-walled shell arch.[9] Depending upon the position of moving loads, the compressive stress concentrates in either the upper or the lower part of the cross section. The comparatively high level of dead load that is given by the material is useful to control the influence of moving weights and to provide sufficient axial load. As a single design criterion, enveloping the range of funicular curves would not be sufficient; the thin-walled arch has to resist bending moments perpendicular to the span that appear particularly with moving loads. The resulting stresses parallel to the bed joints have to be checked carefully during the structural analysis. With respect to this bending effect, a sufficient amount of compressive stress perpendicular to the bed joints (axial load) is necessary to develop the full potential of masonry. In all slender structural members that carry loads under compressive stress, the safety against buckling has to be investigated carefully. Shaping the shell arch in the way suggested has a positive effect on the prevention of buckling, possibly ruling it out completely because the buckling figure of an arch is geometrically similar to the funicular lines of changing asymmetric loads.[10]

## Construction

Before taking on the experimental construction of the first shell arch prototype, we took into consideration the following issues. The orientation of the bed joints had to be perpendicular to the span. To achieve the desired structural behavior in the masonry, the joints had to be made in an expert manner using highly adhesive mortar. Accepting requirements of industrialized building methods, we decided to exploit the advantage of prefabrication, namely the elimination of expensive formwork. The prefabricated elements could be built upright using standard techniques of masonry construction. In a sense, brick itself represents the principle of prefabrication. Of course, the prefabricated elements must meet the highest tolerance requirements in order to fit the final geometry of the structure when assembled on site. To survive transportation without damage, a cement mortar with good adhesion characteristics would need to be used. The resistance of the unloaded masonry elements had to be investigated, especially for the conditions imposed during transportation. Tests to evaluate bending strength showed that the mortar had sufficient adhesion. Fractures usually appeared in the bricks, not in the joints.[11]

Thoughts of prefabricating elements of a shell structure quickly ran to issues of curvature, which are central to the form. The numerous elements that complete one shell are all of varying spatial curvature. Consequently, a flexible formwork that could be used to build all sorts of shaped elements was developed.[12] As is well known, to build a planar brick wall, laying the courses along straight string lines is the proven method. In spatially curved shells, on the other hand, the masonry has no straight joints. The principle of the formwork developed in our research was based on the idea of replacing the traditional straight string lines with spatially curved, thin steel rods that would guide the bricklayer in the same way but along a different path. The guiding steel rods were held at the free end of cantilevering slide bars. These slide bars were clipped into a steel frame. The position of the slide bars was controlled exactly by the lines on a computer plot, thus the highest level of geometric precision was achieved.

The steel rods can be taken as an exact form to follow when laying the bricks. Working with this formwork is comparatively easy. As the bed joints have a constant thickness, the mass of mortar that is taken on the bricklayer's trowel remains constant. The time required for creating masonry in this formwork is about 50 percent greater than for ordinary brick walls. The bricklayers need no particular skill for this kind of work. The prefabricated masonry units were removed

7 Georg Megareus, "Die Kuppel gleicher Festigkeit," *Der Bauingenieur* 20, no. 17/18 (1939): 232–34.

8 See P. Bouguer, "Sur les lignes courbes qui sont propre à former les voûtes en dôme," *Mémoires de l´Academie Royale des Sciences* (Paris, 1734).

9 See Lajos Kollár, *Statik und Stabilität der Schalenbogen und Schalenbalken* (Berlin: Ernst & Sohn, 1973).

10 Martin Speth, "Schalenbogen aus unbewehrtem Mauerwerk," *Das Mauerwerk* 1 (1999): 2–7; idem, "Schalentragwerke aus unbewehrtem Mauerwerk," (Ph.D. diss., University of Stuttgart, in preparation).

11 Bending stresses of this kind would also appear in the completed structure under varying loads. To gain confidence in both the geometry and construction of the initial shell arch, a model made from small blocks of wood was first built at a reduced scale. The model was helpful in that it provided answers to a number of questions that had not been anticipated beforehand.

fig. 268: Positioning of the final element on the first prototype of a shell arch made of plain masonry, 1997
fig. 269: First prototype of a shell arch made of plain masonry, 1997
fig. 270: Shell arches, used as a shelter at the Lower Saxony Building Industry Confederation, 1998. The higher shell according to type b2, the lower according to type b1 in fig. 272

from the formwork after twenty-four hours. Before transporting them to the site, they were laid in sand for two weeks for final hardening. Using two suspension belts, transportation was very easy and safe.

During construction of the arch, the prefabricated elements were supported by only two thin timber ribs. The joints between the prefabricated units were filled with quick-setting, non-shrinking mortar. (When completed, the structure could theoretically operate with dry joints between the bricks.) To take up the horizontal thrust, two tension members of steel were joined to the two ends of the arch; they were stressed by a hydraulic jack during the final phase of the installation (fig. 268).

The first prototype of a shell arch made of plain masonry had a span of 33 feet and a constant thickness of 4.5 inches. The long free edges show the slenderness of this structure. The curvature varies along the span and ends smoothly at the supports (fig. 269). The structure here follows the principle of a two-hinged arch. Although there is no perfect hinge in this structure, the zones of low curvature close to the supports approximate areas of less bending stiffness. Because the deformations of the structure are minimal, these zones of low stiffness simulate structural hinges. The free edges are in a vertical plane, so it is easy to add one arch to the other. If two edges are structurally connected, further advantages of a folded structure may be exploited.

### Morphology

Our experience with this type of shell arch encouraged us to make further investigations into the possibilities, limits, and morphology of shells using this technique. Of course, there is not as much variety in the shell structures of this type compared to reinforced varieties; our shell structures follow the strict rules of their material properties and structural behavior. Nevertheless, they are relatively thin when compared with masonry in common practice.

Two shell arches were used as a shelter at the Lower Saxony Building Industry Confederation.[13] The span of these arches was 49.5 feet and the rise to span ratio was 1:4 (fig. 270). The tension members that resist the horizontal thrust were part of the foundation. The higher we built an arch, the lower were the forces in it; in our understanding of plain brickwork, however, this was not necessarily an advantage with regard to structural behavior. Changing loads and stresses resulting from temperature variations can only be accommodated with a sufficient amount of axial compression perpendicular to the bed joints. (This is why thin shell arches with a high rise-span ratio must be inspected carefully.) In the case of temperature load, using the statically determinate principle of a three-hinged arch is helpful in avoiding dangerous stresses within the construction.


fig. 268


fig. 269


fig. 270

fig. 271: External trass plaster in combination with a hydrophobic paint
fig. 272: The particular morphology of shell arches of traditional masonry: two-hinged arches with a rise-span ratio of 1:8 with a1) positive curvature, a2) negative curvature, and a3) as an inclined shell arch; b1) and b2): three-hinged arches with a rise-span ratio of 1:4 with different positions of hinges (b1, near the ground; b2, about three feet above ground).
fig. 273: Discontinuous roof as shell arch of traditional masonry
fig. 274: First prototype with asymmetric loading in place

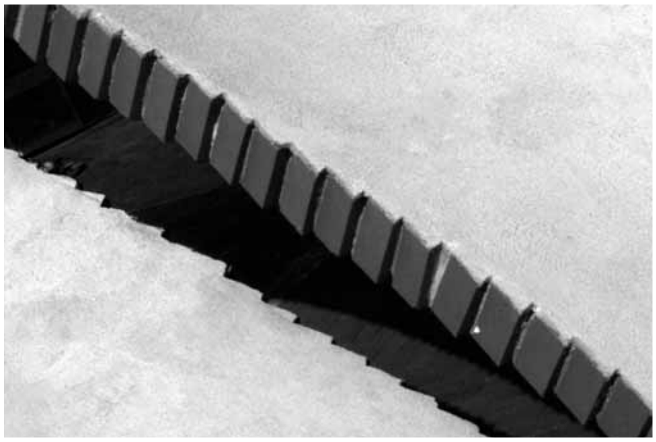


fig. 271

The detail in figure 271 shows the external plaster we put on the shells for waterproofing. We have had good experience with a trass plaster, in combination with a hydrophobic paint (fig. 271).[14]

Concerning the morphology of this type of shell arch, we can say that for small rise-span ratios (1:8, for instance), two-hinged arches are reliable for spans up to 65 feet (fig. 272a). In this shell arch it makes no great difference whether it is positively or negatively curved. Shell arches with higher rise-span ratios of 1:4 should preferably follow the principle of the three-hinged arch (fig. 272b). The hinges do not need to be perfect. With respect to the stiffness of the structure, it is sufficient to shape the shell appropriately. The shape of discontinuous roofs can be seen as a number of catenaries with varying rise-span ratios; thus, traditional masonry is a suitable building material for this type of shell arch (fig. 273).

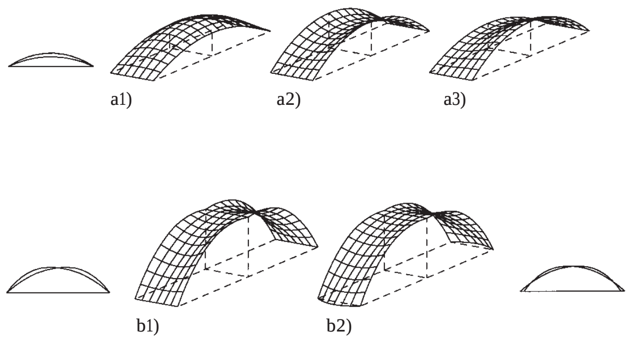



fig. 272

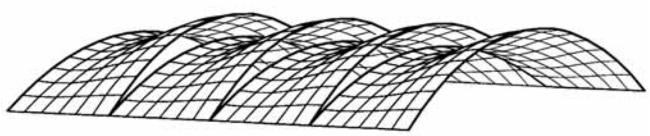


fig. 273

### Structural Analysis

Using available methods of calculation, the elastic behavior of the shell arch under design loads can be simulated accurately, but there is no computational method that can assess the failure of the structure. At present there are no methods of calculation available that accurately describe the mechanical properties of masonry with respect to its anisotropy and the gaping of joints. In such shell arches, the resistance to perpendicular bending effects is reduced significantly by gaping joints. In addition, temporarily gaping joints have lost their adhesion and thus operate only by friction. As a result, the gaping of joints, which is permitted in most of the national codes, should generally not be allowed in this type of construction.

12 Holger Kreienbrink, Henning Schulz, Martin Speth, and Ingo Stelzer, *Vorrichtung zur Herstellung planmäßig gekrümmten Mauerwerks*, German patent specification DE 198 25 101 C2, Munich, 2000.
13 The shells were prefabricated by bricklayers in the first and second years of their apprenticeship. The team of bricklayers changed every two weeks. This practical test made clear that the formwork developed was indeed easy to use.
14 Trass is a material similar to pozzuolana found in the Eifel district of Germany. It is used to give additional strength to lime mortars and plasters. *Larousse Dictionary of Science and Technology*, s. v. “trass.”

fig. 274

fig. 275: Charles Dutert, Machine Exhibition Hall, Paris Exhibition, 1889, perfect hinge


fig. 275

To find the ultimate load-bearing capacity of a shell arch, load tests were undertaken on the first prototype.[15] The goal was to increase the load until failure of the structure occurred. First, ballast was put on continuously as if snow loads were acting on the whole arch. The deflection was measured with high-precision instruments at twelve reference points. Good correlation between theoretical analysis and the measured results was observed in these tests, suggesting that the load could possibly have been increased ten times without any failure or damage to the arch.

The more critical situation is the case in which the load is acting on only one side of the arch (fig. 274). This is the theoretical analysis of a case that is set by German codes, in which half a standard DIN (German engineering standard) snow load is acting on one side of the arch. The structural analysis showed that the compressive stresses were distributed throughout the arch. On the side where the load acts, compression concentrates in the upper part of the section; on the other side, it concentrates at the free edges. This matches the theory of the funicular curves of the arch, as expected. It is very important to avoid tensile stresses parallel to the span with any possible load. By increasing the load these should soon appear, but in this case there was no correlation with the theoretical model. The load had to be increased more and more, until finally testing was stopped due to a lack of additional ballast. By then, eight times the load with which, theoretically, tensile stresses should appear in the free edges had been applied.

These tests, and everything learned while building the shells, show that the models typically employed in the structural analysis of brickwork do not make use of the full potential of this material. This should not lead, however, to an overestimate of the structural capabilities of brick shells. It should be noted that due to moving loads, bending cracks parallel to the span (rather than compressive failure) would cause this type of structure to fail.[16] It should also be stressed that the collapse of a structure of this type is expected to happen spontaneously. This is a significant difference between masonry shell structures and those made of ductile materials. In the latter, failure is usually predictable in advance of a collapse, when deformations increase dangerously.

Taking into account these qualifications, our experience has shown that it is possible to construct shells made of unreinforced, traditionally worked brickwork. This material and structural type should be tested further. Particularly suitable for the construction of shells are the techniques of traditional manual production and prefabrication, which guarantee and exploit brickwork's high degree of stability. Of particular importance is the masonry bond, which enables us to draw on the full potential of classical brickwork. The design of the shell shapes must take into consideration the structural behavior of the material, with all its pros and cons. The variety of possible shapes may be limited compared to those of reinforced concrete construction, but the advantages of very thin unreinforced masonry walls may still warrant its use.

In a sense, we are at a stage of development comparable to that of Charles Dutert (1845–1906) and his designs in steel for the Machine Exhibition Hall at the 1889 Paris Exhibition (fig. 275). The perfectly built hinge guaranteed that the stress on a statically determinate system could be accurately predicted. At the same time, the hinge is also a symbol of the machine itself. The quasi-hinges of our shells developed directly due to the requirements of the material on the supports (fig. 270). In steel structures, perfect hinges became less important, as the full potential of this material—its ductility—was discovered. The question as to whether the semi-hinges will remain or not in our unreinforced masonry shells will have to be left to future experiments investigating this promising type of construction.

15 For a complete review of findings, see Christian Hesse, Otto Heunecke, Martin Speth, and Ingo Stelzer, "Belastungsversuche an einem Schalentragwerk aus Ziegelsteinen," in *Ingenieurvermessung 2000, Eighth International Course on Engineering Surveying,* ed. Klaus Schnädelbach (Stuttgart: Konrad Wittwer, 2000).
16 See Speth, "Schalenbogen ans unbewehrtem Mauerwerk," and idem, Ph.D. diss.

# LIST OF WORKS

Over the last fifty years, Eladio Dieste and his firm, Dieste y Montañez, constructed numerous works in South America. The greatest number of structures were erected in Dieste's native Uruguay, although the firm built quite prolifically in Argentina and Brazil as well. Late in his career, Dieste also had the opportunity to lead in several collaborative projects in Spain. These works—as well as three works built prior to Dieste's association with Eugenio Montañez—are listed here. The works are separated by country and are listed chronologically by date of construction. Key collaborators from within the Dieste y Montañez firm are listed, as are architects with whomthe firm has worked in conjunction. Signature structural or aesthetic features of Dieste's are also listed, where applicable. Starred entries indicate structures illustrated in this volume. Of these buildings, those built in Uruguay are also indicated on the maps following this page.

This list was compiled with the invaluable assistance of the "Archivo General de Obras y Proyectos" of the Dieste firm, supplemented by a smaller but more perfected version of this list compiled by Gonzalo Larrambebere. Generous factchecking was provided by other members of Dieste y Montañez, especially Eduardo Dieste and Walter Vilche. This list also draws on earlier published sources—primarily Juan Pablo Bonta's book *Eladio Dieste* (1963); "Eladio Dieste, el maestro del ladrillo," published in *Summa: Colección Summarios* (July 1980); and *Eladio Dieste: 1943–1996* (1996), edited by Antonio Jiménez Torrecillas. Additionally, informed and valued assistance on the Brazilian works was provided by Cristina Carvalha, and on works in the Argentinian province of Córdoba by Pedro Reyna.

Despite the attention from Dieste's own firm and others, many details remain uncertain and some records are incomplete. These weaknesses are especially evident for the sections devoted to Argentina and Brazil. For the works in Brazil, even dates are missing. In that section of the list, dated works are listed chronologically, followed by the undated works in the order of the "Archivo General." What follows is a list that is as complete and as accurate as conditions permit: we offer it in the hope that students and scholars may use it as a starting point to collectively achieve a fuller documentation of, and appreciation for, the work of Dieste y Montañez.

## MAPS

(A) Ayuí parador
(B) Cítricos Caputto fruit packing plant
(C) Municipal bus terminal
(D) Turlit bus station
(E) Barbiere and Leggire service station, the "Sea Gull"
(F) Refrescos del Norte
(G) Refrescos del Norte water tower
(H) CADYL horizontal silo
(I) Church of St. Peter [San Pedro]
(J) Lanas Trinidad wool industrial complex
(K) Navios horizontal silo
(L) Fagar Cola bottling plant
(M) ADF wool warehouse
(N) Massaro Agroindustries
(O) Church of Christ the Worker
(P) Las Vegas Resort water tower
(Q) TV Communications tower

URUGUAY

(A) Solsire salt silo
(B) Port warehouse
(C) Don Bosco school gymnasium
(D) Montevideo shopping center
(E) Carugatti garage and workshop
(F) Church of our Lady of Lourdes
(G) San Agustín parish center and gymnasium
(H) TEM factory
(I) Dieste house

MONTEVIDEO

## URUGUAY

**Berlingieri House**
Location: Punta Ballena, Maldonado
Client: Berlingieri family
Project Date: 1946
Construction: 1947
Architect: Antoní Bonet Castellana
Technical Statistics: span 20 ft. (6 m)
Features: Dieste's first reinforced brick vaults
Literature: Dieste 1947; Barthel 2001; Bayón 1979; Diehl 1999; Pedreschi 2000; Silvestri 2001

**M.A.U.S.A. Cotton Mill**
Location: Mendoza at Teniente Rinaldi, Montevideo
Client: Tejeduría de algodón M.A.U.S.A.
Construction: 1947
Features: elliptical vault in reinforced concrete with heavy diaphragm arches rising above the vault
Literature: Bonta 1963; Carbonell 1987

**I.P.U.S.A. Paper Factory**
Location: Pando, Canelones
Client: Fábrica de papel I.P.U.S.A.
Construction: 1948
Features: elliptical self-carrying vault in reinforced concrete
Literature: Bonta 1963

**Frugoni Warehouse** [today, Julio César Lestido, S.A.]
Location: Cerro Largo 1729, Montevideo
Client: Frugoni
Construction: 1955
Technical Statistics: area 38,000 sq. ft. (3,500 sq. m); span 72 ft. (22 m)
Features: double-curvature vaults with skylights

**Administración Nacional de Combustibles**, Alcohol y Portland (ANCAP) Warehouse
Location: Capurro, Montevideo
Client: ANCAP
Construction: 1955
Collaborator: Eng. Eugenio Montañez
Technical Statistics: span 26 ft. (8 m)
Literature: Dieste "Selección de problemas" 1993; Bonta 1963; Diehl "Sanft gewellt" 1992

***El Pais* Newspaper Warehouse** [demolished]
Location: Rambla República Argentina y Paraguay, Montevideo
Client: Diario El País
Construction: April–June 1956
Collaborator: Eng. Eugenio Montañez
Technical Statistics: area 23,700 sq. ft. (2,200 sq. m); span 72 ft. (22 m)
Features: continuous single-curvature vaults; sinuses cut between column supports and carrying skylights
Literature: Dieste "Estructuras de cerámica" 1961; Bonta 1963

**Gas Station** [today, Gomería Maryel, S.A.]
Location: Cooper 2099, Carrasco, Montevideo
Construction: 1957
Collaborator: Eng. Eugenio Montañez
Technical Statistics: span 72 ft. (22 m)
Features: double-curvature vault supported on one column at each side
Literature: Bonta 1963

**Club Remeros de Mercedes Gymnasium**
Location: Mercedes, Soriano
Construction: 1957
Technical Statistics: area 14,000 sq. ft. (1,300 sq. m); span 82 ft. (25 m)
Features: double-curvature vaults

**A. Jung, S.A. Textile Mill**
Location: Camino Carlos A. López, Montevideo
Construction: April 1957–October 1957
Technical Statistics: area 44,000 sq. ft. (4,100 sq. m); span 82 ft. (25 m)
Features: double-curvature vaults

**Silos for Banco República** [4 separate locations in four stages]
Location: Cardona, Soriano; Palmitas, Soriano; Tarariras, Colonia; Suárez, Canelones
Client: Banco de la República Oriental del Uruguay
Construction: unknown; September 1958; unknown; November 1957–March 1958
Technical Statistics: area 16,000 sq. ft. (1,500 sq. m) each; span 92 ft. (28 m) each
Features: double-curvature vaults

**Departmental Council of Artigas Gymnasium** [today, Intendencia Municipal de Artigas]
Location: Artigas
Client: Intendencia Municipal de Artigas
Construction: 1958
Collaborator: Eng. Eugenio Montañez
Technical Statistics: area 16,000 sq. ft. (1,500 sq. m); span 85 ft. (26 m)
Features: double-curvature vaults
Literature: Bonta 1963

* **Church of Christ the Worker**, Atlántida
Location: Route 11, km 164, Atlántida, Canelones
Client: Obispado de Canelones (Donation of Alberto Giudice)
Project Date: 1952
Construction: March 1958–July 1960; restoration work begun in 2003 under the direction of Esteban Dieste

Collaborators: Eng. Raúl Romero and Eng. Marcelo Sasson
Technical Statistics: area 5,400 sq. ft. (500 sq. m); average span 52.5 ft. (16 m); maximum span 61.7 ft. (18.8 m); wall thickness 12 in. (30 cm)
Features: double-curvature vaults with integral tie-rods; undulating (ruled surface) walls; subterranean baptistery; campanile with a height of 16 m (52.5 m)
Literature: Dieste "Iglesia" 1961; "Estructuras de cerámica" 1961; 1962; "Diálogos" 1980; *Bóvedas* 1985; "Uruguay" 1987; "Una estética de la ética" 1988; "Estética" 1988; "La Iglesia Atlántida" 1990; "Bauten" 1991; "Reflections" 1992; "Tecnologie" 1996; "Tecnologie" 1996; Anon. "Church" Sept. 1961; Anon. "Eglise" 1961; Anon. "Church" Dec. 1961; Anon. "Brick Shell" 1962; Anon. "Die Kunst der Schale" 1995; Bach 1993; Barthel 2001; Bayón 1979; Bonta 1963; Browne 1988; Bullrich 1969; Cabeza 2000; Carbonell 1987; Collet 2000; Dias Comas 1998; Diehl 1990; Diehl "Lateinamerikanische" 1992; Diehl "Bewehrt" 1992, Diehl "Sanft gewellt" 1992; Fernández 1992; Fernández-Galiano 1998; Flora 1997; Garabelli 1985; Gazzaniga 1996; Goytia 1999; Goytia 2002; Grino 2000; Gutiérrez 1999; Irace 1991; Jiménez 1996; Lyall 1998; Moisset de Espanés 1999; Montaner 2000; Pedreschi 2000; Pérez 1998; Posani 1993; Rasch 1997; Silvestri 2001; Véjar 1994; Vercelloni 1993; Waisman 1989; Waisman 1991; Zeballos 1999.

Carrau y Cía Warehouse
Location: Avenida Dámaso A. Larrañaga 3444, Montevideo
Client: Carrau y Cía
Construction: 1959
Technical Statistics: area 34,400 sq. ft. (3,200 sq. m); span 82 ft. (25 m)
Features: double-curvature vaults with skylights
Literature: Dieste "Estructuras de cerámica" 1961

Inyecta Metal Foundry
Location: Emancipación and Avenida Garzón, Montevideo
Client: Inyecta Metal
Construction: 1959
Technical Statistics: area 19,400 sq. ft. (1,800 sq. m); span 98.5 ft. (30 m)
Features: double-curvature vaults

Banco de Seguros del Estado Garage [today, FRIPUR]
Location: Rondeau 2274, Montevideo
Client: Banco de Seguros del Estado
Construction: May 1959–May 1960
Collaborator: Eng. Eugenio Montañez
Technical Statistics: area 27,000 sq. ft. (2,500 sq. m); span 115 ft. (35 m)
Features: double-curvature vaults with skylights
Literature: Bonta 1963

Electroplast Factory [three stages]
Location: Servando Gómez 2440, Montevideo
Client: Electroplast
Construction: 1960; 1966; 1975
Technical Statistics: area 6,500 sq. ft. (600 sq. m), 8,600 sq. ft. (800 sq. m), and 9,700 sq. ft. (900 sq. m), respectively; span 39.4 ft. (12 m), 52.5 ft. (16 m), and 52.5 ft., respectively
Features: self-carrying vaults

* TEM Factory [today, SUDY-LEVER Warehouse]
Location: Camino Carrasco 5975, Montevideo
Client: TEM, S.A.
Project Date: 1958
Construction: September 1960–March 1962
Collaborators: Eng. Eugenio Montañez, Eng. Carlos Agorio, and Eng. Marcelo Sasson
Architects: Studio Clerk and Guerra
Technical Statistics: area 88,300 sq. ft. (8,200 sq. m); span 141 ft. (43 m)
Features: two parallel series of double-curvature vaults with skylights; interior supports at 33.6 ft. (10.25 m)
Literature: Dieste 1964; 1969; 1975; "Una estética de la ética" 1988; Barthel 2001; Bayón 1979; Bonta 1963; Grino 2000; Jiménez 1996; Silvestri 2001.

* Dieste House
Location: Mar Antártico 1227, Punta Gorda, Montevideo
Client: Dieste Family
Purchase of Property: 1952
Construction: October 1961–April 1963
Collaborators: draftsmen H. Gatti and F. Banderas
Technical Statistics: lot size 43 x 164 ft. (12 x 50 m); area 2,850 sq. ft. (264 sq. m); lateral span 15.75 ft. (4.8 m); longitudinal span 13 ft. (4 m)
Features: self-carrying vaults
Literature: Dieste *Bóvedas* 1985; "Una estética de la ética" 1988; Arana 1980; Arana 1981; Barthel 2001; Bonta 1963; Bossi 1999; Carbonell 1987; Diehl 1999; Gazzaniga 1996; Goytia 1999; Goytia 2002; Jiménez 1996; Pedreschi 2000; Pérez 1998; Silvestri 2001

Dolores Gymnasium
Location: Dolores, Soriano
Client: Intendencia Municipal de Soriano
Construction: January–September 1962
Technical Statistics: area 15,000 sq. ft. (1,400 sq. m); span 98.5 ft. (30 m)
Features: double-curvature vaults

Liceo No. 18 Gymnasium
Location: Avenida Millán 3898, Montevideo
Client: CODICEN
Construction: 1963
Collaborator: Eng. Eugenio Montañez
Literature: Bonta 1963

Pavilion of the Fiat Plant
Location: Carmelo
Construction: 1963
Literature: Bonta 1963

Soccer Stadium “Luis Franzini” [unbuilt]
Location: Montevideo
Project Date: 1963
Literature: Bonta 1963

Autopalace [today, Tecnomadera, S.A.]
Location: General Flores 2775, Montevideo
Client: Darcon, S.A.
Project Date: 1963
Construction: May–November 1964
Collaborators: Eng. Eugenio Montañez and Eng. Raúl Romero
Architect: Acerenza
Technical Statistics: area 32,300 sq. ft. (3,000 sq. m); span 98.5 ft. (30 m)
Features: first self-carrying vaults of this large a span; of variable length and with wide edge slabs
Literature: Barthel 2001; Grino 2000; Jiménez 1996

Banco Popular [today, UTE Administrative Offices]
Location: General Flores 2381, Montevideo
Client: Banco Popular
Construction: July 1964–December 1965
Architect: Mario Paysse Reyes
Technical Statistics: area 19,400 sq. ft. (1,800 sq. m); span 72 ft. (22 m)
Features: 2.2 in.- (5.5 cm-) thick double-curvature vaults with hollow bricks

Frigorífico Carrasco Warehouse [three facilities in three stages]
Location: Camino Carrasco no. 5, Montevideo
Client: Frigorífico Carrasco, S.A.
Construction: November 1964–February 1965; 1968; March–June 1970
Collaborator: Eng. Eugenio Montañez
Technical Statistics: area 21,500 sq. ft. (2,000 sq. m), 15,000 sq. ft. (1,400 sq. m), and 19,400 sq. ft. (1,800 sq. m), respectively; span 82 ft. (25 m), 82 ft., and 85 ft. (26 m), respectively
Features: self-carrying vaults

Sandoz Laboratories
Location: Dámaso A. Larrañaga 4479, Montevideo
Construction: 1965
Technical Statistics: area 16,000 sq. ft. (1,500 sq. m); span 59 ft. (18 m)
Features: self-carrying vaults

Sidney Ross Laboratories
Location: Camino Maldonado 5634, Montevideo
Construction: 1965
Technical Statistics: area 27,000 sq. ft. (2,500 sq. m); span 85 ft. (26 m)
Features: self-carrying vaults

* Lanas Trinidad Wool Industry Complex [four stages]
Location: General Rivera 292, Trinidad, Flores
Client: Lanas Trinidad, S.A.
Construction: March–September 1965
Architects: Lorieto and Queirolo
Technical Statistics: area 25,800 sq. ft. (2,400 sq. m); span 59 ft. (18 m)
Features: self-carrying vaults
Literature: Barthel 2001; Diehl “Sanft gewellt” 1992; Flora 1997; Grino 2000; Jiménez 1996

ADDITIONS
Wool Warehouse
Construction: April–November 1979
Technical Statistics: area 44,000 sq. ft. (4,100 sp. m); span 92 ft. (28 m)
Features: pre-stressed self-carrying vaults

Gilling Plant
Construction: April 1986–April 1987
Technical Statistics: area 61,350 sq. ft. (5,700 sq. m); transverse span 26 ft. (8 m); longitudinal span 131 ft. (40 m)
Features: pre-stressed self-carrying vaults

Scouring Plant
Construction: February 1988–May 1989
Collaborators: Eng. Gonzalo Larrambebere, Eng. Jorge Bliman, Arch. Esteban Dieste, and Tech. Asst. Walter Vilche
Technical Statistics: area 24,750 sq. ft. (2,300 sq. m); span (chord) 41.3 ft. (12.6 m)
Features: self-carrying barrel vault

Epidor, S.A. Warehouse
Location: Arrieta y Vidal, Montevideo
Client: Epidor, S.A.
Construction: April–September 1965
Technical Statistics: area 34,400 sq. ft. (3,200 sq. m); span 82 ft. (25 m)
Features: double-curvature vaults

Erosa Warehouse
Location: Avenida Garzón 1827, Montevideo
Construction: 1965
Technical Statistics: area 25,800 sq. ft. (2,400 sq. m); span 85 ft. (26 m)
Features: double-curvature vaults

* Church of Our Lady of Lourdes [unfinished] and Parish House, Malvín
Location: Calle Michigan and Avenida General Rivera, Malvín, Montevideo
Client: Obispado de Montevideo
Project Date: 1961
Construction: June 1965–August 1968
Collaborators: Eng. Raúl Romero and Arch. Alberto Castro

Technical Statistics: area (church) 8,600 sq. ft. (800 sq. m); maximum span 65.6 ft. (20 m); height of the presbytery tower, 88.6 ft. (27 m)
Features: double-curvature vault and undulating walls in the sanctuary
Literature: Dieste *Bóvedas* 1985; Banfi 1997; Bonta 1963; Carbonelle 1987; Jiménez 1996; Pedreschi 2000; Pérez 1998

Fosfato Thomas Silos [two stages]
Location: Avenida de las Instrucciones y Via Férrea, Montevideo
Client: Fosfato Thomas
Construction: August 1965–February 1967
Collaborator: Eng. Eugenio Montañez
Technical Statistics: area 20,500 sq. ft. (1,900 sq. m) and 16,600 sq. ft. (1,550 sq. m), respectively; span 98.5 ft. (30 m), rise 49.2 ft. (15 m); span 72 ft. (22 m), rise 39.4 ft (12 m), respectively
Features: first silo for material stored with lateral thrust; double-curvature vaults, embedded in the ground to resist the horizontal force of the bulk material

Carlos Patrón Garage [today, Devoto Supermarket]
Location: Lima 1737 y Arenal Grande, Cordón Norte, Montevideo
Client: Carlos Patrón
Construction: September 1965–April 1966
Technical Statistics: area 24,200 sq. ft. (2,250 sq. m); span 105 ft. (32 m)
Features: pre-stressed self-carrying vaults supported on inclined columns
Literature: Dieste 1969

MacGregor Factory
Location: Avenida Garzón 1827, Montevideo
Construction: 1966
Technical Statistics: area 9,700 sq. ft. (900 sq. m); span 85 ft. (26 m)
Features: self-carrying vaults

Distribuidora Americana Salesroom
Location: Paysandú
Client: Distribuidora Americana
Construction: January–November 1966
Technical Statistics: area 25,800 sq. ft. (2,400 sq. m); span 79 ft. (24 m)
Features: self-carrying vaults

* Las Vegas Resort Water Tower
Location: Las Vegas, Canelones
Client: Comisión Balneario Las Vegas
Construction: February–September 1966
Technical Statistics: height 88.6 ft. (27 m); volume 31,700 gallons (120 cu. m)
Literature: Diehl "Bewehrt und eigenwillig" 1992; Diehl "Sanft gewellt" 1992; Jiménez 1996

Frigorífico Cruz del Sur [three stages]
Location: Las Piedras, Canelones
Client: Frigorífico Cruz del Sur
Construction: 1966; 1968; May–December 1970
Collaborator: Eng. Eugenio Montañez
Technical Statistics: area 58,000 sq. ft. (5,400 sq. m), 10,200 sq. ft. (950 sq. m), and 9,700 sq. ft. (900 sq. m), respectively span 82 ft. (25 m); 72 ft. (22 m); 49 ft. (15 m), respectively
Features: self-carrying vaults

Fabex Wool Processing Plant Unit
Location: Trinidad, Flores
Client: Fabex
Construction: May–September 1966
Technical Statistics: area 21,500 sq. ft. (2,000 sq. m); span 72 ft. (22 m)
Features: self-carrying vaults

Cerámicas del Sur Brick Factory
Location: Route 1, km 37.6, San José Department
Construction: 1966
Technical Statistics: area 15,000 sq. ft. (1,400 sq. m); span 65.6 ft. (20 m)
Features: double-curvature vaults

Canelones Fruit Market
Location: Canelones
Client: Intendencia Municipal de Canelones
Construction: November 1966–March 1967
Technical Statistics: area 22,600 sq. ft. (2,100 sq. m); span 98.5 ft. (30 m)
Features: self-carrying vaults

Maldonado Gymnasium
Location: Municipal Campus of Maldonado
Client: Municipality of Maldonado
Construction: January 1967–February 1968
Technical Statistics: area 21,500 sq. ft. (2,000 sq. m); span 108 ft. (33 m); cantilever 23 ft. (7 m)
Features: self-carrying vaults carried on inclined supports that contribute to pre-stressing

Roberto Miles Warehouse
Location: General Santander 1785, Montevideo
Client: Roberto Miles
Construction: February–July 1967
Technical Statistics: area 24,750 sq. ft. (2,300 sq. m); span 82 ft. (25 m)
Features: self-carrying vaults

Roche Laboratories Production Facility [two stages]
Location: Camino Maldonado 6550, Montevideo
Client: Laboratorio Roche
Construction: February–May 1967; July–December 1975
Technical Statistics: area 23,700 sq. ft. (2,200 sq. m) each; span 79 ft. (24 m) each
Features: self-carrying vaults

Madre Paulina Church
Location: Carmelo de Arzadúm 6023 y Oficial 3, Belvedere, Montevideo
Client: Colegio Madre Paulina
Construction: March–December 1967
Collaborator: Arch. Alberto Castro
Architect: Alfredo Solari
Technical Statistics: area 9,700 sq. ft. (900 sq. m); span 75.5 ft. (23 m)
Features: pre-stressed self-carrying vault with edge plates [cañon corrido]

Liceo Bauzá Gymnasium
Location: Lucas Obes 896, Montevideo
Construction: 1967
Technical Statistics: area 11,850 sq. ft. (1,100 sq. m); span 79 ft. (24 m)
Features: self-carrying vaults

RAUSA Sugar Refining Facility [three stages]
Location: Montes, Canelones
Construction: 1967; 1968; 1969
Technical Statistics: area 9,700 sq. ft. (900 sq. m), 8,600 sq. ft. (800 sq. m), and 11,300 sq. ft. (1,050 sq. m), respectively; span 49 ft. (15 m), 59 ft. (18 m), and 59 ft., respectively
Features: self-carrying vaults

Garino Brothers Stationery Printing and Production Facility
Location: Joaquín Requena 1865, Montevideo
Client: Garino Hnos.
Construction: August 1967–September 1968
Collaborator: Eng. Eugenio Montañez
Technical Statistics: area 24,200 sq. ft. (2,550 sq. m); span 88.6 ft. (27 m)
Features: self-carrying vaults

Club Hebraica-Macabi Gymnasium
Location: Camacuá 623, Montevideo
Client: Club Hebraica-Macabi
Construction: February–July 1968
Technical Statistics: area 19,400 sq. ft. (1,800 sq. m); spans 52.5 ft. (16 m), 79 ft. (24 m)
Features: double-curvature and self-carrying vaults

Edasa, Textile Industry Factory [two stages]
Location: Route 1, km 31, San José Department
Construction: 1968; 1979–1980
Technical Statistics: area 43,000 sq. ft. (4,000 sq. m) and 21,500 sq. ft. (2,000 sq. m), respectively; span 115 ft. (35 m) each
Features: double-curvature vaults

CALNU Agroindustrial Complex
Location: Bella Unión, Artigas
Client: CALNU
Construction: February 1968–May 1970
Technical Statistics: area 129,000 sq. ft. (12,000 sq. m); span 82 ft. (25 m); maximum height of columns 75.5 ft. (23 m)
Features: double-curvature vaults

Salón del Automóvil: Exhibition Hall, Centro del Espectáculo [demolished 2002]
Location: Avenida Costanera Parada 3, Punta del Este, Maldonado
Construction: 1969
Technical Statistics: area 31,200 sq. ft. (2,900 sq. m); span 85 ft. (26 m)
Features: self-carrying vaults
Literature: Bayón 1979; Pedreschi 2000

* Church of St. Peter [San Pedro]
Location: Batlle y Ordoñez 622, Plaza Independencía, Durazno
Client: Saint Peter's Parish
Project Date: 1967
Construction: January 1969–May 1971
Collaborators: Arch. Alberto Castro and Eng. Raúl Romero
Technical Statistics: area 8,600 sq. ft. (800 sq. m); transverse span 75.5 ft. (23 m); longitudinal span 105 ft. (32 m); nave width at floor 36 ft. (11 m)
Features: After a fire, St. Peter (built ca. 1880–1920) was rebuilt except for the existing façade and narthex. The roof consists of 3.15 in.- (8 cm-) thick pre-stressed masonry folded plates
Literature: Dieste "Iglesia" 1973; 1987–88; "Una estética de la ética" 1988; "Estética" 1988; "Estética" 1990; "Bauten" 1991; "Reflections" 1992; (Selección de problemas" 1993; Anon. 1995; Arana 1980; Arana 1982; Bach 1993; Barthel 2001; Bayón 1979; Browne 1988; Carbonell 1987; Diehl "Bewehrt" 1992; Diehl "Sanft gewellt" 1992; Garabelli 1985; Garabelli 1991; Gazzaniga 1996; Goytia 1999; Goytia 2002; Grino 2000; Jiménez 1996; Moisset 1999; Montaner 2000; Morales 1991; Pedreschi 2000; Pérez 1998; Rasch 1997; Vercelloni 1993; Waisman 1989; Zeballos 1999.

La Republicana Factory [three warehouses in three stages]
Location: Mirungá 6505, Montevideo
Client: Companía Industrial de Tabacos, S.A.
Construction: March 1969–April 1970; April 1980–July 1981; July 1982–May 1983
Technical Statistics: area 38,750 sq. ft. (3,600 sq. m), 38,750 sq. ft. (3,600 sq. m), and 32,300 sq. ft. (3,000 sq. m), respectively; span 131 ft. (40 m) each
Features: double-curvature vaults

Water Tower, Housing Estate Malvín Norte
Location: Camino Carrasco y Veracierto, Malvín Norte, Montevideo
Client: Cooperativa de Viviendas Malvín Norte
Construction: July 1971–June 1972
Technical Statistics: height: 131 ft. (40 m); volume: 79,250 gallons (300 cu. m)

* Cítricos Caputto Fruit Packing Plant [two stages]
Location: Paraguay y Ferreira, Salto
Client: Citrícola Salteña, S.A.
Project Date: 1971
Construction: September 1971–October 1972 [added facility: 1986–1987]
Collaborators: Eng. Raúl Romero and Arch. Alberto Castro [added facility: Eng. Antonio Dieste and Tech. Asst. Walter Vichle]
Architectural Design: Nestor Minutti
Technical Statistics: area 45,200 sq. ft. (4,200 sq. m); span 152.5 ft. (46.5 m) [added facility: area 31,750 sq. ft. (2,950 sq. m); span 87 ft. (26.5 m)]
Features: double-curvature vault with skylights [added facility: continuous double-curvature vaults without skylight]
Literature: Barthel 2001; Grino 2000; Jiménez 1996; Pedreschi 2000; Pérez 1998

Municipal Bus Terminal, Salto
Location: Latorre y Larrañaga, Salto
Client: Intendencia Municipal de Salto
Project Date: 1971
Construction: September 1973–April 1974
Collaborator: Eng. Raúl Romero
Architectural Design: Nestor Minutti
Technical Statistics: area 12,900 sq. ft. (1,200 sq. m); transverse span 20 ft. (6 m) transverse; double-cantilever maximum 39.8 ft. (12.13 m)
Features: self-carrying vaults of double-cantilever to each side of a single row of central supports
Literature: Dieste "Arquitectura" 1980; "Cáscaras" 1985; "La invenión" 1987; "Una estética de la ética" 1988; "Estética" 1988; "Estética" 1990; Arana 1981; Barthel 2001; Carbonell 1987; Diehl "Sanft gewellt" 1992; Diehl 1999; Flora 1997; Grino 2000; Jiménez 1996; Pedreschi 2000; Pérez 1998; Waisman 1989; Waisman 1991

Club Salto Nuevo F.C. Gymnasium [today, property of the Intendencia Municipal de Salto]
Location: Salto
Construction: 1974
Technical Statistics: area 12,900 sq. ft. (1,200 sq. m); span 92 ft. (28 m)
Features: double-curvature vaults

Durazno Gymnasium
Location: Dr. E. Penza y Saravia, Durazno
Client: Durazno City Council
Project Date: 1973
Construction: March 1974–January 1975
Collaborator: Eng. Raúl Romero
Technical Statistics: area 17,200 sq. ft. (1,600 sq. m); span 147.6 ft. (45 m)
Features: double-curvature vaults
Literature: Barthel 2001; Diehl "Bewehrt" 1992 [misidentified as Trinidad Gymnasium], Diehl 1999; Jiménez 1996; Pedreschi 2000

Horizontal Silo for Rice, Vergara
Location: Vergara, Treinta y Tres
Client: Soc. Anónima Molinos Arroceros Nacionales (SAMAN)
Construction: August 1974–December 1978
Collaborators: Eng. Ariel Valmaggia, Eng. José M. Zorrilla, Eng. Gonzalo Larrambebere, and Eng. Antonio Dieste
Technical Statistics: capacity: 30,000 T; span 98.5 ft. (30 m); height 49.2 ft. (15 m)
Features: embedded double-curvature vaults; 45 degree inclined concrete floor
Literature: Dieste "Una estética de la ética" 1988; "Estética" 1988; "Estética" 1990; "Reflections" 1992; Bach 1993; Carbonell 1987; Gazzaniga 1996; Vercelloni 1993

Cítricos Caputto Distribution Warehouse (today, an auto dealership) [two stages]
Location: Batlle y Ordoñez 2932, Montevideo
Client: Caputto-Citrícola Salteña, S.A.
Project Date: 1975
Construction: January 1976–November 1977 [second stage, refrigerated rooms: 1979]
Collaborators: Arch. Alberto Castro and Eng. Eugenio Montañez
Technical Statistics: area 23,700 sq. ft. (2,200 sq. m); span 111.5 ft. (34 m) [second stage: area 10,750 sq. ft. (1,000 sq. m); span 39.4 ft. (12 m)]
Features: double-curvature vault with skylight [second stage: self-carrying vaults]
Literature: Jiménez 1996

* Barbieri and Leggire Service Station [today, "Puerta de la Sabiduría"]
The service station incorporated a shelter for the gas pumps, nicknamed "La Gaviota" ("The Sea Gull"); it now serves as the "Puerta de la Sabiduría" at the south entry to the city of Salto.
Location of Service Station: Calle Blandengues y Avenida Batlle y Ordoñez, Salto (relocated November 1996)
Client: Barbieri and Leggire
Project Date: 1975–76
Construction: March–December 1976
Present Location of "Puerta de la Sabiduría": Paraje 4 Bocas, Route 3, Salto
Architectonic Design: Nestor Minutti
Collaborators (in relocation): Eng. Ariel Valmaggia and Eng. Antonio Dieste
Technical Statistics (of "Puerta de la Sabiduría"): area 1,025 sq. ft. (95.2 sq. m) 1,500 sq. m; span (chord) 9.2 ft. (2.80 m); height 4 ft. (1.25 m); height of support 13 ft. (4 m)
Features: It is a special self-carrying structure using mixed techniques; 27.9 ft. (8.50 m) on each side of one central column
Literature: Dieste "Reflections" 1992; Barthel 2001, 46; Diehl "Bewehrt" 1992; Diehl "Sanft gewellt" 1992; Diehl 1999; Grino 2000; Jiménez 1996; Pedreschi 2000; Pérez 1998; Silvestri 2001

**Water Tower**, Salto
Location: Route 3 and Route 31, Salto
Client: Intendencia Municipal de Salto
Construction: April–December 1976
Technical Statistics: height: 98.5 ft. (30 m); volume: 39,600 gallons (150 cu. m)
Features: pierced shaft of masonry
Literature: Carbonell 1987

**ANCAP Oil Pipeline Terminal**, Tanktruck Port
Location: Camino Lecoq y Avenida Millan, Montevideo
Client: Administración Nacional de Combustibles, Alcohol y Portland (ANCAP)
Construction: May–October 1976
Technical Statistics: area 21,500 sq. ft. (2,000 sq. m)
Features: self-carrying vaults

**Daymán Thermal Baths**
Location: Salto
Construction: 1976
Technical Statistics: area 16,000 sq. ft. (1,500 sq. m); span 49 ft. (15 m)
Features: self-carrying vaults

**COLSA Metallurgical Industry** [today, Palmolive, S.A.]
Location: Tte. Galeano, Montevideo
Construction: 1976
Technical Statistics: area 37,700 sq. ft. (3,500 sq. m); span 85 ft. (26 m)
Features: self-carrying vaults

* **Ayuí Parador Café**
Location: Rambla Costanera Norte Cesar Mayo Guttiérrez, km 3, Salto
Client: Intendencia Municipal de Salto
Project Date: 1976
Construction: September 1976–May 1977
Collaborator: Arch. Esteban Dieste
Architectural Design: Nestor Minutti
Technical Statistics: area 3,725 sq. ft. (346 sq. m); span 49 ft. (15 m) diameter at supports; 69 ft. (21 m) diameter overall
Features: 49 ft. diameter cone that continues in a 10 ft. (3 m) auto-precompressing protruding eave; supported on 1.58 in. (40 mm) sq. folded sheet metal columns
Literature: Dieste *Bóvedas* 1985; "Estética" 1988; "Estética" 1990; Barthel 2001; Grino 2000; Jiménez 1996; Pedreschi 2000; Silvestri 2001; Waisman 1989

* **Massaro Agroindustries Fruit Processing Plant** [today, Hydro Agri, S.A.]
Location: Joanicó, Route 5 km 37.5, Canelones
Client: Domingo Massaro, S.A.
Project Date: 1976
Construction: September 1976–May 1980; [water tower: 1979]
Collaborators: Eng. Gonzalo Larrambebere, Eng. Ariel Valmaggia, and Arch. Esteban Dieste
Technical Statistics: area 107,600 sq. ft. (10,000 sq. m); area, main vaults 97,000 sq. ft. (9000 sq. m); transverse span, main vaults: 41.7 ft. (12.7 m); longitudinal span, main vaults 115 ft. (35 m); maximum cantilever 54 ft. (16.5 m); height of vault 13.9 ft. (4.23 m); vault thickness 4 in. (10 cm); transverse span, secondary, double-cantilever vaults 41.7 ft. (12.7 m); maximum cantilever 42.7 ft. (13 m) and 44.3 ft. (13.5 m); water tower height 79 ft. (24 m); water tower volume 14,800 gallons (56 cu .m)
Features: pre-stressed self-carrying vaults of catenary directrix
Literature: Dieste "Cáscaras" 1985; 1987–88; "Una estética de la ética" 1988; "Estética" 1988; "Estética" 1990; "Bauten" 1991; "Reflections" 1992; "Tecnologie" 1996; Barthel 2001; Carbonell 1987; Diehl "Bewehrt" 1992; Diehl "Sanft gewellt" 1992; Gazzaniga 1996; Grino 2000; Jiménez 1996; Pedreschi 2000; Pérez 1998; Rouyer 1997; Waisman 1989; Waisman 1991

* **Cooperativa Agrícola de Young Limitada** (CADYL) Horizontal Silo
Location: Avenida Montevideo 3517, Young, Rio Negro
Client: CADYL
Project Date: 1975
Construction: November 1976–June 1978
Collaborator: Eng. José M. Zorrilla
Technical Statistics: area 38,750 sq. ft. (3,600 sq. m), for 30,000 T; span 98.5 ft. (30 m); height: 49 ft. (15 m)
Features: grain silo of double-curvature vaults, embedded to absorb lateral thrust
Literature: Dieste "Arquitectura" 1980; 1987–88; "Bauten" 1991; Barthel 2001, 22; Diehl 1999; Fernández-Galiano 1998; Grino 2000; Jiménez 1996; Morales 1991; Pedreschi 2000; Pérez 1998; Waisman 1991

**León Iorio Sheet Metal Production Facility**
Location: Camino Mendoza and Aparicio Saravia, Montevideo
Construction: 1977
Technical Statistics: area 21,500 sq. ft. (2,000 sq. m); span 72 ft. (22 m)
Features: self-carrying vaults

* **Refrescos del Norte, Coca-Cola Bottling Plant** [plus additional water tower] (today, Fénix, S.A., Factory)
Location: Route 3, Paraje 4 Bocas, south entry to Salto
Client: Refrescos del Norte, S.A.
Project Date: 1976–77 [water tower: 1978]
Construction: April 1977–May 1980 [water tower: 1979]
Collaborators: Eng. Antonio Dieste and Arch. Esteban Dieste [water tower: Eng. Antonio Dieste]
Architectural Design: Nestor Minutti (plant only)
Technical Statistics: area 38,750 sq. ft. (3,600 sq. m); longitudinal span 82 ft. (25 m); transverse span 41.7 ft. (12.7 m) [water tower: height 79 ft. (24 m); volume 13,200 gallons (50 cu. m)]
Features: pre-stressed self-carrying vaults; complementary structures: entrance portal, offices, auxiliary works
Literature: Dieste "Estética" 1988; "Estética" 1990; "Tecnologie" 1996; Barthel 2001; Carbonell 1987; Cubría 1980; Diehl "Sanft gewellt" 1992; Jiménez 1996; Pedreschi 2000; Silvestri 2001

* **Port Warehouse, Julio Herrera y Obes Depot** [today, Depósitos Montevideo, S.A.]
Location: Rambla 25 de Agosto, Montevideo
Client: National Port Administration represented by architect Nelson Bascou
Project Date: 1976
Construction: October 1977–May 1979
Collaborators: Eng. José M. Zorrilla, Arch. Esteban Dieste, and Tech. Asst. Walter Vilche
Technical Statistics: area 45,200 sq. ft. (4,200 sq. m); span 164 ft. (50 m); rise 21 ft. (6.5 m)
Features: double-curvature vaults; new vaults carried on the modified walls of a burned out warehouse built ca. 1860–80
Literature: Dieste "La invención" 1987; "Una estética de la ética" 1988; 1987–88; "Estética" 1988; "Estética" 1990; "Bauten" 1991; "Reflections" 1992; Arana 1980; Arana 1981; Arana 1982; Barthel 2001; Browne 1988; Carbonell 1987; Delgado 1996; Diehl 1991; Diehl "Bewehrt" 1992; Fernández-Galiano 1998; Goytia 1999; Goytia 2002; Grino 2000; Jiménez 1996; Morales 1991; Moisset 1999; Pedreschi 2000; Pérez 1998; Rouyer 1997; Silvestri 2001; Waisman 1989; Waisman 1991

**Arrozur, S.A. Rice Processing Facility**
Location: Department Treinta y tres
Construction: 1978
Technical Statistics: area 10,750 sq. ft. (1,000 sq. m); span 65.6 ft. (20 m)
Features: double-curvature vaults

* **San Agustín Parish Center Multipurpose Hall and Gymnasium**
Location: Justino Zabala Muniz 5591, Montevideo
Client: Asociación San Agustín
Project date: 1977
Construction: January 1978–January 1980
Collaborators: Arch. Esteban Dieste and Tech. Asst. Walter Vilche
Technical Statistics: area 5,400 sq. ft. (500 sq. m); transverse span 42.7 ft. (13 m)
Features: self-carrying vaults

* **Carugatti, S.A. Construction Equipment Garage and Workshop**
Location: Avenida Italia 4079, Montevideo
Client: H. Carugatti, S.A.
Construction: September 1978–August 1979
Technical Statistics: area 12,900 sq. ft. (1,200 sq. m); span 65.6 ft. (20 m)
Features: self-carrying vaults

**Francis, S.A. Factory**
Location: 21 de Abril 2620, Montevideo
Construction: 1979
Technical Statistics: area 10,750 sq. ft. (1,000 sq. m); span 39.4 ft. (12 m)
Features: self-carrying vaults

**Neosul Factory** [for Ionas plasticas]
Location: Aizpurúa 2092, Montevideo
Construction: 1979
Technical Statistics: area 5,400 sq. ft. (500 sq. m); span 26 ft. (8 m)
Features: self-carrying vaults

**Larrañaga Television Studio, Channel 12**
Location: E. Compte and Riqué 1276, Montevideo
Construction: 1979–1980
Technical Statistics: area 8,600 sq. ft. (800 sq. m); span 65.6 ft. (20 m)
Features: self-carrying vaults

**Juan B. Ferrando, S.A. Metal Industry Facility**
Location: Camino Oncativo, Montevideo
Construction: 1979–1980
Technical Statistics: area 32,300 sq. ft. (3,000 sq. m); span 105 ft. (32 m)
Features: double-curvature vaults

**(Rowing) Club Remeros**, Salto
Location: Rambla Costanera Norte Cesar Mayo Gutiérrez, Salto
Client: Salto Rowing Club
Project Date: 1978
Construction: June 1979–May 1980
Collaborators: Arch. Esteban Dieste, Eng. Antonio Dieste, and Tech. Asst. Walter Vilche
Architect: Ambrosoni
Technical Statistics: area 5,400 sq. ft. (500 sq. m); transverse span 52.5 ft. (16 m); longitudinal span 88.6 ft. (27 m)
Features: self-carrying vaults
Literature: Diehl 1999; Jiménez 1996; Pedreschi 2000; Silvestri 2001

* **Turlit Bus Station** [today, Agencia Central, S.A.]
Location: Cerrito 66 y Avenida Uruguay, Salto
Client: Turlit
Project Date: 1979–80
Construction: April–August 1980
Collaborators: Eng. Antonio Dieste and Tech. Asst. Walter Vilche
Architectural Design: Nestor Minutti
Technical Statistics: area 9,700 sq. ft. (900 sq. m); lateral span 19 ft. (5.75 m); maximum front cantilever 47 ft. (14.4 m); rear cantilever: 45 ft. (13.7 m)
Features: five self-carrying vaults in a variation on double-curvature vaults as at the Salto Municipal Bus Terminal or at Massaro; asymmetric loading to either side of the single line of supports is brought to equilibrium with tension members at the end of the rear vaults.
Literature: Dieste "Estética" 1988; "Bauten" 1991; Carbonell 1987; Jiménez 1996; Pedreschi 2000; Rasch 1997; Silvestri 2001; Vercelloni 1993

Urupez Fish Processing Facility
Location: Playa Verde, Maldonado
Construction: 1980
Technical Statistics: area 25,800 sq. ft. (2,400 sq. m); span 65.6 ft. (20 m)
Features: double-curvature vaults

Lordix, S.A. Factory
Location: Avenida Central 4608, Montevideo
Construction: 1980
Technical Statistics: area 16,000 sq. ft. (1,500 sq. m); span 52.5 ft. (16 m)
Features: double-curvature vaults

Colorín Gallery
Location: Miguelete and D. Fernández Crespo, Montevideo
Construction: 1980
Technical Statistics: area 5,400 sq. ft. (500 sq. m); span 33 ft. (10 m)
Features: self-carrying vaults

Central Lanera Uruguaya Wool Warehouse [today, Conaprole Depot]
Location: Camino de las Tropas 1969 y Route 5, Belvedere, Montevideo
Client: Central Lanera Uruguaya
Construction: June 1980–December 1982
Collaborators: Eng. José M. Zorrilla, Arch. Alberto Castro, and Tech. Asst. Walter Vilche
Technical Statistics: area 97,000 sq. ft (. 9,000 sq. m); span 131 ft. (40 m) and 65.6 ft. (20 m)
Features: three bays of double-curvature vaults

Van Dam, S.A. Candy Factory
Location: Batlle and Ordóñez 6247, Montevideo
Construction: 1981
Technical Statistics: area 27,000 sq. ft. (2,500 sq. m); span 98.5 ft. (30 m)
Features: double-curvature vaults with skylights

Lanera Santa María Wool Processing Facility [three stages; stages two and three, warehouses]
Location: Aparicio Saravia and Rafael, Montevideo
Construction: 1981; 1983–1984; 1984–1985
Technical Statistics: area 16,000 sq. ft. (1,500 sq. m); 19,200 sq. ft. (1,780 sq. m); 21,500 sq. ft. (2,000 sq. m), respectively; span 65.6 ft. (20 m); 82 ft. (25 m), stages one and two, respectively
Features: double-curvature vaults; [third stage: self-carrying vault]

Empresa Constructora Álvaro Palenga, S.A. Warehouse
Location: Emancipación, Montevideo
Construction: 1981–1982
Technical Statistics: area 25,800 sq. ft. (2,400 sq. m); span 92 ft. (28 m)
Features: double-curvature vaults

Navíos Horizontal Silos (three units in three stages)
Location: Recinto Portuario, Nueva Palmira, Colonia
Client: Corporación Navíos, S.A.
Construction: December 1981–September 1982; January–December 1987; February 1989–September 1990
Collaborators: Eng. José Martín Zorrilla (first and second stages), Eng. Gonzalo Larrambebere (third stage), and Tech. Asst. Walter Vilche (all stages)
Technical Statistics: area 29,000 sq. ft. (2,700 sq. m) each; span 88.6 ft. (27 m) each; capacity: 27,000 T each
Features: pre-stressed barrel vault embedded in earth for lateral support of grain

College of the Marist Brothers Gymnasium
Location: 8 de Octubre 2977, Montevideo
Construction: 1982
Technical Statistics: area 8,600 sq. ft . (800 sq. m); span 98.5 ft. (30 m)
Features: double-curvature vaults with skylights

Army General Command Sports Center and Pool
Location: Br. Artigas, Montevideo
Construction: 1982
Technical Statistics: area 18,300 sq. ft. (1,700 sq. m); span 95 ft. (29 m)
Features: self-carrying vaults

Church of Fátima
Location: Brito del Pino, Montevideo
Construction: 1982–1983
Technical Statistics: area 5,400 sq. ft. (500 sq. m); span 82 ft. (25 m)
Features: self-carrying vaults

América Housing Complex Water Tower
Location: Camino Durán y Yegros, Colón, Montevideo
Client: Banco Hipotecario del Uruguay, América Housing Complex
Project Date: 1979
Construction: August 1982–November 1983
Collaborators: Eng. Antonio Dieste and Tech. Asst. Walter Vilche
Technical Statistics: height 131 ft. (40 m); volume 103,000 gallons (390 cu. m)

* Don Bosco School Gymnasium
Location: Maldonado 2128, Palermo, Montevideo
Client: Society of San Francisco de Sales
Project Date: 1983
Construction: May 1983–December 1984
Collaborators: Arch. Esteban Dieste and Tech. Asst. Walter Vilche
Technical Statistics: area 10,250 sq. ft. (954 sq. m); span 80 ft. (24.40 m)
Features: double-curvature vaults with skylights; external tie rods
Literature: Barthel 2001

Trinidad Gymnasium
Location: Trinidad, Flores
Client: Intendencia Municipal de Flores
Construction: 1983–1984
Technical Statistics: area 30,700 sq. ft. (2,850 sq. m); span 111.5 ft. (34 m)
Features: double-curvature vaults
Literature: Diehl "Bewehrt" 1992 [misidentification of Durazno gymnasium]; Goytia 2002; Moisset 1999

CEDEMCAR Gymnasium
Location: San Carlos, Maldonado
Client: Intendencia Municipal de Maldonado
Construction: 1984
Technical Statistics: area 9,700 sq. ft. (900 sq. m); span 82 ft. (25 m)
Features: double-curvature vaults

Elbio Perez Rodríguez Warehouse
Location: San José Department
Construction: 1984
Technical Statistics: area 1,950 sq. ft. (180 sq. m); span 49 ft. (15 m)
Features: self-carrying vaults

* Montevideo Shopping Center [two stages]
Location: Luis Alberto de Herrera 1380, Buceo, Montevideo
Client: Montevideo Shopping Center, S.A.
Project Date: 1983
Construction: January 1984–May 1985 [addition: July–December 1988]
Collaborators: Eng. José M. Zorrilla, Eng. Gonzalo Larrambebere, Arch. Alberto Castro, Arch. Esteban Dieste, and Tech. Asst. Walter Vilche
Architects: Gómez Platero-López Rey
Technical Statistics: area 105,500 sq. ft. (9,800 sq. m), first stage; transverse spans: 26 ft. (8 m) and 52.5 ft. (16 m) [addition: area 43,000 sq. ft. (4,000 sq. m); spans of 26 ft. (8 m) and 33 ft. (10 m)]
Features: double- and simple-curvature vaults; pre-stressed undulating masonry walls; water tower
Literature: Dieste "La invención" 1987; 1987–88; "Una estética de la ética" 1988; "Estética" 1988; "Estética" 1990; "Bauten" 1991; "Reflections" 1992; "Selección de problemas" 1993; Anon. "Montevideo" 1986; Anon. "Die Kunst der Schale" 1995; Bach 1993; Barthel 2001; Carbonell 1987; Delgado 1996; Diehl "Bewehrt" 1992; Diehl "Sanft gewellt" 1992; Goytia 2002; Grino 2000; Jiménez 1996; Moisset 1999; Montaner 2000; Morales 1991; Pedreschi 2000; Pérez 1998; Vercelloni 1993; Waisman 1989; Waisman 1991

Church of the Maronite Brothers
Location: Molinos de Raffo 926, Montevideo
Construction: 1984–1985
Architect: Alberto Castro (for Dieste y Montañez)
Technical Statistics: area 9,150 sq. ft. (850 sq. m)
Features: self-carrying barrel vaults

Water Tower, Canelones
Location: Route 101, km 26, Canelones
Client: Centro de Investigación y Desarrollo
Construction: 1985
Technical Statistics: capacity 26,400 gallons (100 cu. m)

* Television Tower, Channel 9
Location: Avenida General Artigas y Guabirá, Maldonado
Client: Telesistemas Uruguayos, Canal 9
Project Date: 1985
Construction: November 1985–September 1986
Collaborators: Eng. Antonio Dieste and Tech. Asst. Walter Vilche
Technical Statistics: height of masonry shaft 197 ft. (60 m); height of concrete mast 20 ft. (6 m); diameter at base 11.5 ft. (3.50 m)
Features: pierced reinforced masonry tower
Literature: Dieste "La invención"1987; "Una estética de la ética" 1988; "Estética" 1990; "Bauten" 1991; Asensio Cerver 1992; Barthel 2001; Carbonell 1987; Jiménez 1996; Morales 1991; Pedreschi 2000; Waisman 1989; Waisman 1991

Azucitrus, S.A. Agroindustry Complex
Location: Camino Roldán, Paysandu
Construction: 1986–1987
Collaborators: Eng. Antonio Dieste and Tech. Asst. Walter Vilche
Technical Statistics: area 97,000 sq. ft. (9,000 sq. m); span 98.5 ft. (30 m)
Features: two units with double-curvature vaults; offices and other accessory buildings
Literature: Diehl 1999

Tops Fray Marcos, S.A. Wool Processing Plant [three stages]
Location: Fray Marcos, Florida
Construction: November 1986–October 1987; January–June 1988; October 1994–June 1995
Collaborators: Eng. Jorge Bliman and Tech. Asst. Walter Vilche
Technical Statistics: area 48,400 sq. ft. (4,500 sq. m), 21,500 sq. ft. (2,000 sq. m), and 21,500 sq. ft. (2,000 sq. m), respectively; span 82 ft. (25 m) (first stage)
Features: double-curvature vaults
Literature: Diehl "Bewehrt" 1992

Maldonado Agricultural Market Water Tower [unbuilt]
Location: Agricultural Market, Maldonado
Client: Municipality of Maldonado
Project Date: 1987
Technical Statistics: height 76 ft. (23.15 m); volume 10,560 gallons (40 cu. m)
Features: pierced shaft of masonry; inverted truncated cones

CINCELCUR Factory
Location: Arribeños 3532, Montevideo
Construction: 1987
Technical Statistics: area 9,150 sq. ft. (850 sq. m); span 82 ft. (25 m)
Features: double-curvature vaults

Bridge over the Toledo Creek [unbuilt]
Location: National Route 6, crossing the Arroyo Toledo
Client: Ministry of Transport and Public Works, Uruguay
Project Date: 1987
Collaborator: Eng. Pablo Castro
Features: a double-curvature system for the span; supports employing conoidal ruled surfaces analogous to those of the church at Atlántida.
Literature: Dieste "La invención" 1987

ANCAP Fuel Pipeline
Location: Paysandú
Client: Administración Nacional de Combustibles, Alcohol y Portland (ANCAP)
Construction: 1987–1988
Collaborators: Eng. José M. Zorilla, Eng. Antonio Dieste, and Tech. Asst. Walter Vilche
Features: subsurface pipeline for transmission of fuels from the Uruguay River to a subsurface tank

Lanas Trinidad/Durazno Wool Warehouse [two stages]
Location: Camino Nacional near Route 14, outside of Durazno
Client: Lanas Trinidad, S.A.
Construction: Three central buildings, 1988–1990; two lateral buildings, 1991–1993
Collaborators: Eng. Gonzalo Larrambebere, Eng. Jorge Bliman, and Tech. Asst. Walter Vilche
Architect: Andrea Queirolo
Technical Statistics: area 107,600 sq. ft. (10,000 sq. m); 64,600 sq. ft. (6,000 sq. m), respectively; span 98.5 ft. (30 m)
Features: continuous and discontinuous double-curvature vaults

Lanera Piedra Alta, Wool Industry Plant
Location: Florida Department
Client: Lanera Piedra Alta
Construction: 1989–1990
Collaborators: Eng. Gonzalo Larrambebere, Eng. Jorge Bliman, and Tech. Asst. Walter Vilche
Technical Statistics: area 80,700 sq. ft. (7,500 sq. m); span 131 ft. (40 m)
Features: double-curvature vaults; water tower, offices, and accessory constructions

Navíos Pier
Location: Recinto Portuario, Nueva Palmira, Colonia
Client: Corporación Navíos, S.A.
Construction: 1990
Collaborators: Eng. Jorge Bliman and Tech. Asst. Walter Vilche
Technical Statistics: length: 394 ft. (120 m)

* Fagar Cola Bottling Plant [two stages]
Location: Paso Antolín, Tarariras, Route 22 km 12, Colonia
Client: Refrescos Fagar, S.A.
Construction: April 1991–May 1992; April 1995–February 1996
Collaborators: Eng. Gonzalo Larrambebere and Tech. Asst. Walter Vilche
Technical Statistics: area 53,800 sq. ft. (5,000 sq. m) and 21,500 sq. ft. (2,000 sq. m), respectively; span between columns 81 ft. (24.80 m); transverse span 42 ft. (12.85 m); front cantilever 42 ft. (12.80 m) [water tower: height 85 ft. (26 m), tapering from 14 ft. (4.25 m) to 11.83 ft. (3.6 m)]
Features: pre-stressed continuous self-carrying vaults [water tower: solid brick cylindrical shaft]
Literature: Goytia 1999; Goytia 2002; Moisset 1999; Pedreschi 2000;

* Solsire Salt Silo
Location: Avenida General Flores 4441, Montevideo
Client: Solsire, S.A.
Construction: September 1992–April 1994
Collaborators: Eng. Jorge Bliman and Tech. Asst. Walter Vilche
Technical Statistics: area 33,400 sq. ft. (3,100 sq. m), capacity 20,000 T; span 93.5 ft. (28.5 m); height 42.7 ft. (13 m)
Features: continuous double-curvature vaults with skylights; designed to take lateral thrust of salt to height of 13 ft. (4 m); tie-rods in concrete floor
Literature: Pedreschi 2000

* A. Dewavrin Fils (ADF) Wool Warehouse
Location: Route 5, km 39.5 Joanicó, Canelones
Client: A. Dewavrin Fils, S.A.
Project Date: 1991
Construction: November 1992–September 1994
Collaborators: Arch. Alberto Castro, Eng. Gonzalo Larrambebere and Tech. Asst. Walter Vilche (on the principles of Eladio Dieste, but without his participation)
Technical Statistics: area 100,000 sq. ft. (9,300 sq. m); span of barrel vaults 33 ft. (10 m); span of double-curvature vaults with skylights 82 ft. (25 m) and 131 ft. (40 m)
Literature: Goytia 1999; Goytia 2002; Jiménez 1996; Pedreschi 2000;

Colegio Nuestra Senora del Lujan, Multipurpose Hall
Location: W. Beltran 1868, Montevideo
Construction: 1993
Collaborators: Arch. Esteban Dieste and Tech. Asst. Walter Vilche
Features: barrel vault

Colegio Pastorino, Multipurpose Hall
Location: 9 de Junio 5653, Montevideo
Construction: 1993–1994
Features: barrel vault

Club Social Empleados BPS
Location: Uruguay y Gaboto, Montevideo
Construction: 1994–1995

Collaborators: Eng. Gonzalo Larrambebere and Tech. Asst. Walter Vilche
Technical Statistics: area 8,600 sq. ft. (800 sq. m)
Features: double-curvature vaults with skylights

Hipercentro Devoto Sayago Water Tower
Location: Ariel y Bell, Montevideo
Construction: 1995
Collaborators: Eng. Gonzalo Larrambebere and Tech. Asst. Walter Vilche
Technical Statistics: capacity: 42,800 gallons (162 cu. m)

* Navíos Horizontal Silo 4 (Silo Alfonso Soler Roca)
Location: Recinto Portuario, Nueva Palmira, Colonia
Client: Corporación Navíos, S.A.
Construction: June 1996–June 1997
Collaborators: Project Eng. Gonzalo Larrambebere, Eng. Verónica Sanz, Arch. Bernardo Striewe, and Tech. Asst. Walter Vilche (on the principles of Eladio Dieste, but without his participation)
Technical Statistics: area 77,500 sq. ft. (7,200 sq. m); span 147.6 ft. (45 m); length 525 ft. (160 m); capacity: 75,000 T
Features: double-curvature vaults; curved end walls of masonry
Literature: Pedreschi 2000

"Todo Música," Montevideo Shopping Center
Location: Ariel y Bell, Montevideo
Construction: 1997
Collaborators: Eng. Gonzalo Larrambebere and Tech. Asst. Walter Vilche
Technical Statistics: area 9,700 sq. ft. (900 sq. m)
Feature: barrel vault

Torres Nauticas Gymnasium and Multipurpose Hall
Location: Tomás de Tezanos 1107, Montevideo Department
Construction: 2000–2001
Collaborators: Eng. Gonzalo Larrambebere and Tech. Asst. Walter Vilche
Technical Statistics: area 7,500 sq. ft. (700 sq. m)
Feature: barrel vault

ARGENTINA

TERKA, S.A.
Location: Salta y Jujuy, Partido San Justo, Province of Buenos Aires
Construction: 1965
Technical Statistics: area 2,100 sq. m (22,600 sq. ft.); span 72 ft. (22 m)
Features: double-curvature vaults

Melian S.C.A., Steel and Metal Industry [four stages]
Location: Pan-American Highway km 25, Bancalari, Partido Tigre, Province of Buenos Aires
Construction: 1966; 1972; 1972; 1973
Technical Statistics: area 23,700 sq. ft. (2,200 sq. m) 6,500 sq. ft. (600 sq. m), 6,500 sq. ft. (600 sq. m), and 7,500 sq. ft. (700 sq. m), resepctively; span 105 ft. (32 m), 49 ft. (15 m), 98.5 ft. (30 m), and 39.4 ft. (12 m), respectively
Features: double-curvature vaults (first, second, and fourth stages); self-carrying vaults (third stage)

Bianchetti, S.A. [five stages]
Location: Routes 202 and Pan-American Highway, Bancalari, Partido Tigre, Province of Buenos Aires
Construction: 1967; 1970; 1973; 1974; 1974
Technical Statistics: area (first three stages) 12,900 sq. ft. (1,200 sq. m), 3,500 sq. m (37,700 sq. ft.), and 8,600 sq. ft. (800 sq. m), respectively; span 52.5 ft. (16 m), 105 ft. (32 m), and 72 ft. (22 m), respectively
Features: double-curvature vaults (first four stages); self-carrying vaults (fifth stage)

Balder, S.A.
Location: M. T. de Alvear 777, Partido de San Martín, Province of Buenos Aires
Client: Balder, S.A.
Construction: 1967
Technical Statistics: area 620 sq.m (6,700 sq. ft.); span 59 ft. (18 m)
Features: self-carrying vaults

Mois Chami, S.A.
Location: Olleros and Amenabar, Buenos Aires
Construction: 1968
Technical Statistics: area 11,850 sq. ft. (1,100 sq. m); span 36 ft. (11 m)
Features: self-carrying vaults

Confitería Aloha Coffee Shop
Location: Pan-American Highway km 16, Partido Tigre, Province of Buenos Aires
Client: Confitería Aloha
Construction: 1968
Technical Statistics: area 11,850 sq. ft. (1,100 sq. m); span 49 ft. (15 m)
Features: self-carrying vaults

Galería Laprida Shopping Arcade
Location: Lomas de Zamora, Partido Lomas de Zamora, Province of Buenos Aires
Construction: 1969
Technical Statistics: area 5,400 sq. ft. (500 sq. m); span 49 ft. (15 m)
Features: self-carrying vaults

Ediciones de Contabilidad Moderna, S.A.
Location: Route 8 km 29, Partido San Miguel, Province of Buenos Aires
Construction: 1969
Technical Statistics: area 490 sq. m (5,300 sq. ft.); span 18 m (59 ft.)
Features: double-curvature vault

Hotel Samoa
Location: Pan-American Highway km 12, Partido del Tigre, Province of Buenos Aires
Construction: 1970
Technical Statistics: area 11,850 sq. ft. (1,100 sq. m); span 36 ft. (11 m)
Features: self-carrying vaults

Restaurant Carlo III
Location: Av. Del Libertador and Orione, Partido S. Fernando, Province of Buenos Aires
Construction: 1971
Technical Statistics: area 5,300 sq. ft. (490 sq. m); span 39.4 ft. (12 m)
Features: self-carrying vaults

Cageao Automotores, S.A. Auto Dealership
Location: Avenida Francisco Beiró and Emilio Lamarca, Buenos Aires
Construction: 1971
Technical Statistics: area 5,400 sq. ft. (500 sq. m); span 52.5 ft. (16 m)
Features: self-carrying vaults

FANACOA Mayonnaise Factory
Location: Pan-American Highway km 10, Partido San Isidro, Province of Buenos Aires
Construction: 1971
Technical Statistics: area 5,400 sq. ft. (500 sq. m); span 52.5 ft. (16 m)
Features: self-carrying vaults

UZAL, S.A. Factory
Location: Route 2 km 119, Partido Chascomus, Province of Buenos Aires
Construction: 1971
Technical Statistics: area 43,000 sq. ft. (4,000 sq. m); span 65.6 ft. (20 m)
Features: self-carrying vaults

Laboulage Church
Location: Laboulage, Province of Córdoba
Construction: 1971
Technical Statistics: area 5,400 sq. ft. (500 sq. m); span 65.6 ft. (20 m)
Features: self-carrying vaults

Galería Alvear Shopping Arcade
Location: Alvear 50, Partido San Isidro, Province of Buenos Aires
Construction: 1971
Technical Statistics: area 7,500 sq. ft. (700 sq. m); span 29.5 ft. (9 m)
Features: self-carrying vaults

Industrias Plásticas Panamericanas, S.A. [four stages]
Location: Pan-American Highway km 30, Partido Tigre, Province of Buenos Aires
Construction: 1972; 1975; 1977; 1977
Technical Statistics: area 31,200 sq. ft. (2,900 sq. m); 4,100 sq. ft. (380 sq. m), 14,000 sq. ft. (1,300 sq. m), and 12,900 sq. ft. (1,200 sq. m), respectively; span 124.7 ft. (38 m) (first three stages) and 98.5 ft. (30 m) (fourth stage)
Features: double-curvature vaults (first three stages); self-carrying vaults (fourth stage)

Polinor, S.A. [two stages]
Location: Kenenedy and Uruguay, Partido San Fernando, Province of Buenos Aires
Construction: 1973; 1981
Technical Statistics: area 17,200 sq. ft. (1,600 sq. m) and 7,000 sq. ft. (650 sq. m), respectively; span 79 ft. (24 m) each
Features: double-curvature vaults

Galería del Norte Shopping Arcade
Location: Alvear 43, Partido San Isidro, Province of Buenos Aires
Construction: 1972
Technical Statistics: area 8,600 sq. ft. (800 sq. m); span 52.5 ft. (16 m)
Features: self-carrying vaults

Restaurant Gran Colón
Location: Paseo Colón 443, Buenos Aires
Construction: 1973
Technical Statistics: area 8,100 sq. ft. (750 sq. m); span 52.5 ft. (16 m)
Features: self-carrying vaults

Partido Mercedes Central Bus Station
Location: Route 5 km 100, Partido Mercedes, Province of Buenos Aires
Construction: 1973
Technical Statistics: area 17,200 sq. ft. (1,600 sq. m); span 65.6 ft. (20 m)
Features: self-carrying vaults

Empresa Lineas Maritimas Argentina (ELMA) General Warehouses [two stages]
Location: Puerto Nuevo, Buenos Aires
Construction: 1974; annex 1976
Technical Statistics: area 37,700 sq. ft. (3,500 sq. m) and 16,000 sq. ft. (1,500 sq. m), respectively; span 82 ft. (25 m) and 72 ft. (22 m), respectively
Features: self-carrying vaults

Bagley, S.A. Food Industry
Location: San Miguel de Tucumán, Province of Tucumán
Construction: 1974
Technical Statistics: area 12,900 sq. ft. (1,200 sq. m); span 79 ft. (24 m)
Features: double-curvature vaults

Max Juda, S.A.
Location: Alvear s/n, Partido San Martín, Province of Buenos Aires
Construction: 1974
Technical Statistics: area 11,850 sq. ft. (1,100 sq. m); span 105 ft. (32 m)
Features: self-carrying vaults

J. Charrúa y Cía., S.A.
Location: Benito Juárez, Partido Benito Juárez, Province of Buenos Aires
Construction: 1974
Technical Statistics: area 48,400 sq. ft. (4,500 sq. m); span 82 ft. (25 m)
Features: self-carrying vaults

Madera Panamericana, S.A. [two stages]
Location: Pan-American Highway and Route 197, Partido Tigre, Province of Buenos Aires
Construction: 1975; 1977
Technical Statistics: area 33,400 sq. ft. (3,100 sq. m) and 24,750 sq. ft. (2,300 sq. m), respectively; span 98.5 ft. (30 m) each
Features: self-carrying vaults

Norte Supermarket
Location: Alvear 900, Partido San Isidro, Province of Buenos Aires
Construction: 1975
Technical Statistics: area 22,600 sq. ft. (2,100 sq. m); span 82 ft. (25 m)
Features: self-carrying vaults

Automóvil Club Argentina Local Service Station
Location: Villa Maria, Province of Córdoba
Client: Division de Proyectos de Obra del A.C.A.
Construction: 1976
Contractor: Singenser Cia.
Collaborators: Espacio, Estudio de Estructuras; Field Arch. Gregorio Yalangozian
Technical Statistics: area 16,000 sq. ft. (1,500 sq. m); span 79 ft. (24 m)
Features: self-carrying vaults

CABSHA, S.A. Candy Factory
Location: San Miguel de Tucumán, Province of Tucumán
Client: CABSHA, S.A.
Construction: 1977
Technical Statistics: area 38,750 sq. ft. (3,600 sq. m); span 65.6 ft. (20 m)
Features: double-curvature vaults

LUSOL, S.A.
Location: Pan-American Highway, Ramal Pilar, Partido Tigre, Province of Buenos Aires
Construction: 1977
Technical Statistics: area 19,400 sq. ft. (1,800 sq. m); span 72 ft. (22 m)
Features: double-curvature vaults

FOLIMAD, S.A.
Location: Pan-American Highway km 13, Bancalari, Partido Tigre, Province of Buenos Aires
Construction:
Technical Statistics: area 22,600 sq. ft. (2,100 sq. m); span 75.5 ft. (23 m)
Features: self-carrying vaults

Bortolin y Cía., S.A.
Location: Villa Adelina, Partido San Isidro, Province of Buenos Aires
Construction: 1978
Technical Statistics: area 35,500 sq. ft. (3,300 sq. m); span 115 ft. (35 m)
Features: self-carrying vaults

Longvie Paraná, S.A. Home Appliances Factory
Location: Parque Industrial Paraná, Province Entre Rios
Construction: 1978
Technical Statistics: area 84,500 sq. ft. (7,850 sq. m); span 124.7 ft. (38 m)
Features: double-curvature vaults

LANICO, S.A.
Location: Lobos, Province of Buenos Aires
Construction: 1979
Technical Statistics: area 27,000 sq. ft. (2,500 sq. m); span 65.6 ft. (20 m)
Features: double-curvature vaults

Juan Minetti y Cía., S.A. (now Gruppo Minetti, cement producers)
Location: Córdoba/Málagueño Province of Córdoba
Construction: 1979–1980
Technical Statistics: area 29,000 sq. ft. (2,700 sq. m); span 88.6 ft. (27 m)
Features: self-carrying vaults

Brown Boveri, S.A. [two stages]
Location: Uruguay s/n, Partido San Isidro, Province of Buenos Aires
Client: Brown Boveri, S.A.
Construction: 1980; 1986
Technical Statistics: area 19,400 sq. ft. (1,800 sq. m) and 5,400 sq. ft. (500 sq. m), respectively; span 65.6 ft. (20 m) each
Features: self-carrying vaults

Ciccone Hnos. y Lima, S.A. [two stages]
Location: Pan-American Highway km 12, Partido Tigre, Province of Buenos Aires
Construction: 1981; 1987
Technical Statistics: area 86,000 sq. ft. (8,000 sq. m) and 12,900 sq. ft. (1,200 sq. m), respectively; span 85 ft. (26 m) each;
Features: self-carrying vaults

Centro Deportivo Nacional (CEDENA) Sports Training Center
Location: Republiquetas and Av. Libertador Gral. San Martín, Buenos Aires
Construction: 1983
Technical Statistics: area 25,800 sq. ft. (2,400 sq. m); span 124.7 ft. (38 m)
Features: double-curvature vaults

Norte Supermarket
Location: América, Partido San Martín, Province of Buenos Aires
Construction: 1985
Technical Statistics: area 27,000 sq. ft. (2,500 sq. m); span 69 ft. (21 m)
Features: self-carrying vaults

Autoservicio Mayorista La Loma Store
Location: José León Suarez, Partido San Martín, Province of Buenos Aires
Construction: 1986
Technical Statistics: area 28000 sq. ft. (2600 sq. m); span 95 ft. (29 m)
Features: self-carrying vaults

Frigosol Supermarket
Location: Villa Gesell, Province of Buenos Aires
Construction: 1986
Technical Statistics: area 24,750 sq. ft. (2,300 sq. m); span 88.6 ft. (27 m)
Features: self-carrying vaults

Decorinter, S.A.
Location: Pan-American Highway km 11.5, Partido Tigre, Province of Buenos Aires
Construction: 1988
Technical Statistics: area 28,000 sq. ft. (2,600 sq. m); span 101.7 ft. (31 m)
Features: self-carrying vaults

Astilleros Gamma, S.A. Shipyard
Location: Junin, Partido San Fernando, Province of Buenos Aires
Construction: 1989
Technical Statistics: area 25,800 sq. ft. (2,400 sq. m); span 82 ft. (25 m)
Features: self-carrying vaults

Confitería N/S Open Coffee House
Location: Costanera Norte, Buenos Aires
Construction: 1993
Technical Statistics: area 5,400 sq. ft. (500 sq. m); span 65.6 ft. (20 m)
Features: self-carrying vaults

BRAZIL

* Centro de Abastecimiento, S.A. (CEASA) Produce Market

Growers' Pavilion
Location: Avenida Farrapos, Porto Alegre, Rio Grande do Sul
Client: Ministry of Agriculture
Project Date: 1968–69
Construction: 1969–1972
Architectural Design: Carlos Maximiliano Fayet and Claudio Araujo
Technical Statistics: area 141,650 sq. ft. (13,160 sq. m); span: 98.5 ft. (30 m); width of building 154 ft. (47 m); length of building 920 ft. (280 m)
Features: double-curvature vaults with skylights; 77 stalls

Traders' Pavilion
Technical Statistics: area 43,0000 sq. ft. (40,000 sq. m); transverse span 16.4 ft. (5 m); longitudinal span 82 ft. (25 m)
Features: pre-stressed self-carrying vaults with edge slabs and thin beams

Vehicular Entrance Portico
Technical Statistics: longitudinal span 108 ft. (33 m)
Features: pre-stressed double-cantilever self-carrying vaults, a single line of support
Literature: Dieste 1975; "Arquitectura" 1980; "Estética" 1988; Anon. "Die Kunst der Schale" 1995; Barthel 2001; Carbonell 1987; Gazzaniga 1996; Grino 2000; Jiménez 1996; Montaner 2000; Pedreschi 2000; Pérez 1998; Waisman 1989.

Maceió Produce Market
Location: Maceió, Alagoas
Construction: 1971
Technical Statistics: area 80,700 sq. ft. (7,500 sq. m); spans 88.6 ft. (27 m) and 82 ft. (25 m)
Features: continuous double-curvature vaults flanked by self-carrying vaults at right angle.
Literature: Dieste 1975; Barthel 2001; Garabelli 1985

Rio Metro Maintenance Hangar
Location: Avda. Presidente Vargas 2700, Rio de Janeiro
Client: Metropolitano de Rio
Construction: 1971–1979
Collaborator: Eng. Eugenio Montañez
Technical Statistics: area 560,000 sq. ft. (52,000 sq. m); span (chord) 23 ft. (7 m); longitudinal spans 65.6 ft. (20 m) and 75.5 ft. (23 m)
Features: self-carrying vaults
Literature: Barthel 2001. Fernández-Galiano 1998; Grino 2000; Jiménez 1996

CEASA Produce Market
Location: Curitiba, Paraná
Client: Centrais de Abastecimiento do Paraná
Construction: May 1972–February 1976
Architectural design: Nelson Andrade, João Rodolfo Stroeter and Assoc.
Technical Statistics: area 359,000 sq. ft. (33,320 sq. m)
Features: self-carrying vaults

CEASA Produce Market
Location: Goiânia, Goiás
Client: Ministry of Agriculture
Construction: 1972–1976
Architectural design: Arch. Carlos M. Fayet and Arch. Claudio Araujo
Technical Statistics: area 248,000 sq. ft. (23,000 sq. m)
Features: self-carrying vaults

CEASA Produce Market
Location: Rio de Janeiro
Client: Ministry of Agriculture
Construction: 1973
Architectural Design: Carlos M. Fayet and Claudio Araujo
Technical Statistics: area 1,600,000 sq. ft. (150,000 sq. m); transverse span 23 ft. (7 m); longitudinal span 115 ft. (35 m)
Features: self-carrying vaults

Cold Storage Warehouse
Location: Ijuí, Rio Grande do Sul
Construction: 1974
Technical Statistics: area 172,000 sq. ft. (16,000 sq. m); longitudinal span 98.5 ft. (30 m)
Features: self-carrying vault

Farol Grain Silo
Location: Estrela, Rio Grande do Sul
Construction: 1978–1979
Collaborator: Eng. Ariel Valmaggia
Technical Statistics: capacity 30,000 tons; transverse span 98.5 ft. (30 m); height 52.5 ft. (16 m)

Cooperativa Regional Triticola Serraja (COTRIJUI) Soy Bean Oil Factory
Location: Rio Grande, Rio Grande do Sul
Construction: 1978–1979
Collaborator: Eng. Gonzalo Larrambebere
Technical Statistics: area 37,700 sq. ft. (3,500 sq. m); transverse span 111.5 ft. (34 m)
Features: double-curvature vaults

Cooperativa Regional Triticola Serraja (COTRIJUI) Agroindustry Buildings
Location: Rua das Chácaras, Ijuí, Rio Grande do Sul
Features: self-carrying vaults; numerous small vaults in large groupings

Cooperativa de las Valuruguai Wool Industry Plant
Location: Uruguiana, Rio Grande do Sul
Construction: pre-1988
Technical Statistics: area 258,000 sq. ft. (24,000 sq. m)
Features: double-curvature vaults

Cooperativa de las Valuruguai Wool Depot
Location: Uruguiana, Rio Grande do Sul
Client: Coopertiva de las Valuruguai
Construction: 1988
Collaborator: Eng. Gonzalo Larrambebere
Technical Statistics: area 53,800 sq. ft. (5,000 sq. m); longitudinal span 67 ft. (20.45 m); transverse span 20 ft. (6 m)
Features: self-carrying vaults

Centro de Tecnologia Mineral (CETEM)
Location: Avenida Ipê 900, Ilha da Cidade Universitária, Rio de Janeiro
Technical Statistics: area 89,000 sq. ft. (8,300 sq. m); transverse span 20 ft (.6 m); longitudinal span 82 ft. (25 m)
Features: self-carrying vaults

Serviço Social da Indústria (SESI) [Workers' Social Services]
Location: Avenida Nossa Senhora da Candelária, Corumbá, Mato Grosso do Sul
Technical Statistics: area 58,000 sq. ft. (5,400 sq. m); transverse span 20 ft. (6 m); longitudinal span 108 ft. (33 m)
Features: self-carrying vaults

SESI
Location: Fortaleza, Ceará
Technical Statistics: area 28,000 sq. ft. (2,600 sq. m); transverse span 33 ft. (10 m); longitudinal span 49 ft. (15 m)
Features: self-carrying vaults

SESI
Location: Avenida Geremário Dantas 342, Tanque, Jacarepaguá, Rio de Janeiro
Technical Statistics: area 54,000 sq. ft. (5,000 sq. m); transverse span 26 ft. (8 m); longitudinal span 115 ft. (35 m)
Features: self-carrying vaults

Serviço Nacional de Aprendizagem Industrial (SENAI) [National Program of Industrial Education]
Location: Marechal Deodoro, São Paulo
Technical Statistics: area 37,700 sq. ft. (3500 sq. m); transverse span 26 ft. (8 m); longitudinal span 115 ft. (35 m)
Features: self-carrying vaults

Portocel Specialized Port Terminal
Location: Barra do Riacho, Espírito Santo
Technical Statistics: area 194,000 sq. ft. (18,000 sq. m); transverse span 39.4 ft. (12 m); longitudinal span 118 ft. (36 m)
Features: self-carrying vaults

Centro Tecnológico (CENTEC) (today, Centro Federal de Educação Tecnológica da Bahia [CEFET])
Location: Salvador, Bahia
Technical Statistics: area 97,000 sq. ft. (9,000 sq. m); transverse span 16.4 ft. (5 m); longitudinal span 82 ft. (25 m)
Features: self-carrying vaults

Computadores Brasileiros (COBRA)
Location: Rio de Janeiro
Technical Statistics: area 150,000 sq. ft. (14,000 sq. m); transverse span 20 ft. (6 m); longitudinal span 92 ft. (28 m)
Features: self-carrying vaults.

CESA-COFRIGO Cold Storage Warehouse
Location: Caxias do Sul, Rio Grande do Sul
Technical Statistics: area 108,000 sq. ft. (10,000 sq. m); longitudinal span 105 ft. (32 m)
Features: self-carrying vault

COTRIJUI Social Center
Location: Rio Grande, Rio Grande do Sul
Technical Statistics: area 53,800 sq. ft. (5,000 sq. m); longitudinal span 98.5 ft. (30 m)
Features: self-carrying vault

Transportadora Perola Garages
Location: Curitiba, Paraná
Technical Statistics: area 43,000 sq. ft. (4,000 sq. m); longitudinal span 72 ft. (22 m)
Features: self-carrying vaults

Curtume Isa Couros, Curtiembre (Leather Industry)
Location: Uruguaiana, Rio Grande do Sul
Technical Statistics: area 75,300 sq. ft. (7,000 sq. m); longitudinal span 65.6 ft. (20 m)
Features: double-curvature vaults

Sports Center
Location: Pelotas, Rio Grande do Sul
Client: Jose Braga and others
Construction: 1995–96
Structural Project: Gonzalo Larrambebere (on the principles of Eladio Dieste, but without his participation)
Architect: Singoala Miranda
Technical Statistics: area 34,450 sq. ft. (3,200 sq. m); longitudinal span 82 ft. (25 m); transverse span 19 ft. (5.8 m); tower height 62 ft. (19 m); elevated tank capacity 2,300 gallons (8.7 cu. m)
Features: Pre-stressed self-carrying vaults; water tower with pierced shaft and tanks below ground as well as elevated

Transmission Tower, Educational Television of Campo Grande
[Not properly a work of Dieste y Montañez. Listed here as the firm did work on the calculations of this, the tallest reinforced ceramic tower to date.]
Location: Parque de los Poderes, Campo Grande, Mato Grosso do Sul
Construction: 1991–92
Architect: Roberto Montezuma
Structural Project: Eng. Ariel Valmaggia
Collaborator: Eng. Gonzalo Larrambebere
Technical Statistics: height 328 ft. (100 m), plus metal antenna of 52.5 ft. (16 m); external diameter at base 16.75 ft. (5.10 m); diameter at a height of 282 ft. (86 m; point where the shaft was no longer constructed from the interior), 8 ft. (2.46 m).
Features: pierced tower

SPAIN

Camino de los Estudiantes [Students' Street], University of Alcalá
Location: Campus of Universidad de Alcalá de Henares
Client: Ministerio de Fomento
Project Date: 1994–1995
Construction: 1996–1998 (unfinished); resumed 2003
Collaborators: Arch. Carlos Clemente, Arch. Ana Marín, Asst. A. Carnicero, and Tech. Asst. Walter Vilche
Technical Statistics: lateral span: 13.8 ft. (4.2 m)
Features: 52 pergolas of double-cantilever self-carrying vaults, each 98.5 ft. (30 m) long; three ceramic cones, each with a diameter of 82 ft. (25 m) and over 66 ft. (20 m) high
Literature: Grino 2000; Jiménez 1996; Pedreschi 2000; Pérez 1998; Rasch 1997

Church and Parish Center, Nuestra Madre del Rosario [Our Mother of the Rosary]
Location: Calle Salvador Dalí s/n, Mejorada del Campo, near Madrid
Client: Diocese of Alcalá de Henares
Project Date: 1993
Construction: 1995–1997
Collaborators: Arch. Carlos Clemente, Arch. Juan de Dios de la Hoz, Arch. José L. de la Quintana, and Tech. Asst. Walter Vilche
Technical Statistics: area of church 5,900 sq. ft. (545 sq. m); area of parish center 2,500 sq. ft. (230 sq. m)
Literature: Jiménez 1996; Pedreschi 2000

Church of the Holy Family
Location: Torrejon de Ardoz, near Madrid
Client: Diocese of Alcalá de Henares
Construction: 1997–98
Collaborators: Arch. Carlos Clemente, Arch. Juan de Dios de la Hoz, Arch. José L. de la Quintana, and Tech. Asst. Walter Vilche
Technical Statistics: area 5,400 sq. ft. (500 sq. m)
Literature: Gazzaniga 1996; Pedreschi 2000

* Church and Parish Center, San Juan de Ávila
Location: Calle Reyes Magos s/n, Alcalá de Henares, east of Madrid
Client: Diocese of Alcalá de Henares
Construction: 1996–97
Collaborators: Arch. Carlos Clemente, Arch. Juan de Dios de la Hoz, Arch. Ana Marin, and Tech. Asst. Walter Vilche
Technical Statistics: area of church 5,400 sq. ft. (500 sq. m); area of parish center 2,500 sq. ft. (230 sq. m)
Features: double-curvature vaults; undulating walls
Literature: Barthel 2001; Clemente 1998; Flora 1997; Grino 2000; Jiménez 1996; Pedreschi 2000

Church of Santa Cruz, Coslada
Location: Coslada, near Madrid
Client: Diocese of Alcalá de Henares
Construction: 1998
Architects: Carlos Clemente, Juan de Dios de la Hoz, and José L. de la Quintana
Calculations by Dieste y Montañez: Tech. Asst. Walter Vilche
Literature: Pedreschi 2000

Church of Nuestra Señora de Belén
Location: Alcalá de Henares, near Madrid
Client: Diocese of Alcalá de Henares
Construction: 1998
Architects: Carlos Clemente, Juan de Dios de la Hoz, and José L. de la Quintana
Calculations by Dieste y Montañez: Tech. Asst. Walter Vilche
Literature: Pedreschi 2000

BIBLIOGRAPHY

### Works by Eladio Dieste


"Bóveda nervada de ladrillos 'de Espejo.'" *Revista de Ingeniería* (Montevideo) 473 (Sept. 1947): 510–12.

"Causas de un derrumbe parcial en la estructura del nuevo edificio para la Facultad de Arquitectura de Montevideo." *Revista de Ingeniería* (Montevideo) 478 (Feb. 1948): 102–05.

"Iglesia en Montevideo." *Informes de la Construcción* (Madrid) 127 (Jan. 1961): 148–60.

"Estructuras de cerámica armada." *Revista de la Facultad de Arquitectura* (Montevideo) 3 (Sept. 1961): 15–25.

"La chiesa di Atlántida in Uruguay." *Costruire* (Milan) 12 (July/Sept. 1962): 39–46.

With Eugenio Montañez. *Estructuras cerámicas.* Montevideo: [s.n.], 1963, 22 pp. [Originally published in *Revista de Ingeniería*, 657–60 (1963).]

With Eugenio R. Montañez. "Double-Curvature Shell of Reinforced Ceramic." In *Proceedings: World Conference on Shell Structures* (1962). Ed. S. J. Medwadowski et al., Washington, D.C.: National Academy of Sciences, 1964: 69–74.

"Campamento de estudios." Montevideo: Facultad de Ingeniería, 1968, 53 pp.

"Estructuras de cerámica armada." *Habitat* (Montevideo) 1, no. 2 (Sept. 1969): 8–14.

"Acción del viento sobre pilares de sosténde bóvedas de empuje eliminado; cálculo de torres de mampostería calada; viga alta: variación de la tension vertical debida al peso proprio." Montevideo: Facultad de Ingeniería, Aula de Grandes Estructuras, 1970, 11 pp.

"Estructuras plegadas." Montevideo: Oficina de Publicaciones de la Facultad de Ingeniería, 1970, 8 pp.

"Técnica y subdesarrollo." *CEDA: Revista del Centro de Estudiantes de Arquitectura* (Montevideo) 34 (Feb. 1973): 1–5.

"Técnica y subdesarrollo." *Summa* (Buenos Aires) 70 (Dec. 1973): 17–18.

"Acerca de la cerámica armada." *Summa* (Buenos Aires) 70 (Dec. 1973): 45–46.

"Iglesia de San Pedro." *Summa* (Buenos Aires) 70 (Dec. 1973): 46–49.

"Torres-García y nuestra tierra." In Joaquín Torres-García. *Testamento artístico.* Colección Vaconmigo. Montevideo: Biblioteca de Marcha, 1974, 201–10.

"La experiencia individual como método: Acerca de la cerámica armada." *Summa* (Buenos Aires) 85 (Jan. 1975): 43–51.

"Eladio Dieste, Uruguay." Interview by Damián Bayón and Paolo Gasparini (ca. 1976). In Bayón and Gasparini, *Panorama de la arquitectura Latinoamericana.* Barcelona: UNESCO, 1977, 176–97. In English: Bayón and Gasparini. *The Changing Shape of Latin American Architecture: Conversations with Ten Leading Architects.* New York: John Wiley, 1979, 190–213.

*Pandeo de láminas de doble curvatura.* Montevideo: Ediciones de la Banda Oriental, 1978.

"Arquitectura y construcción." In "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 84–93.

"La inevitable invención tecnológica." In "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 93–95.

"Diálogos con Dieste." Interview by Mariano Arana and Lorenzo Garabelli (1978). In "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 96–101.

"Las cáscaras autoportantes de directriz catenaria." *Anais XXI Jornadas Sul Americanas de Engenharia Estructural* (Rio de Janeiro) 2 (1981): 267–86.

"La cerámica armada," *Formas para la construcción* (Córdoba, Argentina) 5 (Oct. 1982): 57–109.

"Eladio Dieste," *Summa: Colección temática* (Buenos Aires) 2 (1983).

"La formación básica del ingeniero: El acento de la formación debe ponerse en las materias básicas." *Encuentro Nacional de Ingeniería* (Montevideo) (1984): 127–28.

*Cáscaras autoportantes de directriz catenaria sin timpanos.* Montevideo: Ediciones de la Banda Oriental, 1985.

With Eugenio R. Montañez. *Bóvedas arco de directriz catenaria en cerámica armada.* Montevideo: Officina Regional de Ciencia y Tecnología de la UNESCO para América Latina y el Caribe, 1985, 49 pp.

"Ingeniero Eladio Dieste: su obra." Interview. *Revista del Colegio de Profesionales de la Ingeniería* (Entre Rios, Argentina) 2 (June 1985).

"Terre cuite armée: Réalisation d'Eladio Dieste." *CETEC Informations* (Toulouse) 87 (Sept./Oct. 1985): 6–11.

"Dialogando com o mestre da cerâmica armada." Interview by Lorenzo Garabelli and Mariano Arana. *Projeto* (São Paulo) 81 (Nov. 1985): 74–79.

"Cáscaras cilíndricas autoportantes. Elección de la directriz. Sugerencia para el análisis de las cáscaras en plasticidad." *Seminario: La Ingeniería Estructural Sudamericana en la década del 80*. Montevideo (1986): 135–55.

*Pandeo de láminas de doble curvatura.* Second ed., Montevideo: Ediciones de la Banda Oriental, 1986.

"Estación de omnibus en Salto." *Summa: Colección Temática* (Buenos Aires) 19 (June 1987): 49.

"La invención inevitable." *Summa: Colección Temática* (Buenos Aires) 19 (June 1987): 43–47.

"Proyecto del puente sobre el arroyo Toledo." *Summa: Colección Temática* (Buenos Aires) 19 (June 1987): 48.

*Eladio Dieste: La estructura cerámica.* Ed. Galaor Carbonell. Colección Somosur. Bogotá, Colombia: Escala, 1987. [English summaries]

"Uruguay: La Arquitectura de Eladio Dieste." *Periferia* (Seville) 8/9 (Dec. 1987–June 1988): 27–37.

"Una estética de la ética." Interview by Alberto Petrina. *Summa* (Buenos Aires) 247 (March 1988): 23–32.

"Estética y diseño en ingeniería=Aesthetic and Design in Engineering." *OP. Colegio de Ingenieros de Caminos, Canales y Puertos de Cataluña* (Barcelona) 7/8 (1988): 78–93.

"Terre cuite armée." *L'Architecture Mediterrenné* (Sept. 1988).

"El nuevo muelle del puerto de Nueva Palmira." *Construir* (Montevideo) 1 (Nov. 1988): 63–76; 2 (Sept. 1989), 71–78.

"Estética y diseño en ingeniería." *BASA* (Tenerife, Spain) 11 (Jan. 1990): 6–21.

"La Iglesia Atlántida." *BASA* (Tenerife, Spain) 11 (Jan. 1990): 22–29.

"Fundación de máquinas: Algunas consideraciones generales y soluciones concretas." *Construir* (Montevideo) 3 (Jan. 1990): 65–68.

"Descripción de algunos equipos para la construcción de bóvedas." *Revista de Ingeniería* (Montevideo) 3rd series, vol. 3, no. 9 (1991): 8–21.
"Bauten mit bewehrten Ziegelschalen=Reinforced Brick Structures." *ZI, Ziegelindustrie International* 44, no. 10 (1991): 557–63. [German and English]
"Un teorema básico para estructuras laminares." *Construir* (Montevideo) 5 (June 1991): 83–85.
"Some Reflections on Architecture and Construction." *Perspecta* 27 (1992): 186–203.
"Estética y diseño." *Trazo: Revista del Centro de Estudiantes de Arquitectura* (Montevideo) 24 (Nov. 1992): 60–67.
"Selección de problemas y soluciones aplicadas." *Revista de Ingeniería* (Montevideo) 15 (Dec. 1993): 74–84.
"La resistenza a las fuerzas horizontals: Un teorema básico de estructuras laminares." *Jornadas de Ingeniería structural* (Montevideo) 2 (1993): 163–70.
"Poetica ed estética della struttura." In *Eladio Dieste—Frei Otto. Esperienze di architettura: Generazioni a confronto.* Ed. Luca Gazzaniga. Milan: Skira, 1996, 13–20.
"Tecnologie appropriate e creatività." In Eladio Dieste and C. Gonzales Lobo. *Architettura: Partecipazione sociale e tecnologie applicate.* Milan: Jaca Book, 1996, 7–47.
"Tecnologie appropriate e creatività." In *Architettura e società: L'America Latina nel XX secolo.* Ed. Ramón Gutiérrez. Milan: Jaca Book, 1996, 41–51.
"Eladio Dieste: Construcciónes con poesía," Interview by Mario Delgado Aparain and Pablo Vierci. *MonteVIdeEO* XX (December 1996): 2–11.
*Eladio Dieste: 1943–1996.* Ed. Antonio Jiménez Torrecillas. Trans. Michael Maloy and Harold David Kornegay. Seville: Consejería de Obras Públicas y Transportes, 1996. Includes "La cerámica armada=Reinforced Masonry," 33–36, and "Escritos del autor=Writings by the author," 217–89: ("Arquitectura y construcción=Architecture and Construction;" "La invención inevitable=The Inevitable Invention;" "Técnica y subdesarrollo=Technology and Underdevelopment;" "La conciencia de la forma=The Awareness of Form;" and "Arte, pueblo, tecnocracia=Art, People, Technocracy"). [Spanish and English]
*Eladio Dieste, 1943–1996: Métodos de cálculo.* Supplementary vol. Seville: Consejería de Obras Públicas y Transportes, 1996.
*La Conciencia de la forma.* Mario Jacob, Uruguay, 1997. VHS: System PAL, 54 min.
"Las Tecnologías apropiadas y la creatividad." In *Arquitectura Latinoamericana en el siglo XX*. Ed. Ramón Gutiérrez and Graciela María Viñuales. Barcelona: Lunwerg, 1998, 41–51.
"Eladio Dieste: en la parte que no se ve." Interview by Lucio Muniz. In L. Muniz, *Uruguayos de memoria.* Colección Enfoques, Montevideo: Editorial Fin de Siglo, 1998, 23–40.
"La plasticità della struttura." *Casabella* 684/685 (Jan. 2001): 69.

Works about Eladio Dieste

[Anonymous works are listed first, in chronological order]

"Voûtes en terre cuite. Une église en Uruguay, l'église paroissiale de Christ Ouvrier à Atlántida." *Tuiles et Briques* (Paris) 47 (1961): 19–25.
"Église paroissiale d'Atlántida, Montevideo, Uruguay," *L'Architecture d'Aujourd'hui* 32, no. 96 (June/July 1961): 88–89.
"Church at Atlántida, Uruguay." *Architectural Review* 130, no. 775 (Sept. 1961): 173–75.
"Church at Atlántida, Uruguay." *Kokusai Kentiku* 28 (Dec. 1961): 54–55.
"Una obra maestra de la arquitectura moderna en el Uruguay." *El Pais* (Montevideo), 11 March 1962.
"Brick Shell Construction: Church at Atlántida." *Progressive Architecture* 43 (April 1962): 124, 160–65.
"Montevideo Shopping Center." *Summa* (Buenos Aires) 221–222 (Jan.–Feb. 1986): 82–84.
"Casa Dieste, Montevideo, Uruguay, 1962." *Mur* 3 (1992): 26–27.
"Die Kunst der Schale: Bewehrte Ziegelschalen des uruguayischen Bauingenieurs Eladio Dieste." *Deutsche Bauzeitung* 129, no. 2 (Feb. 1995): 120–29; English summary, 187.
"Eladio Dieste [exhib. rev.]." *3a Bienal Internacional de Arquitetura de São Paulo.* São Paulo: Fundação Bienal de São Paulo and Instituto de Arquitectos do Brasil, 1997, 136–41.
"Exposición de la obra del ingeniero Eladio Dieste, 1943–1996 [exhib. rev.]." *Arquitectura* 310 (1997): 101.
"Huit portraits d'ingénieurs: Eladio Dieste, défendre une autre culture constructive." *Architecture intérieure-créé* 277 (1997): 35; English summary, 18.
Adell Argilés, Josep Maria. "Las bóvedas de la Atlántida." *Informes de la construcción* (Madrid) 44, no. 421 (Sept.–Oct. 1992): 113–23.
Anderson, Stanford. "Eladio Dieste: Principled Builder and Master of Structural Art." *a+u* (Tokyo) 395 (August 2003): 63–75; "Feature: Eladio Dieste," 76–137. [Japanese and English]
Arana, Mariano, Lorenzo Garabelli, and José Luis Livni. "La Vivienda: Protagonista de la arquitectura nacional," *CEDA* (Montevideo) 34 (Feb. 1973): 33–46.
Arana Sánchez, Mariano. "Más allá de la técnica." In "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 74–83, 109–12.
———. "L'Architecture en Uruguay, une approche critique." *Techniques & Architecture* 334 (Mar. 1981): 128–33.
———. "Construir o presente respeitando o passado: A lição de Dieste." *Projeto* (Saõ Paulo) 39 (Apr. 1982): 23–25.
———. "Eladio Dieste." In *Arquitectura Latinoamericana en el siglo XX*. Ed. Ramón Gutiérrez and Graciela María Viñuales. Barcelona: Lunwerg, 1998, 312–13. (Italian ed., Milan: Jaca, 1996.)
———. "Eladio Dieste: Techniques and Poetics." In *Latin American Architecture: Six Voices.* Ed. Malcolm Quantrill. College Station, Tex.: Texas A&M University Press, 2000, 21–29.
Bach, Caleb. "Making Bricks Soar." *Américas* 45, no. 2 (March 1993): 38–45.
Banfi, Hernán. "Eladio Dieste." *Arquitectura digital* 1, no. 1 (Sept. 1997): 24–28.

Barthel, Rainer. *Eladio Dieste: Form und Konstruktion*. Munich: Lehrstuhl für Hochbaustatik und Tragwerksplanung, Technische Universität München, 2001.

Bonta, Juan Pablo. *Eladio Dieste*. Arquitectos americanos contemporáneos, vol. 8. Buenos Aires: Instituto de Arte Americano e Investigaciones Estéticas, 1963.

Bossi, Agostino. "Casa Dieste, Montevideo," *Area—Revista di architettura e arti del progetto* (Milan) 46 (Sept./Oct. 1999): 64–76. [Italian and English]

Browne, Enrique. *Otra arquitectura en América Latina.* Mexico City: Gustavo Gili, 1988, 49, 53, 113–18, 144.

Bullrich, Francisco. "Technology and Architecture." In *New Directions in Latin American Architecture*. New York: Braziller, 1969, 54–72.

———. "Uruguay." In *Arquitectura latinoamericana 1930/1970*. Barcelona: Gustavo Gili, 1969, 61–66.

Cabeza Lainez, José María, and José Manuel Almodóvar Melendo. "Las bóvedas de cerámica armada en la obra de Eladio Dieste. Análisis y posibilidades de adaptación a las condiciones constructivas españolas." In *Actas del tercero Congreso Nacional de Historia de la Construcción*. Ed. Amparo Graciani Garcia. Madrid: Instituto Juan de Herrera, 2000, 1: 135–42.

Campioli, Andrea. "Senza dettaglio: architetture di Eladio Dieste." *Costruire in Laterizio* (Faenza, Italy) 52/53 (July/Oct. 1996): 228–31.

Carbonell, Galaor, ed. See Dieste, *Eladio Dieste: La estructura cerámica*, Bogotá, 1987.

Clemente, Carlos. "La construcción con cerámica armada: Iglesia de San Juan de Ávila en Alcalá de Henares." *Informes de la Construcción—Instituto Eduardo Torroja* (Madrid) 49, no. 453 (Jan./Feb. 1998): 41–53.

———. "Iglesia de San Juan de Ávila en Alcalá de Henares: Dieste en España," *Ars Sacra* (Madrid) 7 (Sept. 1998): 8–35.

———. "La obra de Eladio Dieste en el corredor del Henares." *WAM: Web Architecture Magazine* 7 (1999): 3–7.

———. "Eladio Dieste: Poeta de la ingeniería [obituary]," *Ars Sacra* (Madrid) 14–15 (Sept. 2000): 136.

———. With Juan de Dios de la Hoz. "Tres nuevos templos en la Diócesis de Alcalá de Henares." *Ars Sacra* (Madrid) 0 (May 1996): 17–31.

Collet Lacoste, Francisco, and Diego Neri Spiller. "Informe técnico: Restauración del templo parroquial Cristo Obrero y Nuestra Señora de Lourdes." Research report, Collet–Neri Estudio de Arquitectura, Montevideo, 9 November 2000.

Cubría, Norberto. "Algunas reflexiones a propósito de la obra de Eladio Dieste." In "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 102–10.

Dias Comas, Carlos Eduardo. "Memorandum latinoamericano: La ejemplaridad arquitectónica de lo marginal=Latin American Memorandum: The Architecturally Exemplary Nature of the Marginal." *2G* (Barcelona) 4 (1998): 129–44.

Diehl, Karl Ludwig. "Eladio Dieste: Revolution im Ziegelbau=Eladio Dieste: A Revolution in Brick Architecture." *ZI, Ziegelindustrie International* 43, no. 6 (June 1990): 326–33. [German and English]

———. "Armierte Ziegelschalen für grosse Spannweiten=Reinforced Brick Shells for Large-Span Roofs." *ZI, Ziegelindustrie International* 44, no. 9 (Sept. 1991): 482–86. [German and English]

———. "Lateinamerikanische Ziegelarchitektur als Ausdruck des eigenständigen Weges und als Abgrenzungsversuch zur Architektur der hochindustrialisierten Länder=Latin American Architecture in Brickwork as the Expression of an Independent Movement and an Attempt to Distinguish It from the Architecture of the Highly Industrialized Countries." *ZI, Ziegelindustrie International* 45, no. 1 (Jan. 1992): 31–39. [German and English]

———. "Bewehrt und eigenwillig: Der Ziegelbau des Eladio Dieste in Uruguay." *Bauwelt* 83, no. 11 (Mar. 13, 1992): 527, 546–61.

———. "Sanft gewellt wie die Hügellandschaft Uruguays: Eladio Diestes armierte Ziegelschalen=In Gentle Waves Like the Hills of Uruguay: Eladio Dieste's Reinforced Brick Shells." *Daidalos* 43 (15 Mar. 1992): 76–85. [German and English]

———. "Die bewehrten Ziegelschalen von Eladio Dieste." *Bautechnik* 69, no. 6 (June 1992): 314–21.

———. "Tragwerk und Ornament=Supporting Framework and Ornament." *ZI, Ziegelindustrie International* 8 (1999): 57–63. [German and English]

Fernández, Roberto. "Desert and Selva: From Abstraction to Desire. Notes on the Regionalist Dilemma in Latin American Architecture." *Zodiac* 8 (1992–93): 122–59.

Fernández-Galiano, Luis. "Un continente sumergido=A Submerged Continent [exhibition review]." *AV Monografías=AV Monographs* (Madrid) 69/70 (Jan.–Apr 1998): 164–67. [Spanish and English]

Flora, Nicola, and Vicente del Amo Hernandez. "Eladio Dieste. Continuità e ripetizione: Chiese gemelle in Uruguay e in Spagna=Eladio Dieste. Continuity and Repetition." *Area—Revista di architettura e arti del progetto* (Milan) 35 (Nov./Dec. 1997 ): 28–39. [Italian and English]

*Formas* [multiple authors]. "Cerámicos," sp. no. *Formas para la construtión* (Córdoba, Argentina) 5 (Oct. 1982).

Garabelli, Lorenzo, and Mariano Arana. "Eladio Dieste." In *Amérique latine: Architecture 1965–1990.* Ed. Jorge Liernur et al. Tendances de l'architecture contemporaine. Paris: Editions du Moniteur, 1991, 166.

García-Herrera, Adela. "Los premios=Distinctions." *AV Monografías=AV Monographs* (Madrid) 75–76 (Jan.–Apr. 1999): 219. [Spanish and English]

Gazzaniga, Luca, ed. *Eladio Dieste—Frei Otto. Esperienze di architettura: generazioni a confronto.* Quaderni dell'Accademia di architettura Mendrisio, vol. 2. Milan: Skira, 1996.

Goytia, Noemí. "Eladio Dieste: La alta tecnologia de un mundo en desarollo." *Marina Waisman* (Córdoba, Argentina) 2 (June 1999): 59–65.

——— .With Daniel Moisset. "Un caso singular: La Obra de Eladio Dieste," *Diseñar con la estructura.* Córdoba, Argentina: Ingreso, 2002, 275–99.

Grompone, Juan. "Eladio Dieste, maestro de la ingeniería." Unfinished draft of a thesis, University of the Republic, Montevideo, ca. 1994. Held in the Dieste y Montañez Archive, Montevideo.

Grino, Sylvia. "Reference Eladio Dieste: 34° de latitude sud." *amc: Le Moniteur architecture* 107 (May 2000): 70–81.

Gutiérrez, Ramón. “Sense and Sensuality: Engineer and Architect Eladio Dieste Infuses the Tradition of Brick Building with Modernist Logic.” *Architecture* 88, no. 8 (Aug. 1999): 57–59.

Irace, Fulvio. “Documenti di architettura. Uruguay: Una chiesa di Eladio Dieste, 1959=Architectural Portfolio. Uruguay: A Church by Eladio Dieste, 1959.” *Abitare* 296 (May 1991): 206–15. [Italian and English]

Jiménez Torrecillas, Antonio, ed. See Dieste, *Eladio Dieste: 1943–1996*, Seville, 1996.

Kawaguchi, Mamoru. “The Structural Design of Eladio Dieste,” *a+u* 395 (August 2003): 122–31 (Japanese and English).

Lyall, Sutherland. “At the End of the Century: One Hundred Years of Architecture [exhib. rev.].” *Architectural Review* 204, no. 1220 (Oct. 1998): 17.

“Maldonado Television Tower: Eladio Dieste.” In *New Architecture. 5: Communication Towers/Torres de communicación*. Ed. Francisco Asensio Cerver. Barcelona: Atrium, 1992, 194–99.

Marquez, J. “Iglesia Atlántida.” *Revista C.A.* (Faenza, Italy) 41 (Sept. 1985): 130–31.

Marti Aris, Carles. “Eladio Dieste.” *DPA: Revista del Departamento de Proyectos arquitectónicos de la Universidad Politécnica de Cataluña* 15 (1999): 12–17, 26–31, 58–63.

Montaner i Martorell, Joseph. “Eladio Dieste.” In *Dizionario dell'architettura del XX secolo*, 6 vols. Ed. Carlo Olmo. Turin: Umberto Allemandi, 2000, 2: 210–13.

Moisset de Espanés, Daniel. “Eladio Dieste y la creatividad tecnológica.” *Marina Waisman* (Córdoba, Argentina) 2 (June 1999): 66–73.

———. *Intuición y razonamiento en el diseño structural*. Colección El arte de construir. Bogotá: Escala, 1992.

Morales, Carlos. “Eladio Dieste.” *Mimar: Architecture in Development* 11, no. 4 (Dec. 1991): 70–75.

Noelle, Louise. “Nueve libros sobre arquitectura latinoamericana.” *Anales del Instituto de Investigaciónes Estéticas* (Mexico City) 62 (1991): 218–22.

Ochsendorf, John, and Joaquín Antuña. “Eduardo Torroja and ‘*cerámica armada*’.” In *Proceedings of the First International Congress on Construction History*. Ed. Santiago Huerta. Madrid: Instituto Juan de Herrera, 2003, 3: 1527–36.

Pagès, Yves. “Eladio Dieste: Innovation et materiaux traditionnels.” *amc: Le Moniteur architecture* 115 (April 2001): 28–32.

Paula, Jorge di. “Eladio Dieste: Trascendencia de una experiencia creadora.” *Trama* (Quito, Ecuador) 12 (1979).

Pedreschi, Remo. *Eladio Dieste*. The Engineer's Contribution to Contemporary Architecture. London: Thomas Telford, 2000.

———. With Braj P. Sinha and Fiona McLachlan. “The Remarkable Buildings of Eladio Dieste.” *Ibstock Design: Plinths* 5, no. 8 (July 1996): 12–15.

Pérez Escolano, Víctor. “Rigore e autenticità nell'opera di Eladio Dieste=Rigor and Authenticity in the Work of Eladio Dieste.” *Lotus International* 98 (1998): 84–110.

Piaggio, Juan Martín. “Eladio Dieste: L'ingengno e l'architettura.” *Costruire in Laterizio* (Faenza, Italy) 52/53 (July/Oct. 1996): 156–79.

———. *Leggero come un mattone: L'Architettura de Eladio Dieste*. Parma, Italy: Industria Leterizi Giavarini S.p.A., 1997.

———. “Eladio Dieste, o la ligereza del ladrillo.” *Ars Sacra* (Madrid) 7 (Sept. 1998): 7.

———. “La Ligereza en la obra de Don Eladio.” *WAM: Web Architecture Magazine* 7 (1999): 7–8.

———. “Progetto e costruzione: San Juan de Ávila ad Alcalá, Madrid.” *Costruire in Laterizio* (Faenza, Italy) 71 (Sept./Oct. 1999): 18–25.

———. “Eladio Dieste: Una casa d'abitazione.” *Costruire in Laterizio* (Faenza, Italy) 82 (July/August 2001): 48–51.

Posani, Juan Pedro, and Alberto Sato. “Thoughts from the Tropics.” *Zodiac* 8 (1993): 48–83.

Rasch, Horst, and Undine Pröhl. “Uruguay: Zauberei mit Ziegeln.” *Häuser* (Hamburg) (May 1997): 70–74.

Rouyer, Rémi. “Eladio Dieste.” In *L'Art de l'ingénieur, constructeur, entrepreneur, inventeur*. Ed. Antoine Picon. Paris: Centre Pompidou, 1997, 147, 274.

Sarrablo, Vicente, Francisco L. Almansa, and Pere Roca. “Eladio Dieste: La estructura cerámica armada.” *WAM: Web Architecture Magazine* 7 (1999): 1–3.

Silvestri, Graciela. “Dieste: Modernità senza conflitti.” *Casabella* 684/685 (Jan. 2001): 60–67; English trans., 170–72.

Véjar Pérez-Rubio, Carlos. “Four Surveys of Contemporary Latin American Architecture.” *Design Book Review* 32/33 (Spring/Summer 1994): 11–15.

Vercelloni, Matteo. “Forze in equilibrio.” *Costruire* (Milan) 125 (Oct. 1993): 240–44.

Vergalito, Vittorio. “Obras con amor proprio.” Interview by Pablo Vierci. *MonteVIdeEO* XX (December 1996): 13–15.

Waisman, Marina. “La unidad recuperada: Eladio Dieste, formas y técnicas.” *Arquitectura viva* (Madrid) 18 (May–June 1991): 35–39.

———. With César Naselli. “Eladio Dieste.” In *10 Arquitectos Latinoamericanos*. Seville: Consejería de Obras Públicas y Transportes, Dirección General de Arquitectura y Vivienda, 1989, 150–69.

Zeballos, Sergio. “Ethics/Æsthetics.” *UME* (Melbourne) 11 (ca. 1999): 58–61.

INDEX

SUBJECTS

PROPER NAMES

## FIGURE CREDITS

Edward Allen: figs. 67-71, 83, 193, 212
Stanford Anderson: figs. 21, 37, 95, 104, 119, 142, 143, 170, 195, 210, 213
Yoshihiro Asada/*a+u*, Tokyo: figs. 3-9, 11-13, 17-20, 22, 26-30, 35, 38, 40, 42, 43, 45, 46, 49, 51, 52, 55, 57, 62, 66, 82, 90, 92-94, 101, 103, 107, 115, 121, 126-129, 132-134, 137-139, 141, 144-149, 151, 159, 161-164, 168, 176, 183, 184, 188, 190-192, 194, 200-209, 214, 215, 218-220
Tim Becker: figs. 237-252
Boston Public Library, Boston, Massachusetts, Print Department: figs. 75-78
Fernando Cassinello, *Bovedas y cupulas de ladrillo* (CIDE: Madrid: 1969): figs. 236
Carlos Clemente, Madrid: figs. 54
Columbia University in the City of New York, Avery Architectural and Fine Arts Library, Guastavino Archive: figs. 72-74
Carlos Contrera, Montevideo, Uruguay: portrait (1996), page 12
Catedra Gaudi, Barcelona: fig. 79
Vicente del Amo, Granada, Spain: figs: 10, 15, 16, 23, 33, 36, 39, 44, 58, 63, 64, 84-89, 96, 98-100, 113, 117, 118, 122, 123, 125, 131, 140, 150, 155-158, 166, 173, 175, 180, 181, 185, 197, 211,
Antonio Dieste: figs. 32, 256
Eladio Dieste, "Bóveda nervada de ladrillos 'de Espejo.'" *Revista de Ingeniería* (Montevideo) 473 (Sept. 1947): 510–12. fig. 108
Dieste y Montañez, Montevideo: figs: 1, 2, 14, 111 (with diagram by John Ochsendorf), 171, 178, 179, 222-234
Dieste y Montañez/Gonzalo Larrambebere: figs: 25, 53, 187, 216, 217
Dieste y Montañez/Vicente del Amo: figs: 24, 31, 34, 50, 56, 59-61, 65, 97, 102, 120, 124, 130, 135, 136, 152-154, 167, 169, 174, 186, 189, 198, 199,
Drewes + Speth, Hannover: fig. 259
Eidgenössische Technische Hochschule (ETH), Zurich, Maillart Archive: figs. 81, 114
Gustave Eiffel, *La Tour de Trois Cent Metres* (Paris: Imprimerie Mercier, 1900): fig. 80
Lisa Grebner: fig. 112
Heinz Isler, Zurich: fig. 116
Institute for Structural Design and Research, Hannover: fig. 275
Julie Méndez Ezcurra, Buenos Aires, Argentina: fig. 221
Luis Moya Blanco, *Bovedas Tabicadas* (Madrid: Dirección General de Arquitectura, 1947).: figs. 235, 260
Remo Pedreschi: fig. 165, 172, 182
Remo Pedreschi and Braj Sinha: figs. 253-255
Nancy Royal, LLC, Boston: figs. 48, 91, 160
Mario Salvadori and Robert Heller, *Structure in Architecture* (Englewood Cliffs, NJ: Prentice-Hall, 1963): fig. 106
Julius Shulman, Los Angeles: frontispiece, figs. 41, 47, 110, 177,
Martin Speth: figs. 258, 261-267, 268-274
Torroja Institute, Madrid: fig. 109
United States Patent Office, Washington, DC: Patent 947,177: fig. 105
Mark West, Winnipeg, Canada: fig. 196

Edward Allen is an architect with more than fifty buildings to his credit. He was a member of the Massachusetts Institute of Technology faculty for thirteen years and is the author of nine books on architecture and building, many of which set the standard for works on building technology. His twin passions for brickwork and structures led him to the works of Rafael Guastavino and Eladio Dieste.

Kent Anderson is an artist and educator living in Vancouver, British Columbia, Canada. He is the director of the Sculpture Department at Kwantlen University College, Vancouver. At present he is working on a large-scale sculpture and video installation that has its origins in his earlier interest in architecture.

Stanford Anderson has been a professor of history and architecture at the Massachusetts Institute of Technology since 1963. His position as head of the Department of Architecture began in 1991. Among the books to his credit is the definitive work *Peter Behrens and a New Architecture for the Twentieth Century* (2000). A collection of essays in his honor titled *The Education of the Architect: Historiography, Urbanism, and the Growth of Knowledge* appeared in 1997, edited by Martha Pollak.

Timothy P. Becker is a designer and builder practicing in Seattle, Washington. His work in Spain was funded by a Fulbright/Hays research grant.

Lucio Cáceres Behrens, a civil engineer, is head of the Highway Department at the Faculty of Engineering of the Universidad de la República in Montevideo, and has served as the Minister of Transport and Public Works in Uruguay since 1995. As members of the country's intellectual movement of the twentieth century, Cáceres' and Dieste's families have long had a close relationship, Cáceres himself being a student and colleague of Dieste.

Antonio Dieste, one of Eladio Dieste's eleven children, trained as a structural engineer at the Universidad de la República in Montevideo. He collaborated in his father's firm and is today a partner in the engineering firm of Castro y Dieste in Montevideo.

Gonzalo Larrambebere is the director of projects and construction at the office of Dieste y Montañez, S.A. He teaches at the Faculty of Engineering of the Universidad de la República in Montevideo and has given lectures on shells and other structures of reinforced brick throughout South America, Europe, India, and the United States.

John Ochsendorf is assistant professor of building technology in the Department of Architecture of the Massachusetts Institute of Technology. Trained in structural engineering at Cornell and Princeton universities and the University of Cambridge, he currently conducts research on masonry mechanics, structural theory, and the history of construction.

Remo Francesco Pedreschi received his Ph.D. from the University of Edinburgh, Scotland, where he is a reader in the School of Arts, Culture, and Environment. He is the author of a book on the work of Eladio Dieste, which appeared in 2000 in the series The Engineer's Contribution to Contemporary Architecture, of which he is the co-editor. He is currently at work on a book about Jean Prouvé.

Braj Sinha is professor emeritus at the University of Edinburgh, Scotland, where he received his Doctor of Science. He has carried out research on structural masonry for over thirty-five years and co-authored or edited several books. He is also executive director of the International Council of Masonry Engineering for the developing countries.

Martin Speth teaches structures and structural design at the Institute for Structural Design and Research, University of Hannover, Germany. An associate of Drewes + Speth, Beratende Ingenieure im Bauwesen, Hannover, he has realized a number of building projects since 1995.