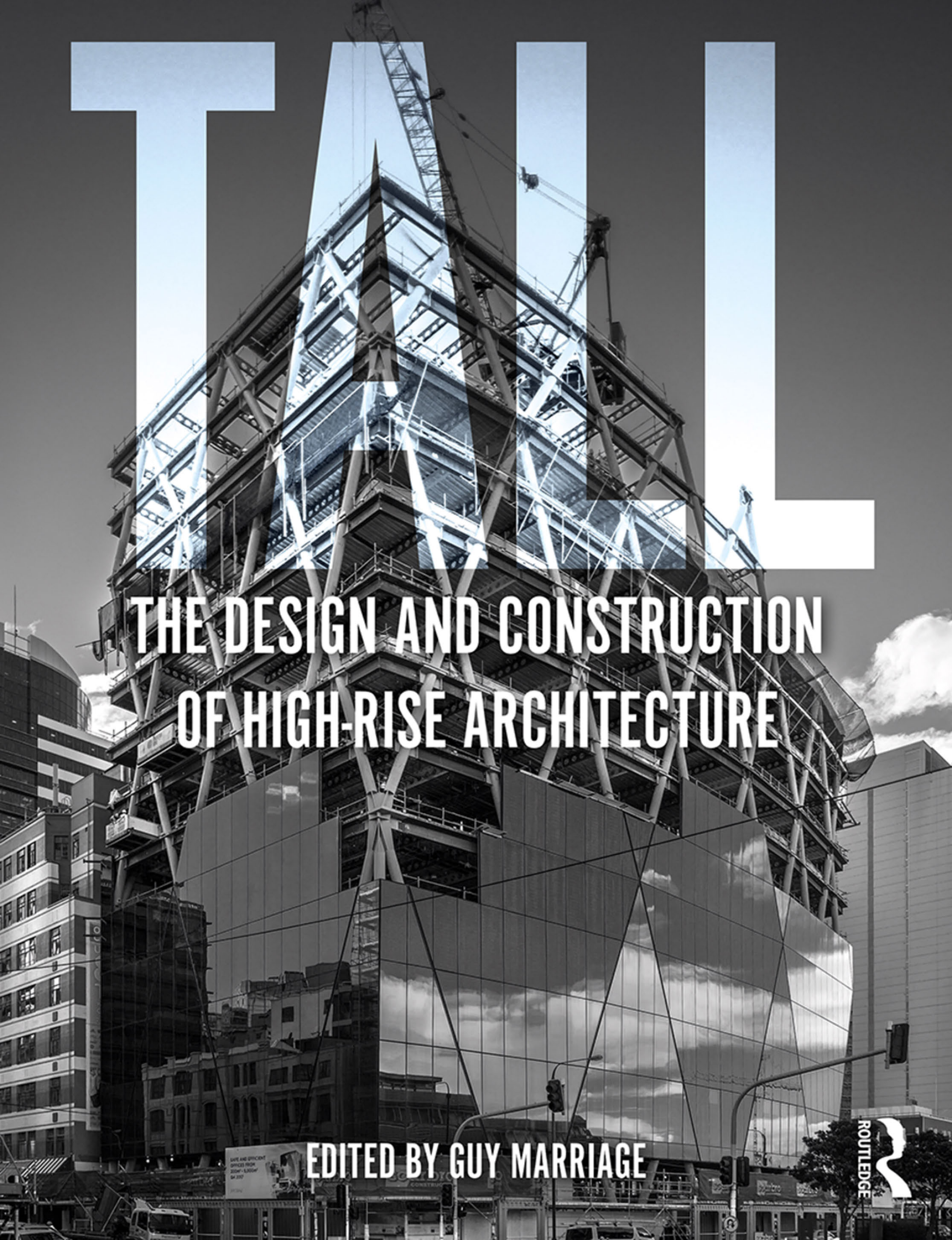
TALL

THE DESIGN AND CONSTRUCTION OF HIGH-RISE ARCHITECTURE



EDITED BY GUY MARRIAGE

ROUTLEDGE

Tall

This is a guide to both the basics and the details of tall building design, delving into the rudimentary aspects of design that an architect of a tall office building must consider, as well as looking at the rationale for why and how a building must be built the way it is.

Liberally illustrated with clear, simple black and white illustrations showing how the building structure and details can be built, this book greatly assists the reader in their understanding of the building process for a modern office tower. It breaks down the building into three main components: the structure, the core and the façade, writing about them and illustrating them in a simple-to-understand manner. By focusing on the nuts and bolts of real-life design and construction, it provides a practical guide and desk reference to any architect or architecture student embarking on a tall building project.

Guy Marriage is an architect, registered in Britain and in New Zealand. Now teaching construction, design and building science at Victoria University of Wellington in New Zealand, he gained construction experience from over two decades in practice, with 11 years working in architectural practices in London including Colman Architects, Jestico + Whiles and Foster + Partners. Returning to New Zealand in 2000, he worked for seven years at the Studio of Pacific Architecture and was one of the founding directors of First Light Studio in 2012. He has experience in projects that range in scale from small homes, prefabricated houses, apartment buildings, shopping centres, multi-storey office buildings, and two of the largest underground railway stations in London at the Jubilee Line extension. In 2016 he designed and built his own house, which was featured on Grand Designs New Zealand.

For further details, please visit: www.tallconstruction.org

‘Skyscraper design has emerged as one of the most important and most complex tasks facing builders today. *Tall: the design and construction of high-rise architecture* explains how skyscrapers are conceived, designed, and built in remarkably clear prose, breaking down their economic and technical requirements into lucid chapters. Along the way, Guy Marriage presents a readily accessible guide to building structures, materials, economics, and finishes, covering the whole life of a tall building from its conception to its disassembly. *Tall: the design and construction of high-rise architecture* is an important addition for students and practitioners in a range of fields, from engineering and architecture to finance and facilities management, and makes for an essential companion for anyone navigating the tightly integrated systems and spaces of a skyscraper in design or construction.’

– Thomas Leslie, FAIA, Iowa State University/ Northwestern University

Tall

The design and construction of high-rise architecture

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Contents

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Huge thanks go to the illustrator of much of this book, Lauren Hayes, who has done a fantastic job – I hope you will agree. We shared the task of illustration, but her ability has grown wonderfully. Thank you also to Gerard Finch, Emma Fell, Brittany Irvine, and Tegan Wardle, who also helped with some of the illustrations and of course a big thank you to Andy Spain for his wonderful photo of XXCQ that graces the front cover of the book. My thanks go to the co-sponsors of the Summer Scholarship program at Victoria University of Wellington (Te Herenga Waka) that helped create this book: Victoria University and First Light Studio. Thank you all, especially to my fellow directors at First Light, and my colleagues at Victoria University, who have put up with my time spent on this book.

Finally, the class of the Third Year Construction paper at Victoria University over a number of years deserve special thanks for both inspiring the book as well as providing feedback on successive drafts as it evolved. It is a hard task to get a large class onto a construction site in these safety-conscious times, so the book has been written and illustrated in a manner that will hopefully be of use to architecture and engineering students around the world to more fully understand the design and construction process of the buildings they design.

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Abbreviations

AAC	Aerated autoclaved concrete
ACM	Aluminium Composite Material
AHU	Air Handling Unit
BIM	Building Information Modelling
BMS	Building Management system
CAD	Computer Aided Design
CLT	Cross Laminated Timber
CNC	Computer Numerically Controlled
DALI	Digitally addressable lighting interface
DPC	Damp Proof Course
DPM	Damp Proof Membrane
DSF	Double skin facade
ESD	Environmentally Sustainable Design
EWP	Engineered Wood Products
FAR	Floor to Area Ratio
FCL	Finished Ceiling Level
FCU	Fan Coil Unit
FFL	Finished Floor Level
FLC	Floor Levelling Compound
FSL	Finished Slab Level
FSC	Forestry Stewardship Council
FRR	Fire Resistance Rating
GA	General Arrangement
GFA	Gross Floor Area
GRC	Glass reinforced concrete
GRP	Glass reinforced plaster
HVAC	Heating, Ventilation + Air Conditioning
IBC	International Building Code
IGU	Insulating glazing unit
LSF	Light Steel Framing
LED	Light Emitting Diode
LVL	Laminated Veneered Lumber
mPa	megapascal (pressure/load)
MS	Mild steel
MTC	Massive Timber Construction
NLA	Net Lettable Area
NZBC	New Zealand Building Code
OSB	Oriented Strand Board

PCG	Project Control Group
PM	Project Manager
PSI	Pounds per Square Inch (pressure/load)
PV	Photo-voltaic
PVC	PolyVinyl Chloride
QA	Quality assurance
QC	Quality control
RC	Reinforced concrete
RCP	Reflected Ceiling Plan
RE/SE	Rebated Edge / Square Edge
SE	Structural Engineer
SPD	Staircase Pressurisation Duct
SLS	Serviceability limit state
UB	Universal Beam
UC	Universal Column
ULS	Ultimate limit state
U/S	Underside
VAV	Variable Air Volume
VRV	Variable Refrigerant Volume

Contributors

Dr Nabil Jose Allaf studied architecture at the National School of Architecture in Nantes. After working as a practicing architect in France, he completed his PhD under supervision of Associate Professor Andrew Charleson at Victoria University in New Zealand. His PhD work is a seminal work on the integration of seismic retrofit and architecture in existing unreinforced masonry buildings, approaching seismic structures through their capacity to enrich architectural qualities.

Gerard Finch is a PhD Candidate in the School of Architecture at Victoria University of Wellington. His doctoral research looks at how to design building systems to facilitate material reuse and/or high-value recycling in an economically successful manner at the end of the structure's useful life and is centred on a series of design-build projects. Prior to undertaking this research, Gerard has worked briefly in two medium-sized architectural firms in Malaysia, been involved in statistical damage analysis of residential dwellings in the 2011 Christchurch earthquake and tutored in the fields of Built Environmental Science, Construction, Design Communication and Critical Theory.

Lauren Hayes is a student of architecture at Victoria University of Wellington with an adept hand at drafting many of the illustrations you see in this book. Originally from Christchurch, she studied graphics and design at Cashmere High School before pursuing her dream of becoming an architect. At the time of publication, she has begun her master's degree at the Eindhoven University of Technology in the Netherlands.

Guy Marriage is an architect, registered in Britain and in New Zealand. Now teaching construction, design and building science at Victoria University of Wellington in New Zealand, he gained construction experience from over two decades in practice, with 11 years working in architectural practices in London including Colman Architects, Jestico + Whiles and Foster + Partners. Returning to New Zealand in 2000, he worked for seven years at the Studio of Pacific Architecture and was one of the founding directors of First Light Studio in 2012. He has experience in projects that range in scale from small homes, prefabricated houses, apartment buildings, shopping centres and multi-storey office buildings to two of the largest underground railway stations in London at the Jubilee Line extension. In 2016 he designed and built his own house, which was featured on Grand Designs New Zealand.

John Sutherland ONZM (B Arch [Wales]) is still in practice at 86 years old. He has relatively recently returned to Jasmax, the large New Zealand practice he was with for 30 years from 1996, finishing up as a director. His architectural career has not been straightforward. Starting as a senior project architect at JASMaD, he moved into being a technical specialist on building industry information and preparing technical literature for manufacturing and supplier clients. He was responsible for designing a new window suite for the Joinery Manufacturers Federation. This led to writing NZ Standards documents on windows and curtain walls and the development of many contacts overseas with colleagues with the same interests, leading to involvement with international research organisations such as CBI and ICBEST. In 1981 he went teaching Law, Practice, Management and Construction Technology as a Senior Lecturer at the University of Auckland School of Architecture. Back in practice in 1988, he was involved with the façade design for the tallest building in Wellington, the 28 storey Majestic Centre. Immediately after that, JASMaD, now Jasmax, won the competition to design and deliver The Museum of New Zealand (Te Papa), and he was one of three directors that saw the project completed successfully. He was responsible on the Te Papa project for leading a façade design team which involved Arup. In 1996 he left the firm to become the foundation Head (HOS) at the Unitec School of Architecture, teaching the same subjects and adding 'High Performance Cladding' that he had taught in Auckland School. He remained as HOS for 4 years and then stayed on as an Adjunct Professor until he was head-hunted to be a Façade Consultant, first with Aurecon and then Mott MacDonald. This career lasted from 2008 to 2017, when an opportunity arose to return to his Alma Mater. His business card says, 'Back where I belong'.

Preface

Knowledge is power, and so the control of the knowledge on a project is a very powerful role. Know how, but also know *why*. This book has been written expressedly with the architecture student in mind, disclosing some of the secrets of the architect – what they do not usually teach you in architecture school. This book examines the day to day work of the architects and others involved in planning, designing, resolving and detailing the construction of tall, multi-storey, commercial buildings. It touches on tall residential towers, but mainly focuses on office buildings, although the structural systems to both types of tower are often common.

Tall: The design and construction of high-rise architecture will take you from general principles of design (such as: align your planning grid to your structural grid) and continue on into intricate detailing issues (such as: how to design curtain wall façade details that will not leak). It will become a vital reference book for all architecture students from the start through to the final year of their studies. Practical and pragmatic, the text has been written by experienced practitioners who wish they had known then, what you can know now.

The purpose of this book is to spread greater knowledge, so that we can all gain by building better buildings for our cities, with the most modern construction technology. The concept for this book is, however, very old.

Architects need to know a wide range of information, encompassing both the practical aspects of the strict structural logic behind design, as well as the poetic: the artistic imperative leading us on. Vitruvius put this clearly many years ago, in his famous book on the education of the architect.

1 The architect's expertise is enhanced by many disciplines and various sorts of specialised knowledge; all the works executed using these other skills are evaluated by [their] seasoned judgement. This expertise is born both of practice and of reasoning. Practice is the constant, repeated exercise of the hands by which the work is brought to completion in whatever medium is required for the proposed design. Reasoning, however, is what can demonstrate and explain the proportions of completed works skilfully and systematically.

2 Thus architects who strove to obtain practical manual skills but lacked an education have never been able to achieve an influence equal to the quality of their exertions; on the other hand, those who placed their trust

> entirely in theory and in writings seem to have chased after a shadow, not something real. But those who have fully mastered both skills, armed, if you will, in full panoply, those architects have reached their goal more quickly and influentially.
>
> (Vitruvius 1999: 21)

Although these words were written 2,000 years ago, they're still just as true today. You need to know the theory and you also need to know the practical. This book will help you with both.

Vitruvius wrote about the design and construction of many types of buildings in Roman times: the military fort, various sizes of palaces, luxurious residential villas, stables, and indeed whole cities. He did not, however, write about multi-storey office spaces: hence this book.

There are many other books which discuss the design and construction of tall buildings, but most of them are aimed at engineering students. They are mostly written from a structural engineering point of view, dealing with stresses, bending moments and how to calculate inter-story drift. If that is what you are seeking, look elsewhere. Books aimed at architecture students tend to focus on glossy photos of completed buildings, taken by obsessively orthogonal architectural photographers with a passion for unobstructed vistas: i.e. no people. There is little discussion of the design rationale of the building, the process of construction or how the completed design was attained. One exception to this is Stephanie Williams' excellent book (Williams 1989) on the genesis of just one single building: the Hong Kong and Shanghai Bank headquarters building in Hong Kong (architect: Foster and Associates, 1985). If you really want to know just how complex and difficult a high-rise commercial building project can be, then I recommend that you seek out a copy of this book.

The authors of this book all live in New Zealand (Aotearoa), a small country far away from most of the world where there is a strong awareness of the destructive power of earthquakes. I grew up in the small city of Napier, which was completely destroyed by an earthquake in 1931 (with 256 deaths) and was subsequently rebuilt in just two years in the Art Deco style. In 2010 and 2011, strong earthquakes in the province of Canterbury caused significant – massive – damage to the central business district of the city of Christchurch, with 187 deaths. The earthquakes destroyed most of the brick-faced Victorian-era buildings and the subsequent demolition of the majority of the more modern concrete buildings has caused an intense interest in how to strengthen buildings against earthquakes. In 2013 and 2016, further massive earthquakes caused damage to the small town of Kaikoura, completely wiped out the coastal highway and the coastal railway line on the South Island (Te Wai Pounamu), but also caused many issues with large

buildings in the capital city of Wellington, one hundred and fifty kilometres away on the North Island (Te Ika a Maui).

There is therefore a strong focus on seismic issues portrayed within this book. These same seismic concerns will apply to students in California, Japan, Italy, New Zealand and other countries beset with seismic issues, while students in more stable areas such as in the centre of continents may find this focus not quite as relevant to them. The principles in this book are aimed at all students of modern architecture, however, and apply equally to them all: the need to know how and why modern materials and modern construction systems work, and how to design them to work together.

If you are keen to know more about the subject of structure and seismic isolation, I would recommend that you seek out three books by Andrew Charleson, namely *Structure as Architecture: A Source Book for Architects and Structural Engineers* (Charleson: 2006), *Seismic Design for Architects – Outwitting the Quake* (Charleson: 2008), and the most recent, co-written with Andriana Guisasola, *Seismic Isolation for Architects* (Charleson and Guisasola: 2017). These are an excellent series of books by an experienced engineer, but, importantly, they are written for an architectural audience. And of course, there is now this book, as well.

The book you hold in your hands is about the price of a dozen or so cups of coffee, which would normally last you only a week or two and leave you wide awake and wanting more. By contrast, this book will not only leave you more knowledgeable, but should last you a lifetime.

Guy Marriage,
Aotearoa New Zealand, 2019.

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01

Chapter One

Introduction

Introduction

Guy Marriage

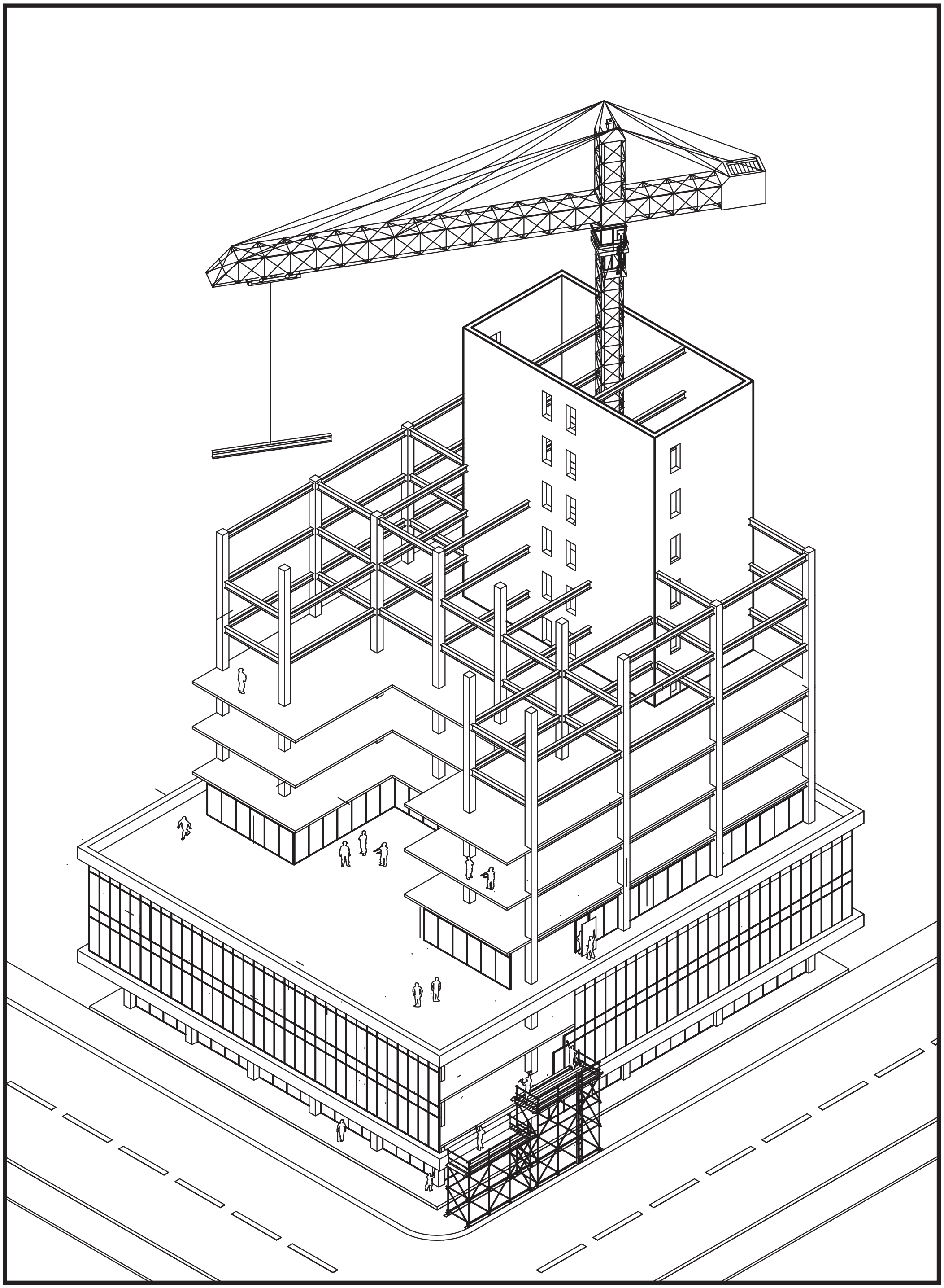

Figure 1.1 The high-rise under construction

1.0 Introduction to the building and the team

A multi-storey building is built using very different systems from a single storey building, and so both the design and the construction need special thought when going upwards. The sky is the limit! The principles, however, are all broadly the same, whether your building is five stories high or 50.

When designing a multi-storey building, there are three main elements to the building. First, there is the building structural framework: beams and columns which support the floors. The structure is there to cope with two very different forces, i.e. gravity and lateral forces, and to safely carry these loads back down to earth.

The second main element is a core, containing vertical circulation, facilities and numerous services. The core may or may not also be a structural element: there can sometimes be more than one core. We explore the core in detail, looking at the structure, the services, how to thread them under the floor slabs of the office floors.

The third element is the façade. Primarily, the external façade is there to keep the weather out, but it is also the main part that the public sees. This guide will help you understand basic principles on how all three primary elements come together to make a building and how you might design and construct that building.

There are a number of various other factors that influence the design, such as Height, Function, Structure, Form, Wind load, Daylight, Ventilation, etc., and these will be examined in more detail as we move through the building. Before we look at the design and examine the construction, who are the people involved?

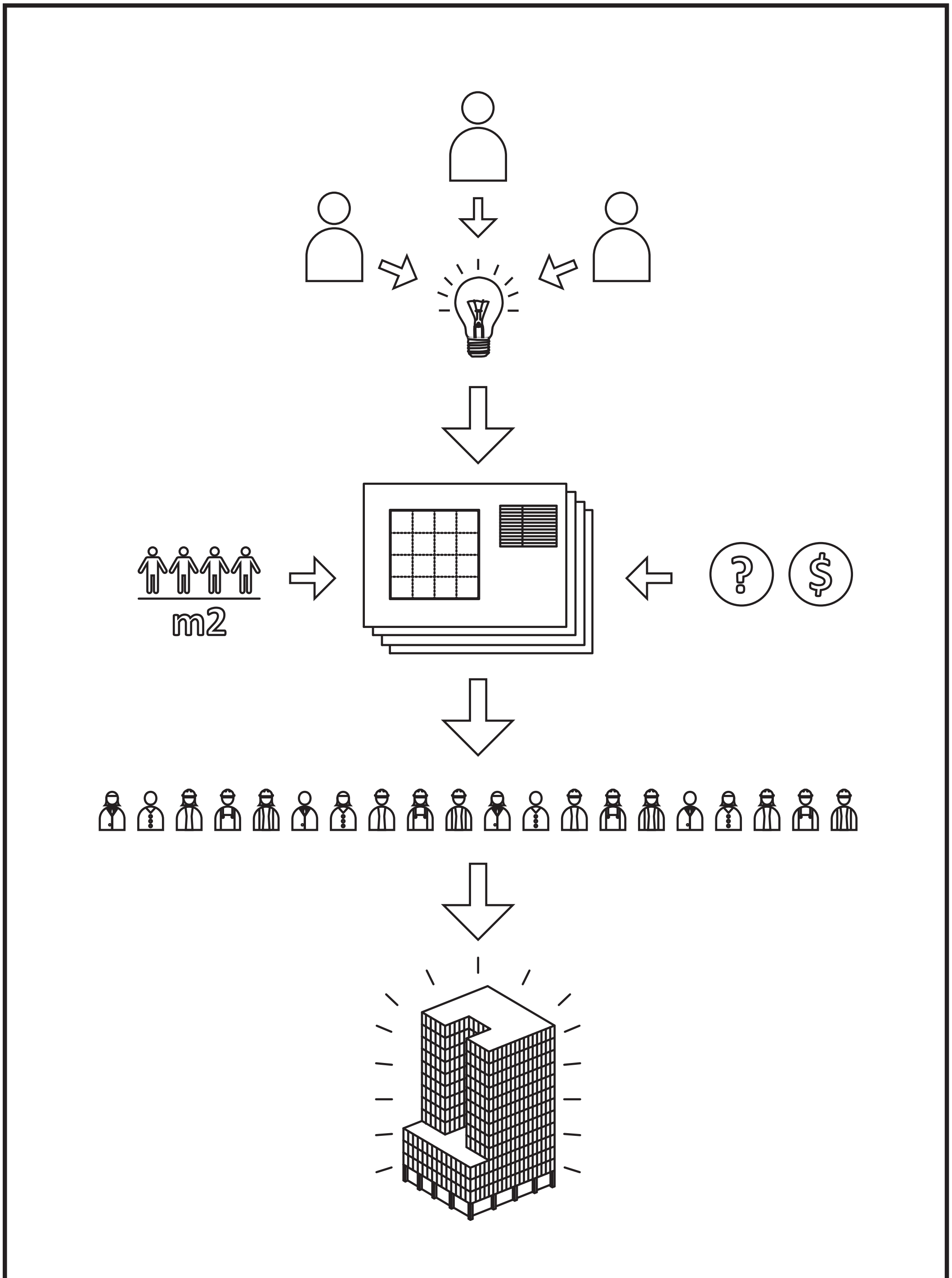

Figure 1.2 Diagram of the building process

1.1 Project team

High-performance building design teams need an integrated design team right from the beginning. You may think that buildings are designed by one person, possibly the hero, an architect sitting alone in a studio with a sketchbook and a pencil or a laptop and some software. You're wrong. Large buildings only come about through the concerted efforts of many minds working together, each performing their own tasks, both in the design phase and the construction phase. Architect does not mean just one person, but a whole team of maybe 5, 10, 20 or more people, from all ethnicities and genders (refer to Figure 1.2). It's a team thing – the bigger the project, the bigger the team. Let's meet the team.

Architect

The Architect is traditionally the lead consultant on a building project, designing the project and liaising between the client and the builder. Architects also used to undertake all the project management of a project. With the increasingly large scope of work that architects have to undertake in the modern world on large building projects, the architect will focus on the design of the building and the integration of all other consultants' work. Increasingly, on larger projects, this is likely to involve the use of Building Information Modelling (BIM) to build a virtual model before building the physical building. At present, the BIM co-ordination role is led by the architectural team, although in time this may become an increasingly separate role. Remember: knowledge is power, and so the control of the knowledge on a project is a very powerful role.

Engineer

Engineers are a hugely important part of the building process and they specialise in many different roles. Engineers are usually educated first in Civil Engineering principles and then in their speciality area later. Their education is extremely different from that given to students in a school of architecture (Marriage and Gamman, 2017). They understand and practice calculations, not the wider, more varied range of subjects that architecture students have. The various different specialisations of Engineers that tend to be on construction projects include:

Civil Engineer – generalist but expert on things connected with the ground – roads, wastewater, etc.

Geotechnical Engineer – specialists in the soil and foundations that your building will sit on.

Structural Engineer – specialists in the forces that keep a building up safe and sound: the structural frame.

Mechanical Engineer – design and analysis of heat, power, engines and air-conditioning systems.

Hydraulic Engineer – dealing with liquids in pipes (oil and water), including fresh / foul water.
Electrical Engineer – generation and distribution of electricity for power and lighting.
Fire Engineer – specialists in escaping from fire, stopping fire spreading, controlling fire.
Traffic Engineer – analysis of flows of vehicles to and from your building site.

Of all these types of engineers, there is one specialist discipline that you will be working closely with most of all and will be planning the building's structural system with you: the Structural Engineer.

Structural Engineer

The Structural Engineer (SE) plays a crucial role in the design of any large building, as they will be calculating loads from gravity, wind and seismic action, as well as masterminding structural solutions to resist those loads. Architects need to work very closely with the SE when designing a large building, and lines of responsibility must be closely observed. It is crucial that you understand that items such as column size and beam size, and all bolt sizes for connections are either designed by the SE or are checked and confirmed as adequate by the SE. While you can propose a beam or bolt size on a drawing, the SE must check this size is adequate, and ultimately the SE has overall responsibility for specifying these items.

Project Manager

The Project Manager (PM) is often now a key part of the building process, increasingly running the interface between the client and the rest of the building team, including the architect. A good PM will facilitate the building process, keep track of progress of all the consultants and contractors and will issue the paperwork associated with this. PMs need to be expert in all forms of communication, both clearly written and carefully spoken. Building projects may have several PMs, with some acting for the Contractor, others acting for the Client and others just co-ordinating processes on site.

Quantity Surveyor

The Quantity Surveyor (QS) also has a key role in the project, as they provide financial advice to the architect, the engineers and the project managers – as well as to the client. The client will frequently remind you that it is <u>their</u> money that you are spending. The QS will measure the plans and drawings at each important stage of the process and provide financial advice on likely costs. While the QS is not a specialist in design, they are specialists in knowing where money

is being spent too lavishly and they will often suggest 'value engineering' of certain details if they feel that money can be saved in that area. The architect and the client need to decide whether the proposed savings are a good idea or would compromise the design. QS services in the future will increasingly be based off BIM data instead of measuring off drawings.

Environmentally Sustainable Design (ESD) Advisor

The ESD Advisor is the person on the project who looks at the big picture. Discussions between the Architect, Structural Engineer and ESD Advisor should happen at the earliest stage, looking at the basic aims of the building: after all, this is a place for people to spend one third of their working lives. The ESD advisor will put forward proposals to make the building as good for people and as good for the environment as it can be. That may include strategies for daylight, fresh air, low-energy solutions and low-impact sustainable working environments. The earlier the Architect has this conversation, the better the building can be.

Other consultants

Depending on the size of the project, there may well be more consultants on the project, brought in from time to time. These are project-specific roles that will be needed only on certain projects, such as Acoustic consultant, Façade Engineer, Maintenance advisor and Lift / Elevator consultant.

1.2 Construction team

Contractors

The Contractors are the most crucial element of any building process – they are the people who get the building built. They will sign a legal Contract for the construction of a building based upon the team's combined drawings and specifications and so any changes to that legal Contract can incur extra charges. The clearer, more understandable and more complete the drawings are, the better for all. The sooner the Contractors can be made part of the building team, the better. While traditionally contractors may have a large work force of employees ready to put on any project, increasingly nowadays the workforce is made up of many sub-contractors.

Sub-contractors ('subbies')

These are people and companies who will contract to undertake a small portion of the total work in which they specialise. Sub-contractor work could include a 'package' as small as a single person on site fixing just a few items or could be as large as the 'entire external envelope'. This can lead to excellent results for speed and efficiency if everything is going well and is well co-ordinated – but can be a disaster if the design team has not co-ordinated their information in every way. Increasingly, a BIM model will be used to co-ordinate the subbies' built work, while the Contractor's PM will control the subbies' various trades, activities and appearance on site. Subbies will often be required to submit their own 'shop drawings' (precise, dimensioned, fully working drawings) of their proposed built scope in answer to the consultant's proposed 'schematic drawings' which show a more generalised scope of works.

1.3 The Client

Developer. Client. Owner. Funder. These may or may not be the same person or organisation. There are important distinctions between the terms. The developer is the organisation undertaking the project of getting a new building designed and constructed. The client is the person you or your company is working for. The owner is the organisation that may own the building now or perhaps only when it is finished. The funder is the people who source the money. You, as an architect, will be working only for your client, but they may also be the developer.

Tenant

The tenant is the company who ends up leasing all or some of the space in the building. While once companies used to fund their own developments and own their own buildings, that is pretty unusual practice nowadays. Now most companies just lease space from a building owner, who may have bought the base building from a developer. Base build buildings are also known as 'shell and core'. Consequently, it is increasingly common for the 'base build' architect to have no contact at all with the eventual end users of the building – the employees of the tenant. The 'fit-out' stage of the building is, therefore, often undertaken by another wholly different architect and team.

All these consultants and the lead contractor will form with the Client what is often called the Project Control Group (PCG). When a project is in planning or on site, PCG meetings will be held frequently to check on progress. Having met the team, let's now look at some of the other aspects of the development process.

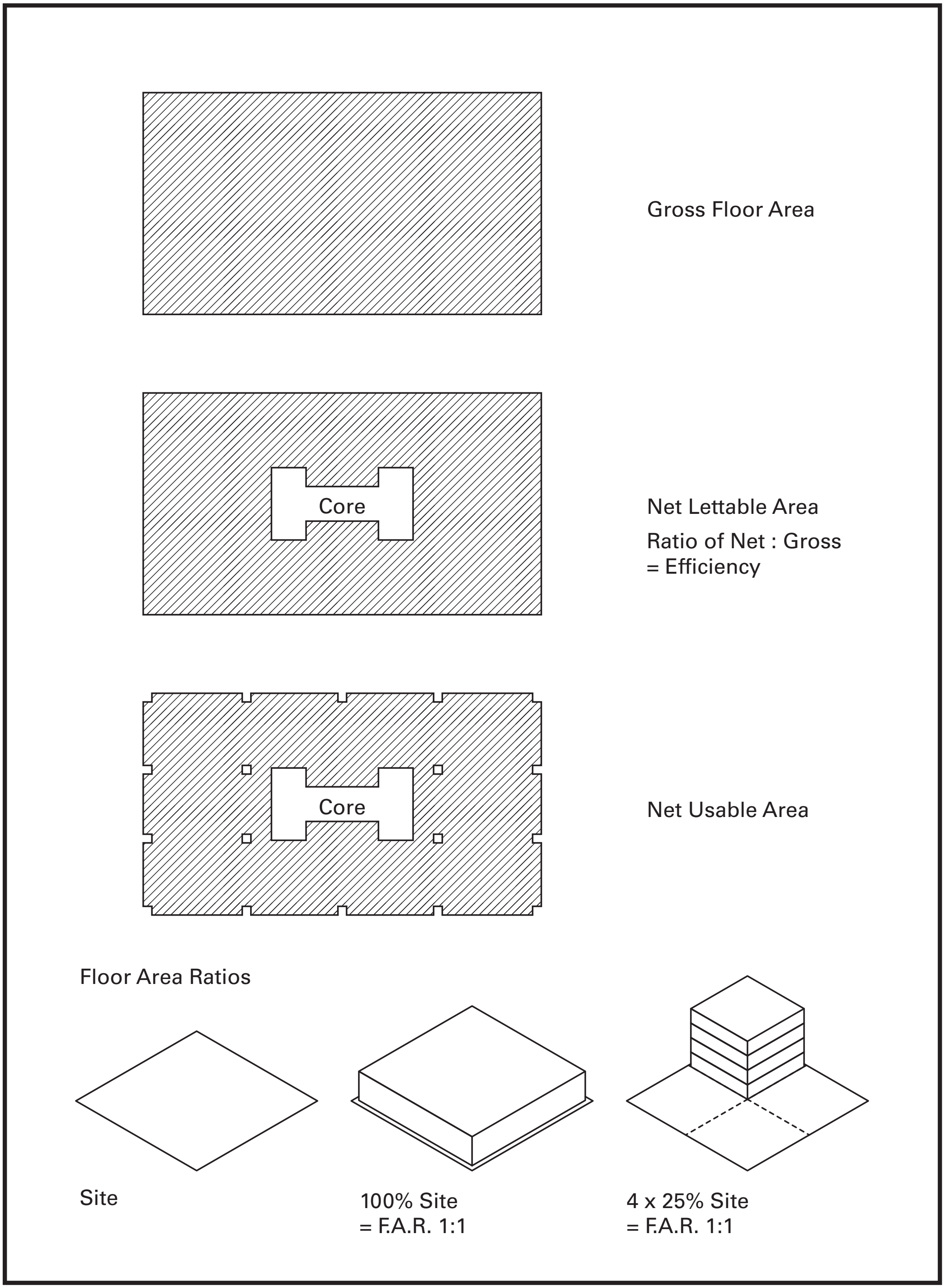

Figure 1.3 Gross, net, FAR

1.4 Developer guidelines

Net to gross

A developer of any building must construct the full extent of the building works: the gross floor area (GFA). GFA is measured to the outside edge of the building on every floor and includes everything within that boundary. The GFA is, therefore, the total amount of floor space that gets built (refer to Figure 1.3).

The net lettable area (NLA) is the amount of floor space that the owner can rent out to the tenant of the building – a significantly smaller amount than the GFA. The developer typically tries to have as high a ratio of 'net to gross' (NLA to GFA) as possible. This ratio measures the efficiency of the floor plates in the building – areas like the lifts and the stairs are part of the gross area, but not part of the net lettable. A developer will want a highly efficient floor plate – around 80 per cent, i.e. they will be able to charge rent on 80 per cent of the total building floor space they have built.

There is also another measure sometimes used in calculations: the net usable area (NUA). The tenant and the architect will always want the NUA to be as close to the NLA as possible: no wasted space. The aim for the developer is to have happy tenants who do not mind paying the rent on their space, but also to maximise the rentable floor space. Rent is then charged on the NLA space on a basis of $X per m^2 per year (or sq ft / year).

Who decides what is lettable?

The Building Owners and Managers Association (BOMA) publishes a booklet of guidelines as to what is considered lettable space and what is not (BOMA.org). Typically, the tenant will pay rent on every part of the floor right up to the inside of the perimeter wall – right up to the inside face of the external glazing – which is one reason why in many modern buildings, façades are very thin and flat.

Floor to area ratio

Developers also want to know how much space they can get overall in relation to the size of the actual physical site. This is calculated by looking at the amount of GFA and comparing it to the size of the site itself. This is known as the Floor to Area Ratio (FAR). A building one storey high that takes up the entire site has a FAR of 1:1, as does a building two stories high that only takes up half the site. But a building that is four stories high, built over half the site, will have a FAR of 2:1, while a building that is 30 stories high, built over just a third of the available site area, will have a FAR of 10:1 (refer to Figure 1.3).

Some cities will permit only a certain maximum ratio of FAR, while others may require a minimum. This way, city development bodies can have an effect on the densification of the available land. Los Angeles, for instance, has a 13:1 FAR in place, while Berlin has a flat 22m height limit. The cities, therefore, grow in very different ways.

1.5 Metric versus imperial

This is a tricky but important discussion. In France the metric system has been used for over 200 years (since the French Revolution in 1795), in Europe since 1865, in the UK since 1965, in New Zealand since 1969, in Australia since 1970 and in just three remaining countries in the world they still use 'imperial' measures, i.e. feet and inches. Surprisingly, one of these three remaining non-metric countries is the USA. More surprisingly, John Quincy Adams proposed the metric system for the USA back in 1821, but perhaps even more surprisingly, the USA actually signed the Metric Conversion Act in 1975 (Braybrooke, 1980). So, technically, the USA is metric – it is just that the country is very slow in its adoption of the metric system and the people of the USA largely refuse to use it. Curiously, the Americans have metricated just the inch so far in construction, so instead of saying half an inch, a quarter of an inch or five-eighth's of an inch as they used to, designers instead use 0.5 inch, 0.25 inch, and 0.625 inch, meaning they mix base 10 numbers with base 12 – while the workers on site stick with a five-eighth's spanner. That's just awkward.

My advice: stick to base 10 numeracy all the way and go metric (refer to Figure 1.4). It is a far simpler system than imperial, especially on complex projects. The key advantage with metric is that weights and areas and lengths all interact seamlessly. No more worrying about pounds, ounces, bushels, barrels, acres, etc. – instead, everything relates in a base 10 counting system. One kilogram = one litre of water = one cube measuring 100mm square. One thousand of those equals one tonne and measures a metre wide, high and long.

This book is unashamedly metric, as is the majority of the world, but for American readers it also includes imperial measurements (inside brackets). Note that while schoolchildren, Europeans and dressmakers use centimetres, in most of the building world we stick to either millimetres or metres – so that same 2400mm length can be easily written also as 2.400m.

A strictly accurate conversion of a figure such as two feet long (2′ 0″) would measure 609.6mm and three feet, six inches (3′ 6″) would be an awkward 1066.8mm. The construction world metricated these dimensions years ago to be a nice round 600mm and 1050mm. The 'imperial' 8-foot × 4-foot building products module was rationalised to 2400 × 1200. Most of the time in this book I'll use the rounded equivalent dimension to simplify matters.

Be warned, however, that despite the UK and the USA being officially metric, land agents (realtors) in America and England still quote figures in square feet (sq ft) rather than square metres (m^2). A handy figure to remember then is that there are 10.764 sq ft in 1 m^2 – refer to Table 1.1 for more (also refer to figure 1.4).

Table 1.1 Conversion between m^2 and sq ft.

m^2	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
sq ft	10.7	21.5	32.3	43.0	53.8	64.6	75.3	86.1	96.8	107.6
m^2	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
sq ft	118.4	129.4	139.9	150.7	161.4	172.2	183.0	193.7	204.5	215.3

How are you going to plan out your building? Site and Planning are covered more in Chapter 2, but you have only three key functions available to you in a tall building project: retail, commercial and residential (Chapter 15). What follows is just a brief look.

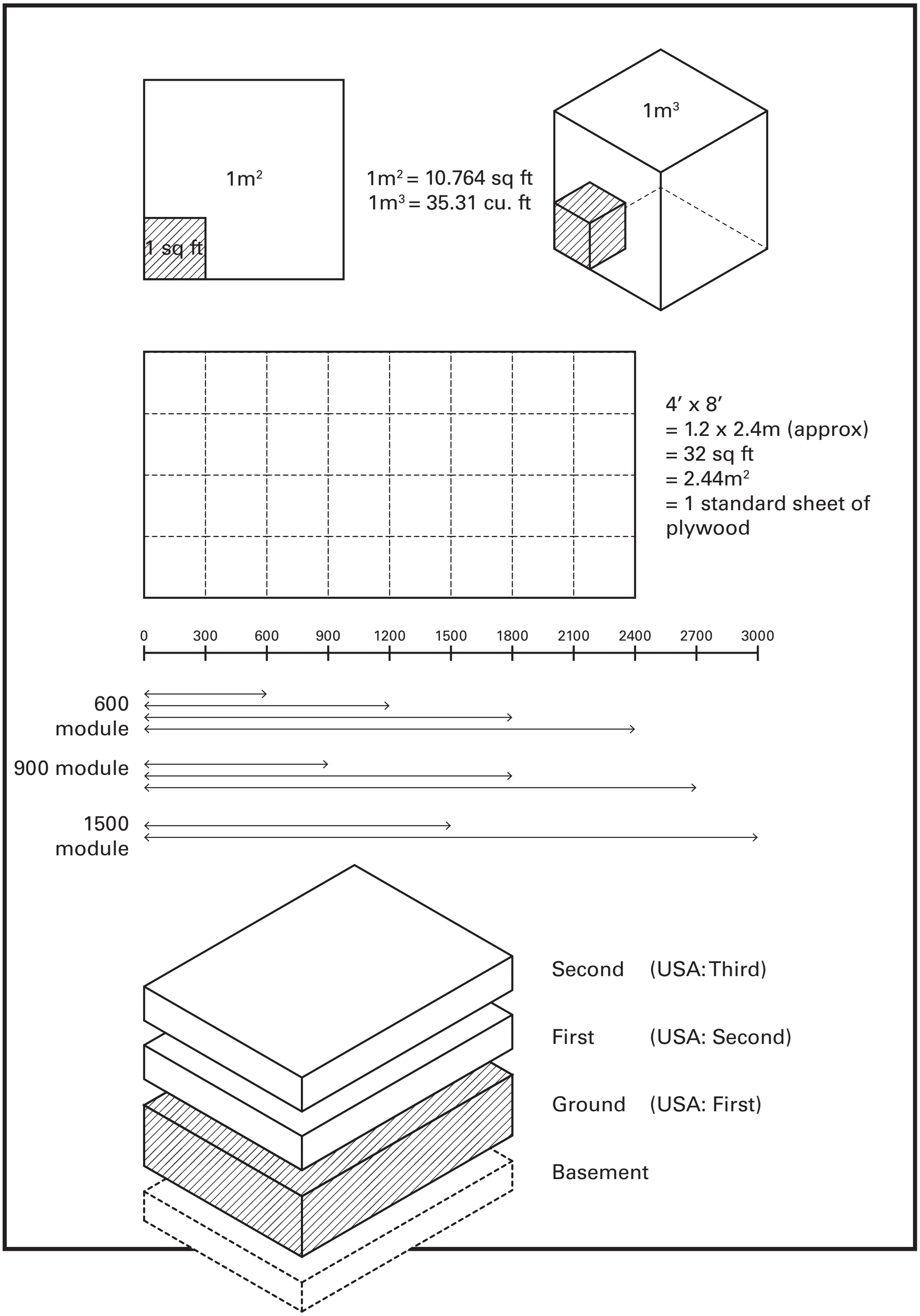

Figure 1.4 Modules, areas, volumes

1.6 Retail space

Retail space in highly sought-after areas attracts exceedingly high rental rates. Space at the front of the building next to the street is likely to be valued at a higher rate than space hidden away out the rear (the rental rate will vary and is subject to fierce negotiations). It is important to maximise retail space and open up the street frontage for maximum flexibility. Rent is normally highest on ground floor retail spaces along the 'Golden Mile' in any city – this is Regent Street or New Bond Street in London and 5th Avenue in New York (refer to table 1.2). New York's Manhattan is viewed as the most expensive retail real estate in the world, leasing on 5th Avenue in 2015 for US$37,000/m^2 (US$3,500/sq ft) for the ground floor. At that rate, there is pressure on the designer to maximise that retail! Every bit counts!

Curiously, though, while retail works well on ground floors, humans are essentially fairly lazy beasts at heart and so upper and lower floors nearly always secure significantly lower retail rental rates than the ground floor. Upper floors are, therefore, best suited for commercial leasing: office space.

1.7 Office space

You may know the old saying – what are the three most important factors in real estate? Answer: Location, location, location. Leasing costs for office space will vary considerably within a city, judged by the quality of the space but mostly by one factor: where is it? Incidentally, in New Zealand we have another old saying – what is the most important thing in life? Answer in Maori: He tangata, he tangata, he tangata (it is people, it is people, it is people). No matter how important your building is, always remember the humans inside it. That is who we build for!

Table 1.2 shows that rents can vary hugely around the world.

If a building has 1000m^2 of office space per floor renting out at, say, US\$350/m^2/year, this equates to a rental cost of \$350,000 per year, per floor. If there are ten floors of office space, that could equal rent of \$3.5million a year! Big buildings mean big money. Now you know why the Developer drives an Aston Martin and you don't.

Table 1.2 Reported rents, in US $, per area, per annum

Rent	New York	London	Wellington
Ground floor retail US$/m² (US$/sq ft)	(5th Avenue) $37,000/m² ($3,437/sq ft) (Average NY) $7,029/m² ($653/sq ft)	(New Bond St) $14,200/m² ($1,320/sq ft) (Average London) $2,398/m² ($222/sq ft)	(Lambton Quay) $1,700–$1,800/m² ($158–$167/sq ft) (Average Wellington) $846/m² ($79/sq ft)
Upper floor office US$/m² (US$/sq ft)	(Uptown) $473/m² ($44/sq ft) (Midtown) $678/m² ($63/sq ft) (Downtown) $592/m² ($55/sq ft)	(Mayfair) $1,507–$1,636/m² ($140–$152/sq ft) (Canary Wharf) $538–$678/m² ($50–$63/sq ft)	(Lambton Quay) $350–$400/m² ($32–$37/sq ft)

Source: Colliers Market Retail Report 2017, www.colliers.co.nz/; Commercial Observer, https://commercialobserver.com/2017/06/downtown-office-asking-rents-reach-all-time-high-cbre/; Oktra, www.oktra.co.uk/insights/how-much-does-london-office-space-cost-in-2019/; Squarefoot, www.squarefoot.com/ny/new-york/office-space; Rent NY Office, www.rentnyoffice.com/category/new-york-city-office-market/

Sources: The Register 2016, Capital Realty, Oktra.co.uk, squarefoot.com, rentnyoffice.com, colliers.co.nz, commercialobserver.com

1.8 Area per person

In the 1960s, before personal computers were on every desk, an office worker in the USA was expected to survive with just 5m^2 of space each: less than a third of the space we now have on average in a modern office (Joedicke, 1962). Design targets increased to a minimum of 10m^2 per person in the 1990s (not counting hot-desking). More space and better-quality space help retain workers. The current low unemployment rate may be 'encouraging business owners to make working environments more attractive' (Hutching, 2017).

Area allocated per worker depends on what sector you work in. For instance, state-sector employees in New Zealand occupy an average of 16m^2 each, while private sector employees average 18.1m^2 each: overall, an average of 17.2m^2 per person. This obviously affects office building design in the capital, where most of the government workers are, as Wellington averages 16.4m^2, while Auckland workers get a larger 18.1m^2. In case you wonder if you are in the wrong job, please note the following: in New Zealand lawyers' offices average 22.2m^2 per person (refer to Figure 1.5).

Table 1.3 Area per person in office buildings

	America in the 1960s (aim)	London in the 1990s (aim)	Lawyers in NZ in 2017 (actual)	Wellington (Government workers)	Auckland (Office workers)
Office space per person m^2 (sq ft)	5.0 m^2 (53.8)	10.0 m^2 (107.6)	22.2 m^2 (239.0)	16.4 m^2 (176.5)	18.1 m^2 (194.8)

Sources: Joedicke 1962, Hutching 2017

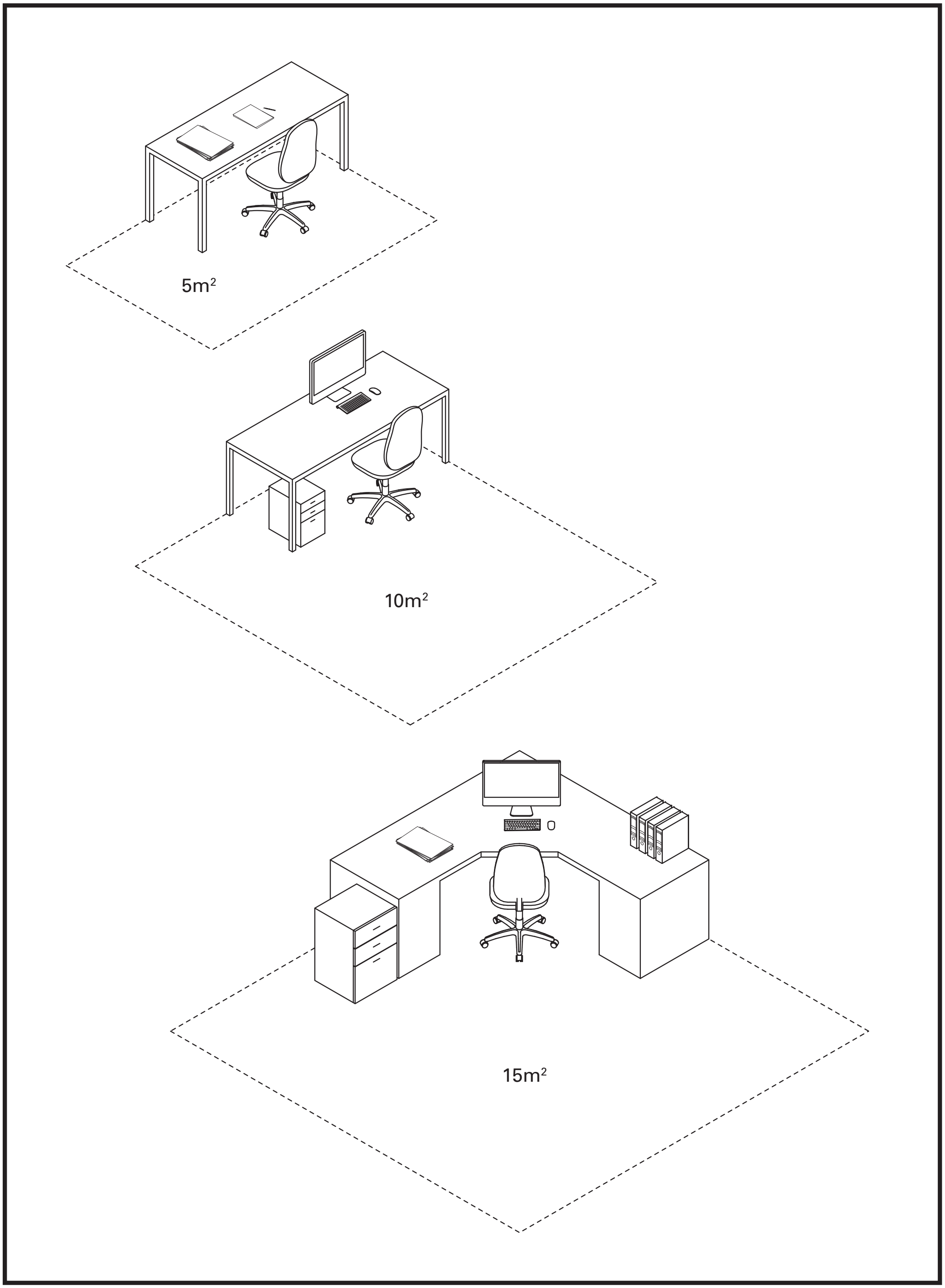

Figure 1.5 Area per person

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02

Chapter Two

Site: planning

Site: planning

Guy Marriage

2.0 Planning your building

Every site is different, with differing advantages or disadvantages. The size of the building will depend on the size and shape of the site available and the wishes of the client or developer, as well as the local regulations. The client may have something definite in mind or may leave it up to the architect and engineer to explore the possible extents of the project. You will face a classic design quandary: is your design driven from the inside, outwards (i.e. Form Follows Function), or is it driven from the outside, looking inwards (i.e. External Appearance rules!)?

The answer, of course, is that both are equally important. The internal environment should be welcoming and comfortable for the occupants inside, with good access to air, light and views out. The exterior is the visible face of the building and is an expression of both the Client's desire and the architect's ego, as well as a literal diagram of the engineer's structural prowess. Think of the building as a giant stack of dollar bills, and you may have the closest analogy yet. Was it always like this?

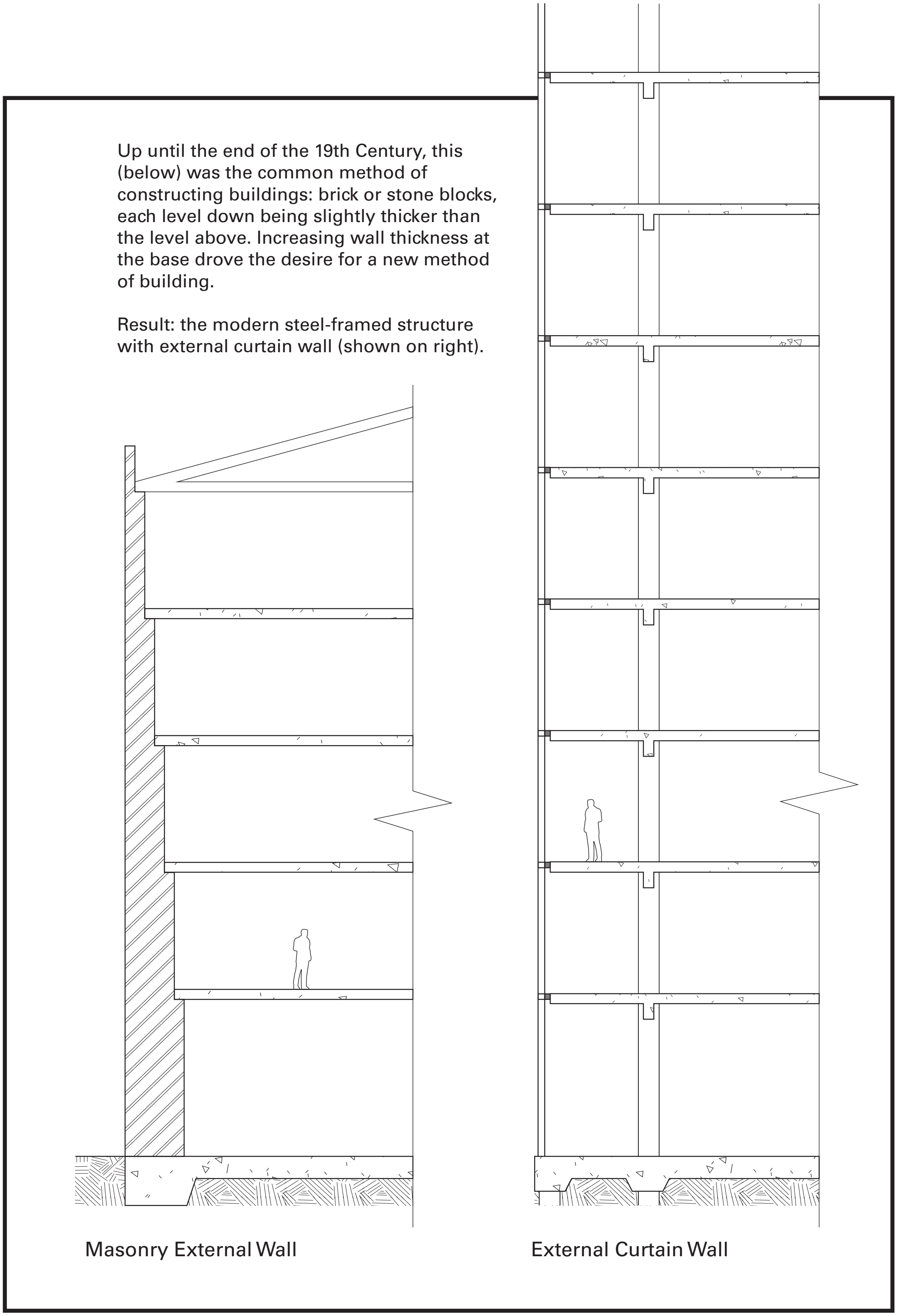

Figure 2.1 Masonry vs curtain wall

2.1 A quick history of tall modern buildings

Traditionally, European buildings were predominantly made of massive solid heavy materials like blocks of stone or a matrix of smaller units mortared together like bricks. Tall buildings layered stone on top of stone, forming an external wall that grew thicker at the base, but after several storeys, the load on the masonry got too heavy and the building could get no higher (refer to Figure 2.1). In Central Business Districts (CBD) built worldwide in the late 1800s and early 1900s, masonry buildings were often built right up to the front boundary and hard up against buildings on either side. This created a wall of buildings: streets became canyons of brick and stone. Manhattan Island in New York is famous for this canyon effect, thankfully brought into focus by the 1916 zoning byelaws that introduced mandatory setbacks at certain levels for light and air. Many cities, worldwide, were built like this right up until the end of the 1940s. World War II destroyed much of this style of architecture right across Europe and broadly speaking, when it came to rebuilding after World War II, buildings around the world were built differently. Materials were in short supply after the war; masonry simply wasn't fast enough and couldn't go tall enough for office buildings, and there was a new architectural movement that had come out of the Bauhaus in Europe and was taking over the world: Modernism.

With the advent of the crisp, clean, minimalist, Bauhaus design ethos, buildings inspired by the Modernist movement have been built all over the planet. Multi-storey buildings go hand in hand with Modernism. The invention of the steel column and beam system changed everything as a means of constructing buildings and allowed architects and builders to do away with solid load-bearing walls. Very simply, it permitted an architect to design a building that had thin, strong, vertical columns, connected by strong narrow beams supporting large areas of open floor space. This could make a building possible with no external load-bearing walls in a very industrial means of construction (refer to Figure 3.1).

The external façades of most of the modern towers you see around you can be removed and replaced if need be – there is no reliance on the visible external wall for support. This is exemplified by Lever House (refer to Figure 16.9) in New York where a tall Modernist tower rose from a pedestrian plaza and low-level podium (architect: Gordon Bunshaft of Skidmore Owens and Merrill: 1952). Many thousands of Modernist tower blocks have risen since: few are as spatially well-proportioned and carefully detailed as Lever House.

Throughout the 1960s and 1970s the typical tall building approach was a 2–3 storey podium of building built up to the street frontage, with a tower springing up behind surrounded by daylight and fresh air. Some buildings had towers descending to the ground and meeting the pedestrian plane in a public plaza. In the 1980s, office towers in many cities were also often rotated at 45 degrees on-site

to fit the planning regulations (such as Auckland), breaking up the line of the street to allow more fresh air and sunlight to surround the building. By the 1990s, tower buildings around the world were becoming curved and more freeform in shape and since the 2000s, computer software allows for extremely adventurous shapes for tower construction. We are now in a situation where almost anything is possible in terms of design. However, there is one thing that will always stay as a constant focus for us, as Eminem sang in *8 Mile*: '…back to reality: ope, there goes gravity' (Mathers: 2002). Gravity should be an architect's number one concern: it certainly is the engineer's concern. In New Zealand and other seismic areas, earthquakes are a close second.

In the ever-changing world in which we live, there are few hard and fast rules dictating the exact form of buildings, so that plazas, podiums, Modernist towers and freeform super-modern curving shapes can all be valid responses to the design of the building. However, all of these options have several basic premises that need to be addressed: the building form has to maximise floor space, it has to make the best possible use of the site, it has to be pleasant to occupy and most of all, it has to align with the client's budget expectations – the client will remind you of that often!

2.2 Floor to floor heights

Three key dimensions govern the gross size of your building: the size of the floor plate, the number of storeys and the height of each floor (Figure 2.2). The 'floor to floor' height will vary depending on the span of the beams between columns, the method of construction and the amount of services required in each ceiling on every floor. The floor to floor height is measured from finished floor level (FFL) of one floor to FFL of the next floor: normally the same height above the last floor for all the office floors (refer to Table 2.1).

The 'floor to ceiling' height, on the other hand, is the most important thing for the tenant leasing the space. The floor to ceiling height needs to be clear of any obstructions or intrusions to enable any office partitions to be constructed to a standard, constant height.

For most office buildings, above the ceiling there will be all the services like air ducts, lighting, sprinkler pipes and wiring. This needs to exist in the same physical zone as all the floor beams for the floor slab over. Altogether that makes up about 1.0m to 1.4m of structure and services, which sets out your typical floor to floor height (refer to Table 2.1). This will vary as the beam depth and slab thickness vary (refer to Figures 2.2 and 14.1).

Table 2.1 Floor to ceiling vs floor to floor – clear heights needed – indicative only

	Car parking buildings (minimum)	**Residential** bedrooms (minimum)	**Basic quality offices** (minimum)	**Good quality offices**	**High Quality offices**	**Retail** (varies)
Floor to Ceiling in m (feet & inches)	2.1 (6′ 10.6″)	2.4 (7′ 10.5″)	2.5 (8′ 2.4″)	2.7 (8′ 10.3″)	3.0 (9′ 10.1″)	4.5 (14′ 9.2″)
Floor to Floor in m (feet & inches)	Varies on span	2.7 (typical) (8′ 10.3″)	3.5 (typical) (11′ 5.8″)	3.8 (typical) (12′ 5.6″)	4.2 (typical) (13′ 9″)	5.5 (typical) (18′ 0.5″)

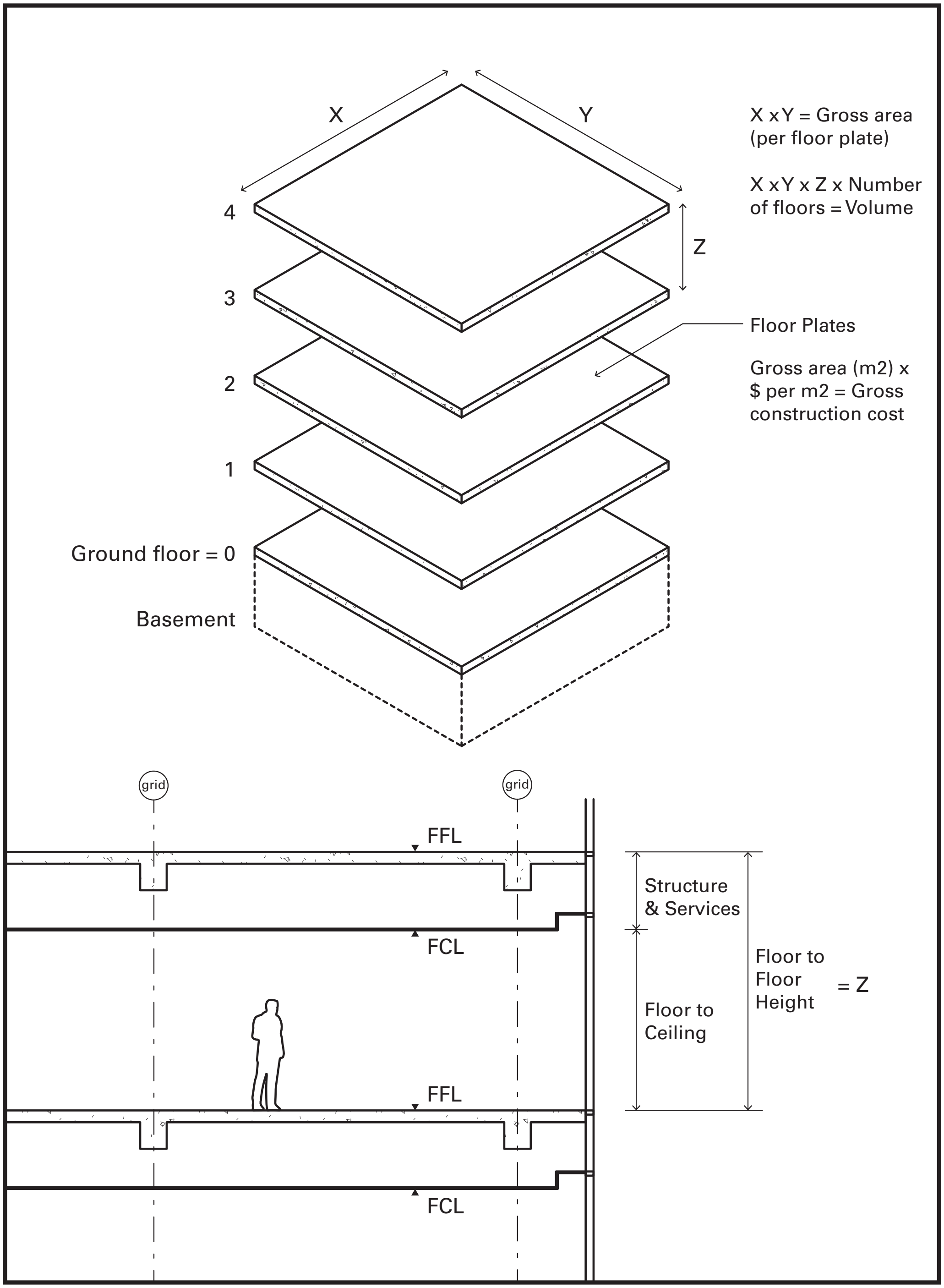

Figure 2.2 Floor to ceiling, floor to floor

2.3 The grid

A grid helps plan out a building and helps builders work to a plan. The use of a two-dimensional grid to set out the building and control its dimensions is a common planning device, used on most large buildings for the last few thousand years. Grids do not necessarily have to be rectangular: after all, Stonehenge (architect: unknown) has a radial grid, as does the Gherkin (architect: Foster and Partners). The grid lines become a highly useful common reference point to locate all building elements in the vicinity, regardless of where and when they occur in the construction process.

There are two types of grids that are important: a structural grid (which sets out where the primary structure is) and a planning grid (which is a system to help plan out where rooms, desks, windows and services might be located). The spacing of the two grids should coincide coherently, i.e. the structural grid should coincide at intervals with the planning grid (refer to Figure 2.3). But where? And how?

2.4 Structural grid

Here are some guiding principles to start with. The first step is to logically organise the structural grid. This decision will differ depending on the size and shape of the site, the structural system that the architect and engineer want to use, the ground conditions and the building size. The engineer will recommend the building to have a simple, regular (often square or rectangular), structural layout of columns to support the building, and the distance between the columns of the structural grid will depend directly on the depth of the beams and on the materials used. The resulting structural grid will *always* pass through the very centre (in the plan) of any structural columns and beams. Once the structural grid is set, it is crucial that you DO NOT change the grid.

Structural elements need to continue right down to the foundations so that the enormous heavy gravity load is safely located on solid ground. The columns will need to have direct support underneath from a thickened ground / basement slab as part of the foundations, while the support for that foundation slab may continue far underground: either on a ground slab directly above piles drilled into the ground, or on a raft of piles, or on a 'floating raft' of concrete. The advice of the Geotech Engineer will help the Structural Engineer design the foundation system and decide whether or not the building requires piles. Later, in Chapter 7 there will be more information on piles and foundation systems. For most buildings, assume that for every column, there will be at least one pile directly under the centre of the column, reaching deep into the ground.

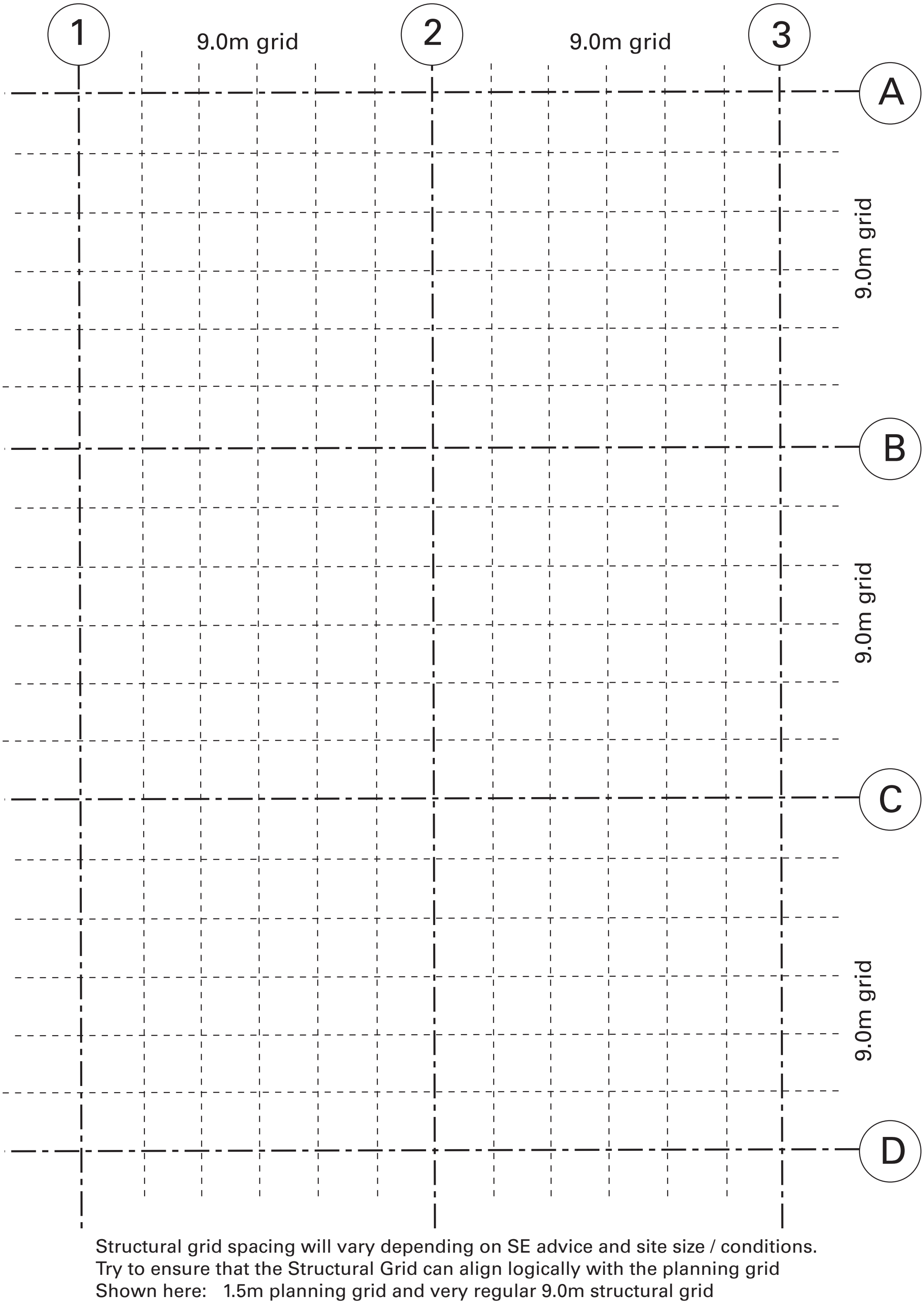

Figure 2.3 Structural grid coordination with planning grid

2.5 Planning grid

The office planning grid is at a finer scale than the structural grid: it relates more to people than to structure. Ideally the structural grid and the planning grid should coincide with the structural grid to repeat as a multiple of the planning grid. The planning grid should also try and tie in with the façade, particularly if there is a chance of offices constructed around the building perimeter. But how do you do this?

In the non-metric world, planning grids are based around imperial units, e.g. a repeating module of 2 feet, 3 feet, 4 feet, 5 feet or 6 feet. In our modern metric world, and allowing for modern furniture sizes, those dimensions have been metricised to be 600, 900, 1200, 1500 or 1800. Which one to choose?

Some buildings use 1200mm as the primary repeating module (such as Foster Associates' Hong Kong and Shanghai Bank in Hong Kong), which ties in well with material sizes based on a 2400 × 1200 (8′ × 4′) sheet size, but perhaps surprisingly, this is uncommon.

In Japan, buildings are often designed around the size of the traditional tatami mat, and this has been taken into the modern Japanese construction system with a metricised tatami mat size of 1800 × 900 (6′ × 3′) for plywood sheets. Rooms in Japan are still often quoted in terms of number of tatami mats rather than sq ft or m^2. One mat = approx. 1.62 m^2 (18 sq ft).

While it may seem logical for metric designers to use a 1000 module, planning module spacings at 1000 or 2000 results in spaces that are small and uncomfortable. Additionally, you will find very little furniture that is 1000 wide, so this dimension is not usually chosen. Office buildings, of course, always need to relate most to the people within and need to be highly flexible to suit any possible furniture layout.

In the 1950s, planning grids for open-plan office buildings were based around desking modules, with recommendations of 4′ 1.25″ (1250mm), 4′ 11″ (1500mm), 5′ 2″ (1580mm) or 6′ 2″ (1880mm) as spacing for seating (Joedicke: 1962). So many module sizes to choose from – how do you make a decision?

For a good plan module that works for most offices, I recommend that the planning module size of 1.5m (1500mm) is used (4′11″). American students may prefer to use a 5-foot module. The 1.5m module dimension is widely used for designing office buildings, as it easily scales up to 3m, 4.5m and 6m, all of which are comfortable spaces for an office. It also sub-divides neatly into either 3 × 500 slices or 2 × 750 widths – and 750 is a common desk width.

So, if we consider a potential 1.5m wide planning grid on the upper floors in both directions, how does that relate to the structural grid? Where do you place your columns? The simplest way is to make sure that the structural grid is a direct multiple of the 1.5m planning grid (refer to Figure 2.3).

2.6 Car parking grids

For buildings to be situated above basement car parking, integration of the structural grid should tie in not just with the planning grid on the upper floors but must also tie in with the car parking grid down below (refer to Figure 2.4). It is crucial that columns in the building above always sit above columns in the basements below to avoid having to build deep transfer beams. The spacing of the cars in the basement will, therefore, often have a strong effect on the planning of the building above (Henley, 2007). Although the size of cars can differ enormously, car park space planning assumes that a standard sized space will accommodate 90 per cent of cars.

Standard car park sizes differ between various countries and can even differ between cities in the same country, but typically for most countries around the world, a car park will be based on a module 2.5m wide × 5.5m long (8′ 2″ × 16′ 5″). Most importantly, room must be left for the structural columns to be integrated into this layout as well. If all cars are about the size of a Honda Civic, a 2.5m wide spacing permits 800mm (2′ 7.5″) between parked cars to open the car doors. After all, you are unlikely to get two Rolls Royce limousines parked next to each other in an average office building unless your clients are very, very wealthy. Maybe for those office schemes in Dubai. . .

Bigger standards apply in America of course: 2.75m wide × 6.1m long (9′ × 20′) is typical and this may rise in size, as America continues to sell pick-up trucks like the Ford F150 (America's biggest selling vehicle in 2018; for sizes, refer to table 2.3 below).

Room must be left for a 6–7m (19′ 8″ to 22′ 11″) wide central vehicle manoeuvring aisle. A width across a car park will often be based around a 5m–7m–5m rhythm for car-parking spaces, as long as it can integrate with spacing for structural columns. Cars are bigger in America, so allow more room there and assume a

Table 2.2 Car parking spacing: coinciding between structural and planning modules

Car parking	2 cars per bay	3 cars per bay	3–4 cars per bay	4 cars per bay	5 cars per bay	5–6 cars per bay	6 cars per bay
Bay width in m (feet & inches)	7.5 (24′ 5″)	9.0 (29′ 6.3″)	10.5 (34′ 5″)	12.0 (39′ 4.4″)	13.5 (44′ 3.5″)	15.0 (49′ 2.5″)	16.5 (54′ 4″)
Planning multiple × 1.5m bays	5 × 1.5	6 × 1.5	7 × 1.5	8 × 1.5	9 × 1.5	10 × 1.5	11 × 1.5
Comments	Excellent for 2 cars	Excellent for 3 cars	Tight for 4 cars	Excellent for 4 cars	Excellent for 5 cars	Excellent for 5 cars	Excellent for 6 cars

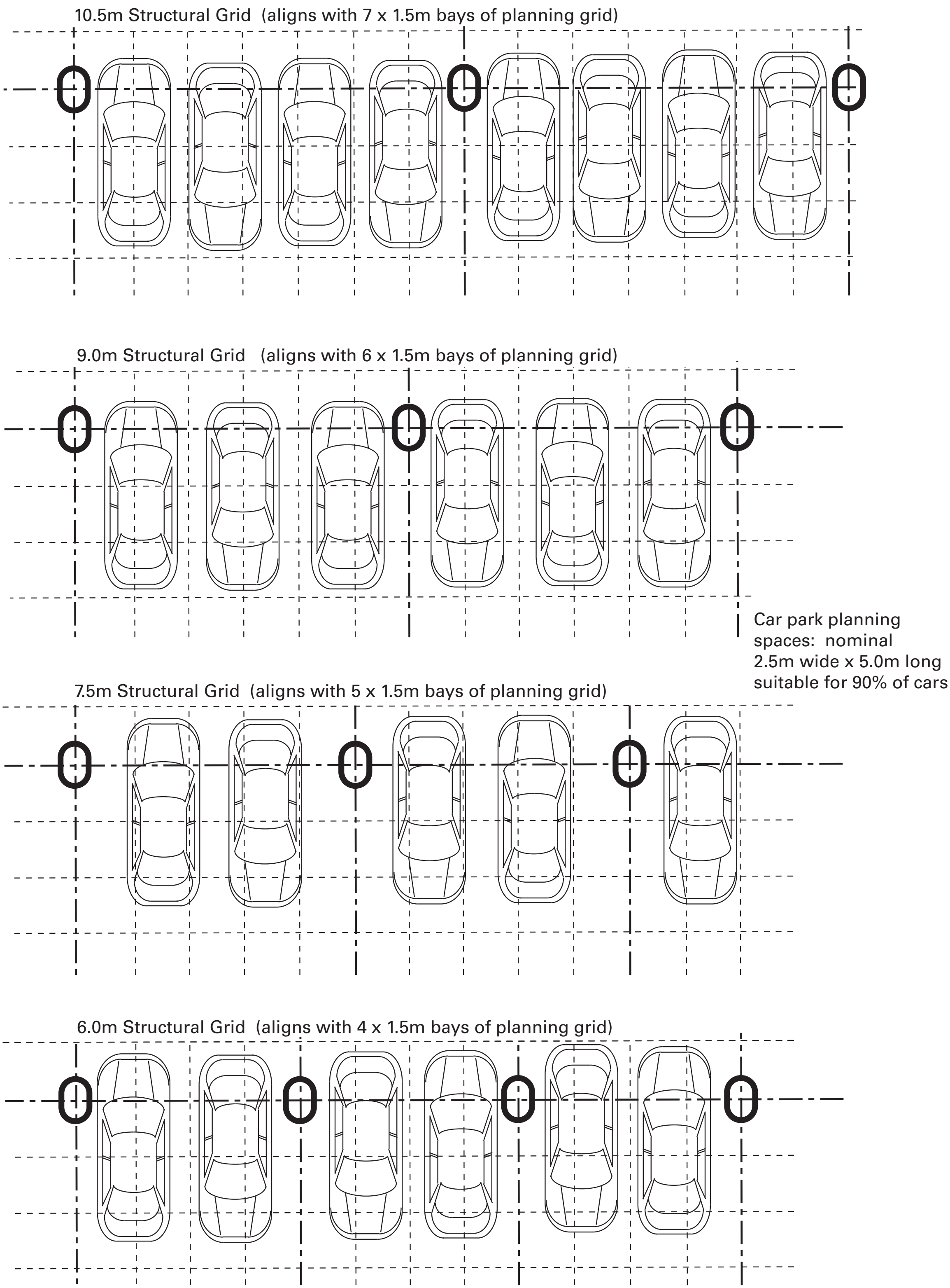

Figure 2.4 Structural grid integrating with planning grid and car parking grid

Table 2.3 Some worldwide typical car sizes (dimensions rounded – not including wing mirrors)

Cars	**Smart 4Two** (micro)	**VW Polo** (sub-compact)	**Honda Civic** (compact)	**Mazda 6** (mid-size)	**Rolls Royce** (luxury)	**Ford F150** (truck/ SUV)
Length in m (feet & inches)	2.7 (8′ 10″)	3.95 (12′ 11″)	4.4 (14′ 5″)	4.7 (15′ 5″)	5.8 (19′ 0″)	6.2 (20′ 4″)
Width in m (feet & inches)	1.6 (5′ 3″)	1.68 (5′ 6″)	1.7 (5′ 7″)	1.8 (5′ 11″)	2.0 (6′ 6″)	2.0 (6′ 6″)
Height in m (feet & inches)	1.55 (5′ 1″)	1.45 (4′ 9″)	1.44 (4′ 8.7″)	1.45 (4′ 9″)	1.63 (5′ 4″)	1.95 (6′ 4″)

spacing of 17′ – 24′ – 17′ is needed. More space needs to be allowed where the car is parked against a wall to allow doors to open comfortably, and of course, vehicle access ramps are long and take up a lot of space in basement car parking too, with a maximum slope of 1 in 8 being common.

The position of your neat simple grid of columns in the basement will affect the layout of desks and offices 50 floors above the basement and vice versa: the position of columns in office spaces way up high will have an effect on parking down in the basement. Take time to set it right and lock it in early on.

In the not-too-distant future, all this concern about integrating with car parks may be irrelevant if we start doing away with the need for car parks in buildings due to autonomous self-driving vehicles. Even small pod-like vehicles may become more normal with less car use overall, while electric scooters are becoming a big (small) thing in 2019. I'm still waiting for hoverboards!

However, bicycle parking is already a very important part of modern office design, and secure bike parking and clothes-changing facilities for cyclists are increasingly design considerations for building design. Leave extra space for bikes and e-bikes – they are going to become increasingly popular means of transport around a city. But we're not rid of cars yet, so for the immediate future, thinking about car park design is still integrally important to the design of the building above.

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03

Chapter Three

Structure: steel

Structure: steel

Guy Marriage

3.0 Structure

A multi-storey building will typically have a structural system supporting the floors based around a strict, simple, structural assembly of columns and beams. The columns will be laid out to a structural grid and take all the gravity load of the building down to the foundations. The beam is the horizontal load-bearing element and spans directly between each vertical column. The floor slab at each level will sit on top of those beams. This is the system of building that we use today for almost every tall building – vertical columns, horizontal beams, a slab over the top and an external non-load-bearing façade. The floor plates will be simply shaped, with as few columns as possible that interrupt the internal space.

In small towers, i.e. low-rise buildings, the primary load experienced by most buildings will be gravity. In active seismic areas like Japan, Chile, California, New Zealand and Italy, the primary concern for most tall building designers will be the seismic forces generated by earthquakes: lateral forces shaking the ground beneath the building from side to side and even generating considerable sudden forces upwards. We discuss these issues more in Chapter 6.

In tall buildings and especially in super-tall buildings, the lateral wind loadings can also be immense – larger even than forces of earthquakes. A building like the Burj Khalifa (world's tallest building) has been designed with three giant buttresses to combat extreme lateral wind forces due to the immense force of high wind speeds hitting the tall façades / elevations high up on the building (refer to Figure 6.6). These wind forces will be higher at the corners of the building – hence, many tall buildings are being designed with aerodynamics in mind. Wind forces can act on a building façade in both a negative as well as a positive manner – i.e., the wind doesn't just push against a building; sometimes it actually sucks.

To stop this pressure on the façade and to resist lateral forces, all buildings need bracing. Lateral forces such as wind load and earthquake load may be resolved in lower-height buildings largely via the strength in the column/beam junction via a 'moment frame' (Charleson: 2005). Taller buildings will require far more bracing, i.e. separate diagonal braced elements or shear walls in the building to resist those forces (for more on this, refer to Chapter 6). The type of bracing will depend on the materials used, so let's examine the possible materials.

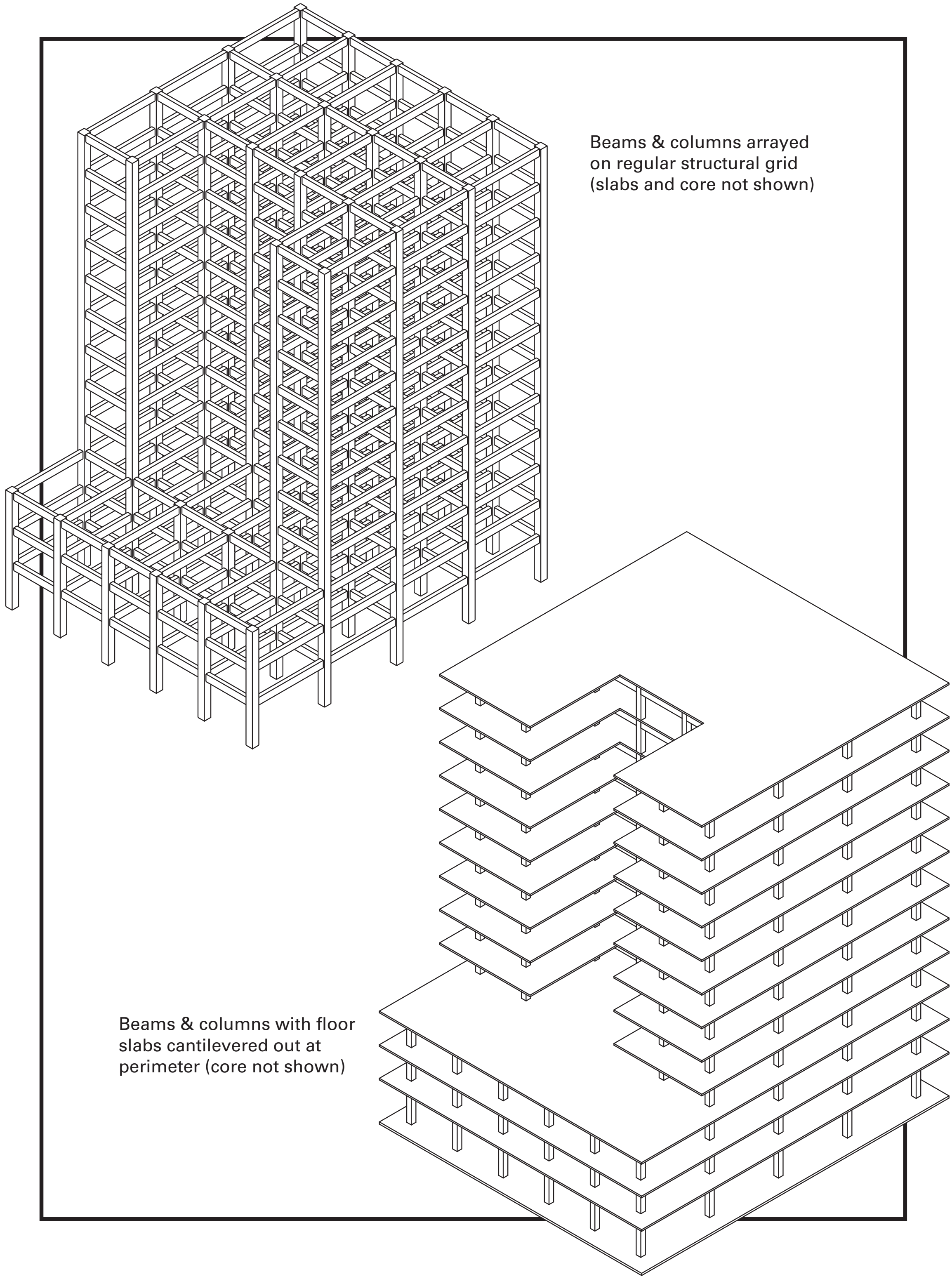

Figure 3.1 Beam, columns, slabs

3.1 Structural framework materials

Structural systems for multi-storey buildings are usually either steel, reinforced concrete or a combination of the two. Steel columns are less bulky than reinforced concrete columns, but steel is badly affected by extreme heat and so *always* needs fire protection: steel melts at 1375° C (2507° F). Concrete columns will be slightly larger than steel but have inherently inbuilt fire resistance due to the heat-resistant mass of the concrete protecting the steel reinforcing (see Chapter 4). Beams connect those columns and typically a steel column will support steel beams, and a concrete column will support concrete beams.

More recently, the invention of beams and slabs of engineered timber makes timber a third structural option for some multi-storey buildings (see Chapter 5). Timber columns will be larger, but do not actually burn right through: the outer layer will char, and the inner part of the timber will stay intact. A building with timber columns will most likely have timber beams, as the timber beams are strong and light – much lighter than steel or concrete.

Element materials can be mixed (i.e. concrete columns with steel beams) but it is simpler to stick with one system to assist in construction detailing, and it makes life much more straightforward for the engineers when they have only one type of material to calculate. Columns are the most important part of any structure – if the columns fail, then the building risks collapse. But let's not talk about collapse – the building will be designed with the engineer and constructed so that will not happen. It is good to know a little more about the structural characteristics of each material you are going to build with. Let's start with steel.

3.2 The Materials

A steel foundry will smelt iron ore to create iron (Fe) by burning off all impurities through blasting the molten metal with oxygen (O). A small amount of carbon (C) is retained, mixed with the iron and this creates steel. More working of the steel and more additives of other elements can create different types of steel, including high-strength steel and stainless steel, with added chromium (Cr) and nickel (Ni). Steel is incredibly strong, dense and heavy – a cubic metre of steel weighs over 7.8 tonnes (about 17,200 lbs, or 4–5 cars), so usually only a thin slice of steel is needed (the actual weight will vary dependant on the alloys of the steel). Varying the thickness of steel just by a few millimetres can significantly affect its strength and weight. Steel is ductile, meaning that it can bend a little and spring back into shape easily without yielding. All structural steelwork needs to have adequate fire protection measures (refer to section 3.9 later in this chapter).

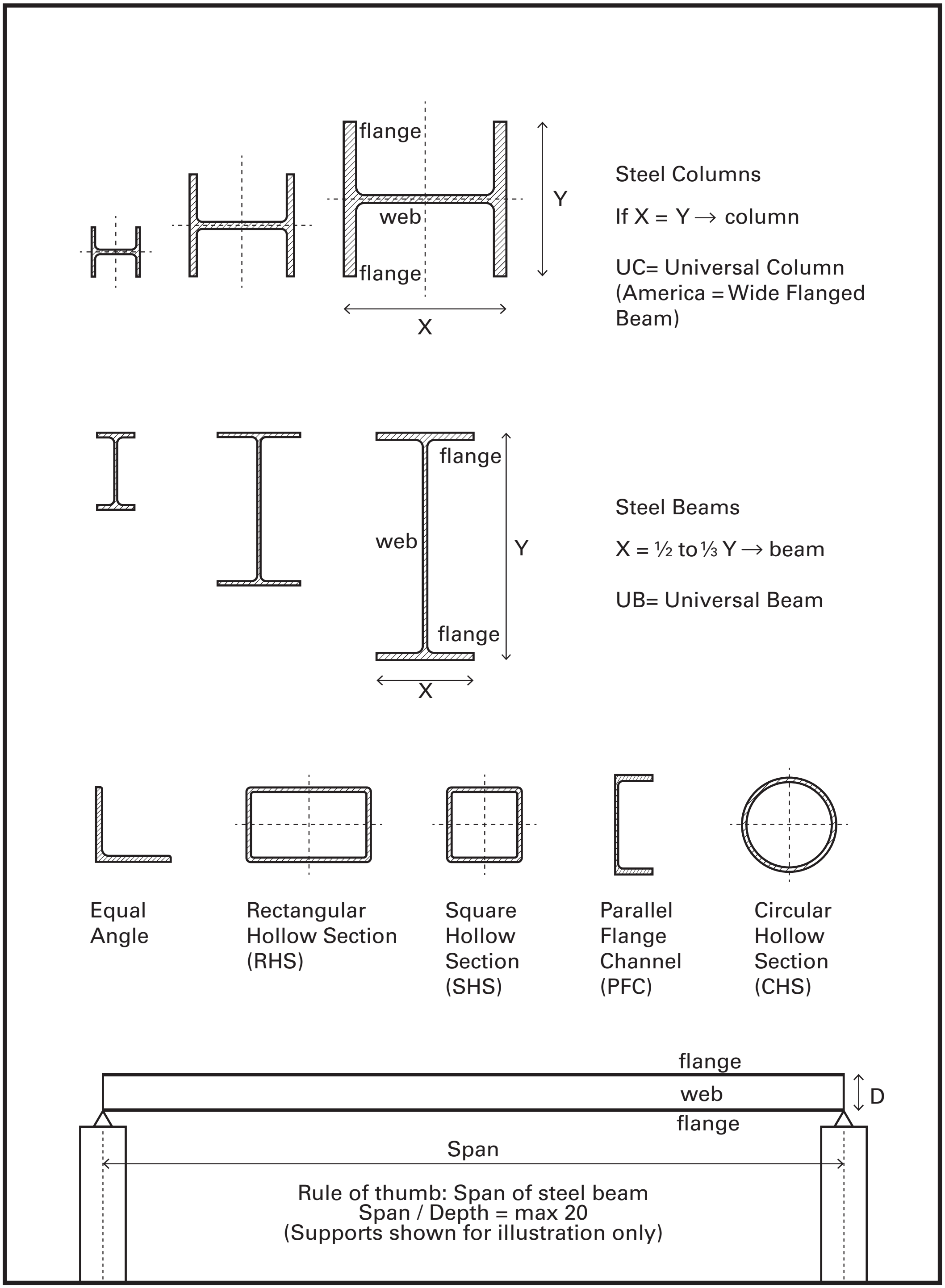

Figure 3.2 Steel sections

3.3 Steel structure – H columns

The construction of a steel-framed building typically involves mild steel columns with a cross-section shaped like a capital **H**, which is roughly an equal size in both the X and Y directions (refer to Figure 3.2). Columns have a web (the centre) the same length as the flanges (the part at each end). When steel columns were first developed, these flanges would have been fixed to the web with a row of red-hot steel rivets, but now they are simply hot rolled to precise shapes, including this classic **H** shape. The steel sections are all derived from the initial British sizing of steel in inches but in a globally applicable (metric) system. Modern steel sizes are known as Universal Column (UC) or Universal Beam (UB) sizing. This means the steel product will be made to a standard range of sizes in many countries around the world (refer to Table 3.1 and Figure 3.2).

Some countries still have their own range of mild steel beam and column sizes. America has American Standard Beams (ASB) and Wide Flange beams (designated with a W), both still measured in inches (Ching et al, 14). Europe has an HEA and HEB steel range, while in India they have Indian Standard Beams (ISMB). In other countries, like Australia, New Zealand and the UK, they use the UC sizing as standard.

Steel is specified (and usually costed) by weight per length: kilograms per metre length (kg/m) in the metric system, while in America it will be specified as pounds per foot (lb/ft). The heavier the column, the thicker the steel it is made from, and, therefore, the resulting member is stronger as it gets heavier. The heavier the structure is, the more expensive it will be. A column may have almost the same dimensions externally but with slightly thicker flanges it will have different weights and, therefore, a different strength. Table 3.1 shows column example sizes from the UC range, so you can see how they relate to the imperial sizes they are descended from. Larger sizes above 310 UC will typically be made to order.

Table 3.1 Steel column sizing

Columns	**200 UC**	**250 UC**	**310 UC**
Depth range in mm (inches)	203–210 (8″)	254–260 (10″)	305–311 (12″)
Width range in mm (inches)	203–205 (8″)	254–256 (10″)	305–309 (12″)
Flange thickness in mm (inches)	11–14 (0.5″)	14–17 (0.6″)	15–25 (1.0″)
Weight range in kg/m (lb/ft)	46–60kg (30–40 lb)	73–90kg (49–60 lb)	96–158kg (64–106 lb)

A 310 UC will be a column about 310 × 310 (12″ × 12″) in cross-section. The actual sizes vary as the thickness of the column webs and flanges increase, so that you may have a 310 UC 96 (i.e. weighing 96kg per metre – about 64 lbs per foot) or a 310 UC 158 (i.e. weighing 158kg/m). In the latter case, the web and flanges are slightly thicker. The engineer will calculate how strong the column needs to be and will specify the size and strength of the column (and therefore the weight). On small steel columns, the flange is only about 10mm thick (refer to Table 3.1). On a really big structure, the custom-made columns may be something like 800 × 800 (32″ × 32″) in size, with web and flanges of 30mm thick (or more) and weigh several hundred kg per metre.

As steel is strong, but heavy and expensive, the engineer's job is to use the lightest steel size that they can to adequately resist the gravity and lateral loads. While the columns may come in a single-storey height and be bolted together at every floor, it is more typical now that they will come to the site in a 2 or 3 storey length – as long as can comfortably fit on the back of a large truck, with web stiffeners and cleats (connector plates) already welded on. This will help accuracy and speed on the construction site. Bolt holes in the cleats should line up accurately, and a tap or two from a large sledgehammer will normally see the building structure click (loudly!) into place.

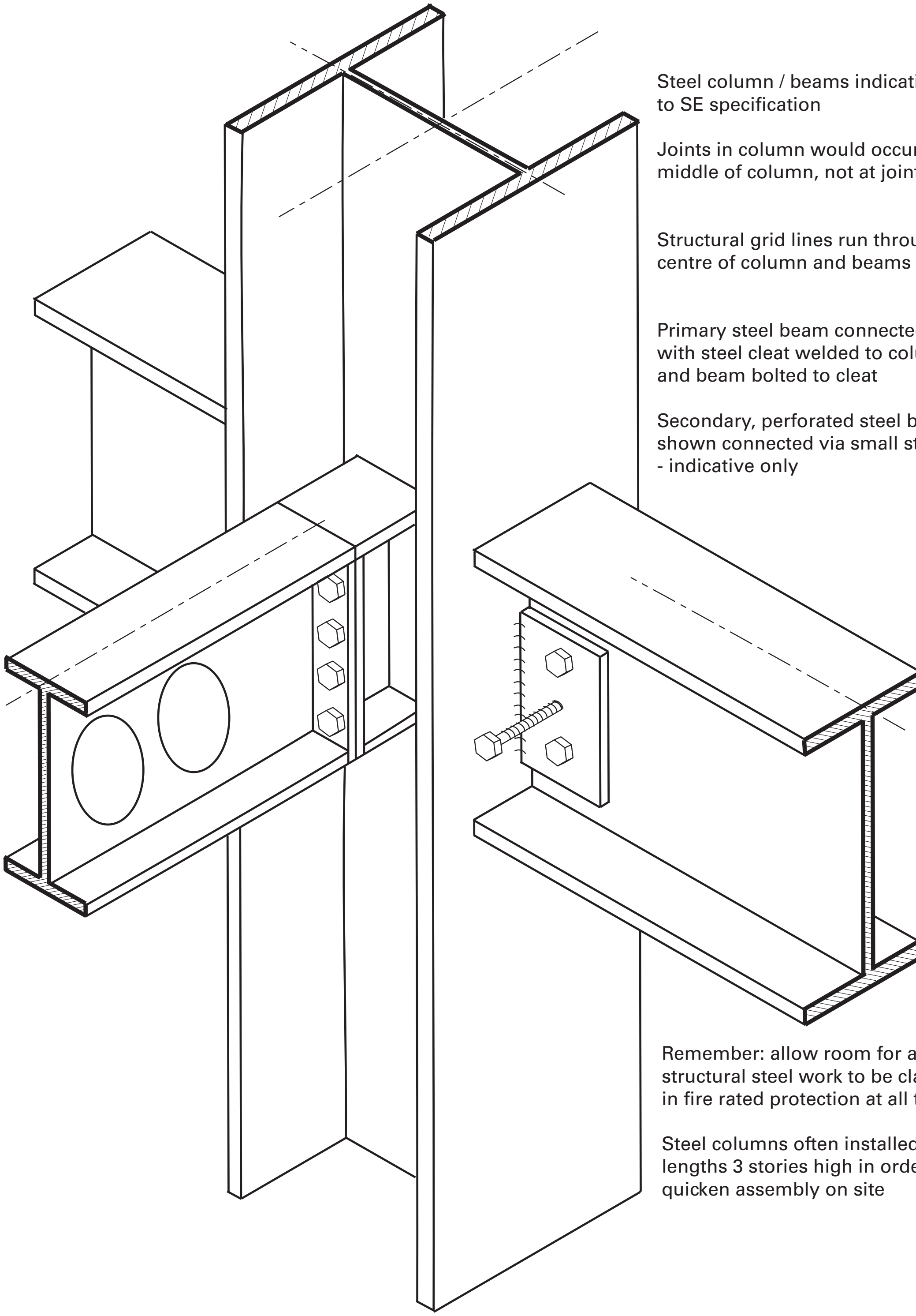

Figure 3.3 Typical steel column/beam junction (slab not shown)

3.4 Circular Hollow Section steel columns

Steel-framed buildings can also use steel Circular Hollow Sections (CHS) for columns: a little more expensive than a UC, but they achieve a great appearance when left exposed internally (refer to Figure 3.5). Columns made from CHS work well in certain structures, as their load characteristics have identical strength in all directions, and they can often be effectively fire-rated from the inside by filling them with concrete which absorbs the heat. Note that while *columns* can be made from CHS, *beams* generally are not. CHS are often used as structural bracing members in steel-framed buildings.

Square Hollow Sections (SHS) and Rectangular Hollow Sections (RHS) are a lot less common as columns in large buildings, as they are not as efficient – they use more steel to achieve much the same strength as an **H**-shaped column (refer to Figure 3.2). On some projects, steelwork shapes and sizes will only be available as specially constructed members, calculated and specified by the SE when the sizes required are larger than standard steel sizes. Specially fabricated steel columns may be made as box-section columns, for instance, requiring special and extensive welding along the seams. The new tall Commercial Bay tower being erected in Auckland, New Zealand (architects: Warren and Mahoney, 2019), has extensive custom-made rectangular box-section columns and bracing elements.

3.5 Steel structure – I beams

Columns in a steel-framed building are connected together by beams at every floor – usually every column has floor beams connecting to it from at least two directions (and normally four directions). Typically, all the tops of the beams should align at the same level. While the actual structural steel profile is set at the time of rolling the steel from red-hot forged steel in the steel foundry, the beams and columns normally have considerable work done to them in the steel fabricator's factory before they reach the site. Web stiffeners are installed where stress levels are expected to be high. Bolt holes are pre-drilled. Small pieces of steel called cleats are welded onto the columns and beams in the factory to speed up erection/assembly on-site. This achieves high-strength joints under good controlled conditions so that they can be simply bolted together at the final assembly (refer to Figure 3.3).

Extra pieces of steel are welded into the flanges as stiffeners at any joints, as welding is a process that makes a joint as strong as the original steel itself. The Structural Engineer (SE) will specify all welded connections, such as fillet welds (the steel weld forms a small raised scar) or butt welds (a cleft in the steel is welded and then ground flat). Critical structural welds can be x-rayed or otherwise tested before they leave the factory so that the building contractor knows that the steel members can support the building adequately. On-site, most of the fixings will be bolted together in order to speed up steelwork assembly.

Table 3.2 Steel beam sizing

Beams	200 UB	310 UB	360 UB	410 UB	460 UB	530 UB	610 UB
Depth in mm (inches)	198–207 (8″)	298–307 (12″)	352–359 (14″)	403–406 (16″)	454–460 (18″)	528–533 (21″)	602–612 (24″)
Width in mm (inches)	99–134 (5″)	149–166 (6″)	172 (6.7″)	178 (7″)	190 (7.5″)	209 (8″)	228 (9″)
Approximate Span in m @ 20:1 (feet)@ 20:1	4.0 (13′ 1.5″)	6.2 (20′ 4″)	7.2 (23′ 7″)	8.2 (26′ 11″)	9.2 (30′ 2″)	10.6 (34′ 9″)	12.2 (40′ 0″)
Weight range in kg/m (lb/ft)	18–30 kg (12–20)	32–46 kg (21–31)	44–57 kg (29–38)	53–60 kg (35–40)	67–82 kg (45–55)	82–92 kg (55–62)	101–125 kg (67–84)

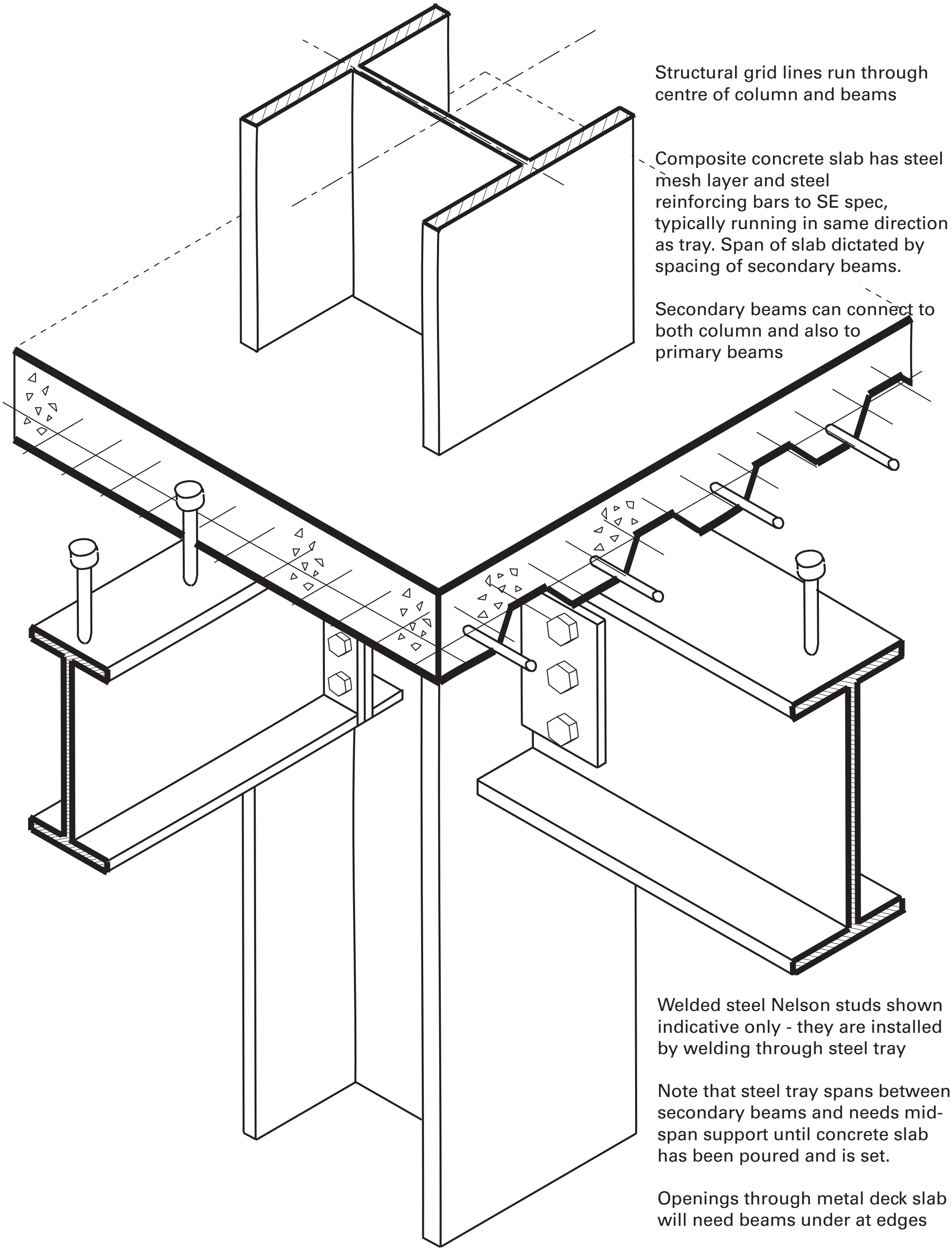

Figure 3.4 Typical steel column/beam/slab junction

3.6 Universal Beams

Steel beams – often still called I beams – are tall and thin: proportionally, about a third to a half as wide as they are deep. Beams have a much longer web (the centre) than the flanges (the two ends), as the beam is working heavily resisting the gravity loads that run vertically down the building. The Universal Beams (UB) sizing system means that a beam called a 610 UB 125 will be 610 (24”) deep and will weigh 125kg/m (83lb/ft) at about 230 (9”) wide. A rough guide is that a steel beam can comfortably span about 20 times its depth, so if columns are planned at every 9m (29’ 6”), then a steel beam to span that distance will be around 450mm deep (18”), and a beam 610 deep (24”) can span 12m (40’). That gives you a clue as to what sort of spacing the columns may need to be (refer to Table 3.2).

We can also easily forecast that a 610 UB 125 at 12m long will weigh at least 1500kg (125kg × 12m) i.e. 1.5 tonne (3306 lb), and at a rough price of new steel at approx. US$400/tonne, it may cost three to four times that cost when fabricated into a finished beam. The cost goes up again when cut and complete with cleats and welded stiffeners, etc. The size and shape and fixing points of a beam need to be thoroughly organised before manufacture. The wonderful thing about steel is that it can be cut and re-welded on-site if need be – the bad news is that it can still show those mistakes if the welds are not high quality. Steel beams can be completely recycled, which is great. Globally, about 60 per cent of steel is recycled and in the USA this rate rises to about 83 per cent of all steel: your old car may live on inside your shiny new steel beam.

All the holes are pre-drilled and cut with extreme accuracy in the steel fabricator’s factory (nowadays usually cut with a computer-controlled water-jet or plasma cutter). If the beam/column connection has only one bolt, this becomes a ‘pin joint’ and it means that the two members can swivel around each other. Normally, we don’t want pin joints at beam/column junctions and so there will be four or six bolts or more, depending on what the engineer specifies. Sometimes the engineer will specify a welded connection when absolute rigidity is required, and sometimes bolts are specified that will slip at a certain load so that the building can absorb energy under extreme quake conditions.

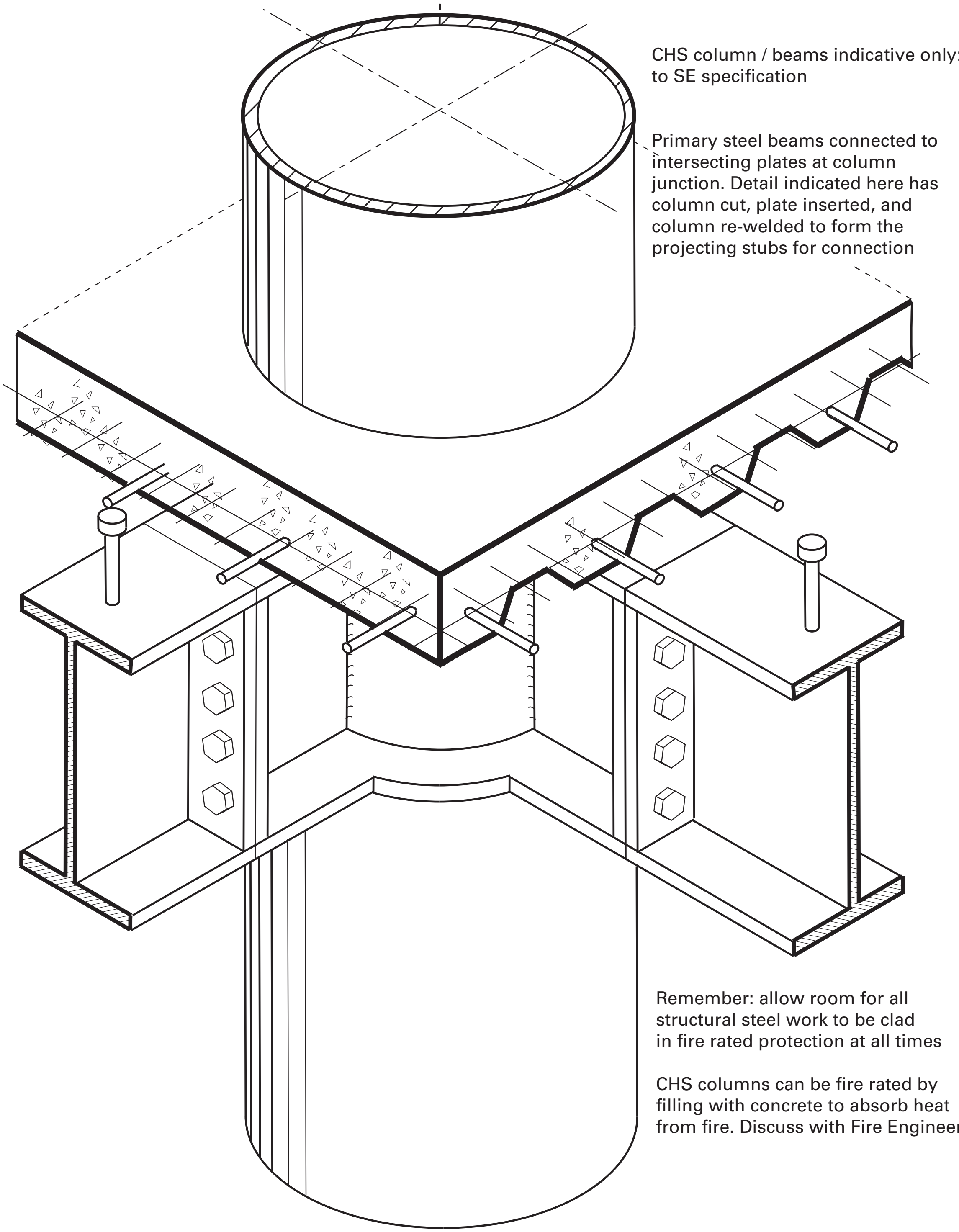

Figure 3.5 Typical CHS column/beam/slab junction

3.7 Speed and quality of steelwork

When the Empire State Building was being constructed in New York (architect: Shreve, Lamb and Harmon, 1931), connections were made with red-hot rivets that were hammered into place and which shrank as the steel rivet cooled down, ensuring a really nice tight fit: one of the reasons why the Empire State Building is still in such good shape today.

They worked fast back in those days too: during the construction of the Chrysler Building in New York (architect: William van Allen, 1929), building was proceeding at such a furiously fast pace that the Bethlehem Steel Works in Pennsylvania was pumping out steel beams and columns as fast as it could, getting them straight onto the train to New York (3 hours away). The beams were arriving on-site still warm from the foundry.

Nowadays, however, steelwork is often planned out months ahead and the raw steel beams may even (depending on the country you're in) be imported from overseas, leaving the local companies just the work to cut the correct beam lengths and fabricate the joints. Imported steel often comes from China or elsewhere in Asia, as they can make and sell steel cheaper than Western countries. Steel needs to be made to very high-quality standards. You may not be able to tell the difference in quality except through a microscope or via testing, but a deficit in quality can have a significant effect on strength and longevity of the steel. Sometimes there are scandals about companies importing cheap, poorly made steel: the issue is a political minefield. It is very hard to make a profit in the steel world today, as business is so cut-throat: all over the world, steel plants are being bought out and closed down. Nonetheless steel is a very strong, highly recycled, easily worked structural solution for buildings and so is still vitally important for construction of large buildings today.

3.8 Steel tray decking for floor slabs

A steel-framed building will typically have a lightweight profiled steel tray decking (often shaped like a series of trapezoids and commonly known by their trade names) spanning from beam to beam, fixed to the steel beams below with big steel pegs known as arc-welded steel studs, shear studs or Nelson studs. The steel studs are installed by using a sharp blast of electricity to burn a hole right through the steel decking, physically arc-welding the stud to the beams and forming a rigid connection. Steel mesh is then laid over the top of the steel decking and a concrete topping is poured, with the mesh in the concrete enabling the composite slab to work as one large diaphragm floor (refer to Figures 3.4 and 3.5). The concrete slab will be between 75mm at its thinnest and normally about 150mm at the thickest point: again, the SE will specify this. Buildings with steel composite floors suffered from little damage in the 2016 Kaikoura quakes in New Zealand, whereas several buildings with precast concrete floor systems suffered reasonably extensive damage to the precast flooring. This may mean that more engineers will be specifying steel decking in seismic zones in the future.

Steel tray decking for concrete floors is common in NZ and many other places around the world, but it is important to note that the strength of steel decking is highly directional: this means that it will have good strength in one direction but little strength in the other direction. This can affect the position and sizes of holes cut for risers and penetrations through the slab, etc. Steel tray decking is very floppy and bouncy before the concrete topping is added and cured. Because of this bendability, steel tray decking will usually require extensive propping to the middle of the span while the concrete is being laid and during the curing period. When set, the concrete topping, the steel tray deck and the shear studs combine to form a composite beam in the direction of the span.

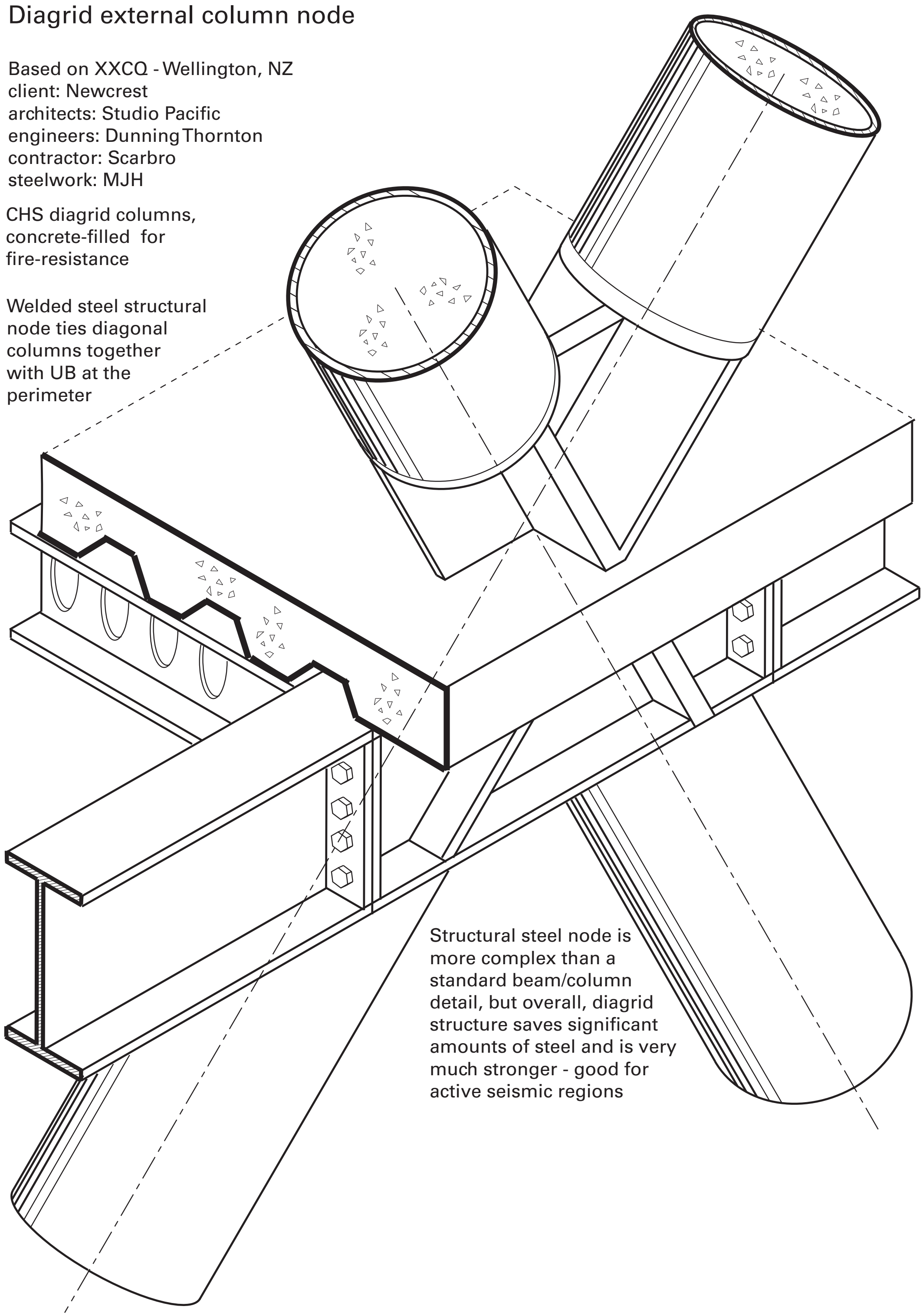

Figure 3.6 Column node on external diagrid building

Detailing

This includes items as small as the diameter of bolts on structural connections, as well as the size and placement of reinforcing steel. No architect nor student of architecture should include notes such as ‘4 × M12 bolts’ (4 × half inch bolts) unless they really truly and honestly know that four bolts (metric size 12mm diameter) can carry that load safely. Have you spoken to an engineer about your drawing details? If not, then do NOT specify these items. If you are pretty sure, but do not know for sure, just note: ‘bolted connection to SE’s specification’. Do not expose yourself to risk by specifying things you have no knowledge of or authority to specify. On any real-life project, ask the SE to specify all structural sizes.

3.9 Fireproofing steel

Steel structural framing is incredibly strong but can become weak when the temperatures are extremely hot, so the steelwork will always need to be fire protected in some way. This will typically be done with an external layer of fire-resistant material, either hard or soft, but completely non-combustible, such as heavy protective fire-resistant boards, soft fire-protective wrapping or sprayed-on vermiculite. The visual simplicity of the steel is therefore typically covered up and hidden from view. Older sprayed-on fire protection used to be asbestos-based – now illegal to be installed, as it is proven to be the cause of life-threatening lung diseases.

Steelwork such as CHS columns can be filled with concrete, which absorbs heat from the fire and helps stop steel getting too hot. Cost, performance and availability will dictate which fire protection system is specified. For standard steel column sections, the need to fire-rate often means the columns are covered in a bulky plasterboard box over the top of the fire-rating. Steel beams, being more commonly hidden in the ceiling, may have different fire-rating systems – perhaps sprayed on rather than solidly boxed.

Increasingly common nowadays, fire protection can also be done with a painting system known as an 'intumescent paint' (tumescent means 'to swell'), or 'intumescent fire coating', where the chemicals in the special paint will swell up and provide a thick layer of insulation – but only when they get super-hot. However, intumescent coatings are expensive and limited in scope and may not provide all the fire-rating necessary for large structural members such as a column. If you want a system that is inherently fire-rated, you will need to look at concrete.

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04

Chapter Four

Structure: concrete

Structure: concrete

Guy Marriage

4.0 Concrete

Concrete is a human-made substance, with a key ingredient being Portland hydraulic cement. Cement itself is created through a chemical reaction induced between clay and limestone. The calcium oxide (lime) mixture is mixed, dried and then fired in large kilns until it breaks down into a fine dry powder. This extremely energy-intensive procedure for cement produces much CO_2 gas. One tonne of CO_2 is produced for every tonne of Portland cement that is made, so one cubic metre (m^3) of concrete will emit approximately one tonne of CO_2 in the process and end up weighing around 2500kg.

When the Portland cement is combined with aggregate (crushed stone) and water, the resulting mixture is liquid and sloppy at first. Poured into formwork, it takes on any shape you require. The water sets off a chemical catalyst reaction in the calcium-based cement and 'hydration' occurs – a chemical process where heat is given off, the water is transformed and the cement mixtures bond tightly to the aggregate via a matrix of crystals. The resulting concrete sets rock hard.

Concrete was used long ago by the Romans and indeed the dome of the mighty Pantheon in Rome is all Roman-era concrete, still in excellent condition and still the world record holder for largest unreinforced concrete dome in the world (43.3m or 142 ft diameter). For a 2000-year-old building, it has a remarkably sophisticated construction with a coffered ceiling and several different types of concrete used, with mixes using variable amounts of aerated pumice and tufa with pozzolana (a volcanic dust from Mt Vesuvius) to achieve a very lightweight result. We still use volcanic ash and pumice in some admixtures today, but the modern equivalent is the use of 'fly ash' from industrial chimneys, which can sometimes be used in place of cement – to save from further production of CO_2.

When wet concrete is poured on-site, it is called 'in-situ' concrete (Latin for 'made in place'). All foundation concrete is in-situ, i.e. cast hard against the solid earth the building sits on. Later on, we explore foundation systems in more depth. But first, how do we form concrete to suit our aims?

4.1 Reinforced concrete structures

Concrete is good in compression, as hard to crack as stone. Concrete is *not* good in tension, so we add rods of reinforcing steel to it – the two materials work well together. The steel performs excellently in tension and is woven in a matrix that bonds together with the concrete as it sets. The result is steel-reinforced concrete: normally just called 'reinforced concrete' (RC). Formwork (also known as shuttering or boxing) is erected as a box around the edge of the ridged steel reinforcing bars (or rebar) and then high-strength concrete is poured into the formwork and vibrated so that any entrapped air escapes. The concrete smoothly fills up the empty spaces surrounding the steel and sets to the shape of the formwork. Adequate cover to the steel is needed to stop rust, as that can cause extreme damage to the concrete over time. The concrete needs at least 35mm cover of wet concrete over the top of any steel rebar – more if it is exposed to salty wind and rain.

Shuttering and formwork

The great thing about the fluidity of wet concrete is that virtually any shape can be created. Architects and engineers like Pier Luigi Nervi and Felix Candela used the 'plastic' nature of wet concrete to form many exciting thin-skinned building forms back in the 1950s and 1960s. Some people still create genius designs with curving concrete even today: engineer / architect Santiago Calatrava is well known for his curving designs, while few architects could provide as curvaceous a form in their buildings as architect Zaha Hadid could. The ultimate master of curved concrete structures was, of course, Antonio Gaudi, with the work in Barcelona at the Sagrada Familia being an ongoing example – and a very tall expressive building. For most tall office buildings, however, sadly, most of the concrete work is simply flat and vertical.

Concrete will take on any surface pattern in the formwork, so if you want a rough timber texture to the concrete, you need to build the formwork from rough timber. Conversely, smooth flat steel formwork will create smooth flat concrete when complete. Architects Herzog and de Meuron are creating amazing patterns etched into the surface of the concrete through printing patterns in reverse on the formwork. Most typically, special finish tough construction plywood is used to create the formwork, with a slightly oily easy-release finish. Wet concrete can exert considerable forces on the formwork, especially at the base of the pour, so the contractor needs to take considerable care over the quality of the formwork – usually braced and reinforced with removable 'strongback' beams on all sides, bolted together so that they cannot burst open or move in the slightest.

While liquid at first, the concrete sets reasonably quickly so the shuttering can be removed after 24 hours or so. The concrete surface is left exposed while the

concrete is still ‘green’, and it continues to emit heat as it cures and the cement hydrates. Concrete is kept cool and moist while setting to ensure the mass does not dry too fast and shrink or crack rapidly. Concrete gains a lot more strength in the first week but does not achieve its design strength until a full month later.

Shotcrete

There are other ways of applying concrete to a surface of course, with one particular method known as ‘shotcrete’ (a.k.a. gunite or sprayed concrete). Here, quick-setting (rapid-hardening) concrete is sprayed onto a wall, often sprayed over the top of a layer of metal reinforcing bars. The shotcrete sets quickly, so formwork is not needed, and the finished concrete can be trowelled flat or plastered over to create a smooth flat surface. This sort of concrete application is more typically used in earthquake strengthening works or in basement retaining walls, etc. On occasions, the shotcrete mixture itself may be reinforced with small plastic or metal pieces of reinforcing to assist in the binding together.

Concrete cracks

Concrete will shrink as it dries and it can crack as it shrinks, especially in slabs. Get used to it. Note that the top surfaces of suspended slabs are under compression and so typically floors suspended above ground will not show cracks in mid-span.

Concrete slabs poured on grade (i.e. at ground level) are a different matter and generally may crack with irritating diagonal cracks near columns. To avoid cracking in slabs on ground, cuts can be made in the concrete slab about ¼ the way through the slab, but this needs to be cut in the first 24 hours of the slab being laid. With luck and good management, the slab may crack along this induced joint, but micro cracks can and will occur in the concrete, visible on the surface.

Plan out with the SE where the shrinkage control joints should be: position them under future internal walls if possible. Concrete should never show horizontal cracks in columns, as they are always under compression.

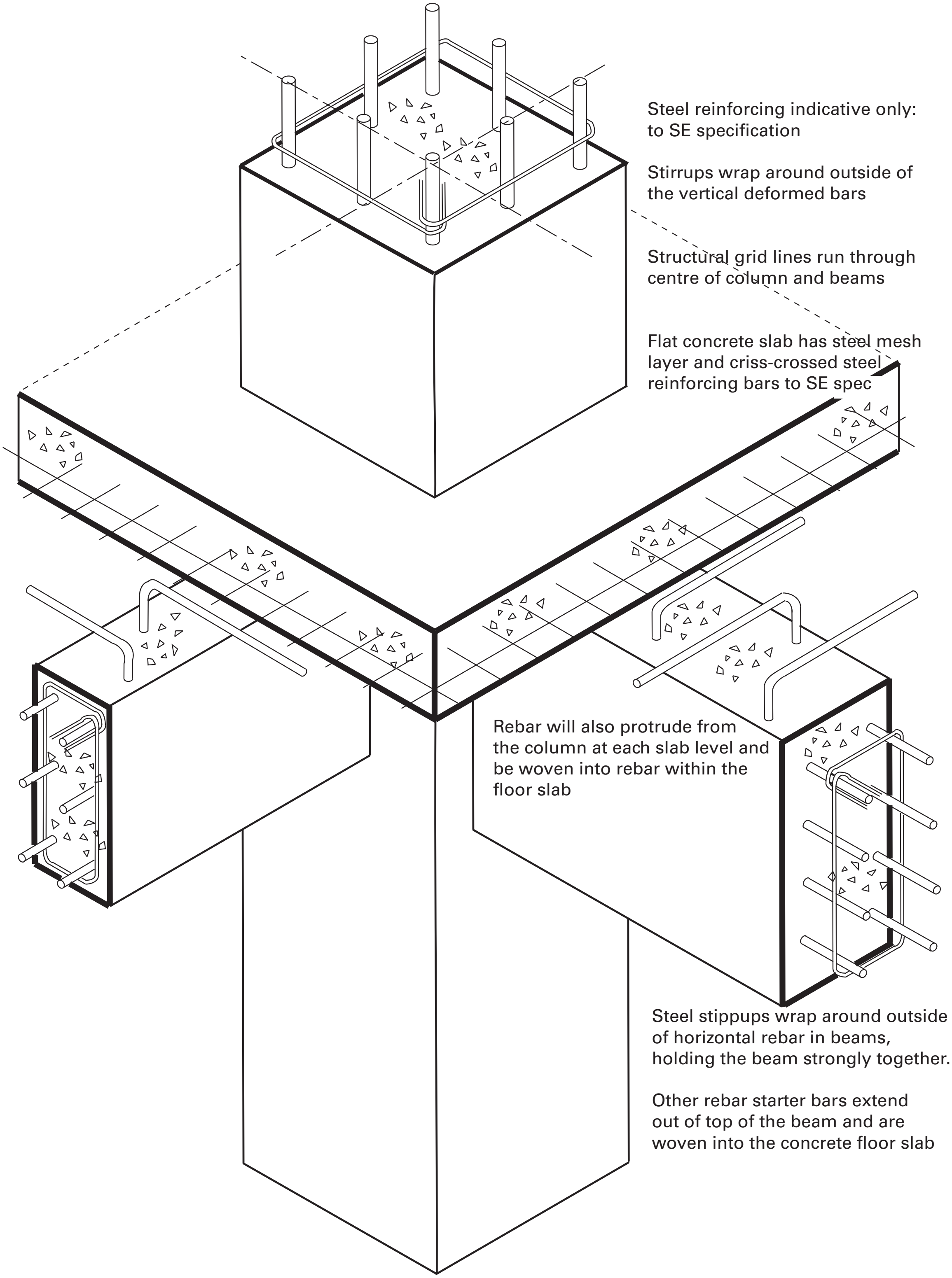

Figure 4.1 Typical concrete column/beam junction with flat slab

4.2 Concrete columns

Columns are the most important part of the building. Concrete column size is dictated by the gravity load: generally, the bigger the building, the greater the loading and the larger the column. Concrete RC columns are larger and more bulky than the steel equivalent. Concrete also acts as inherent fire protection (as long as the cover depth to the steel is adequate) – it has immense thermal mass, so it will take longer for the structure to heat up in a fire. Many thick steel reinforcing bars are arranged vertically inside the perimeter of the column and they are wrapped in thinner steel bars called ties or stirrups, which hold the steel rebar in place. The outer face of the concrete column is then shuttered, concrete is poured and, when set, the shuttering is removed and the finished column emerges. The junctions of column and beam and floor slab are often intricately interwoven with steel rebar – to the SE design of course. If and when seismic action occurs, the concrete column can actually bend a little, allowing the building to flex. The stirrups are positioned to enclose the vertical steel rebar and concrete inside the column.

Sometimes columns are precast, i.e. made in a steel mould off-site in a precasting factory, where the concrete is poured and set under controlled conditions. Precast columns can be craned into position on-site, with the joint between beams and columns being the only part poured on-site. Because of the intricate nature of the reinforcing pattern necessary to resist the forces within a column, steel reinforcing is typically connected on-site, and so sometimes the precast column may be just a thin outer concrete shell, allowing the reinforcing steel to penetrate through the centre of the column and the interior of the column to be filled along with the beam junction.

Standard floor concrete might be designed to bear 25mPa (3626 PSI) in weight, but for certain parts of a multi-storey building (like columns), the concrete needs to be strong enough not to be crushed by the immense loads experienced in the columns. The addition of various additives and extra cement can make the concrete even harder to achieve much higher strength. The SE will specify how hard the concrete needs to be, perhaps 40mPa (5800 PSI) or higher.

4.3 Concrete beams

A ‘primary’ concrete beam will typically span horizontally between two concrete columns and transfer most of the load. Between the primary beams, normally spanning a smaller distance, we have ‘secondary’ beams (typically less deep and closer together). While the concrete beams could be cast in-situ as well, it is now common in some countries to precast all the beams in a factory (it achieves better quality) and bring the RC precast beams to site by truck. The process in the factory is the same as for columns – a steel mould is used, horizontal rebar is laid in the mould, stirrups hold the steel rebar together and concrete is poured into the mould. Typically, when a precast beam comes to the site, it will be smooth on the outside but roughcast on top, with reinforcing steel sticking out each end and out the top. The top is left rough so that it can ‘key in’ with the floor topping slab to come (refer to Figure 4.1). It may sometimes even have a pre-camber, i.e. a curve upwards as specified by the SE, which will level out as the weight of the beam and floor causes it to sag down over time.

The precast beams will be supported off temporary propping and the joints to the columns will be tied together with more rebar and more concrete poured to create a solid joint. The concrete sets hard around the pieces of steel rebar and the steel and concrete effectively become one giant composite beam, with great properties in both tension and compression. Concrete beams are also inherently fire resistant due to their thermal mass. Sitting over the structural array of precast concrete beams, we create a floor by pouring a slab. These slabs can be made in many different ways.

4.4 In-situ concrete flat slabs

With a slab on ground in your typical house, load is distributed evenly to the ground below. With a suspended slab in a multi-story building the slab has to distribute the load first back into the surrounding beams and then down the columns. Flat slab in-situ concrete floors are very common in many countries. Although they may appear the simplest solution, they do require a lot of preparatory work. Specialist thick plywood shuttering is held in place at the underside of the slab with several rows of temporary scaffolding and adjustable steel props. Reinforcing mesh and steel rebar is laid out in a regular pattern, carefully intersecting with the top of the column from the floor below, and the concrete slab is poured to the same depth throughout, level on top. The setting concrete is then finished off with a steel 'float' to get a smooth, hard, flat surface to the floor.

Flat slabs can be great for small spans and are often used in apartment buildings, but the larger spans in office buildings rule this out due to practicalities, as well as being too labour intensive and too slow. The temporary props need to be left in place for some time over several levels so the cost of all this propping mounts up. In large spans, the slabs can get too thick and too heavy. Therefore, for larger spans, contractors tend to favour using precast floor elements that are thinner and lighter.

Table 4.1 Slab thicknesses

Flat slab (mm)	100 thick	150 thick	200 thick	300 thick
Max span in m Indicative only (feet)	2.5m (8′ 2″)	3.5 (11′ 6 ″)	5.0 (16′ 5″)	A flat slab this thick requires a large volume of concrete and is extremely heavy. Consider using an alternative lighter flooring system. Thick slabs are used on grade as basement floor slabs to resist upwards hydrostatic pressure.

4.5 Precast concrete floor systems

Precast floor slabs come in many different variations, usually featuring a concrete base craned into place, with a layer of mesh fixed over the top and then a concrete topping slab poured on top. The topping slab – nominally 60–80mm thick (2”–3”) – is poured to tie the elements together and create a seamless structural surface. The key advantage of precast floor systems is that the process is speedy, and that significant propping is not needed. All of these concrete topped floors will keep fire out for an hour or more, as they make a good fire-rated flooring system, as long as the floor is 75mm (3”) thick or more. The following is a list of some of the most popular types of precast floor systems.

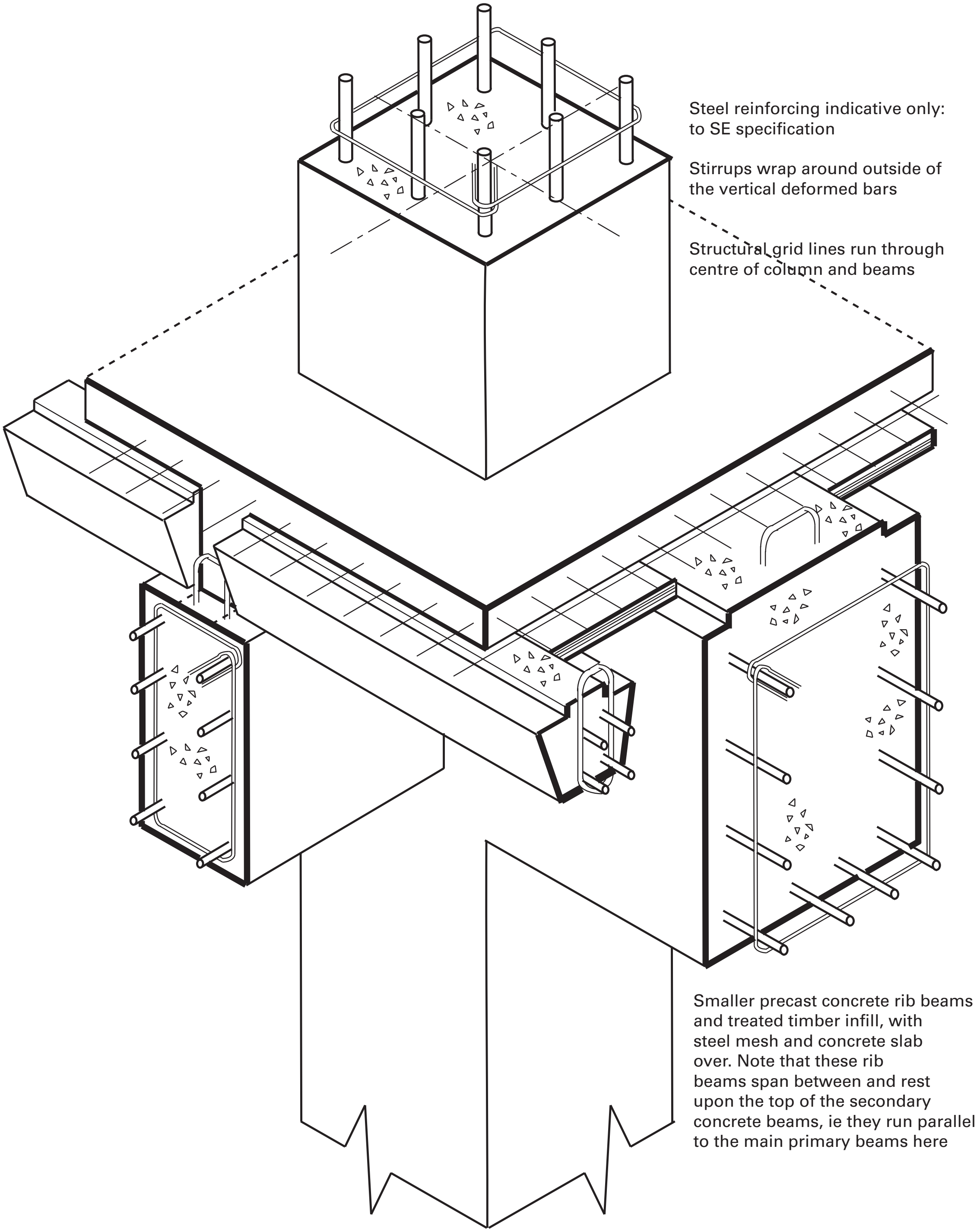

Figure 4.2 Typical concrete column/beam junction with rib beams and timber infill

4.6 Precast rib and infill

A commonly used system for modest spans is rows of concrete rib beams, set about 600mm (2’) apart (refer to Figure 4.2). The ribs are 200mm wide (8”) and not very deep, with steel reinforcing wires running through the bottom of the rib giving it strength. A series of small infill segments sit between the beams, held on by a small ridge on the side of the beam: in Europe, the spaces between rib beams are often infilled with lightweight terracotta hollow bricks, while in the UK, rib beams may be filled in with lightweight concrete blocks. Both of these systems have some thermal and acoustic properties. While there is not a lot of tensile strength in hollow terracotta bricks, they are a relatively lightweight solution, so the whole system is substantially lighter than a solid concrete flat slab.

In New Zealand, a 25mm (1”) timber plank infill is typically used to span between rib beams, with mesh and reinforcing on top as required to form the 75mm concrete topping slab. The timber is permanently cast in place: not as pretty or thermally efficient as a terracotta tile perhaps, but low cost, quick to assemble and strong. These rib beams cannot span great distances, as they are quite shallow, so they will typically be laid to span between the secondary beams only.

Table 4.2 Rib and infill spans (for overall depth, allow for a 75mm (3”) thick topping)

Rib depth in mm	150 deep	200 deep	300 deep
Rib width in mm	200 wide	200 wide	200 wide
Rib spacing in mm	900	900	900
Max span* in m (feet)	6.0 to 8.0m (19’ 8” to 26’ 3”)	7.5 to 9.0m (24’ 7” to 29’ 6”)	10.0 to 13.0m (32’ 10” to 42’ 8”)

* Indicative only. Information source: Stahlton.co.nz

4.7 Precast hollow-core spans

Another very popular system over the last few decades has been ‘hollow core’ spans – flat precast planks with a series of holes cast longitudinally through the concrete, often known by their trade name. The hollow-core spans feature high-tensile steel wire run through the base of the spans that provide the strength to the precast unit via pre-stressing the top and bottom flanges (refer to Figure 4.3). Again, a 75mm (3”) mesh reinforced concrete topping slab is poured on top. Hollow-core spans can be long and they are pre-cambered (cast with a slight upwards curve) so that they can cope with a calculated degree of sagging over time. The holes through the centre are *not* intended for use as places to run services, but merely to save significant amounts of weight. Because the reinforcing steel is run through the bottom web of the span, no cuts can be made to the underside.

Hollow-core spans are typically either 150, 200, 300, or 400mm (6”, 8”, 12” or 16”) deep and 1.2m (4 feet) wide: (see Table 4.3 below). These precast units will typically be laid together at 1200 centres or at 1800 centres with an infill panel between. They span between the primary beams, rendering the use of secondary beams unnecessary. The seating to these beams is crucial and will be detailed by the SE. Due to the long lengths achievable with this type of beam, floors made in this method can be quite ‘lively’, i.e. bouncy. Buildings in Wellington, NZ, with this structural system were checked after the 2016 Kaikoura quakes, as there were some concerns due to the long period of earthquake shaking. Expect some changes to the seating details of these structural systems in the future and possibly a move to more composite floors involving steel, particularly in active seismic areas.

Table 4.3 Hollow-core spans (allow for an additional 75mm (3”) thick topping)

Hollow core Depth in mm	150	200	300	400
Hollow core Width in mm	1200	1200	1200	1200
Spacing with a 600 spacer in mm	1800	1800	1800	1800
Max span* in m (feet)	5.5 to 8 (18′ 0″ – 26′ 3″)	7 to 10 (23′ – 32′ 10″)	10 to 14 (32′ 10″ – 46′)	13 to 17 (42′ 8″ – 55′ 9″)

* Indicative only. Information source: Stahlton.co.nz

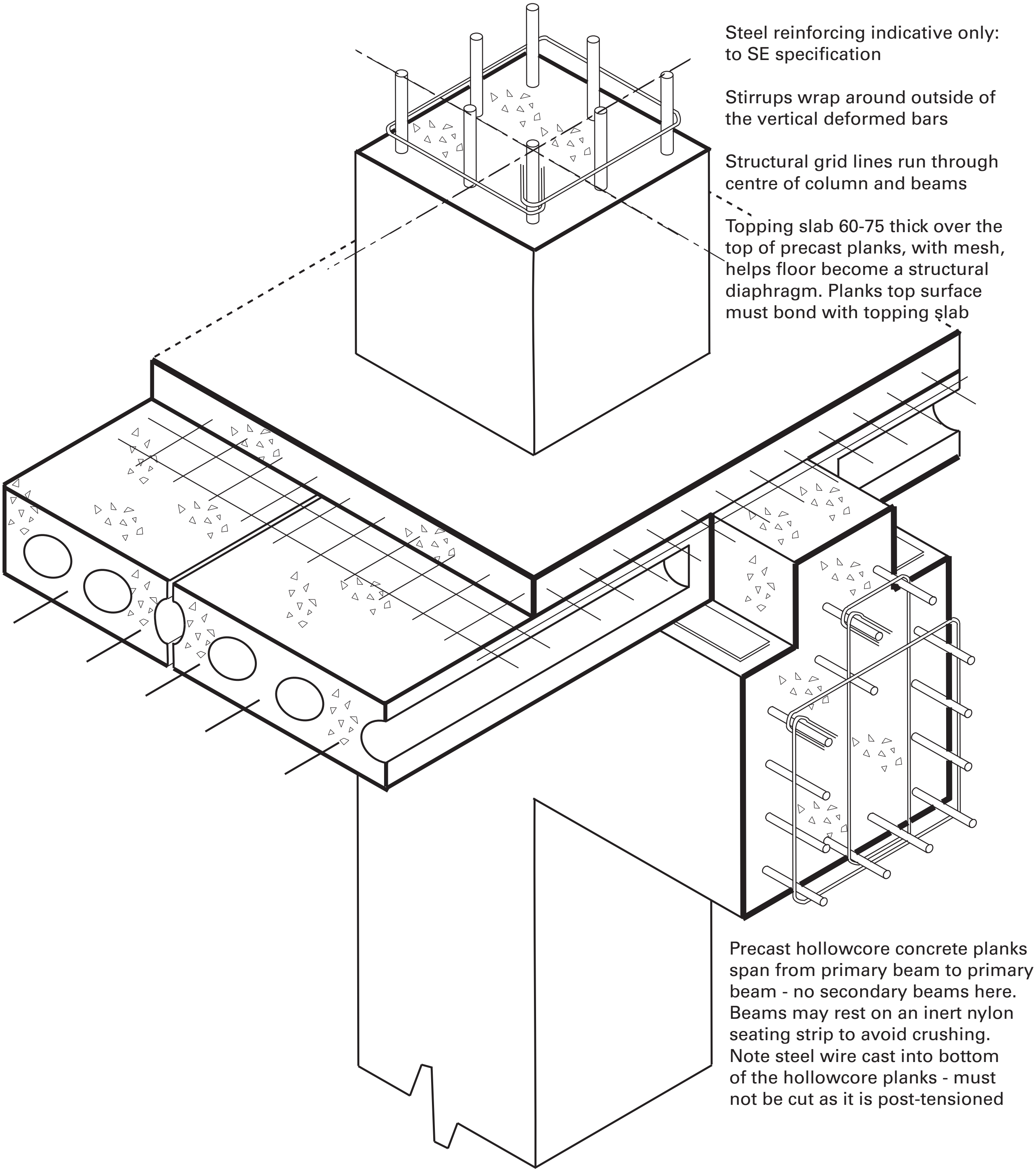

Figure 4.3 Typical concrete column/beam junction with hollow-core precast spans

4.8 Precast Tee beams and Double-Tee beams

For bigger, stiffer spans, Tee beams and Double-Tee beams can be used (refer to Figure 4.4). Here the deep central web of the beam takes all the load, with a broad but thin flat top that supports the topping slab. Very strong beefed-up versions of these Tee beams are now often used as bridge beams on highways, as they can span large distances easily.

This type of beam has often been traditionally supported by engineers using the top lip of the Tee only, but after the Canterbury quakes engineers are likely to be changing the way this beam is supported. While the beam is traditionally supported by hanging it from the top lip, it is very much stronger in maximum seismic events if the Double-Tee beam sits upon a beam below. This can make the Tee system quite thick, but conversely, a lot of extra room for ceiling equipment is gained between the protruding webs. Expect the SE using Double-Tee beams to be very vigilant over the installation and detailing of these beams in any new projects.

Table 4.4 Double-Tee beams (allow for an additional 75mm (3”) thick topping)

Double Tee Depth in mm	200	300	400	500	600
Double Tee Width in mm	1200	1200	1200	1200	1200
Max span in m Indicative only (feet)	5 to 8 (16′ 5″ – 26′ 3″)	7 to 11 (23′ – 36′ 1″)	9 to 14 (29′ 6″ – 46′)	10 to 18 (32′ 10″ – 59′)	12 to 19 (39′ 4″ – 62′ 4″)

* Indicative only. Information source: Stahlton.co.nz

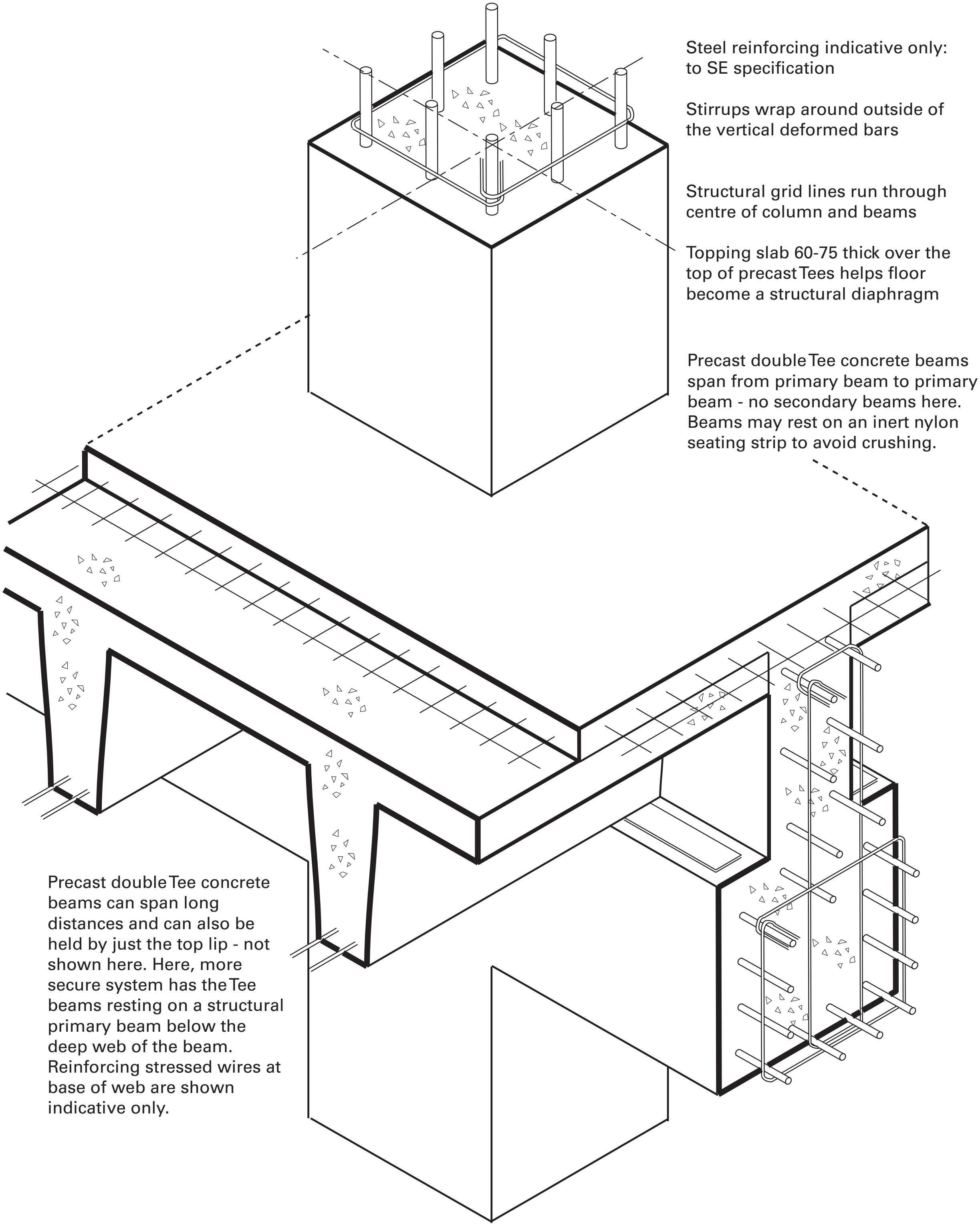

Figure 4.4 Typical concrete column/beam junction with double Tees

4.9 Precast sinusoidal beam units

This is not used often, as it costs significantly more, but the completed structure can look beautiful. The sinusoidal shape of the precast concrete gives it considerable strength while accommodating a void in between ceiling and floor to run services in, and a concave surface below to bounce light off, creating a ready-made sculptural ceiling with significant thermal mass. It has been used to great effect in Portcullis House (architect: Michael Hopkins) next to the British Houses of Parliament, where the structure for the floor is a holistic integration of structure, services and architecture (refer to Figure 4.5).

4.10 Waffle slab

For really large spans that can span well in any direction, waffle slab systems can be used. It allows large, flexible open span spaces but the beams in the waffle are deep and reticulation of services is complex. This system is perfect for large projects with exposed concrete soffits, but unlikely to be used in an office building (Figure 4.4). This will typically require much more preparation in setting up the moulds on-site, which are then filled with reinforcing and concrete is poured. The moulds are then removed once the slab has set and are repositioned for the next floor section. Buildings with waffle slab construction include the National Theatre in London (architect: Denys Lasdun), the mezzanine ceilings in the Metro stations in Washington D.C. (architect: Harry Weese), the Yale Centre for British Art in New Haven, Connecticut (architect: Louis Kahn), and many other large-span art galleries around the world. It is not widely used but can produce beautiful structural results and is immensely strong (refer to Figure 4.5).

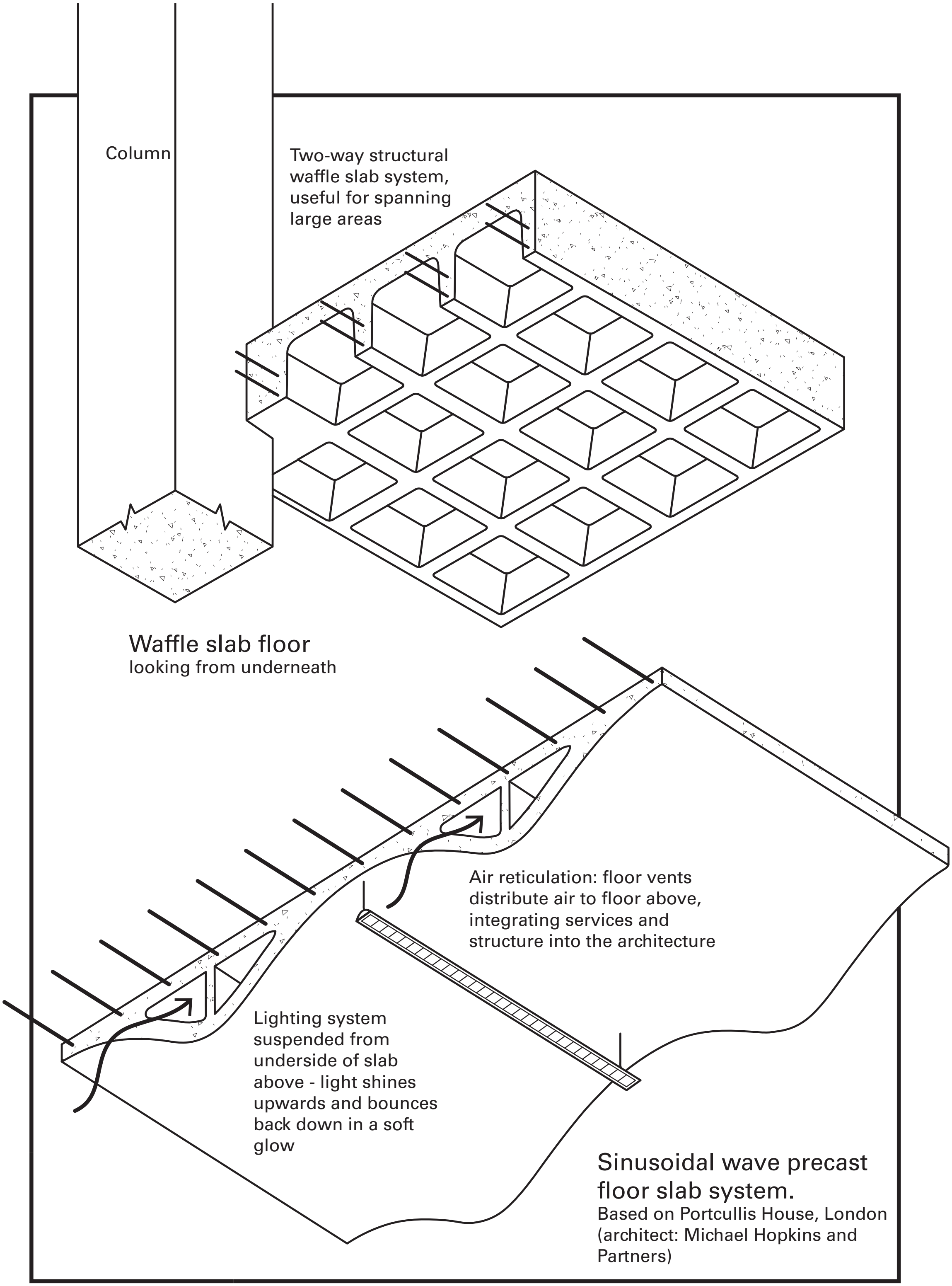

Figure 4.5 Waffle slab and sinusoidal slab

4.11 Some points to remember

The reinforcing steel within the beams and slabs at the junctions of slab to beam and beam to column is very important work, always done by the SE.

You can put a hole through a concrete floor slab, but this hole must *not* cut through a beam in the floor.

You can sometimes core a hole through a concrete beam, but only with the SE agreement and as long as it does not cut through any of the reinforcing steel. Better to plan out where the services need to go first and cast in a void for the services to go through (Chapter 13).

Concrete beams, while they may look flat and straight, can sag under load, over time. The engineer will often specify a degree of pre-camber to counteract this.

Concrete columns can flex to a small degree from side to side an extreme seismic event.

Further reading:

Pier Luigi Nervi

Felix Candela

Zaha Hadid

Antonio Gaudi

Santiago Calatrava

Andrew Charleson – *Structure as Architecture*

05

Chapter Five

Structure: timber

Structure: timber

Guy Marriage

5.0 Structural systems – timber

We are only just at the beginning of a new phase in construction: the use of engineered timber as structural elements. The timber member can be formed in several basic ways, transforming a simple softwood log of spruce, fir or pine into high-strength, highly dimensionally accurate, structural timber components.

Timber (in America: lumber) comes from the harvested wooden logs of tree trunks. Trees take carbon dioxide (CO_2) from the air and H_2O from the ground to create a matrix of lignin and cellulose, i.e. wood, locking the carbon away and thereby helping to combat the rising amounts of CO_2 in our atmosphere.

Traditionally a lot of slow-growing hardwood trees (deciduous species such as oak or ash) were used for building, due to the longevity of the timber and the densely packed cells in the timber. Vast areas of forest around the world have been cut down, destroying animal habitat and rendering the use of rainforest hardwood trees morally repugnant to most architects. The construction industry is now concentrating on harvesting conifers (softwoods) from replanted forests: a much more sustainable approach.

While conifers grow fast and sequester large amount of carbon dioxide as they grow, they also have large cell structures that mean they are more vulnerable to uptake of water. When timber gets wet, it can swell, warp, bend, twist, split or, worst of all, be attacked by mould or eaten by insects. While traditionally logs were sawn, air-dried and used as solid timber beams, now there is a concerted effort to create new, superior-strength materials from timber.

The timber industry now routinely processes many fast-growing evergreen softwood conifers such as *Pinus radiata* (radiata pine) or *Picea glauca* (white spruce). The softwood forests these timbers come from need to be sustainably managed and not virgin growth: check that you only use timber that is Forestry Stewardship Council (FSC) rated. Engineered timber is awarded an FSC-rating, gaining excellent green credentials as a carbon sink. Roughly 450kg of CO_2 is sequestered into every 1 m^3 of softwood timber, resulting in 225kg of carbon being locked up in the timber (Kaufmann, Krotsch and Winter, 2018).

Engineered timber is strong but light (around 500 kg/m^3) and a lot less dense than concrete (2500 kg/m^3) or steel (7800 kg/m^3), but the strength to weight ratio of engineered timber is excellent. It is now being engineered to exploit the potential of the wood, cutting out the weak spots such as knots and creating stronger, more stable timber products. Modern timber glues can help reduce any inclination to bend or warp and also act as a deterrent to bugs and mould. Sizes for timber columns and beams will be slightly larger in comparison to concrete for a similar span, but the structure will weigh substantially less.

Countries with a lot of forests, such as Austria, Canada and, lately, New Zealand are leading in the production of engineered timber products. Universities and the timber industry around the world are joining together to address means of jointing and detailing in this relatively new means of construction. These timber-growing countries are leaders in designing clever timber building systems, especially for resisting extreme seismic situations (refer to section 5.8).

There are also some other aspects to timber that can't be ignored. Timber is slow to conduct heat, meaning it feels warm to the touch. People appreciate that. It also has recognised aesthetic and therapeutic benefits: studies have shown that people feel less stressed in buildings where timber is prevalent (Kaufmann et al, 2018). Prefabricated systems involving engineered timber are a key part of the future for many countries.

First, let's examine some of the likely engineered timber materials you may use.

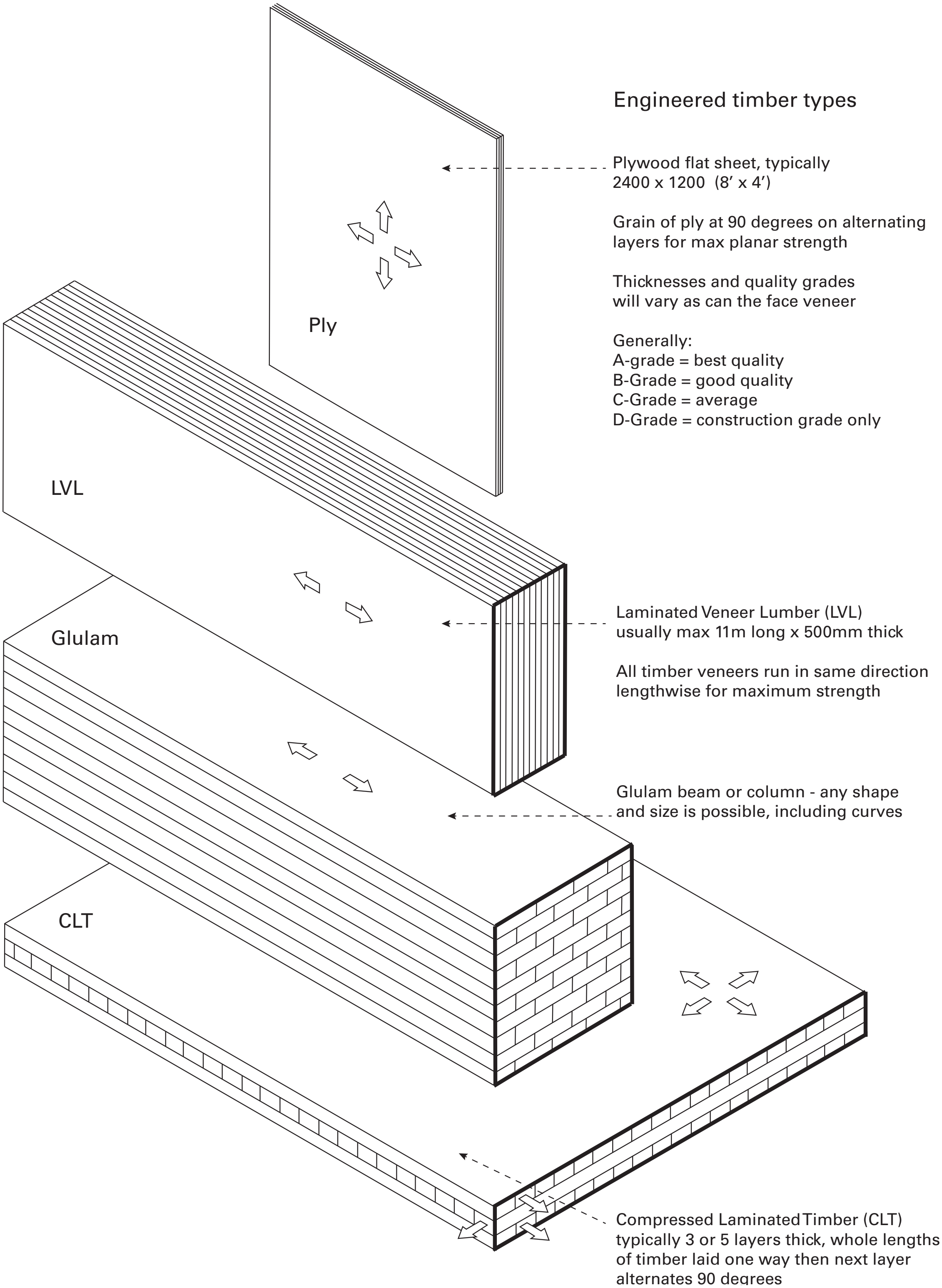

Figure 5.1 Engineered timber types

5.1 Engineered timber systems

- Plywood is made by peeling very thin sheets of timber veneer from logs and gluing them together under heat and immense pressure. Each veneer is typically only 1–2mm thick. The veneers are laid with the grain going first one way, then another layer at 90 degrees to that, repeating till the thickness is desired. With the criss-crossing grain strongly glued together, plywood, therefore, has great strength in a flat plane, good for creating floor diaphragms and wall bracing. Plywood typically comes in sheets based around the standard module 2.4 × 1.2m (8′ × 4′). Ply is readily available in several different thicknesses: 6, 12, 18mm (quarter inch, half inch, three quarter inch, etc.), but specialist structural thicknesses and sizes are available. New engineered timber products are often described as 'plywood on steroids' for good reasons – the results are massive and very strong. Plywood can be used in its 'natural' state or can be treated for longevity (refer to Figure 5.1).
- Glue-laminated timber, or Glulam, is when solid lengths of timber are all oriented in the same direction and glued together to form a structural timber member with great strength and stability. The smaller lengths are often finger-jointed together: the glue and the finger joints are stronger than the timber on its own. Glulam beams can be made up into almost any size and shape that you may require, including curves in large arched structures like sports centres. Glulam's size and shape are pretty much unlimited, while the strong glues used mean that glue can be used in outdoor situations, when sealed or painted (refer to Figure 5.1).
- Laminated Veneer Lumber (LVL) is one of the MTC materials of the future, with an immense strength-to-weight ratio, high-quality machining ability, with great control over quality and dimensions. It is made in a similar manner to plywood, but in LVL the thin veneers of timber (about 3mm thick) all have their grain oriented in one direction only: lengthwise. The glue is put on hot and the LVL is subjected to intense pressure while it sets hard, making it stronger and more dimensionally stable than an ordinary timber beam would be. When the billet of LVL is first created, it is stained with dribbles of dark glue – but when carefully machined, the resulting timber products are high quality, visually stunning, and very, very strong. LVL's use in massive timber buildings will be predominately as CNC-cut columns and/or beams. It can be made up into very long beams around 15m (45′) in length but has a maximum width of about one metre and a max thickness of around 300mm (12″) (refer to Figure 5.1).
- Cross Laminated Timber (CLT) is the other massive timber invention for the future: it uses solid pieces of timber laid in layers with alternating 90-degree orientation (giving strength in both directions) and thus is a good material for flat slabs. Think of it as a strong concrete slab, but much lighter and made of trees. CLT is a naturally sustainable, visually appealing product. It should not be used for columns or beams, although it can be used as part of shear walls.

CLT can come in sizes up to 3 × 11m (9′ × 33′) at present and up to 500mm (20″) thick. CLT will typically be 3 layers thick for walls and 5 layers thick for floors, but thicknesses will depend on the span and the loadings. Slab thicknesses for a multi-storey building spanning 9m or so are likely to be around 130mm (5″) or more, with prefabricated panels of CLT cut with CNC machinery to millimetre-perfect dimensions (refer to Figure 5.1).

Launched in the 1990s by CLT companies in Austria and Germany, there are now several countries with highly automated CLT plants. Austria still leads the way, supplying spruce-based CLT to the whole of Europe, while Canada is leading the CLT push in North America. In the southern hemisphere, the first CLT factory opened in New Zealand in 2013 and in Australia in 2018, both mainly focusing on *Pinus radiata*.

- There are other types of engineered timber available in some countries, such as Nail Laminated Timber (NLT) or Dowel Laminated Timber (DLT) and Oriented Strand Board (OSB), but LVL and CLT are the most important materials for you to understand.

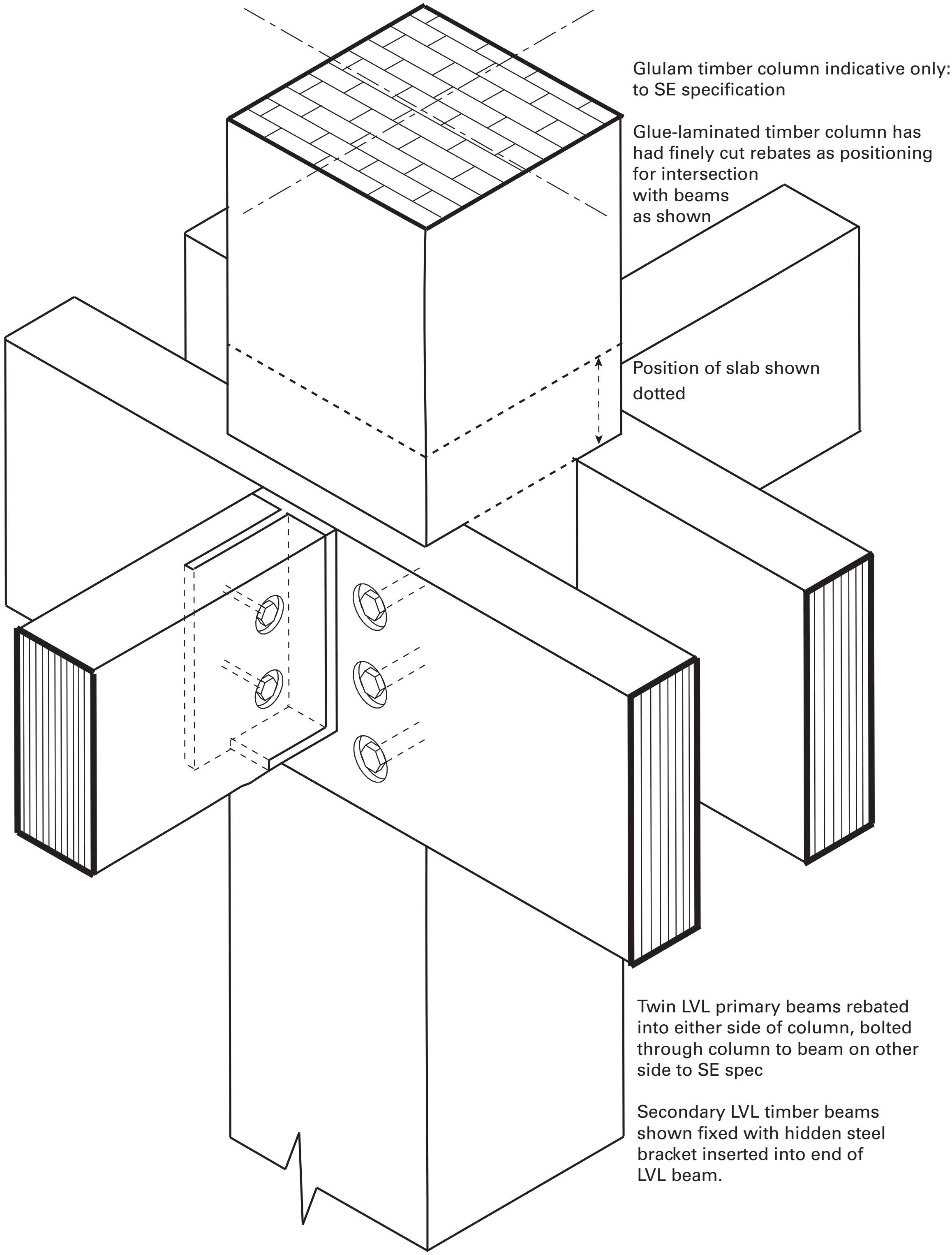

Figure 5.2 Typical engineered timber column/beam junction (slab not shown)

5.2 Timber columns

For office buildings, columns and beams will be LVL or Glulam, while floor slabs will be CLT (refer to Figures 5.2 and 5.3). In countries which are seismically active, reduction of mass is an important driver in structural design: so lighter buildings are desirable. Remember that while steel and concrete beams can span at a length to depth ratio of about 20 to 1, engineered timber beams can span only at a ratio of 13 to 1. When compared to a steel building, either your timber columns will be closer together or your timber beams will be deeper. On the other hand, a timber building will be quite a lot lighter!

Timber columns need to have immense strength and stability primarily in one direction – vertically – and so LVL and Glulam are the only options, as their timber grain is all oriented the same way: vertically up the column. The LVL plant can laminate two or three billets of LVL together (cold glued rather than hot glued) so that columns can be created at much larger sizes that again can rise up two or three floors at a time.

Unlike concrete, there is no time wasted for drying, so timber erection and assembly times can be fast. The timber column could easily be 500 × 500 in cross-sectional size and about 11m (33’) long. Some engineers will create a timber corbel (a projection out of the side of the column or wall) to rest a timber beam on, or the column may be engineered to incorporate a CNC-cut notch in the side, perfectly shaped to accommodate the passing LVL beams (Figure 5.4). Bolt holes can be accurately pre-drilled, their positions determined by the BIM model of the building.

5.3 Timber beams

Timber beams in tall buildings are going to be either LVL or Glulam, again, because all the timber cells are going in one direction – horizontally. Timber beams will be tall and relatively thin: width about a quarter of the depth. Often the best solution for the beam layout is to have two primary beams bolted to the column, one on either side (refer to Figures 5.2 and 5.4). This is a very strong solution, as the beam is continuous and easily connected to the column via bolts right through the column and out the other side. For some buildings, there may be a desire for a pin-joint and so there may be just one large bolt through the centre of the column, but more usually, there will be two or four smaller bolts holding it rigidly intact. Bolt heads may be covered over with timber plugs or left exposed.

Between the large primary beams, smaller secondary beams will be installed perpendicular to the primary beams. They could be connected to the primary beams with steel T-shaped plates. The top of the T is bolted to the primary beam, and the projecting part of the T is slipped into a slot at the end of the secondary beam. Steel or stainless steel bolts connect it together, specified by the SE. The top of all the beams are aligned so that a flat area is prepared, suitable for the CLT slab to be fixed.

Compound beams might also be made with a steel plate, which we call a 'flitch plate' between two timber beams. A flitch plate (sized by the engineer of course) will be a steel (or possibly stainless steel) flat plate (maybe 10mm thick) inserted into a slot cut into the timber and bolted through both beams and steel plate. This will keep the steel hidden and keep it flat but will allow the timber beam to be stronger while staying less deep than it otherwise may have to be. There are concerns from some SEs, though, that introducing large steel connectors to timber may have implications for strength in fires and so more use is being made of long, super-strong screws to stitch the timber systems together on-site.

Table 5.1 Engineered timber beam spans

LVL beam depth in mm	300 deep (12″)	400 deep (16″)	500 deep (20″)	600 deep (24″)
LVL width* in mm	75 (3″)	100 (4″)	125 (5″)	150 (6″)
Max span* in m Indicative only (feet)	6.0m (roof beam) 4.0 (floor beam) (19′ 8″) (13′ 1″)	8.0 (roof beam) 5.3 (floor beam) (26′ 3″) (17′ 6″)	10.0 (roof beam) 6.6 (floor beam) (32′ 10″) (21′ 10″)	12.0m (roof beam) 8.0 (floor beam) (39′ 4″) (26′ 3″)

* Indicative sizing only. Check with your SE.

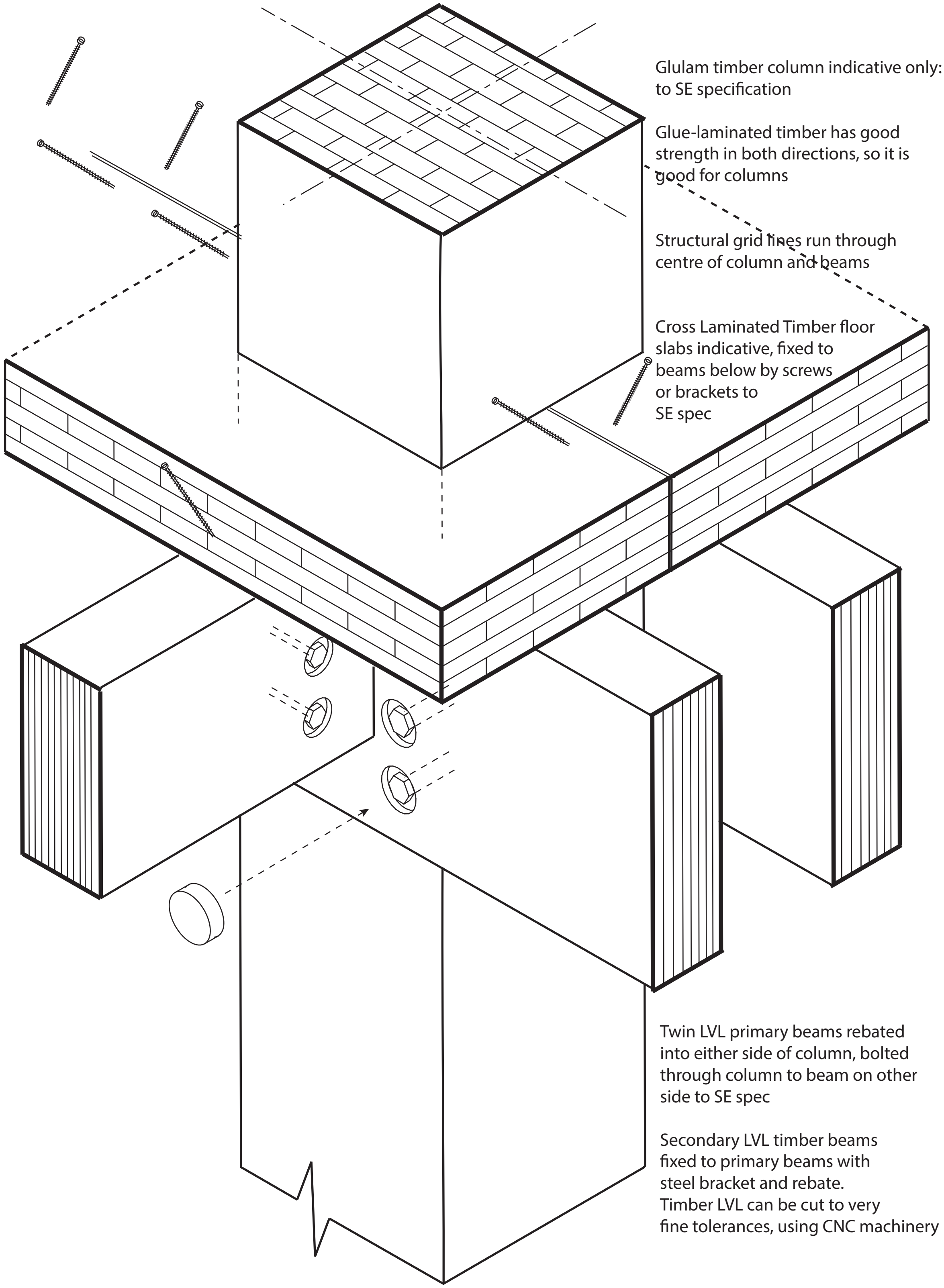

Figure 5.3 Typical engineered timber column/beam/slab junction (with CLT slab)

5.4 Timber floor slabs

CLT floor slabs are a strong building material that can be easily craned into position (refer to Figure 5.2). A CLT slab is inherently a two-way slab, although due to the build-up process (a three-layer slab will have two layers in one direction but only one layer in the other direction), it has more strength one way than the other. For that reason, while it may seem possible to have a flat CLT slab over an area of, say, 9m × 9m, it is more likely to have secondary beams at 3m intervals below the CLT slab. Structural systems are also being developed that mimic advances in concrete timber technology. In the same way that a solid thick concrete slab has been engineered into hollow-core spans in order to save weight and lessen the amount of concrete being used, some MTC buildings are being constructed with a similar sandwich of CLT floors and LVL beams bonded together to create a timber hollow-core solution. Other buildings have been constructed with a ‘double-tee’ structure with twin LVL beams and a lightweight CLT top, all securely screwed or bolted together.

In multi-storey timber buildings, while a CLT floor over LVL beams will provide a perfectly adequate structural solution, in most cases a small concrete topping layer is added to the upper surface of the CLT, around 60mm thick. This adds additional acoustic deadening and will lessen the transmission of sound. It also has some additional reassuring qualities (like fire-resistance) for insurance companies who may be reluctant regarding all-timber buildings.

Table 5.2 Engineered timber slab spans

Flat CLT slab thickness in mm	100	150	200	300
Max CLT slab width in m	3.0	3.0	3.0	3.0
Max span* in m Indicative only (feet)	3.0 (9′ 11″)	4.3 (14′ 1″)	6.0 (19′ 8″)	10.0 (32′ 10″)

* Indicative sizing only. Check with your SE.

Note: CLT slab thicknesses shown are notional only – actual slab thicknesses will vary according to country, i.e. 100mm slab may be 95 or 105 depending on manufacturer.

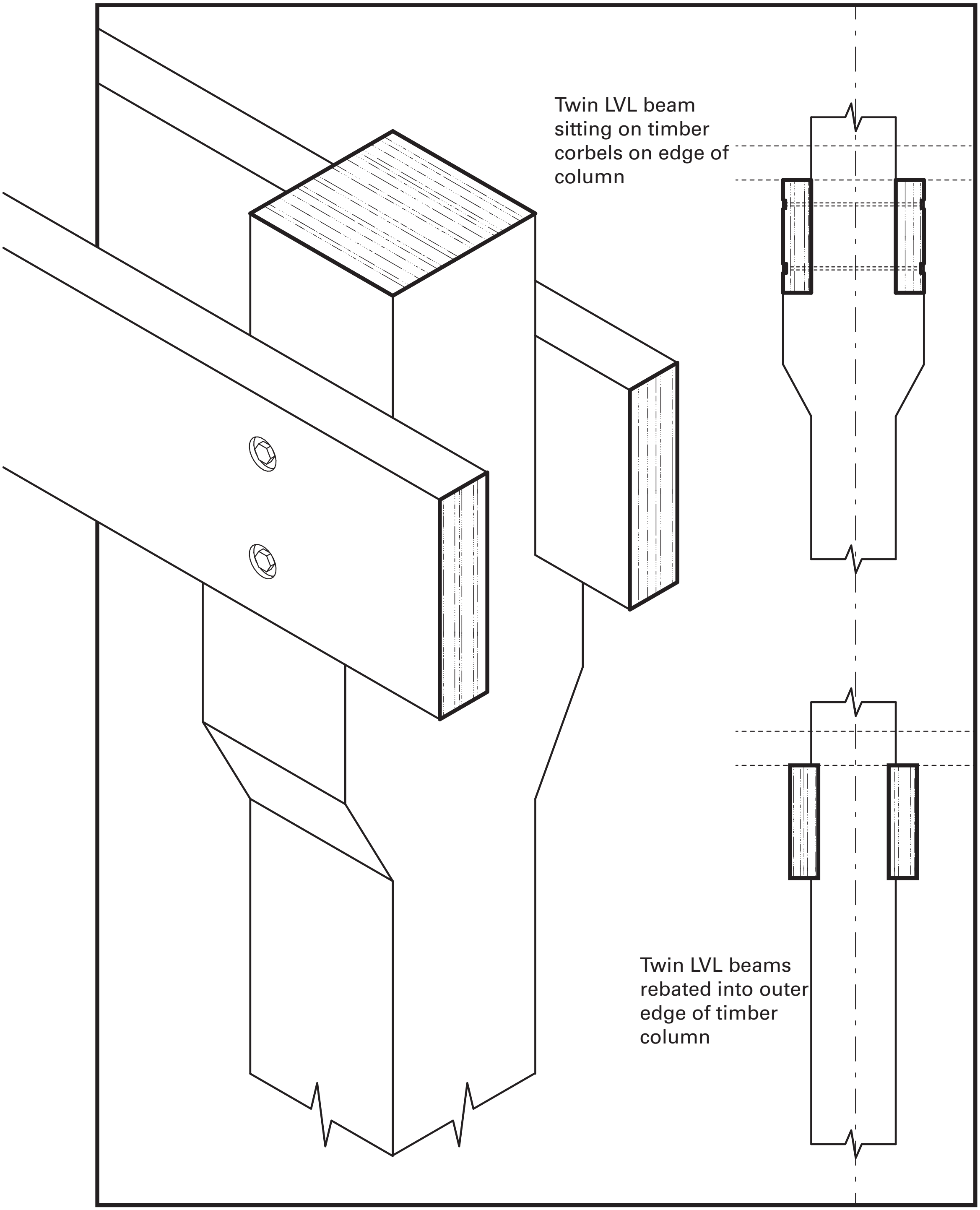

Figure 5.4 Typical timber column and beam junctions

5.5 Massive timber fire-rating

The attitude of many people on first hearing about using timber as a structural system is concern over the possible effects of a fire. Will the building burn down? In a fire, steel beams without fire protection will bend, sag and twist when heated. By comparison, massive timber is, in fact, far safer to build with than steel, as tests have shown that, actually, engineered timber members have excellent resistance to fire. The outside layer of the timber will char and build up a level of resistance that stops the flames from doing any significant structural damage, i.e. it will stay stable and intact beneath the charring. This applies to LVL, CLT, Glulam, etc. The SE will have added a percentage amount to the beam thickness to cover any possible attrition in the case of fire.

As heat from a fire always rises, it is the underside of the floor above that is likely to get hotter rather than the top of the floor below. Fire-rated plasterboard / drywall covering the underside of the timber slab above and a fully sprinklered office space below will protect the building from harm. There is, of course, a desire from people with timber buildings to have the timber featuring a natural-looking timber finish, but flammable finishes like oils or solvent-based polyurethanes must be avoided. Instead, more expensive, less flammable, special coatings need to be specified, possibly with intumescent qualities – but these can go cloudy when exposed to external sunlight over time. Talk to your local fire-resistant-coatings specialist.

5.6 Tall timber residential buildings

Great steps are being made in progressing all-timber, multi-storey buildings, particularly in the case of residential apartment blocks (refer to Chapter 15 for further discussion). With timber for purpose-built housing, the use of CLT walls and floors is becoming more mainstream. Floor slabs (5-layer CLT) are topped with wall panels (3-layer CLT) and screwed together to make incredibly stiff and efficient timber apartments for living in. The entire CLT apartment structure is like a closed cardboard box, strong and rigid with all the sides closed. The CLT finish is often retained internally while the external face is covered over, first with a layer of insulation and finally with a waterproof external cladding.

All over the world, CLT is being used for innovative multi-storey apartment buildings, such as the Murray Grove apartments in London (constructed at 9 storeys in 2009), the 10-storey Forte building in Melbourne (constructed in 2014), the Tree in Bergen, Norway (13 storeys, completed 2013), and the Tall Wood Residence, an 18-storey timber CLT residential building in Vancouver, Canada, completed in 2017 (refer to Kaufman, Krotsch and Winter, 2018).

Apartment inter-tenancy walls are often at centres around 4.5–6.0m apart: good sizes for inner-city apartment living, as full-height, permanent structural divisions for bedrooms, bathrooms and internal circulation patterns. These walls can be created from solid CLT panels: great for apartments, but no good at all for open-plan office spaces. Purpose-designed apartment buildings are very different structures from office buildings and so timber office towers are a lot less common than residential timber towers. The easy simplicity of screwing and bolting together CLT is not at all suitable for open-plan timber office buildings: the frequent structural bays of CLT walls so useful in residential design are completely unwanted in an open-plan office development.

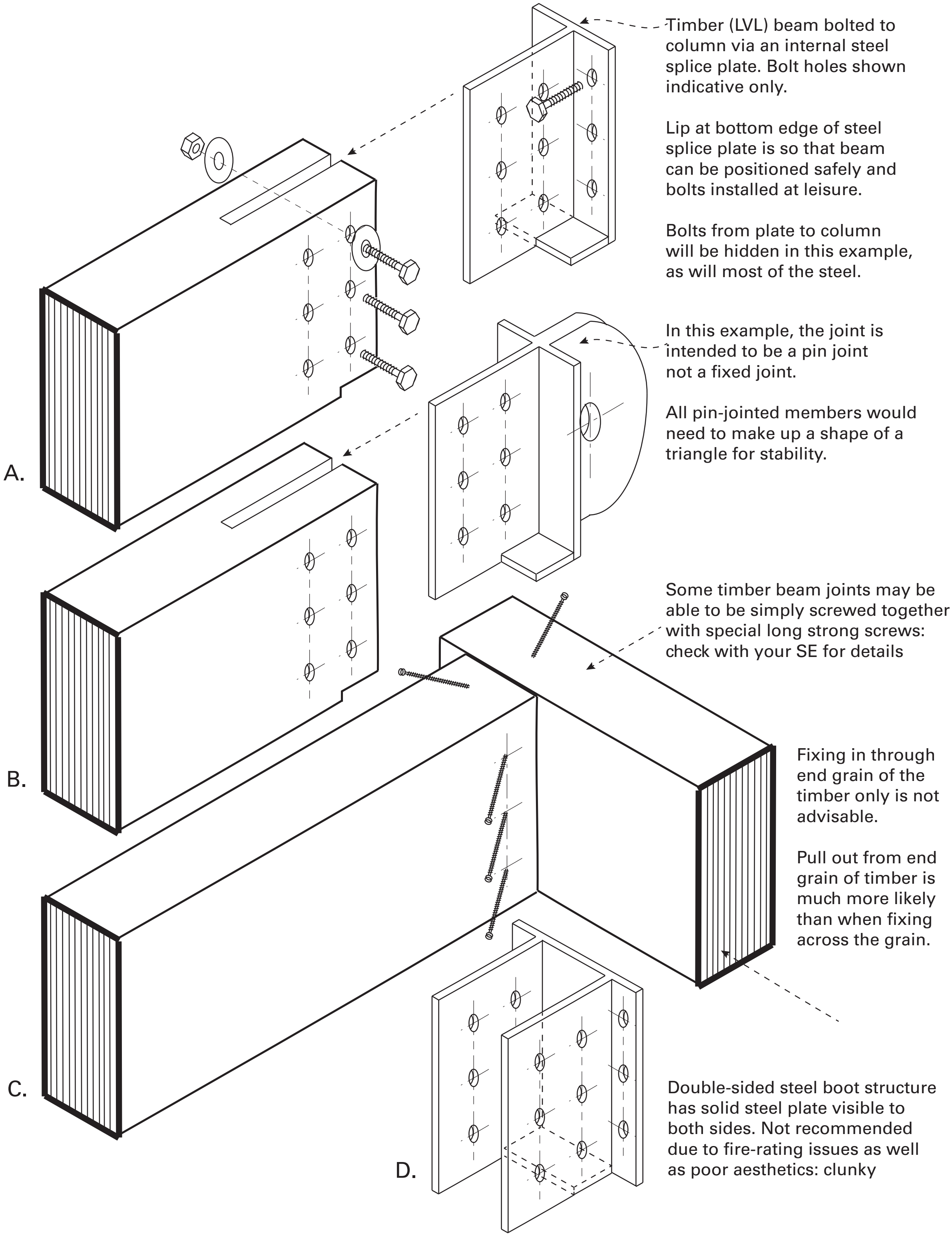

Figure 5.5 Timber beam joints

5.7 Construction detailing of timber

Engineered timber requires rather different detailing skills than concrete or steel. With concrete, the strength of the beam to column joint relies entirely on the arrangement of the reinforcing steel, which then gets covered over with concrete and remains unseen. In steel buildings, exact fabrication of the steelwork cleats and tabs ensures tight tolerances on-site, while there is also the ability for the steel to be cut and re-welded on-site if needed. All of these details are designed and drawn by the SE. The steelwork joints are then typically wrapped in fire protection and lost to view for all time.

By comparison, with timber buildings the details joining materials together have to be perfectly aligned, as they may often be permanently on display, open to the critical viewing by sharp-eyed architects and engineers alike. Here the skill of the architect will be called on a lot more for the detailing phase. The advances in LVL and CLT have been accomplished by the concurrent advances in CNC digital fabrication. Super-accurate machining of the timber columns and beams means that some of the more old-school timber technology is being used again (refer to Figure 5.3).

While concrete beams and columns can all be cast as one solid intersection, and while steel beams and columns can be welded or bolted so that they act as one solid intersection, massive timber construction (MTC) or engineered timber is always going to involve bolted or screwed connections, often utilising a steel connecting plate. Details need to be thought through and detailed very carefully, as you can easily bolt timber together but (obviously) you cannot weld it and the connection details are left on show (refer to Figure 5.5). Modern long timber screw systems like Spax have surprisingly high strength.

The simplest way to join two lengths of timber together is simply with an external steel plate on each side, with bolts extending through from one side to the other. This way, the plate becomes a feature of the design. A more subtle way of joining the timbers is to insert the steel plate back inside the timber by cutting a very careful thin slice into the end of each timber beam, effectively hiding the steel inside the timber. This way, all that can be seen is the head of the bolt and the washer it sits on, often recessed into the timber beam. Even more discrete jointing is possible via long deep screws (like 300mm long Spax screws) or other more sophisticated locking mechanisms.

Remember that *any* time you are bolting timber, a washer must be used to avoid crushing the timber. The great thing about using washers in timber is that the timber can be recessed easily around the washer and bolt so that the end result looks neat and the bolt does not protrude, or the bolt head can be hidden with a snug-fitting timber plug afterwards.

Methods of joining can be combined with more traditional means of connection, such as mortice and tenon joints (a projecting peg is inserted inside a hollowed-out slot) or scarfed joints (where timber beams fix diagonally against other timber beams). Because timber is a natural material, created from living cell structures in the wood, you do need to ensure that the timber is not crushed, and so sometimes a piece of engineered timber will be finished with a steel 'boot' where it is fixed to the concrete slab.

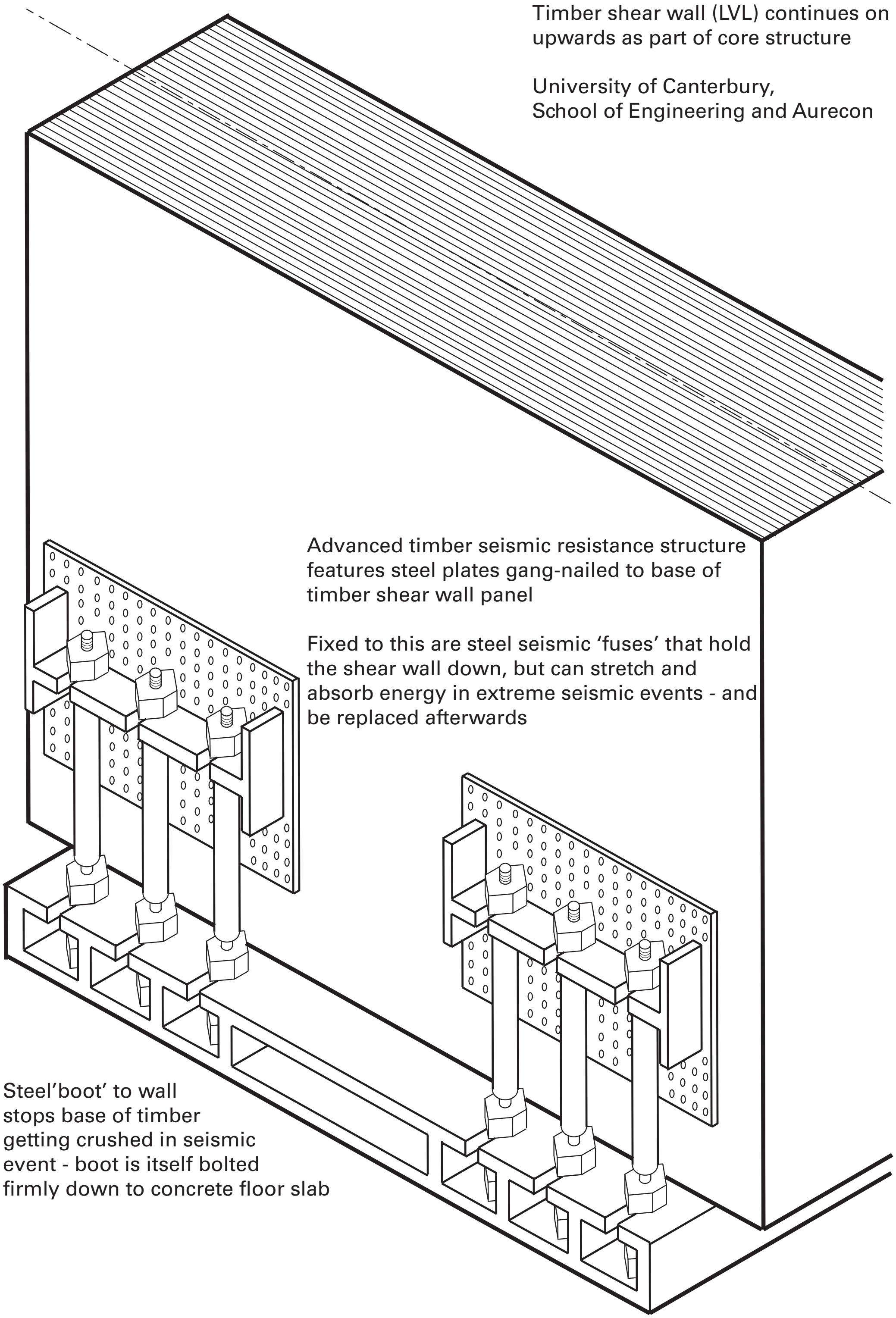

Figure 5.6 Seismic fuse to base of timber shear wall

5.8 Seismic engineering of timber

Steel boots are definitely needed for timber shear walls being created in some recent engineered timber buildings with revolutionary seismic solutions. There are exciting new developments in the field of seismic resistance, particularly in massive timber buildings. The base of the timber shear wall is fitted with a steel boot that allows the wall to take the gravity load and also rock in the most violent seismic events, without crushing the timber (refer to Figure 5.6).

Professors Andy Buchanan, Stefano Pampanin and their team at the University of Canterbury have developed a system for tying timber shear walls down to the ground slab with steel 'seismic fuse' technology (Timber Engineering Research, n.d.). For full coverage of work in this field, I would recommend that you read their research findings directly. The principle is that in the case of massive seismic action (i.e. large earthquakes), the seismic fuses will yield, absorbing some of the energy of the quake. These fuses can then be replaced, without causing any damage to the timber shear walls. This system will work for smaller buildings, but the technology for really tall timber buildings is perhaps yet to come.

University of Canterbury in New Zealand has been advising on the construction of innovative work in new buildings with massive timber. This includes the NMIT building in Nelson (architect: Irving Smith Jack, 2010 and Structural Engineer: Aurecon), where the all-timber building has timber shear walls held securely down onto the foundations (refer to Figure 5.6) with Pres-Lam technology. The use of large pieces of massive timber means that the building can withstand large seismic events and spring back into shape afterwards, with almost zero harm to the structural frame. Expect some massive steps forward with tall timber construction over the next decade.

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06

Chapter Six

Structural systems

Structural systems

Nabil Jose Allaf

6.0 Introduction

This chapter presents a series of different structural systems used in the design and construction of high-rise buildings. These systems are designed to withstand both gravity and lateral loads, the latter resulting from winds and, in earthquake-prone countries, from seismic forces. Some structural systems are more efficient than others in responding to these physical constraints and therefore in achieving greater heights. However, their use and design must also be considered in regard to several factors including, among others, building code, client's programme, cost, time frame, engineering considerations, and architectural concept.

The technical constraints inherent to high-rise buildings might appear at first sight as restraining the architectural reflection. Commonly, the structural system would only spread vertically and imply a redundancy of its layout in order to efficiently carry the loads. This might result in an oversimplified form, often symmetrical, with a repetition of levels resulting in a monotonous façade. It would, however, be incorrect to consider these constraints as limiting architectural reflection, especially when considering the potential architectural role structure may possess.

Due to the considerable amount of structural systems applicable to high-rise buildings, this chapter focuses on some of the key ones, addressing their characteristics as well as their relationships with various architectural qualities. Through this approach, designers can reflect on the use of one system over another in regard to technical but also architectural considerations. The selected systems presented below are based on a classification defined by Khan (1969, 1974) and further developed and updated by Ali & Moon (2007, 2018). They are organised in two categories depending on whether the majority of the components of the main lateral-load resisting structural system are located *internally* or *externally*. Within these categories, the systems are then organised depending on the height limit they can efficiently reach.

6.1 Interior structures

Rigid frames

The structural system of steel or concrete rigid frames represents the simplest approach when designing a high-rise building. It consists of a load-resisting skeleton, composed of columns and beams connected by rigid connections allowing the transfer of bending moment forces between the vertical and horizontal members. The structure, thanks to the bending stiffness of its components, can therefore resist both vertical and lateral loads. The structure is organised along a planar grid, repeating itself on each floor, thus facilitating the transfer of forces generated by the gravity and lateral loads (Figure 6.1). The gravity loads shape the sizes of the vertical members, resulting in progressively larger columns towards the bottom of the building. Regarding the beams, it is the need to resist the increasing lateral forces and to ensure the stiffness of the frames that increases their sizes. A concrete rigid frame system can reach up to 20 storeys in height, where a steel structure has a maximum height of 30 storeys. A greater height implies a risk of excessive horizontal sway.

The grid layout provides some freedom regarding the location of the structure. The structural system can, for instance, take the role of the building core and be placed at the centre of the interior plan, potentially requiring gravity-only columns around. It could also be positioned over the entire interior of the building, thus relating to the 'free-plan' spatial organisation initially recommended by Le Corbusier. This approach provides great freedom to the designers regarding the design of the façade, independent of the main structure, as the columns are retreated from the building's perimeter. Maximisation of the amount of natural light and outside views can then be achieved. This configuration also intends to give greater planning flexibility in comparison to the use of load-bearing walls which are more constraining in regard to circulation and usability of space. However, the footprint of the rigid frames is not negligible and does hinder the usable area around it. Careful reflection must therefore be given to this structural system in regard to the intended function of the building.

Shear wall/Shear truss – frame interaction system

In order to reach greater heights, the rigid frame skeleton can be combined with other structural systems; namely, the braced frame and the shear wall.

Most commonly made from steel, the first system consists of beams and columns creating a frame and diagonal members constituting a bracing system, thus ensuring lateral resistance. Cantilevering from the foundation, the braced frames create a shear truss system, with the diagonal braces generating a web of trusses and the columns performing as vertical chords. The braced frame

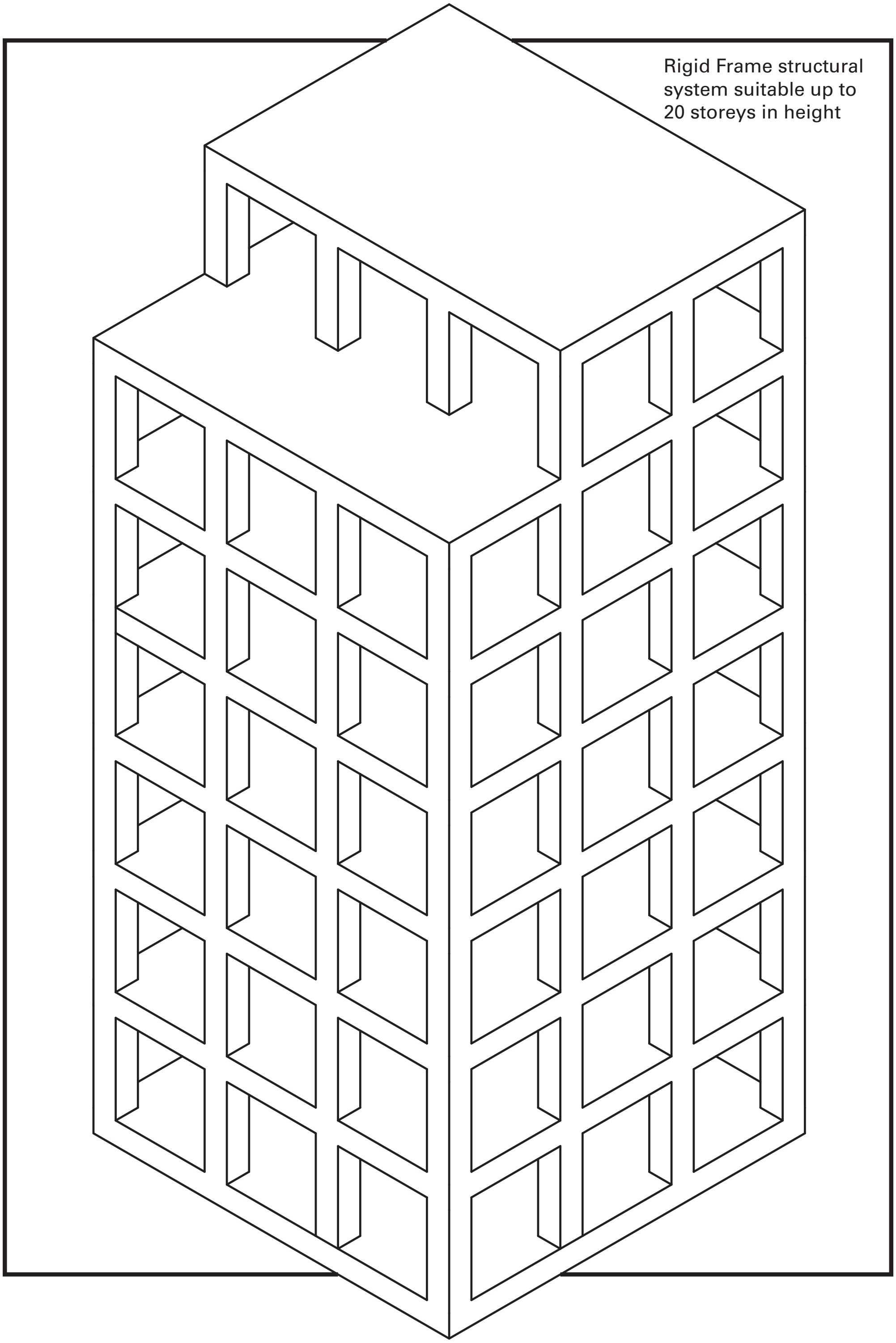

Figure 6.1 Rigid frame system arranged on a planar grid

system can be either concentric or eccentric (Figure 6.2). The concentric braced frame has its diagonal members intersecting at a common point. It possesses different bracing configurations, including among others X and inverted V-bracing, and providing high stiffness. In earthquake-prone countries, where ductility is required, eccentric braced frames are largely used. Often designed as an inverted V-bracing, the eccentric braced frame possesses a space between the braces at the top beam. This creates a fuse region allowing the beam to absorb seismic loads. Although braced frames can be designed to possess slender members, their presence within the interior spaces, around the core, or around the building perimeter needs to be considered in regard to their impact on spatial usability and outside views.

Regarding the second structural system, shear walls are commonly conceived as structural reinforced concrete panels. Like braced frames, they are also designed to resist lateral loads in their own plane but possess greater stiffness. Their structural efficiency and ease of design is considered as an asset. Shear walls can be positioned based on different configurations. They can divide a floor into usable spaces when installed internally. On the contrary, they can be located at the perimeter of the building in order to reduce their internal impact. Finally, they can assume the role of the building's structural core. While the first two options can be relevant depending on the architectural intentions, the designer will need to consider their consequence regarding circulation, functionality, natural light, and outside views. Using the shear walls as the building's core could be relevant, as this would not only avoid interfering with the aforementioned architectural qualities but also potentially encase vertical circulation areas, as well as services.

The combination of rigid frames with shear walls or shear trusses aims at compensating the deflection under lateral loads of one system by another. While the rigid frames deflect in shear mode, the shear walls and shear trusses deflect in bending mode. This implies that the frames restrain the top of shear walls or trusses, while the latter restrain the bottom of the frames. As a result, the building possesses greater lateral rigidity, allowing to reach up to 40 storeys when using braced frames and 70 storeys when designing shear walls. The structural layout of this interactive system is often organised, but not limited, to the shear walls or trusses acting as the building's core and the rigid frame installed internally on a same orthogonal structural grid (Figure 6.3).

Outrigger

This system is composed of a braced frame or shear wall core tied to perimeter columns using outriggers, commonly in the shape of trusses in steel constructions or walls in reinforced concrete structures (Figure 6.5). By connecting the core to the outer structural structure, the outriggers create stiff floors acting as lever arms, which induce compression to the perimeter columns on one side of

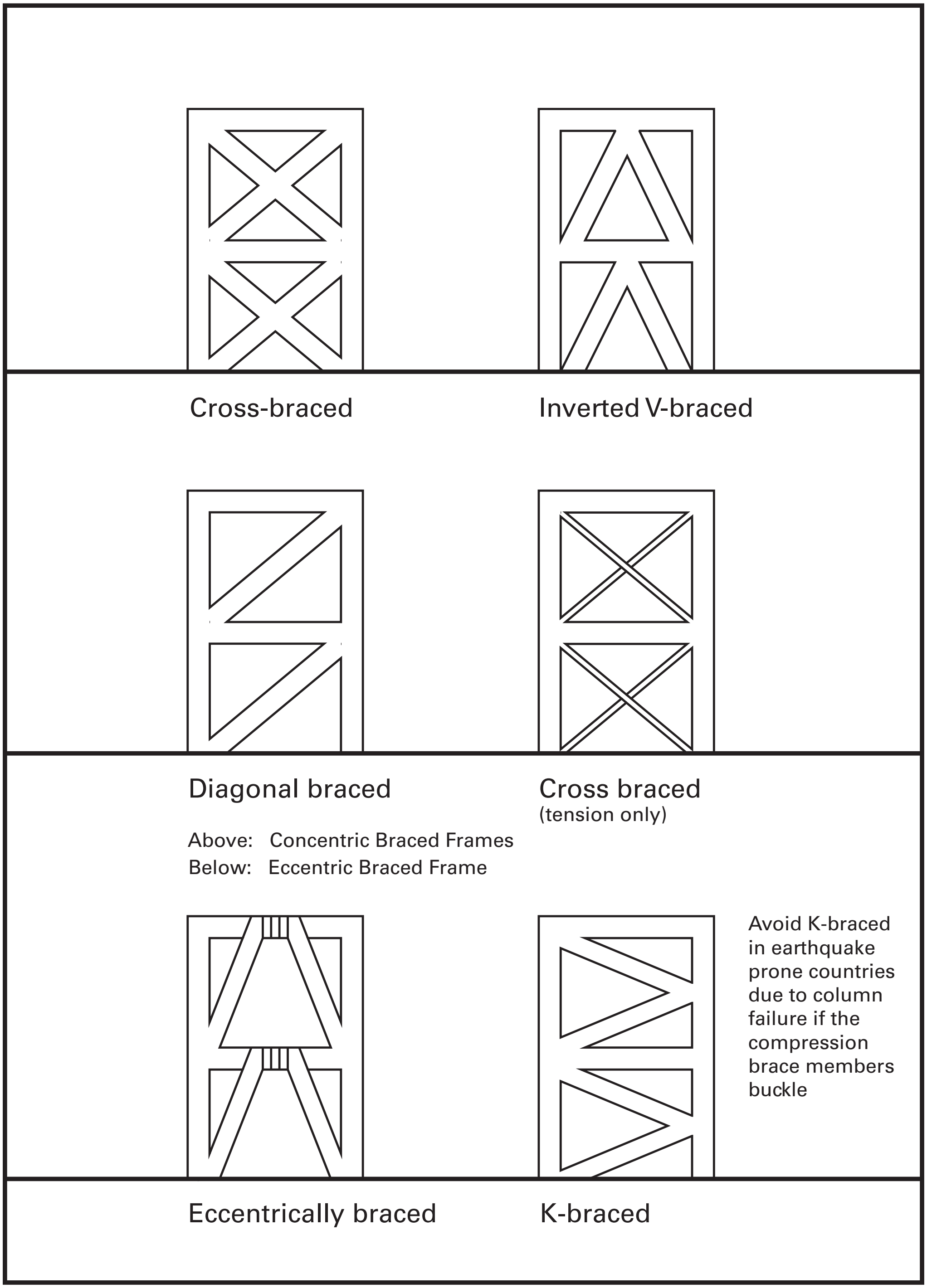

Figure 6.2 Different geometries of concentric and eccentric braced frames

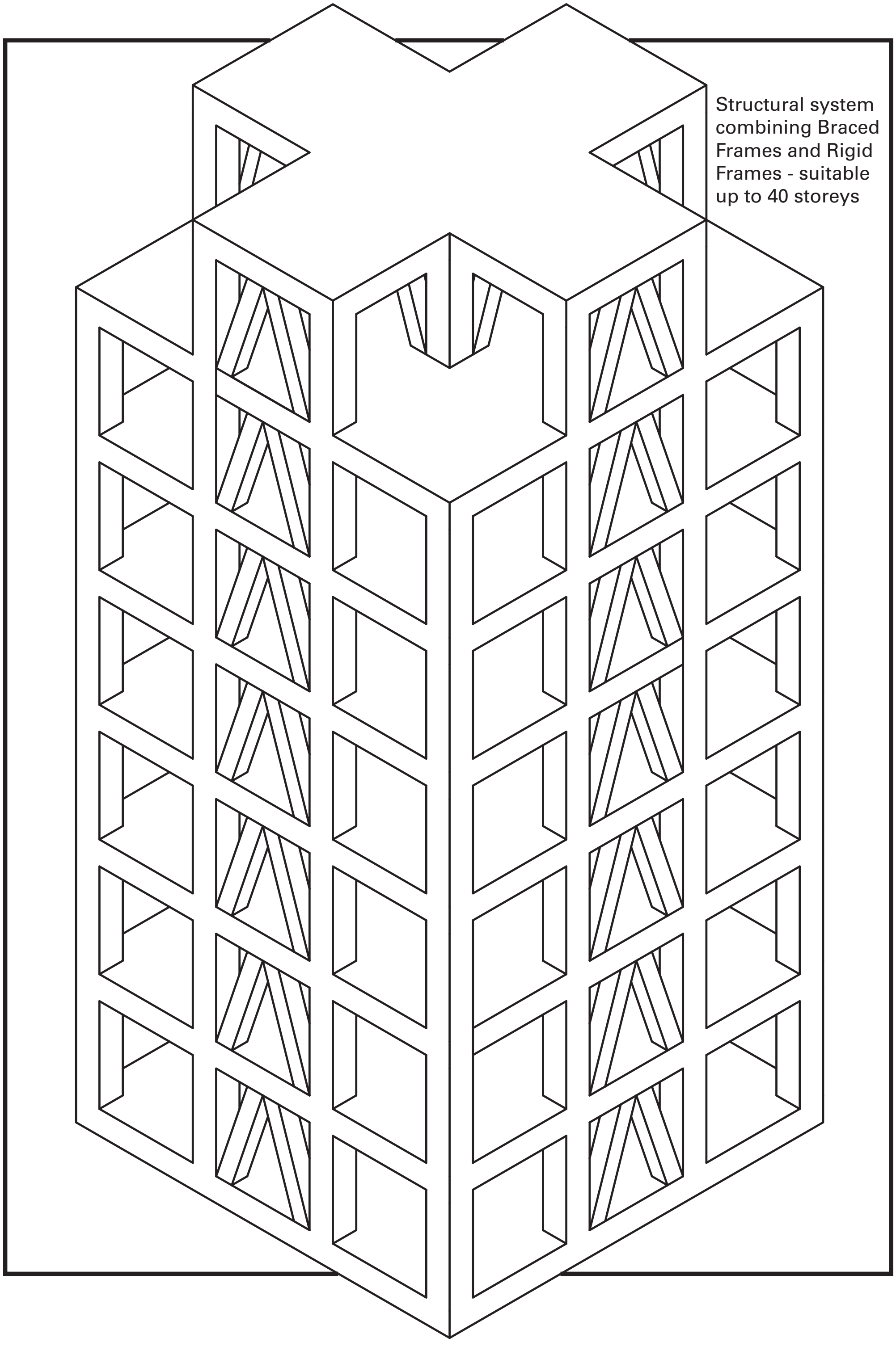

Figure 6.3 Structural system using an interaction of braced frames and rigid frames

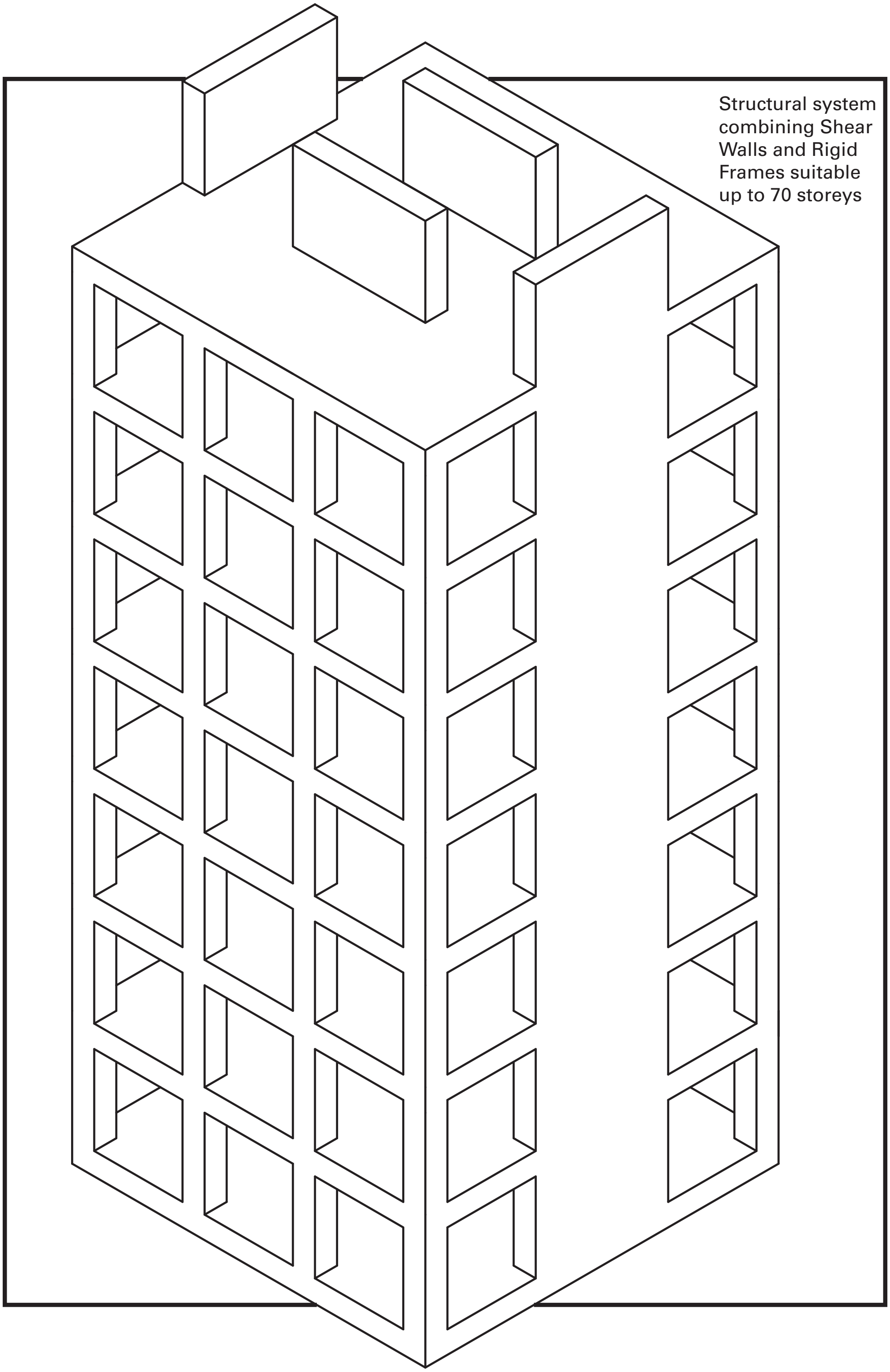

Figure 6.4 Structural system using an interaction of shear walls and rigid frames

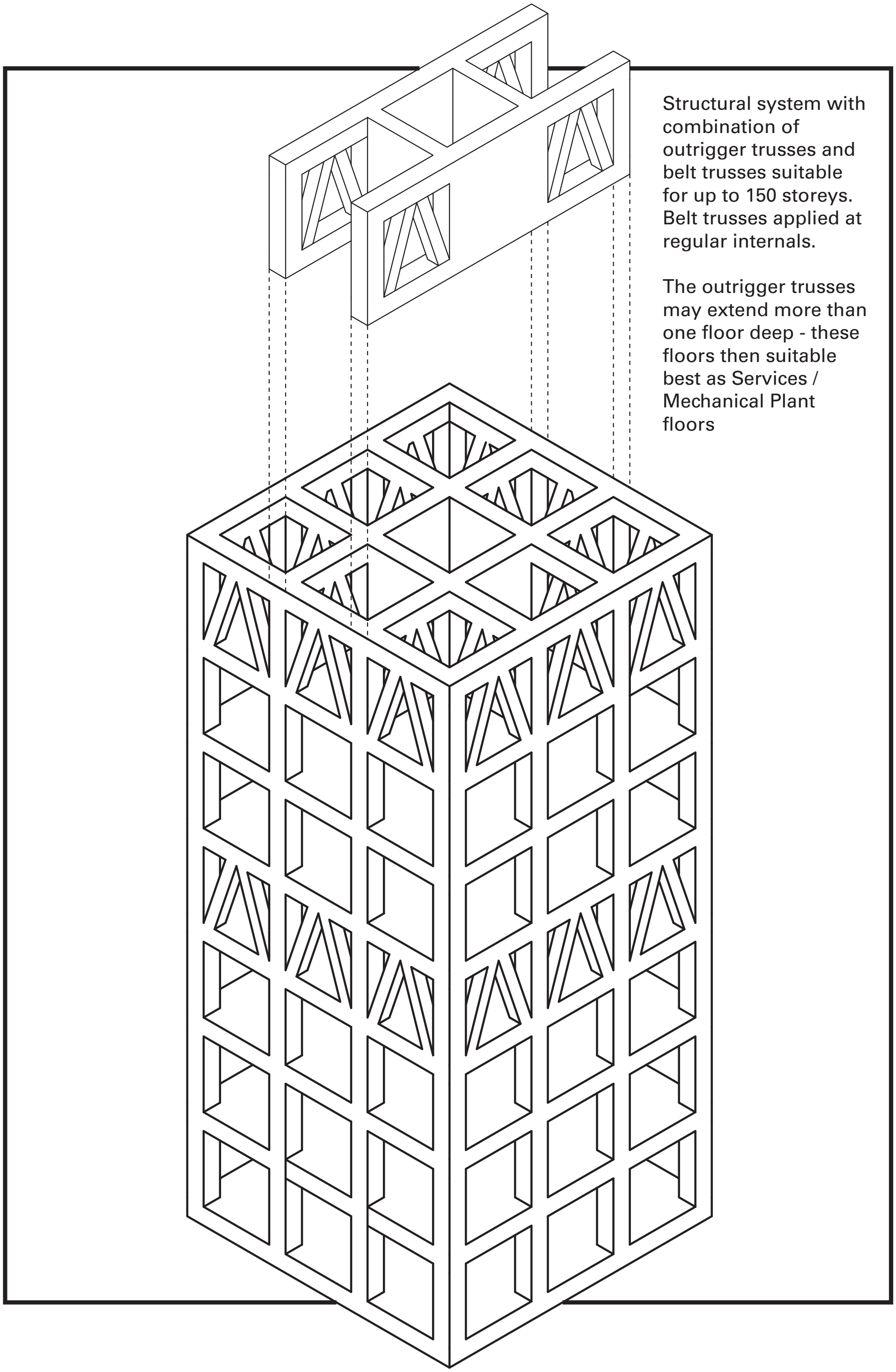

Figure 6.5 Outriggers tying together central shear wall core and perimeter columns. Additionally, surrounding belt trusses connect the peripheral columns

the building and tension to the ones on the other side. As a result, both the overturning moment in the core and the lateral shift of the building are decreased. The outriggers can be located at various floors and are commonly one to two storeys deep. This greatly impacts on the usability of these storeys and it is therefore recommended to use them as mechanical floors.

The outrigger system can be complemented using belt trusses. Located at the same floors as the outriggers, the belt trusses run along the perimeter of the building (Figure 6.5). They give the opportunity to utilise the perimeter columns which are not directly connected to the outriggers in order to further increase torsional stiffness.

When planning on reaching great heights, up to 150 storeys, it is possible to replace the outer columns by mega-columns connected to the outriggers. This approach is appreciable as it reduces the amount of perimeter components, thus providing greater liberty in designing the façades, expressing the building's exterior architectural character, and allowing more natural light in the interior spaces.

Buttressed Core

This system is innovative and rare, as it is designed to reach extreme heights, up to 200 storeys. So far, only one constructed building, the Burj Khalifa (Dubai, Skidmore, Owings & Merrill, completed 2009), physically displays this state-of-the-art system, while two others, the Jedda Tower and the Wuhan Greenland Center, are under construction with reasonable structural variations. The buttressed core system is therefore presented by primarily using Burj Khalifa as a case study.

The 'buttressed core' is a reinforced concrete structural system articulated around a hexagonal shear wall core with three wings connected to it. The structural configuration is based on a tripod concept, with each wing buttressed by the two others. The wings are composed of parallel central walls running from the building's core to their length and terminated by thick crossed 'hammerhead' walls (Figure 6.6). The long central walls and the thick hammerhead walls respectively behave like the webs and the flanges of a beam (Baker, Korista & Novak, 2008). As a result, while the hexagonal core ensures torsional resistance, the wings provide shear resistance and greater moments of inertia. In addition, a series of columns run along the perimeter of the wings and are connected to the interior walls by three-storeys high outrigger walls on five mechanical floors. This ensures that the columns are also part of the lateral resisting structural system. The entire structural system is therefore used to resist both gravitational and lateral loads.

It is important to notice that the building is not symmetrical in order to avoid resonance between the wind vortices and the building. While the structural system

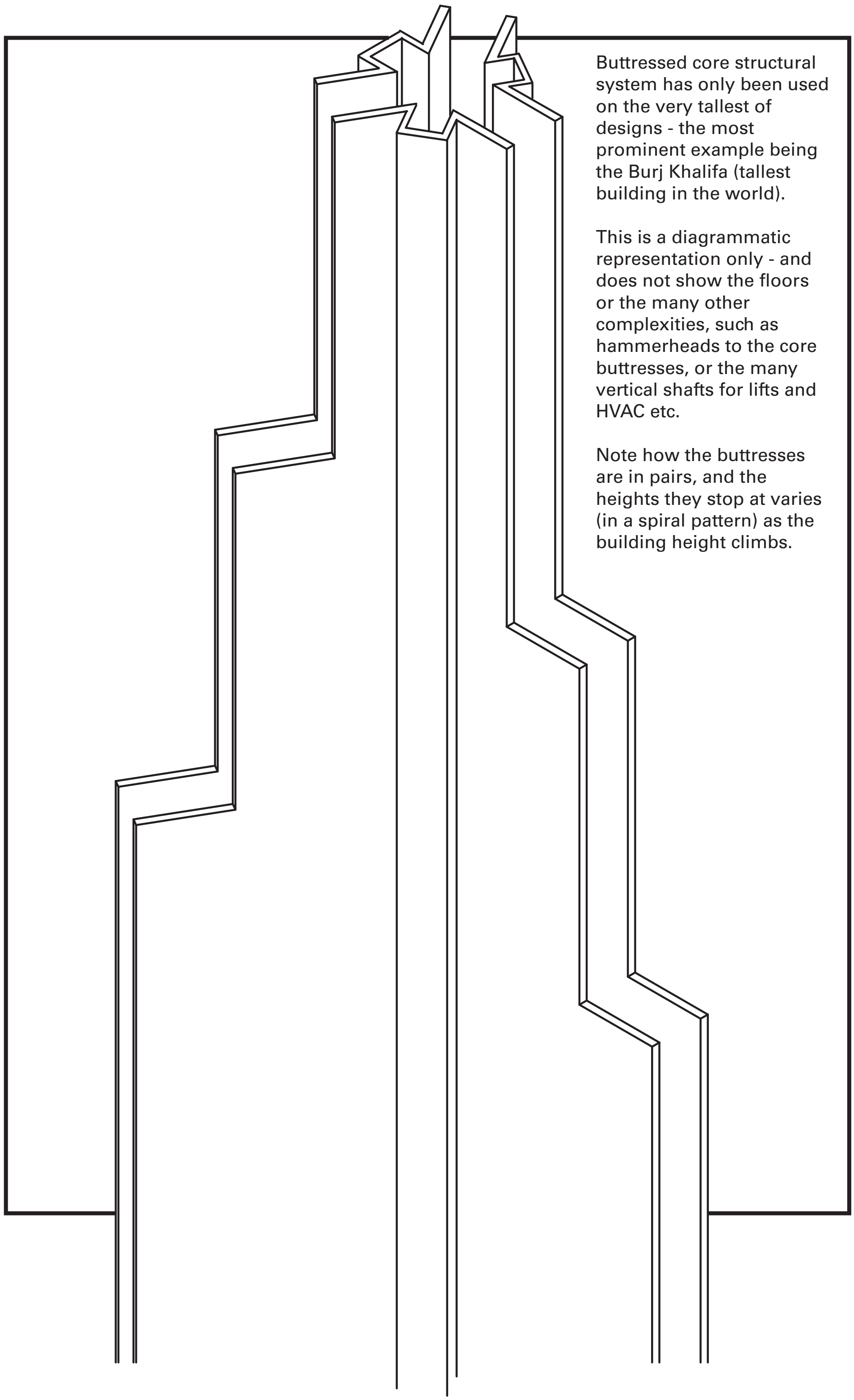

Figure 6.6 Buttressed core structural system

is based on a Y-shaped floor plan, the wings step back in a spiralling sequence as the tower gradually tapers to the top. This configuration, resulting in each wing being distinct, affects the behaviour of the wind vortices which substantially reduces their forces. The setbacks of the wings are aligned on the structural grid, ensuring that the above columns are vertically aligned with the walls below (Baker et al., 2008). Such a structural layout avoids the use of transfer beams, maintaining the structural design particularly effectively.

The Y-shape design is also relevant in regard to natural light and outside views, as the window surface is maximised. However, the width of the wings tends to restrain the natural lighting to the close perimeter spaces. The structural layout mentioned above also reduces planning flexibility, forcing the internal spatial layout to accommodate the main core as well as the parallel central web walls dividing the wings along their length, and the hammerhead flange walls.

6.2 Exterior structures

Tube systems

The tube is a structural system using steel, concrete, or a composite material, allowing the building to act as a hollow cylinder cantilevered from its foundations. It is designed to have its structural components located along the external perimeter of the building. This approach aims at ensuring sufficient resistance to lateral loads while requiring less material than other systems to reach greater heights. Four tube systems are presented below:

Framed tube

The framed tube system displays a series of closely located columns connected to one another using deep beams. The rigid connections between the columns and the beams combined with the peripherical location of the structure create a stiff tube with an increased overturning resistance. This system can be arranged in a circular or triangular form, although it is particularly efficient in a square or rectangular plan. With sufficient resistance to lateral loads from the framed tube system, fewer interior columns are required. They would only carry gravity loads and be commonly located at the core of the building, which provides greater spatial usability (Figure 6.7). The main counterpart of the framed tube lies in its impact on natural light and outside views. With the perimeter columns aligned every 2 to 4 meters, only about half of the façade surface is usable for windows.

Braced/trussed tube

A braced or trussed tube possesses greater stiffness than the above presented system thanks to the presence of diagonal members bracing the frames over several stories. Less peripherical columns are then required and can be spaced further apart, while the depth of the beams can be reduced thus providing greater window surface (Khan, 1969). The diagonal braces intersect the vertical columns on each façade and connect at the same point on the corner columns (Figure 6.8). While resisting lateral loads, the braces also contribute to the transfer of gravity loads alongside the vertical columns. They balance gravity load stresses by transferring axial loads from the more highly columns to the less stressed ones (Taranath, 2004). As a result, the structural system acts as a rigid cylinder possessing great lateral stiffness. The use of mega-columns at the four corners of the building can be considered to reach greater heights in comparison to a conventional braced tube system, passing from a maximum height of 100 to 170 storeys (Ali & Moon, 2018).

Tube-in-tube

This structural system, as its name implies, combines an inner and an outer tube acting together to resist gravity and lateral loads. This system possesses many

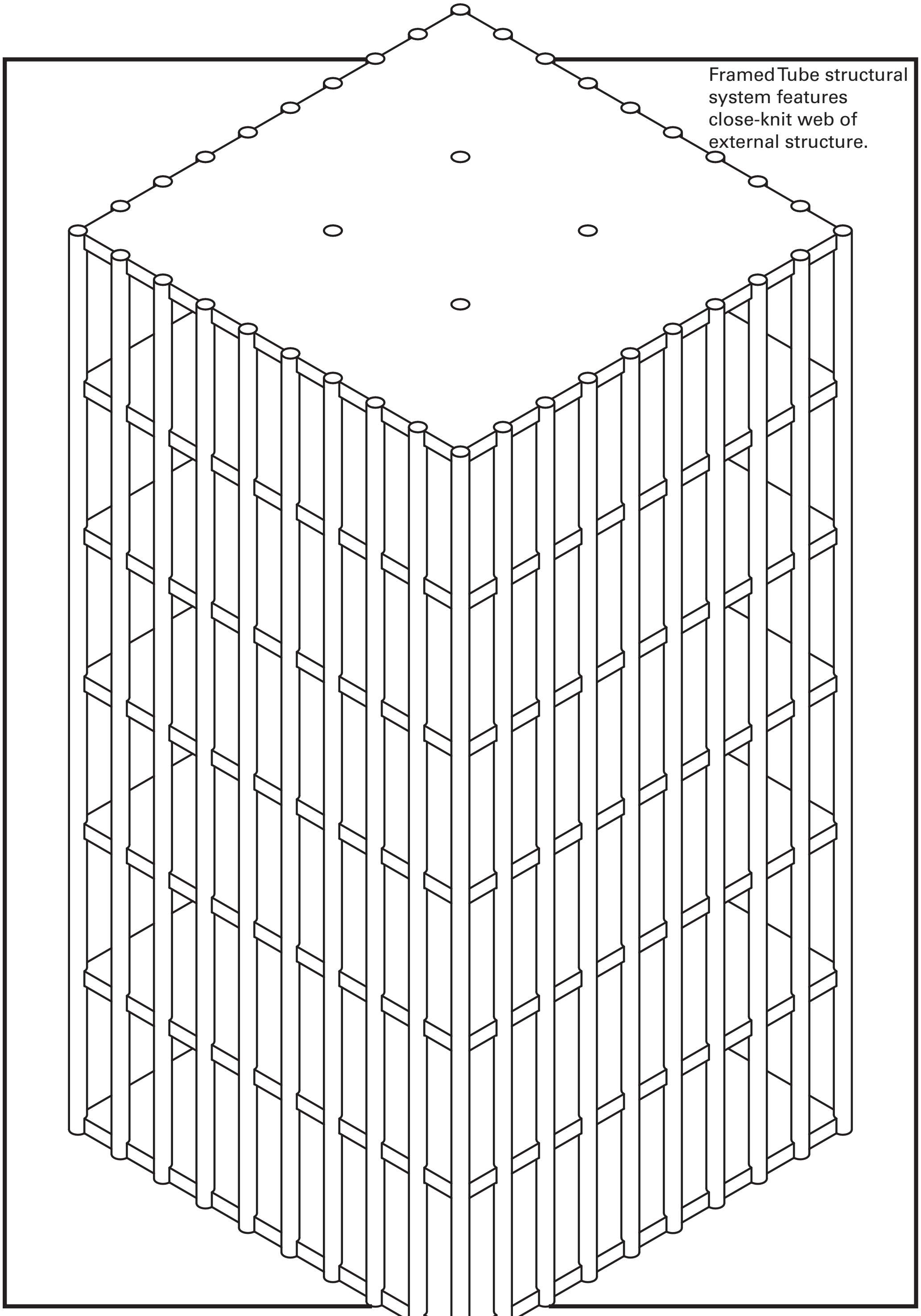

Figure 6.7 Framed tube system located at the perimeter of the building with gravity-only columns located at the centre core

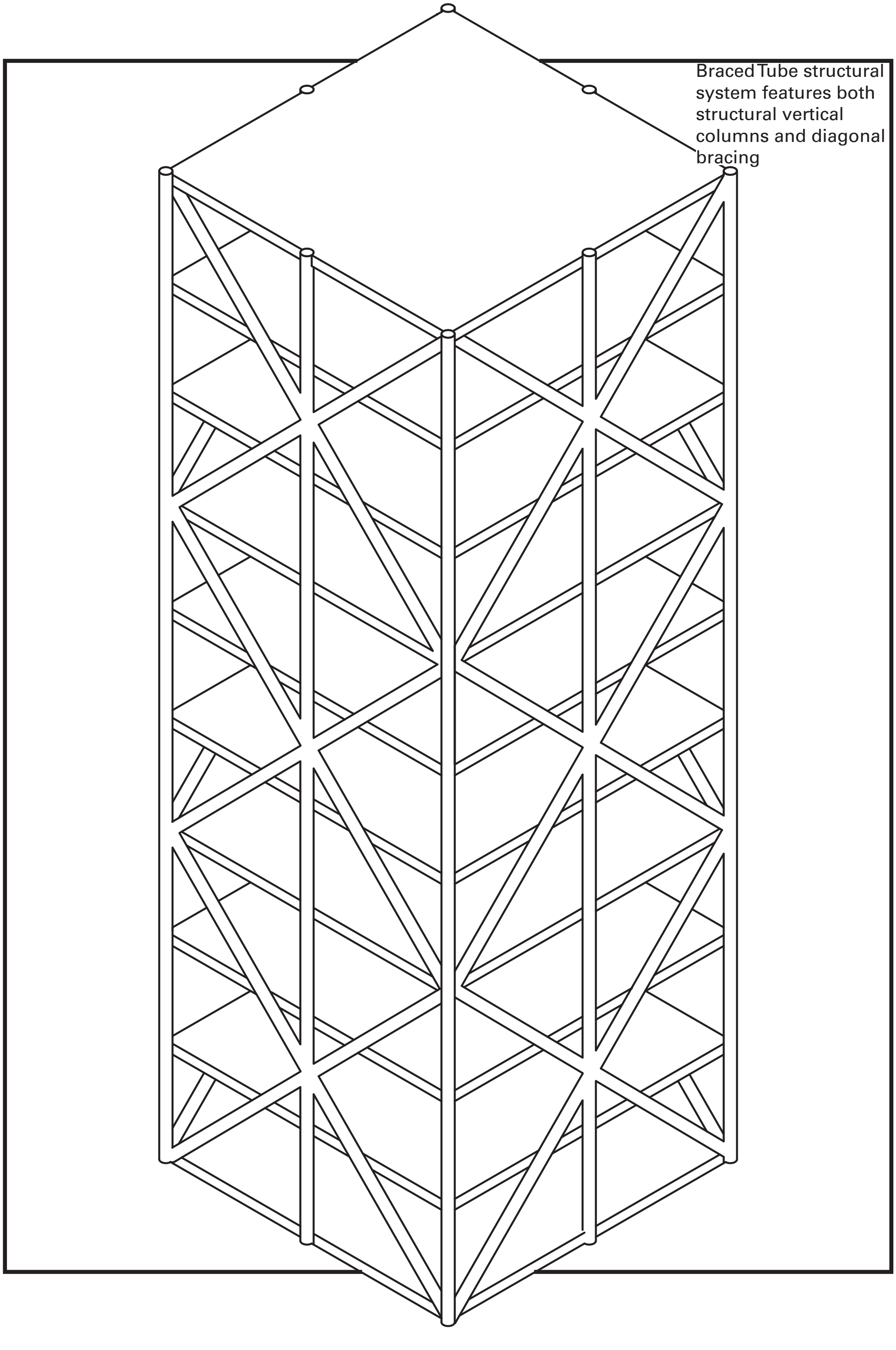

Figure 6.8 Braced tube structural system

structural combinations, as the perimeter tube can be designed using framed tube, braced tube, or diagrids, which can also be used for the core tube in addition to reinforced concrete shear walls (Figure 6.9). The tubes are connected through the floor diaphragm which transfers the lateral loads to both structural systems. It is, however, the external tube that carries most of the gravity and lateral loads due to the greater depth and strength of its structural components. The tube-in-tube system allows using the core tube to shelter lifts and services, while the space in between the inner and outer structures provides planning flexibility.

Bundled tube

This system is designed as a combination of individual framed tubes connected together to act as one single structural tower. It allows reaching greater heights with increased floor surface in comparison to a single slender framed tube. The bundled tube provides freedom in designing the overall architectural character of the building by varying floor plan and height configurations (Figure 6.10). Similar to the Burj Khalifa, the variation of levels impacts on the wind flow, which reduces the building's horizontal sway. The assemblage of tubes increases the stiffness of the building, with the interior frames being more evenly stressed and contributing to the reduction of shear lag. This system does not require the columns to be as close as in the single framed tube system, therefore providing more planning freedom. Yet their presence within the interior spaces needs to be carefully taken into account in regard to the building's functionality and spatial use.

Diagrid systems

The diagrid system is composed of diagonal steel, concrete, or composite inclined columns intersecting in a diamond pattern around the perimeter of the building. The diagrid system does not require the use of vertical columns but relies instead on its diagonal members to resist both gravity and lateral loads. To ensure stiffness and stability, the diamond structure is connected to the edge beams of the floors, called ring beams, thus creating an effective triangulation. The connections between the ring beams and the diagonal members occur at every intersection and most importantly at the nodes of the diamond grid every several storeys. Without the need for vertical columns, and its capacity to achieve convoluted geometries, the diagrid system provides great freedom of design both internally and externally. In a diagrid tower, the structural system is subdivided into modules, each encompassing a single diamond pattern from bottom to top node and commonly extending over several stories. To ensure structural integrity, the building needs to end at a complete module, which implies that the number of storeys directly influences the number and height of the modules. In addition, the diagonal columns need to meet at the nodes at the building's corners (Figure 6.11).

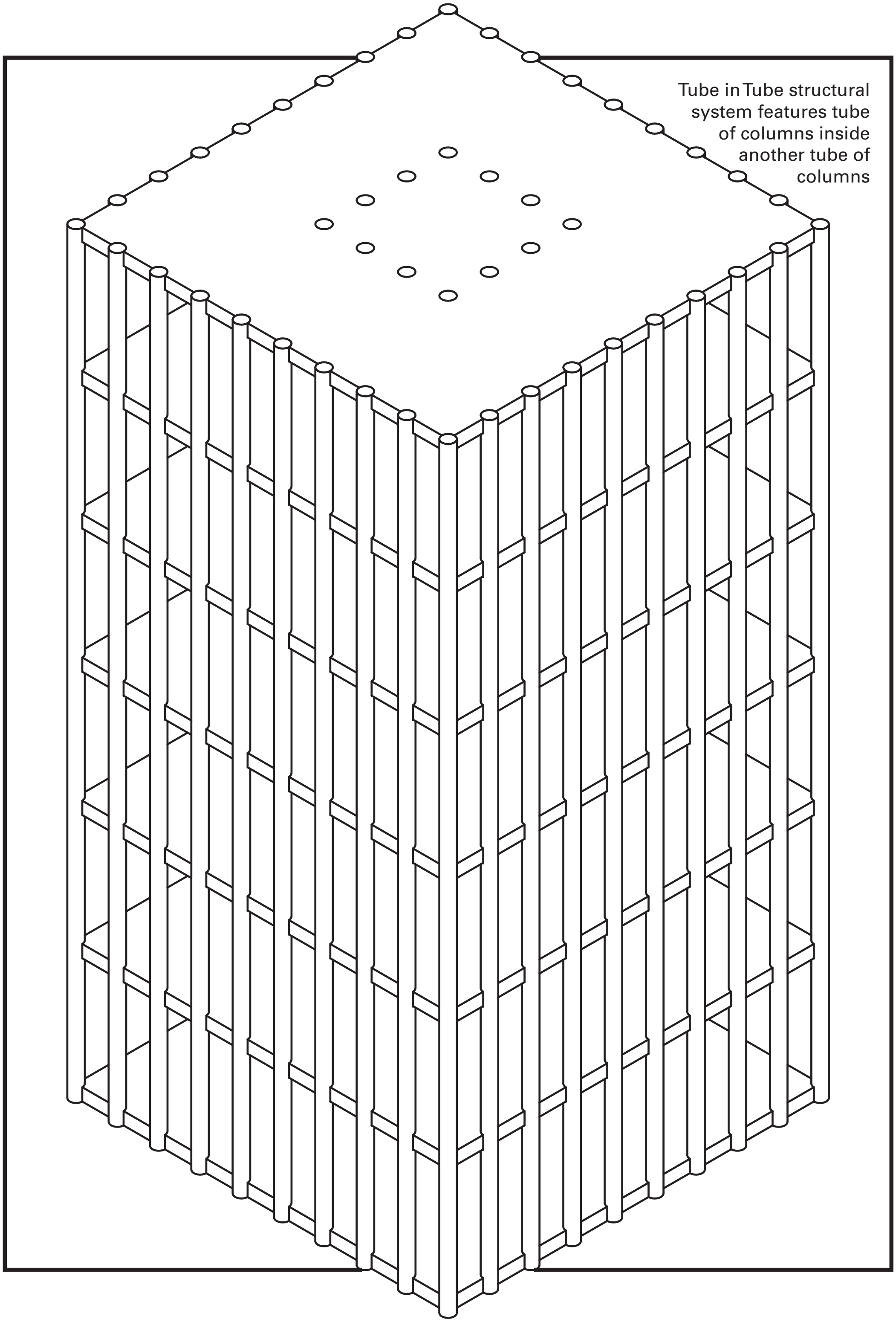

Figure 6.9 Tube-in-tube system: using two framed tubes in combination

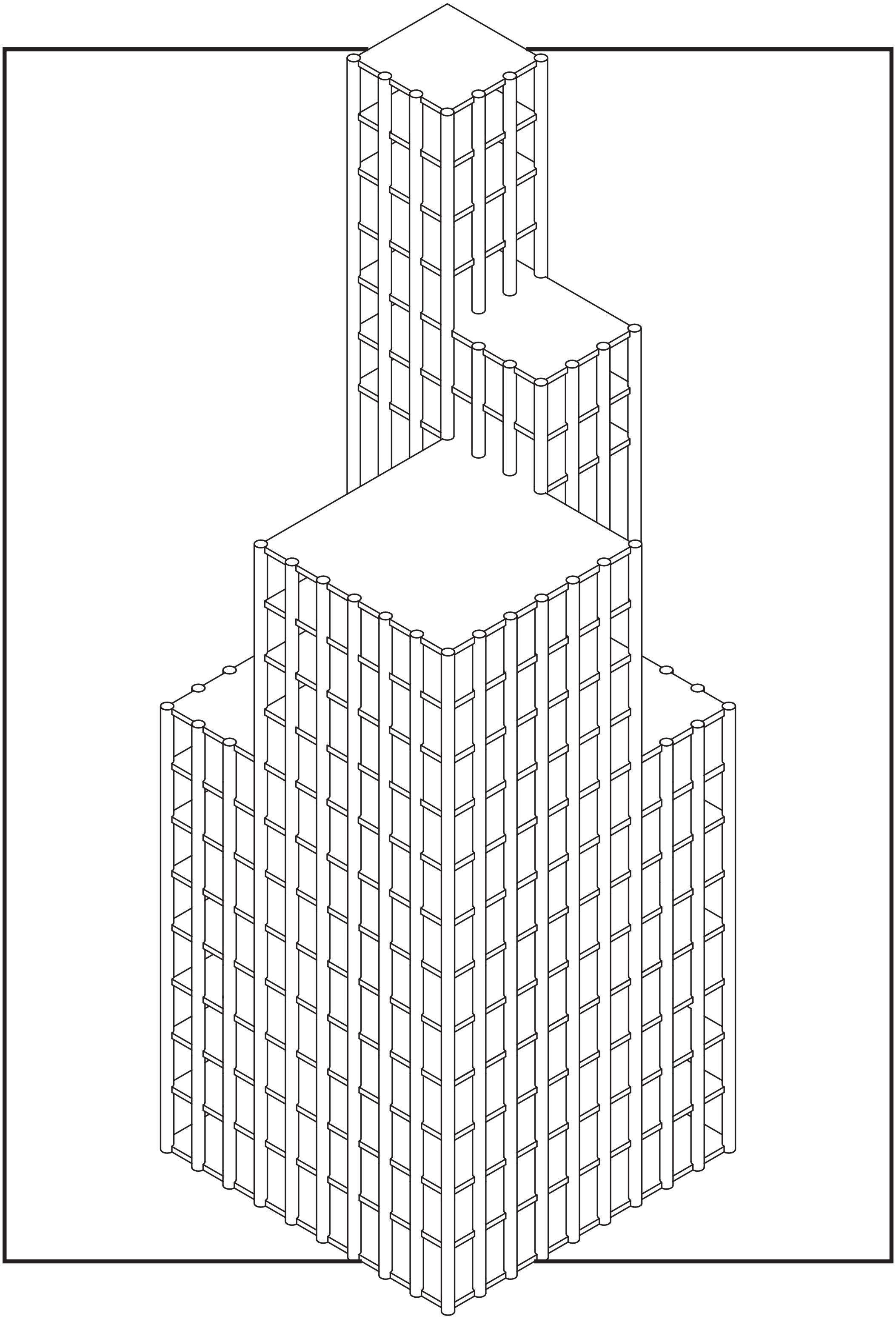

Figure 6.10 Bundled tube structural system

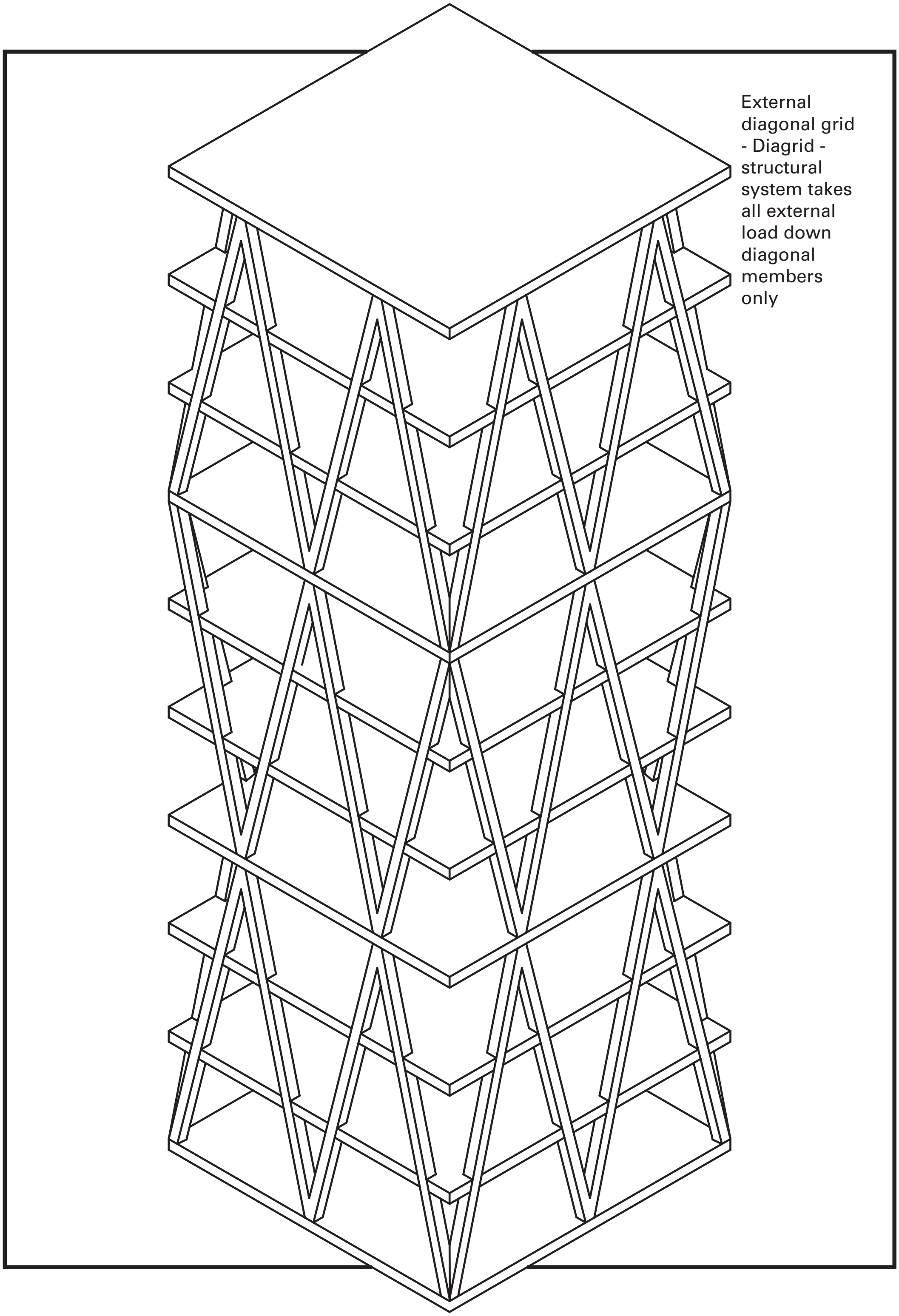

Figure 6.11 External diagrid structural system

The diagrid system can be classified in two configurations: uniform and varying angle diagrids. A diagrid with a uniform angle throughout the modules is relevant for buildings designed to reach 110 storeys with a height to width ratio less than seven. For very slender buildings with a ratio higher than seven and a maximum of 130 storeys, varying angle diagrids are more efficient (Moon, 2008). In this configuration, the modules become smaller as they reach the top of the building, with the steep angle of the diagonals at the bottom progressively becoming wider. The angles variation is justified by the need to more effectively carry gravity loads and resist lateral shear loads and overturning moments. While columns oriented at 90 degrees ensure maximum bending stiffness, they reach highest shear stiffness when inclined at 35 degrees. Therefore, the optimal angle of a diagrid must lie somewhere between these two values. Commonly, based on existing buildings with a diagrid system as their main structure, the selected angles vary between 60 and 70 degrees. More specifically, in-depth research by Moon (2007, 2008, 2009) concluded that a 69-degree angle was the most effective for a uniform diagrid.

6.3 Conclusion

This chapter provided an overview of different key structural systems used in high-rise buildings. Through the description of their characteristics, the logic behind their design, and their inherent constraints, a hint at the breadth of their potential is provided. High-rise buildings can thus be designed using a large range of structural systems, from the most straightforward and simple to the most elaborated and ambitious. It is therefore important to consider the use of a structural system, whether internal or external, not as a simple technical response but as an opportunity to express a strong architectural idea.

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07

Chapter Seven

Foundations

Foundations

Guy Marriage

7.0 Foundations

The foundations are the most under-appreciated part of any building and often one of the most expensive. The proverb “Do not build your house on sand” is as true now as it ever was, yet we build large cities with tall buildings in the desert sands of the Persian Gulf. How? The answer to that is, of course, good foundations. Without good foundations, a building will not have much longevity.

The topic of foundations is a specialist subject that is mostly left up to the geotech engineer, the structural engineer, and the contractor, with the architect taking engineering advice. The architect needs to know how the foundations are built so they can be incorporated into the general building plans. Foundation systems depend mostly on the weight of the building and the condition of the ground beneath. The type of material your building is constructed from will have a huge effect on how much your building will weigh: steel and concrete are far heavier than timber. Changing the structural material may have an effect on the size (and therefore cost) of your foundations.

Let’s have a closer look at what systems there are and how they affect the architecture of the building.

7.1 Materials

The most relevant system for a tall building is the use of piles. Piles have been used for centuries. In Venice, for instance, hardwood timber poles were hammered into the mudflats several hundred years ago, and the stone and brick buildings of the city built on top. Many of those timber foundations will be down there still, centuries later, as water-laden mud is an excellent preservative: no oxygen to aid decomposition. It is only in the intertidal area where timber piles get both wet and dry that any rotting activity will take place. Nowadays, of course, timber is not used for tall building foundations, except for temporary works.

Steel and concrete are the two prime materials used for piling and foundations of tall buildings: mainly concrete. Piles may be used as a perimeter wall to keep the water out and to hold the neighbouring soil in place but are primarily used to counteract the immense point loads being generated at the base of the columns. Steel **H** columns may be driven reasonably easily into the ground, as they have very little cross-sectional area, but as with any steel member in contact with water for years, they will suffer from rust. More likely as a material for piles is concrete: wider, more bulky, and longer lasting, concrete can be hammered into the ground as a precast element. More often, a hole is excavated and concrete is poured in to create the pile in situ, as per the SE calculations and instructions. Each of these piles will vary in size from 0.6m to 2.0m (2′ to 6′ 6″) in diameter – or larger – and may well be over 20m deep. Some of the super-tall buildings in Asia have piles over 80m deep, stretching deep underground (Goman Wai-Ming: 2018). Everything depends on the ground conditions and the size of the building being placed upon it. Changing the building material may affect the depth of the piles, the width of the piles, or whether you need a pile at all. Some ground conditions will dictate a ‘floating raft’ foundation rather than piles: your engineer will advise.

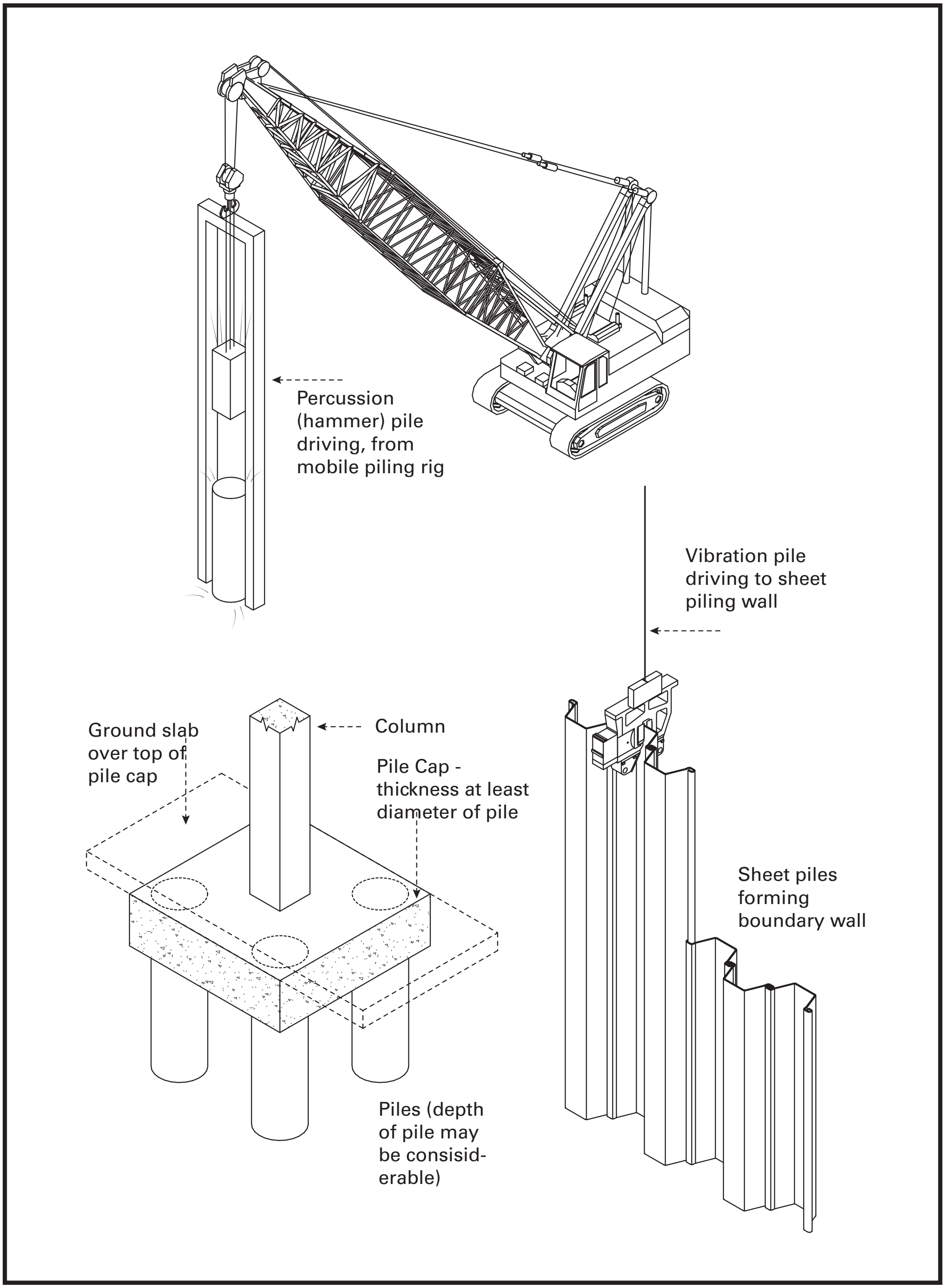


Figure 7.1 Piling methods

7.2 Piles under columns

As a general principle, we can assume that under every column bringing load down a building and into the base foundations, there will be a pile. The taller the building, the stronger and probably deeper the pile will need to be. An end-bearing pile is designed so that it can, if possible, go down to and sit firmly on, solid rock. That works well in cities like Manhattan where the island is built on a sunken mass of solid granite, but is harder in cities like London, where the sub-soil beside the river Thames is a mixture of clay, gravel, silt, and chalk. The geotech and the SE will try to plan the length of piles to get down to solid rock and place the 'point load' of the foundation on the rock. The alternative is to have the pile go down a certain depth, compacting the ground below the large, flat end of the pile and relying on the friction of the soil it passes through. Known as friction piling, the immense gravity force on the ground the pile is passing through effectively holds the pile in place without ever getting down to 'bedrock'. One example of this is Christchurch in New Zealand's Canterbury Plains, where the city's foundations sit on a 500m (1/3 mile) deep bed of river-washed shingle. Another example is Mexico City, where the city is built on the edge of a vast former lake-bed, i.e. deep layers of mud. In both cases, the foundation system used must either be a floating raft or a series of friction piles to try and 'float' the building on the surface of the ground. Roma Agrawal's book *Built* has an excellent discussion on Mexico's problem foundations (Agrawal: 2018).

7.3 Percussion piling

Percussion may sound like a drum kit, but in the case of piling, it is distinctly unmusical. Percussive piling means hitting the piles into the ground, normally by the very crude but extremely effective means of hitting it with a giant 'drop hammer'. In this case, the hammer is a massive steel weight that is raised up on the piling rig and left to drop down and smack the head of the pile, forcing it into the ground (refer to Figure 7.1). This will be repeated many times, noisily, making the ground around the area jump each time the multi-tonne weight is raised and lowered. When the pile no longer moves significantly when hit with the drop hammer, the pile has gone in far enough. The piling rig needs to be held vertical so that the pile goes down straight into the ground, so these piling rigs may be constructed on the back of large trucks with adjustable systems to keep the pile driver vertical, or they may be suspended from large crawler cranes that can move around the site.

Materials for percussion piling can include timber poles, but for large buildings, percussion-driven materials will be either steel H section columns or more likely, precast concrete piles. Once those piles are hammered into the ground, you're not likely to see them again. Foundations are a 'sunk cost' – once in the ground, you're never getting that money back! Unexpected costs in foundation construction usually have catastrophic effects on building budgets.

7.4 Excavated piling

As an alternative to percussion piling, the contractor can opt to dig a hole in the ground for the pile, supporting the perimeter of the pile during excavation with either a temporary or permanent shield. This will often take the form of a steel perimeter casing or tube which is driven into the ground, and the interior of the tube is dug out with a large auger drill. The auger is repeatedly cork-screwed down into the tube and then lifted out, each time emerging with a layer of waste soil. This way the surrounding soil is retained in place, the pile can be dug without any collapse, and a large deep hole is created. A steel reinforcing cage is lowered down inside the empty tube and concrete is carefully poured down the centre of the cage, allowing it to fill the void. Depending on the situation, the steel casing tube may or may not be able to be withdrawn and used again.

There are other methods of excavating holes for piles, including the use of filling the excavated holes with a particular type of water-retaining clay called bentonite. It is a strange substance that is hydrophilic – it loves water and expands when in contact with water. Poured down into an excavated hole for a pile, it can act as a means of keeping pressure on the surrounding soil while the soil in the hole is being excavated. It looks like a sloppy thick grey water, but the piling rig can drop a 'barrette' (a great big sets of jaws) down through the bentonite mix to pick up the gravel at the base of the hole. When the hole is dug to the right depth, concrete is pumped down through a 'tremmie' tube to the bottom of the hole. As the concrete is pumped in, the bentonite is pumped off the top to be used again in the next hole.

7.5 Pile caps

Often the SE will design a system that relies on many smaller piles linked together rather than one larger pile. The friction between the numerous smaller piles will hold the soil together and will cause more friction, meaning that the piles may not need to go down as deep. These groups of smaller piles (maybe four clustered together) are then encased in a thick reinforced concrete slab known as a pile cap, on which the main columns of the building will then sit (refer to Figure 7.1). This pile cap will likely finish just below the general level of the basement floor or be incorporated into it. The columns of the building can then be set out on top of this base slab, knowing that there is a mass of resistance sitting just under the slab, spreading the load out over several piles so that weight can be resolved without concerns of later settlement.

7.6 Sheet piling

Not all piles are circular and made of concrete. Sheet piles are very thin folded steel surfaces that come pre-folded into a repeating trapezoidal shape (Figure 7.1). Sheet piles can clip together with a thin strip at one edge of the pile clipping into the edge of the next sheet pile. Due to this, when carefully assembled, sheet piles can provide a wall that is highly resistant to water ingress. Because they are relatively thin and flat, they can be used quite close to other neighbouring buildings, and so sheet piling is often used mainly as a temporary perimeter piling system. Sheet piles are typically vibrated into place, as hitting them with a giant hammer is likely to bend them – they can slide quickly into sandy or shingle soil, cutting effortlessly into the ground.

7.7 Vibration piling

An alternative to percussion piling is vibration piling, primarily used for sheet piles. The vibration pile driver consists of a large, very heavy piece of machinery atop an enormously strong pair of hydraulic jaws (refer to Figure 7.1). The jaws grip the top of the pile, orient it vertically and then vibrate it, letting the weight of the massive vibrating machine drive the pile into the soil. It is a lot quieter than percussion piling and a lot less invasive to the neighbourhood, as it does not have the massive thump that a hammer-driven piling rig has, so it is far more likely to be used in denser urban environments. Vibration piling of sheet pile walls is commonly seen worldwide, especially in relation to temporary piled walls.

7.8 Temporary piling

Temporary piles (typically steel sheet piles) are installed around the perimeter of the site for a limited period of time to enable excavation of a basement. Once the temporary wall is sunk, the ground inside the piles is then excavated, creating a safe working place several metres underground. To stop the excavation filling up with ground water, de-watering stations are placed to pump the water out. Giant propping beams may be needed to span across the basement excavation, keeping the opposing walls from collapsing in on each other. Once the basement construction is complete, the piling rig with the giant jaws is sent back in again and it grasps the top of the sheet pile, vibrates heavily, and pulls it out of the ground. Easier said than done if the sheet pile has been in the ground for some time! Some piles may be stuck hard and impossible to get out, in which case they are left there. For most sheet piles however, the jaws eventually pull them out and the expensive steel sheet piling can then be used again.

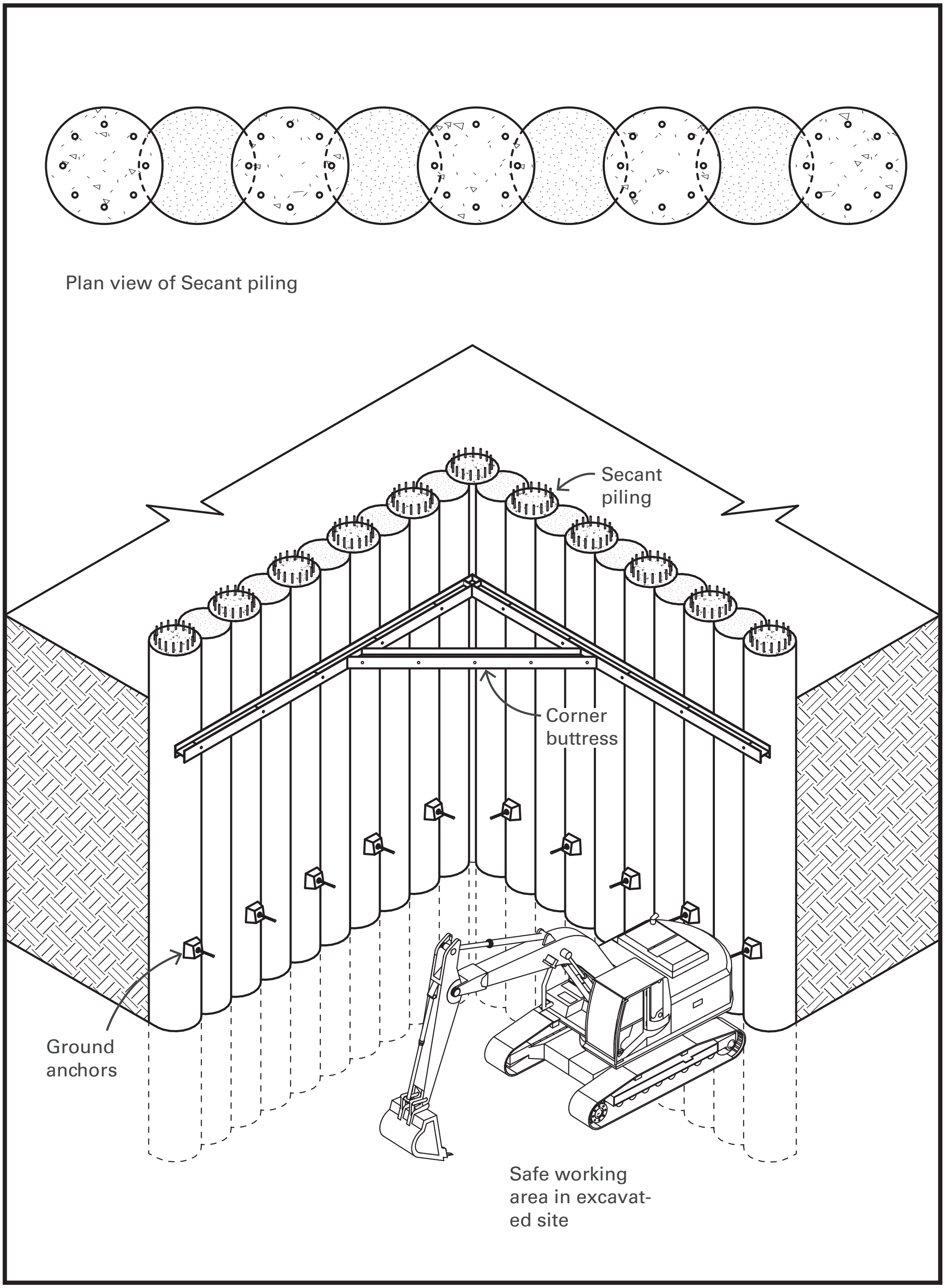


Figure 7.2 Secant piling to excavation

7.9 Perimeter piling

The creation of a strong perimeter wall underground is hugely important if you plan on having underground basements in your multi-storey building. The distance away from the legal boundary of your site will vary depending on conditions and especially depending on whether there are existing neighbouring buildings. You do not, under any circumstances, want to undermine the neighbouring properties, or else the insurers will need to be contacted. Allow a healthy distance to the boundary (Figure 7.3).

The broad principle for you to follow here is that a 45 degree ‘zone of influence’ sits under any point load. If your proposed ground floor or basement floor have a zone of influence that intersects with the foundations of the neighbouring property, you need to move further away. As noted above, perimeter piling may often be made from sheet piling, especially where it is perhaps shallow or close to the neighbours. For deeper, more permanent basement walls, piles are likely to be further away from the neighbouring property and also very deep and much, much stronger. You will need to allow a zone of perhaps 2 or 3 metres (6′ to 9′) to build this strong perimeter wall.

7.10 Secant piling

Very deep excavations need very strong piled walls to create a safe place for construction. This can be created using a method of construction called secant piling (Figure 7.2). Secant piles are made when a long row of piles is excavated and every second hole is filled with low-density mass concrete – without reinforcing steel. Once the concrete has set, the piling rig returns again to dig another hole between two of the mass concrete piles, biting into each of them. This pile hole then has a steel reinforcing cage inserted and is filled with concrete, creating a continuous wall. After the wall is set and cured, the interior of the excavation is dug out, leaving a rough wall of concrete tubes visible. Only every second tube has steel reinforcing. These piles will act as a strong wall, much thicker and stronger than a steel sheet pile wall. Ground anchors are drilled into the ground through the secant wall to hold onto the soil behind the wall, and giant girders are placed horizontally to spread the load along the face of the wall, with props in the corners or from side to side. Dewatering pumps then pump out the water from the base of the excavation, which then lets the contractor build the basement in a very safe, relatively waterproof environment.

7.11 Permanent waterproof basement slab

Basement slabs are pretty important in the whole scheme of things, although architects are minimally involved at this stage. In some cases, just a massive floating basement slab is poured to rest the building on. The 64 storey Masterpiece (K11) building in Hong Kong sits on a concrete raft 3.0m (10’) deep (over bedrock), while the 81 storey Vincom Landmark building in Vietnam relies on an 8.0m thick (26’) slab above 147 piles, each about 85m (278’) long (Goman Wai-Ming: 2018). Moral: ground conditions matter!

There is only one chance to get the basement slab down in the right place, all the necessary services in place, before it becomes permanent. Always place a damp proof course (DPC) down on top of compacted sand ‘blinding’. This DPC is a thick, tough polythene sheet, with all the joints and gaps taped together so it provides a (hopefully) permanent barrier to water. It should stop the ground water rising up through the concrete. The only things that penetrate the layer of the DPC are the piles that will dot the site. Reinforcing will criss-cross the slab, woven into a thick blanket and filled with concrete. The hydrostatic pressure from ground water will be pushing intensely upwards, as well as the weight of the future building weighing down. Wrap the DPC up the outside edge of the slab to join with the wall waterproofing.

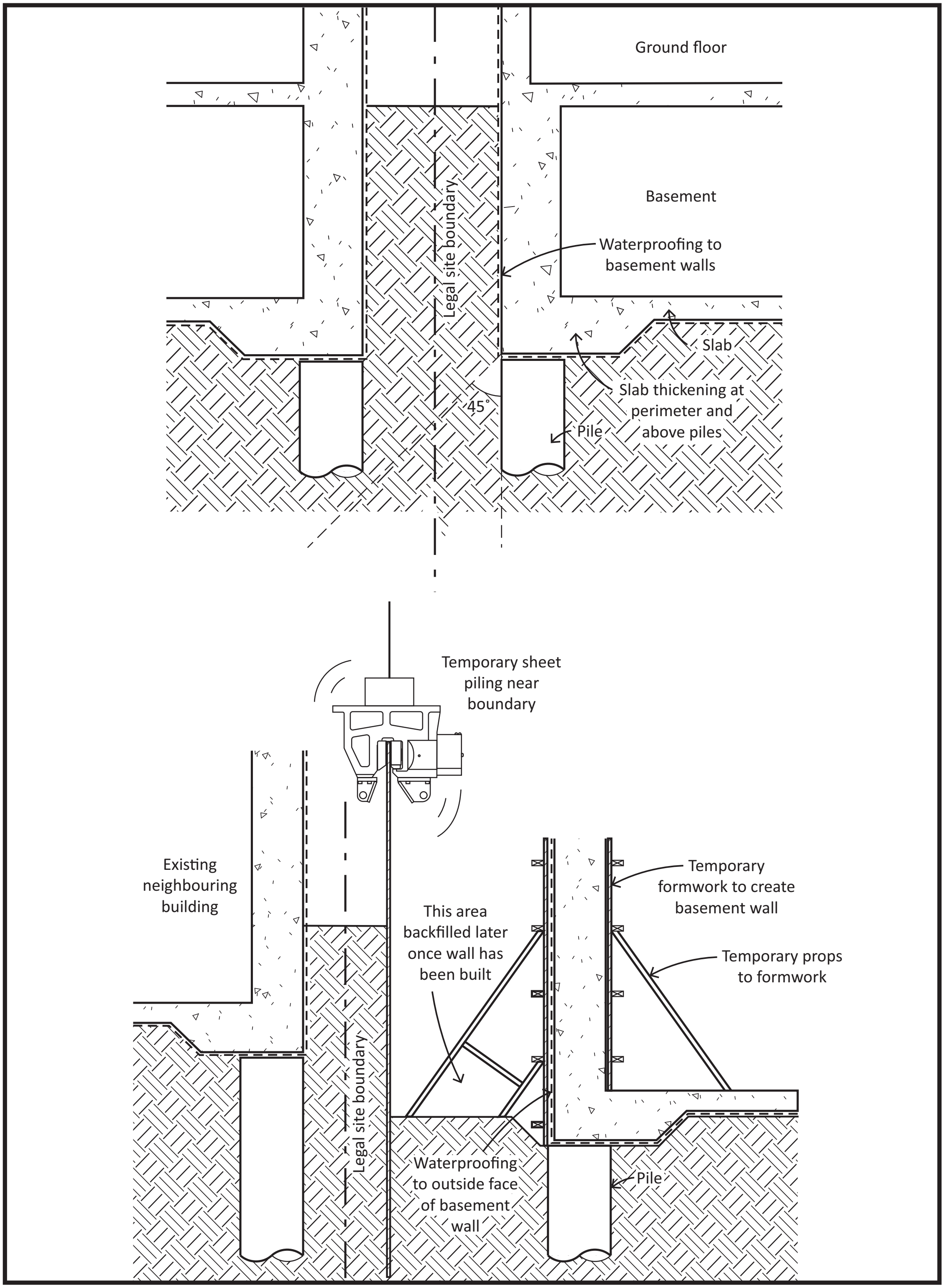


Figure 7.3 Constructing basements near boundaries

7.12 Waterproof basement walls

If the basement walls are being built within a safely excavated hole, shuttering can then be built up to create a clean, strong, straight external basement wall. This wall will be capable of being built to a much higher quality standard than a piled wall, which is likely to be very rough and leaky. Hydrostatic pressures from the groundwater can be immense in a deep basement, so the wall needs to be encased within an external layer of damp proof membrane (DPM). Once the concrete has set, the exterior of this wall can be permanently waterproofed with a sheet rubber membrane or a liquid rubber system painted onto the flat external surface. Another system is the use of a bentonite clay blanket or similar, fixed to the external wall face. It is even possible for certain waterproof membranes to be installed within the shuttering for the concrete to be poured against.

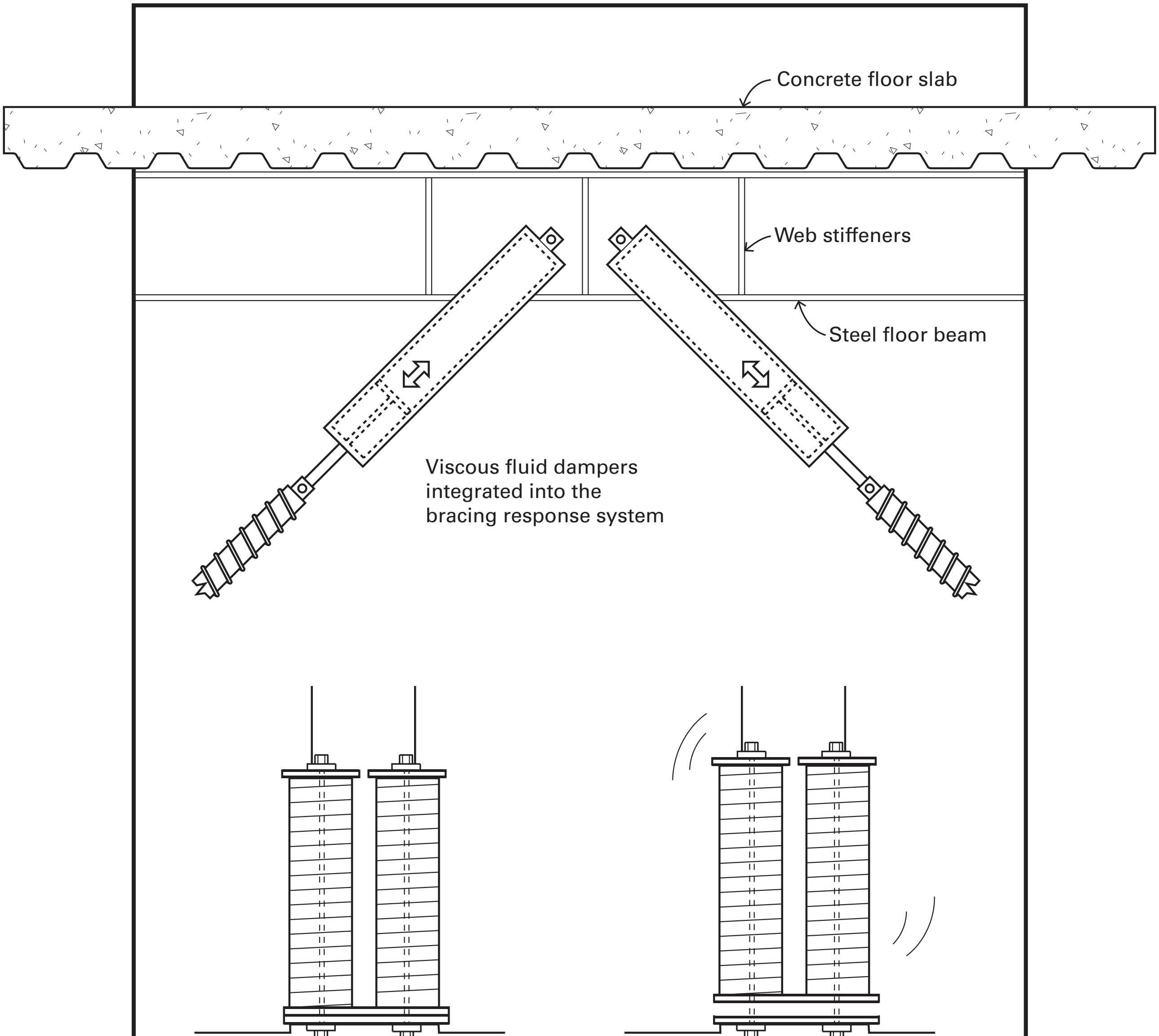
Do all you can to make sure that the basement slab and basement walls are securely waterproofed – you only have one chance at this. If this dryness cannot be achieved, it is so much harder to achieve waterproofing from inside the basement walls. Any water leaking through will be very hard to stop (refer to Figure 7.3).

7.13 Seismic resistance

The old tradition of constructing buildings that sit hard against the neighbouring building may work fine in non-seismic areas, but it is a disastrous policy in areas of high seismic activity. When the earth moves, the buildings sway at different frequencies (according to their height). Small buildings can actually cause intense structural damage to the base of taller buildings by 'pounding' the columns from the side.

Designing for areas prone to large earthquakes means that attention to seismic issues must be kept uppermost in the mind of the architects and the engineers (Palmer and Cattanach, 2018). In strong seismic events, the ground moves rapidly from side to side, as well as moving up and down, when the seismic waves ripple through the ground below the buildings. Therefore, instead of just thinking about a building being subject to gravity and to wind effects becoming greater at the top of a building, the designers need to consider the opposite of gravity – uplift – as well as lateral loads being applied at the bottom of the building rather than at the top. The book *Seismic Design for Architects* (Charleson: 2008) will help you generally design solutions in this area.

One of the key strategies of coping with these unusual movements is by seismic isolation. That means the complete isolation of the structure of the building from the movement of the ground beneath. One seismic isolation strategy is to use viscous fluid dampers which allow the building to move but slows down the acceleration of the mass compared to the ground (refer to Figure 7.4). The building sways, but slower and less violently. This lessens the stress on the structural joints of the building considerably. It is a little like the use of suspension springs and dampers on a car soaking up the bumps from the rough road below. As you can imagine, designing these solutions is quite a difficult task, and to fully understand the scope of possible solutions, you are recommended to seek out another book, *Seismic Isolation for Architects* (Charleson & Guisola: 2016), where the authors take you through the various options in far greater detail than I can here. The greatest result can be gained by full seismic base isolation.



Base-isolating ‘rocking concentric braced frames with Ringfeder spring sliding joint system, in resting state with strong steel springs compressed (as shown at left). In the case of a large seismic event (on right) the building can rock, as the central bolts yield (absorbing energy) but the springs pull the building columns back into place.
Source: Tait, Sidwell, Finnegan, 2013.

Figure 7.4 Fluid dampers and spring systems

7.14 Base Isolation

The principle of base isolation is simple, but the practice can be slow and expensive. Build a ground floor or basement floor fully anchored to the ground with piles. Then create another large foundation that floats above that. In between, insert 'base isolators' under each column that take the gravity load under usual circumstances, but will also yield to sideways – lateral – forces in the case of a large earthquake. That will permit the building above to move differently from the movement in the ground below (refer to Figure 7.5).

The lead/rubber base isolator, invented by Dr Bill Robinson in New Zealand in 1980, is composed of steel plates interspersed with dense rubber layers that allow the load to be taken, with the rubber providing some flexibility in the case of an earthquake. They incorporate a centre that is made from solid lead, a heavy, dense metal with a low melting point. The lead helps take the gravity load in compression, but in the case of an earthquake, an amazing transformation occurs. Energy is transmitted into the centre of the steel and rubber bearing and the heat from this energy is absorbed by the lead core, heating it up and transforming the lead into liquid form. The entire building above the isolators moves from side to side but moves much less violently than the earthquake's shaking. After the earthquake has stopped, the building returns to normal; the lead cools down and becomes solid again, once more taking the gravity load.

The base isolator is installed right at the area where seismic effects are most greatly felt, and so installation of base isolators in the design phase of a building can greatly prolong its life ability to withstand large quakes (Whittaker: 2016). As the effects of the earthquake cause the ground to move violently, the effects on the building are far less pronounced, as the building effectively stays still while the ground moves underneath it. The key thing for the architect and the engineers to take into account is to permit everything to move to and fro in the earthquake. Instead of a basement wall tightly hugging the columns of the building above, in effect everything has to have a 'moat' which permits the building to move. The base isolator may have a range of plus or minus 500mm (20") in all directions horizontally. That means pipes for services as well – particularly liquids. Both fresh water into the building and foul water coming out of the building require flexible couplings capable of moving 500mm in this direction and 500mm in the other direction – that's a total of 1.0m (3' 3") of slack that the services need to have (figure 7.5). It requires a lot more thought, more planning, and lots more finance, but it works. The building and its inhabitants are saved, virtually unscathed.

The seismic isolation does allow for the five key requirements that Charleson notes: movement capability, vertical support, re-centring, restraint, and damping (Charleson & Guisola: 2016). It also allows the building owner to have peace of mind and perhaps to be invoiced lower earthquake insurance premiums, as well

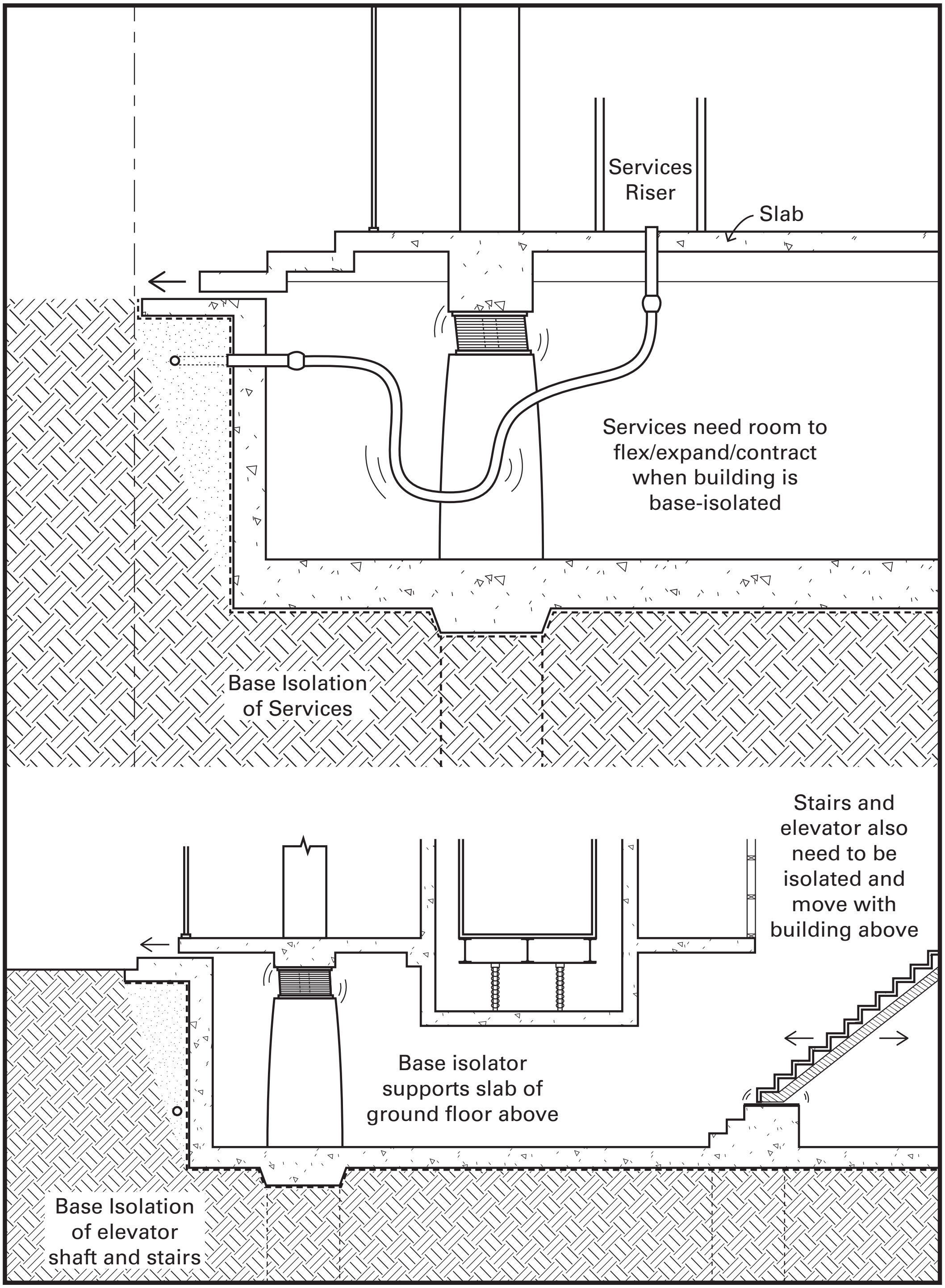


Figure 7.5 Base isolation sections in basement

as significantly lowering the dynamic response of a building. There are other systems for base isolation, including sliding systems, dynamic reaction dampers, rocking springs (Tait, Sidwell, and Finnegan, 2013,) etc., but this chapter primarily shows some of the detailing techniques available with full base isolation. The principles of isolation from quakes and absorption or dilution of seismic energy remain common to them all.

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08

Chapter Eight

Core: planning

Guy Marriage

Core: planning

8.0 The core

A well-designed core is often the key to a tall building's success. With a multi-storey building, there are a lot of services and circulation that need to go up and down the building, and most of these are concentrated in what is called the core. Think of the core as similar to your backbone, which keeps you standing upright. The core usually provides structural support, with both columns and sometimes shear walls that help stiffen the building. The backbone also encases your spinal cord with all its nerves (like power and data cabling), and it aligns with your mouth and throat (a route for fresh air in and out) and your arteries and veins (for your plumbing of vital fluids). The core of the building does all this services circulation too but does additional things as well. It provides a zone for circulation of people by including stairs and lifts (in America: elevators). The core is also the logical place for toilet and washroom facilities to be located, next to the risers for piping and air ducts for fresh air or stale air.

When designing the core, plan out the largest parts of the core first – the stairs and the lifts (Chapter 9). These lifts and stairs need to move through a series of large holes in the floor slabs, all vertically aligned, down to the lowest floor. These voids will create an inherent weakness in the slab as well as a challenge for fire protection. Stopping fire moving up the core is always a key challenge.

After the stairs and lifts, plan where the toilet facilities will go (refer to Chapter 10). They take up a lot of space but need solid slab floor to sit on, not a large void, so these facilities can often be situated over beams. Lastly, look at the best place for the risers and ducts. Try and place them so that they have easy access to the high level of the ceiling. Pay attention to where the beams are, as the ducts and pipes will often have to cross over / under / through the lines of beams. Supertall buildings are notoriously inefficient, as much of the lower floors are taken up with voids for services and lifts. Your core, no matter where it is, needs to be as efficient as possible in its use of space.

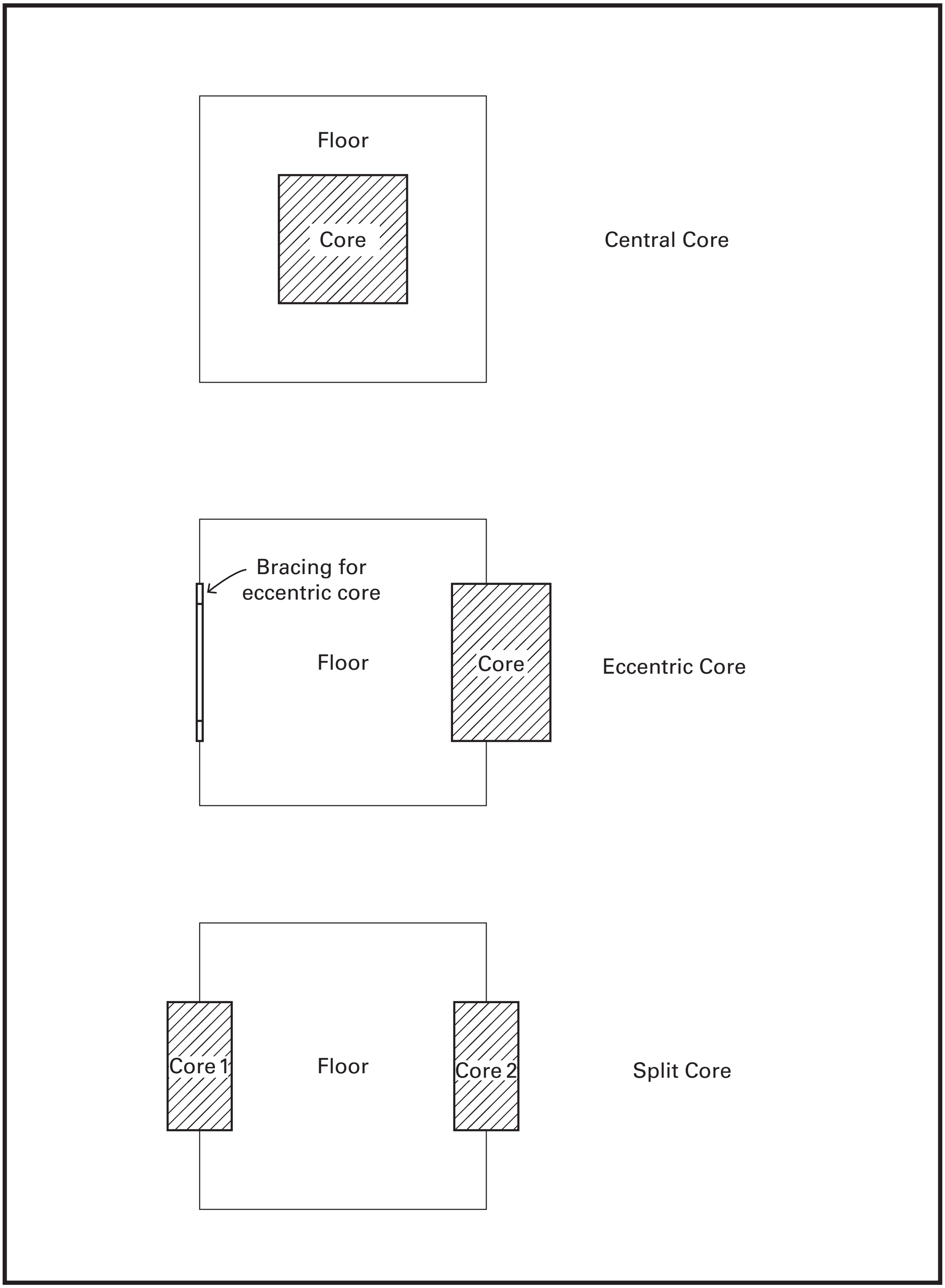


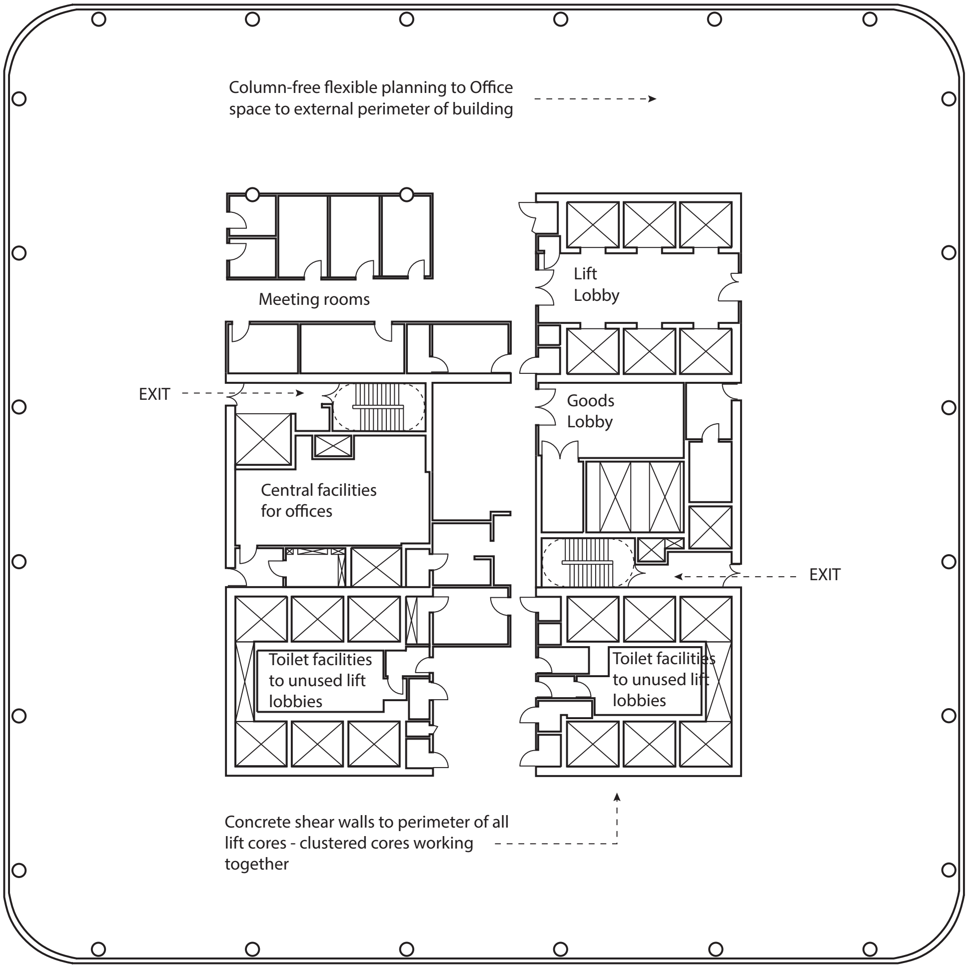
Figure 8.1 Cores: central, eccentric or split

8.1 Central core

The core is often sited in the middle of the building, with a similar amount of space on all sides between the core and the external façade. This ‘central core’ is a strong structural response, like a tree trunk, with roots down into the ground and branches (floors and services) branching off at each office level. Any multi-storey building should always be planned with two or more escape stairs in case of fire or other emergency, spaced as far apart as possible. A central core can contain two fire egress stairs (or escape stairs) with ease on opposite sides of the core: great for fire egress planning (refer to Figures 8.1 and 8.2).

There are, however, also some disadvantages to a central core, including that it breaks up the clear open space inside the tower and blocks one side of the office space off from the other side. This gives you, in effect, a doughnut of space (a ‘racetrack’ floor plan), which can be difficult to space plan into usable office space. On the other hand, everyone gets nearer a window.

German regulations limit the distance from a window that an office space can be to 7.5m, but there is no such regulation in many other countries. Good green building guidelines throughout the world recommend that everyone in an office building should be able to have access to good levels of daylight and fresh air, with natural ventilation if possible. Refer to the plans shown here of centre core buildings, both small and large, in Figures 8.2 and 8.3.

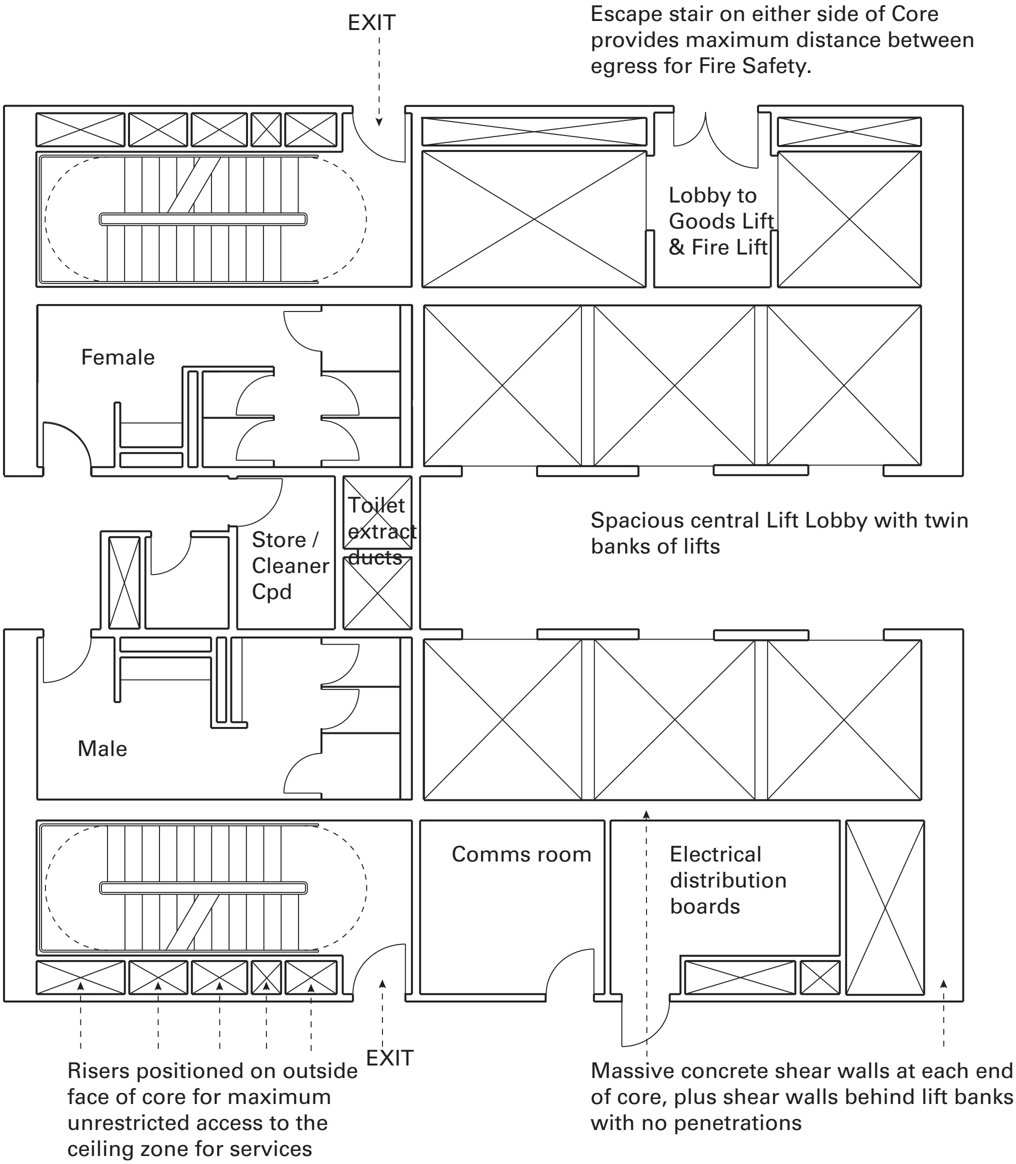


This plan shows an efficiently planned large office building with extensive central core. Lifts / elevators are arranged in blocks of 6 lifts, to reach different groups of floors. Where express lifts are in use, space between banks of shafts is large enough to use as space for Toilet facilities - highly efficient.

Drawing based on HSBC tower, Canary Wharf, London.

Architect: Foster & Partners

Figure 8.2 Centre core building plan – large



Indicative diagram only, modelled on central core building at Greenland Centre, Beijing, architects: SOM.

Figure 8.3 Centre core building plan – small

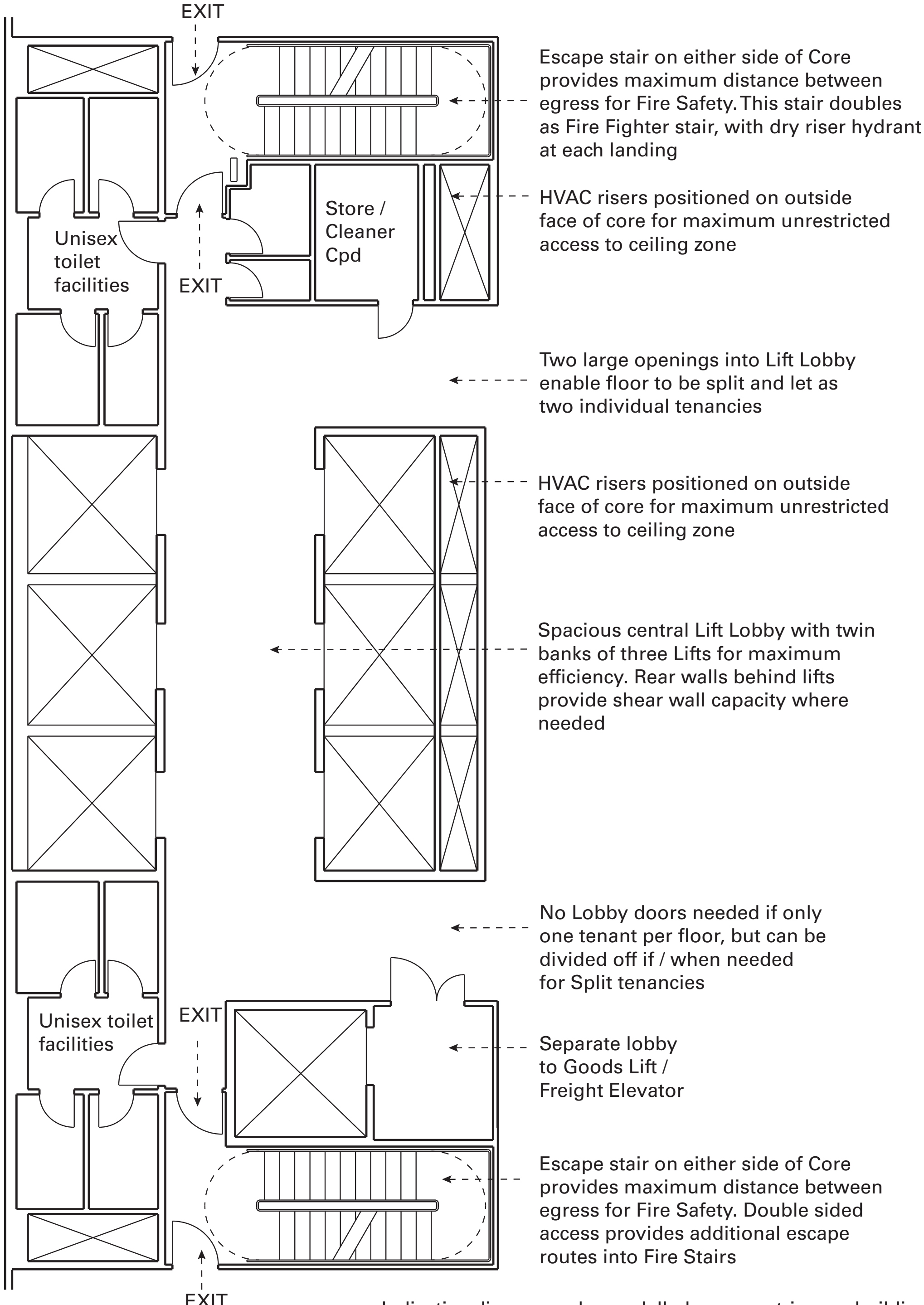
8.2 Eccentric core

As an alternative to central cores, many new office towers have a core off to one side with a large office space in front, maximising the amount of open floor space. This is known as an 'eccentric' core (refer to Figure 8.1). While this is great in providing developers and tenants with large open floor plates, in active seismic areas eccentric cores can put the building under extreme physical stress. When the earth shakes, the core side stays stiffer than the other side of the building, which moves a lot more and can cause a building to twist. If a building twists, it can break off at the columns. If columns break, the building is at danger of collapse.

The CTV and the PGG buildings in Christchurch, both of which collapsed in the 2011 Canterbury earthquake, were both modern eccentric core buildings. In the CTV building, an eccentric core, weak columns, poor connections from the bracing wall to the slab and a massive earthquake caused the building to twist, break columns and collapse. The CTV building collapse killed 115 people: most of them just on one floor alone.

Engineers and architects are therefore *very* cautious about eccentric cores in modern buildings in seismic zones like California, Japan and New Zealand. An eccentric core plan also means that escape to the fire stairs may be difficult, i.e. all escape stairs are on one side of the building. Certainly, if a building has an eccentric core, there needs to be seismic resistance planned for the side of the building away from the core, and this will often take the form of bracing in one or more bays of the structural grid. This is part of the scope of work for the structural engineer.

On the other hand, well-designed eccentric core buildings can offer wonderfully clear, open plan floor spaces. The new XXCQ office building in Wellington is an excellent example of a strong, efficient building with an eccentric core (refer to Figure 8.4), designed by architects Studio Pacific and engineers Dunning Thornton Consultants (completed 2019). The new 122 Leadenhall Building (also now known as 'the Cheesegrater') in London has a core placed completely to one side, giving wide, open, highly flexible floor plates, but presumably also leaving some people a long way from the windows.



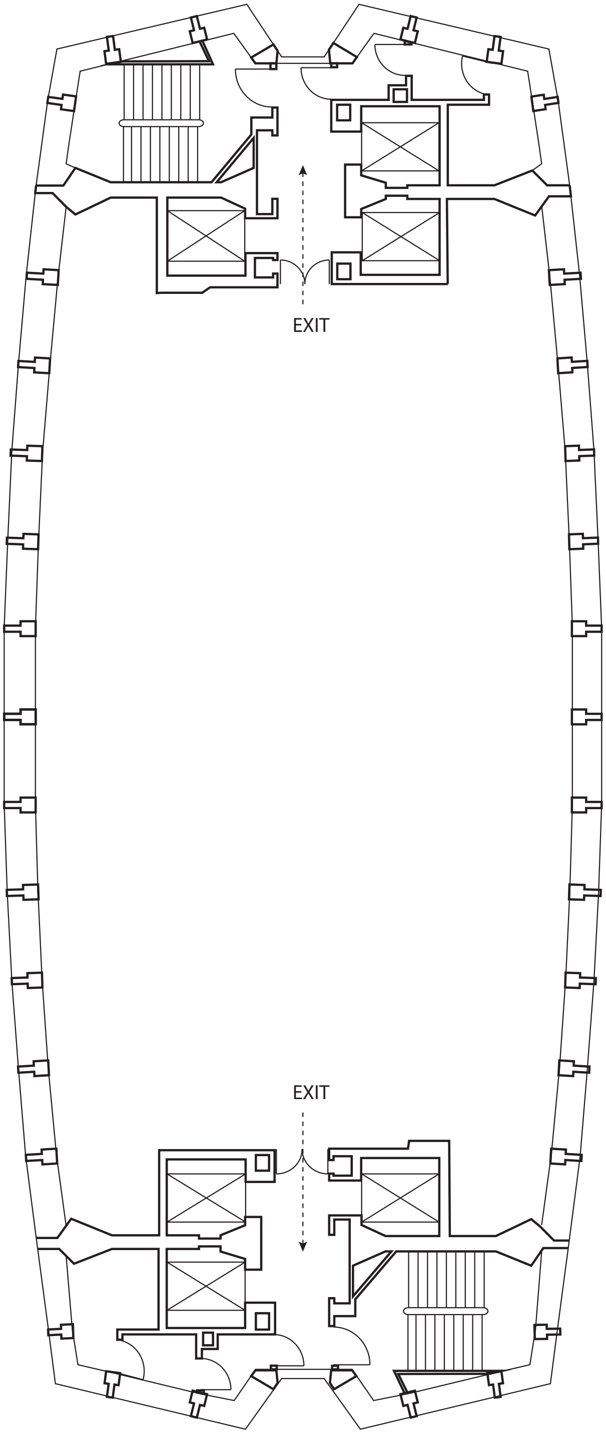
Indicative diagram only, modelled on eccentric core building XXCQ, Wellington, architects: Studio Pacific.
With permission of Newcrest Holdings and Studio Pacific.

Figure 8.4 Eccentric core building plan

8.3 Split core

Some new buildings are planned with a ‘split core’ solution, where two or more cores exist (refer to Figures 8.1 and 8.5). This will typically have the main core (including lifts and at least one stair) in one part of the building and a secondary, minor core elsewhere (which may include just an egress stair and various other services), perhaps on the other side of the building. Services can be split between the major core and the minor core – and indeed, can often enhance the usability of the floors. Some things need to stay together: all the lifts are best grouped in one location for easy access at ground floor. But electrical wiring and air-handling services may well be best split over two cores or more.

The Centrepoint building in London (architect: Seifert, 1961) is a building designed for commercial office use, with a distinct two-core strategy (refer to Figure 8.5) to enable easy tenanting from either end. That was perhaps not the most successful strategy: for whatever reasons (mainly political), the building sat untenanted for many years. It has recently been converted to residential (refer also to Figures 15.6 and 17.6).



Split Core office tower

Escape stair and 3 lifts
at each end of tower

Drawing based on plan of Centre Point Tower, London.

Architect: Seifert and Partners, 1966.

Figure 8.5 Split core building plan

8.4 Core decisions

Considerations for your building include the following planning and design issues:

- Where is the main front entry to the office tower? Off the main street, on a side street or on the corner? Always aim for the main street if you can for a prestigious street address for the occupants. Save the ground floor corner for the retail!
- Function of ground floor. Office space at ground floor is strongly discouraged (except in 'office parks' out in the countryside), and so the purpose of the ground floor space needs to be considered. In areas of high foot traffic, the obvious choice is retail, i.e. shopping.
- Rental rates of ground floor space give the highest return for retail shopping, especially in the 'Golden Mile' (best retail street) of your city, so clear, open space at ground level should be maximised for retail. This puts pressure on space for the entry lobby and escape stairs. Clear unimpeded access to the core is as important as clear exit out from the core, especially in emergencies.
- Ground floor lobby. The entry lobby must extend to the edge of the core for simple and clear access to the lifts and staircases that ascend inside the tower. The lifts and stairs should be connected to the street via a lobby that is not too wide, not too far away; not too close and not too skinny; not too grand and expensive and not at all cheap and nasty. Like Goldilocks and the Three Bears, it needs to be 'just right'. This allows the retail space and rental income to be maximised.

  While stair positions are effectively set out by the maximum escape route distances, the best position for egress stairs is often to position them in the centre of the core. Leave the perimeter of the core for services to travel up and down the building, giving them the maximum chance of opening out into the office floors with minimal interruptions.
- Building users will experience the lift lobby immediately on entering and exiting the building. The route to the lifts on the ground floor needs to be clear and direct, comfortable to access and not hidden around any corners. It should be straight ahead or on one side. The lift user will need to see the call button and the lift indicators.
- Goods entrance. Do you want couriers and tradespeople making deliveries through the front entry, the same as everyone else? What about bulk goods delivery? Rubbish collection? Solution: design a separate back door entry for goods and services to be delivered.
- Car parking. Do you need entry ramps for car parking? If so, you will need a separate entry route for cars, off a side road (if possible) and, if there is room, another separate exit route as well.

8.5 Concrete core construction

While those planning guidelines are universal for all tall buildings, the methods of construction are not. As noted in the previous chapters, structural materials of a core are usually the same as the overall structural solution – but not always. They can be different. One of the key differences arises when the core gets constructed ahead of the rest of the structure.

In any tall building with a structural concrete core, it is usual for the core to be constructed first and to contain substantial bracing for stiffness in the core. The bracing resistance may take the form of in-situ concrete shear walls. The core shear walls *must* follow the gridlines through the centre of each structural grid and span from one column to another. The load taken by the shear wall is thus transferred into the columns and then down into the pile foundation system (Chapter 7).

The formwork for the central core is used to cast the concrete wall in-situ, then the formwork is released and carefully slid upwards to create the next level of the core. This is known as a 'slip-formed' core or a 'jump' core and ensures that the core can be created straight and vertical, with little variation out of plumb. The slip-formed core will typically be at least three to five stories ahead of the steel beams following, allowing the concrete to substantially harden before the beams are fixed to it. In some European, Asian and Middle Eastern countries, concrete cores are normal or even mandatory.

Fixing steel beams to concrete shear walls can be achieved in several different ways. For some buildings, the SE may specify that steel plates are cast into the concrete for steel beams to be connected to later via bolted connections. Alternatively, steel connection plates can be cast flush into the concrete to weld to later. Projecting steel bolts facing outwards can be in the way of the shuttering and are also highly vulnerable to damage. Increasingly, therefore, bolted connections between concrete and steel are made by drilling holes into the concrete and then bolts are fixed into the holes. The chemically setting epoxy-glue anchor bolts, i.e. 'chem-set' bolts are as strong or stronger than the concrete itself.

8.6 Steel framed cores

As an alternative to a concrete core, the core can be made from steel columns and beams at the same time as the rest of the steel structure, with bracing provided by installing structural steel diagonal bracing members between floors. These steel braces, like the steel columns and beams, must all be thoroughly fireproofed, regardless of any walls in between. Steel-framed cores are very common with steel-framed buildings in the USA and many other countries, with light-gauge steel framing (LSF) infill walls between.

Many engineers prefer to work exclusively in steel, as it is a high-quality material with very well-known characteristics. The engineer can therefore predict how the building will perform. All steel-framed buildings can – and indeed do – sway in strong winds and can move considerably in strong seismic events. The important thing is, of course, that they do not yield unexpectedly. Steel technology is often utilised for absorbing seismic energy, with 'plastic' joints designed into the floor beam structure (never the columns) to absorb seismic energy in the case of a major quake. Surviving buildings from the Kaikoura quakes (2016) bear witness to the success of this approach, where just the steel seismic 'hinge' pieces in the core were replaced, rather than the entire building having to be demolished.

Shear walls and bracing in the core need to be as symmetrical and evenly balanced as possible. You will work this out with your SE, but broadly speaking, design for equal stiffness in both the North-South direction and the East-West direction (refer to Chapter 6). Shear walls do not work well with penetrations through them (such as doors), as these openings create a significant weakness and reduce the bracing potential.

8.7 Timber cores

Tall multi-storey timber office buildings are still uncommon in our world in 2019. In Germany and Austria, office buildings of a few floors in height have been constructed using engineered timber over the last few decades, some with timber cores, while in most other countries engineered timber for office buildings is still a very rare occurrence. Making definitive statements at this stage about how these tall office buildings will be constructed in the future is therefore quite a difficult task. In New Zealand, the Nelson Marlborough Institute of Technology (NMIT) responded to a government call for timber buildings by constructing their new arts building completely from timber (Buchanan et al 2011), including timber shear walls in the core using PRESSS technology (architects: Irving Smith Jack, 2010).

Lendlease, a large Australian-based international office building developer, plans to construct their future office buildings mostly from engineered timber, with the 6-storey 25 King St building in Brisbane, Australia, leading by example. Completed in 2018, the 7900m^2 building at 25 King contains Glulam column and beams with spruce CLT floors. Lendlease clearly appreciates that the savings in weight that a timber building gives will allow the entire structure to be built much lighter, be more accurately machined and achieve much faster assembly times on-site. Plus: the tenants love it. The official estimation for 25 King is 4824m^3 of CLT walls and floors, 1415m^3 of Glulam beams and columns and over 112,500 screws and bolts. They also note that the time to grow back the equivalent volume of timber will take as little as 6 hours in the Austrian forests that grew the spruce (Lendlease n.d.).

Inevitably, with an MTC building, high-tech prefabrication of the constituent parts is a compulsory activity. Constructed from a well-resolved BIM / CAD model, the timber columns and beams are accurately milled in the factory from expensive Austrian CNC machinery so that they can seamlessly slip together on-site. Timber LVL beams and CLT floors can be easily connected to and structurally integrated with the concrete core via an extensive bolt fixing of brackets to the concrete. The timber beams then are simply bolted to the protruding steel brackets. The relative light weight of the timber structure lessens the inertia and gravity load on the concrete core. Remember that as the weight of engineered timber is about a quarter the weight of concrete, there is a distinct saving of load on all the members.

8.8 Light steel framing

Regardless of the main structural system used in the building, non-structural walls in a modern tall office building are now almost always built with light-gauge steel framing. It is much lighter than timber framing (typical for NZ) and many times lighter than concrete 'breeze blocks' (used in the UK). It is highly dimensionally accurate in size and while bendy and floppy when picked up individually, the light-gauge stud wall becomes strong and highly rigid when all connected together with rivets. When the plasterboard linings are screw fixed to the light steel framing, the end result is a super-strong, stiff wall. Add enough layers of plasterboard to the framing and it can solve the issue of the fire-rating to the core walls too.

8.9 Fire-rated plasterboard (drywall) walls

Linings for walls are often / typically made from a gypsum-based plaster system encased within two layers of thick paper. Called plasterboard in the UK, Australia and New Zealand, known as drywall in the USA (or wall board, sheet rock, or gyprock), it is more typically known by its trade names such as Gibraltar board. Variations to the boards contain additional layers of wax (for enhanced water-resistance), mesh (for increased resistance to breaking), and more fire-resistant versions. The products work because gypsum is an inert mineral (calcium sulfate dihydrate) and does not burn.

Depending on the function of the wall, the plasterboard may take one layer, two layers, or more. Standard layers are usually around 10, 13 and 16mm (0.4”, 0.5”, 0.6”) and in some countries, it can be used as bracing elements on small buildings. It is not strong enough to provide bracing for tall multi-storey buildings however. One very useful aspect of plasterboard / drywall is that the final position of the plastered walls can be checked and adjusted easily, prior to the final fix, by packing a wall out on one floor to match the position of walls on other floors. Probably every multi-storey building has mistakes and probably all of those are hidden by gypsum-based boards and a lick of paint. Is it still a mistake if nobody sees it?

Each country or manufacturer will have their own wall-board regulations. Some countries will be satisfied with fire-resistant walls created from plasterboard, whereas other countries may state that only solid concrete walls will suffice. Check your local building regulations before starting work designing your core.

8.10 Tolerances

Remember that all dimensions also have a construction tolerance – so while a steel beam will not change size, a concrete slab could easily be 10–20mm thicker or thinner. Also, a loading tolerance can mean that the engineer may plan for the steel beam or concrete floor to have an upward pre-camber of, say, 30mm, which will sag downwards a little under loading, to produce a finished floor level that is mostly back to about zero – but obviously could be a little higher, or lower. You can often feel this slight undulation in the floor as you walk around a building, particularly if it is a large span concrete building.

Horizontal tolerances also need to be taken into account to allow for construction (the edge of the concrete slab on one floor may not be exactly the same as on the floor below) as well as allowing for what is called 'inter-storey drift' (the difference in horizontal position between one floor and another). This is most important on two elements: lift shafts and external façades. Tolerances on a concrete building may be up to 20mm per floor (horizontally and vertically) and it does not matter too much – as long as you have allowed for that possibility and as long as they are not cumulative! For elements such as the guide rails inside a Lift shaft, these must be installed perfectly vertical, even if the shaft itself is not.

8.11 Core finishes

During construction of the tower, the core is often left largely unfinished in order to facilitate the movement of materials up and down the building. Tower cranes may be positioned in lift shafts and may have to be rapidly deconstructed down inside the shaft as the building nears completion. Core construction is often a mix of structural elements such as columns, shear walls and bracing elements, along with large voids for stairs, lifts, ducts and other elements. The core is then clad with light-gauge steel framing (LSF) and clad in plasterboard (USA: drywall), giving an overall (false) impression of solidity. This may be quite far from the truth.

While the finished floor levels (FFL) inside the core need to line up level with the FFL of the general office floor, the build-up of floor materials may be substantially more than the typical thin skin of office carpet. Consider the planning of recessed areas, or rebates, into the slab in the core area to allow for thicker floor finishes such as stone or tiled floors to the lift lobby and toilet facilities.

Core walls around the lifts get heavy use from people with grubby fingers poking at lift buttons and awkward / clumsy couriers banging goods trolleys into the vulnerable projecting corners. Hard-wearing finishes are also needed in front of lift cars, such as stone or tiles, rather than carpet. It is best to ensure that walls near lifts are constructed or finished in easy-clean, long-lasting materials such as stone, metal or timber panelling, and especially at the corners of lift entrances: stainless steel. The next chapter explores lifts.

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09

Chapter Nine

Core: vertical circulation

Core: vertical circulation

Guy Marriage

9.0 Core moves

The core is the place for vertical circulation to take place, especially around lifts / elevators and stairs.

9.1 Lifts (elevators)

Invented by an American man, Elisha Otis, in 1852, the lift (UK) or elevator (USA) or *ascenseur* (France) gained popularity when Mr Otis demonstrated the safety braking system at New York's World Fair in 1854. Otis showed that a clever system of automatically applied brakes could hold the lift in place even if the cables were cut so that the lift car cannot fall down the lift shaft. When the lift was proved safe, the popularity of tall office buildings took off, especially in Chicago and New York at first. Now tall buildings and lifts are inseparable the world over.

When designing your building, you will have one key question early on: how many lifts do I need? The answer will vary based on a number of factors:

- What is the typical floor size, and how many people are on the floor?
- How many floors are there in the building, and what is the height between floors?
- What level of service (LoS) is required, i.e. how long are people prepared to wait for a lift?
- What size lifts can the building accommodate, and how fast can they run?
- How much room is there in your core for lifts, and what is the budget?

All these variables can alter the final answer, so consult an online design guide from one of the manufacturers to gain clues. Here are some basic rules of thumb to help you with your initial design:

- For any building with a public function over one storey high, at least one single lift or a ramp is needed so that all people of all abilities can gain access to the upper floors.
- People are often willing to climb stairs, but that willingness generally stops at about four floors.
- For an office building over four stories high, at least two lifts should be installed, so that if one lift breaks down, another can still be working (obviously, this depends on the size of the floor plates). Refer to Table 9.1 for more.
- In large buildings, there should also be a goods lift: a larger, slower, and more powerful lift where heavy equipment can be transported up the building. This may double as a firefighter's lift in emergency situations.

Table 9.1 Number of lifts (indicative only – dependent on size of building, number of people, level of service, speed of lift, destination control etc)

Influencing factors	**1 lift**	**2 lifts**	**3 lifts**	**4 lifts**	**5 lifts**	**6 lifts**	**more**
Any building with public function	• (min)						
Any office building with an upper floor	• (min)	• pref					
Office building 4 storeys plus (dependent on size, etc)		• (min)					
10 storeys (dependent on size, etc)			• (min)	•	•		
20 storeys (dependent on size, etc)						• (min)	• pref
30 storeys plus (dependent on size, etc)							• (min)
Supertall – 50 plus – call the experts!							•

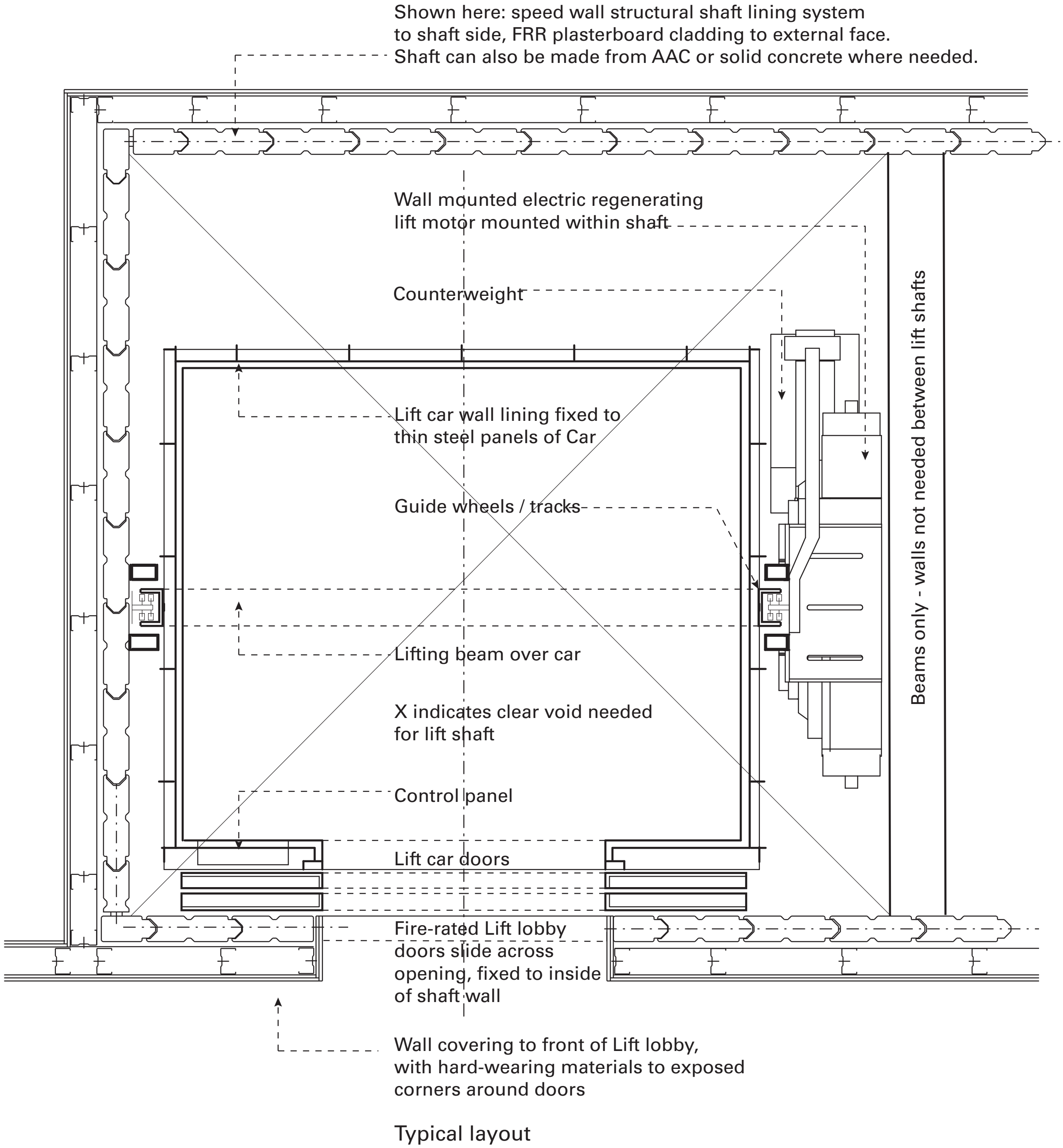

Figure 9.1 Lift plan

9.2 Lift banks

A group of lifts is known as a ‘bank’ of lifts (refer to Figure 9.2). Group the lifts for easy visibility, i.e. plan for three or four lifts in a row or a central lift lobby with lift banks on either side. If you have two banks of lifts facing each other, space them so there is a minimum of 3m (9’) depth across the hallway to the opposite doors. The bigger the building’s lifts, the larger this gap will need to be to allow for more people disembarking the lifts opposite each other at ground floor.

- In very tall buildings, there will be several banks of lifts, i.e. one bank of lifts may serve floors 1–25, while another bank may run an express service up to floors 26–50.
- Lifts are expensive pieces of equipment to install, run and maintain, so there is always a battle over the desire for more lifts vs the cost of the lost rent from the floor space they take up. But a building that is under-provisioned with lifts will not get good rentals – high rentals demand good lift service!

9.3 Lift lobby (elevator lobby)

The main entry lobby is on the ground floor of the building, allowing level access to the lifts. At least one of the egress stairs will also normally open into this ground floor entry lobby so that in the case of the lifts being out of service, then building occupants can use the stair instead. Finishes in the lift lobby are normally hard-wearing (stone or tiles), as there is a lot of pedestrian traffic walking through this area. Modern lifts no longer need to have buttons inside. Instead, you can preselect your floor as you enter the lift lobby, and the electronic lift controller will send your lift to your desired floor.

Lift lobbies also occur on each upper floor and may be enclosed if the floor is shared by more than one tenant. As the type or number of tenants is normally unknown at the time of designing an office building, it is best if your typical office floor can be flexible enough to incorporate a lift lobby or still work without one (refer to Figure 8.2).

9.4 Lift shafts (elevator shafts)

The lift shaft needs to maintain a 100 per cent clear route up and down through the floor slabs: absolutely no other services in the lift shaft. Because lift shafts are a perfect route for fire and smoke to move from floor to floor, the shafts need a high level of fire-rated resistance (FRR) to ensure that flames cannot spread upwards. It is mandatory in some countries for lift shafts to be created from reinforced concrete, but not compulsory in all. Assembling scaffolding inside the shaft could cause severe program delays, so lift walls are now often 'speed wall' – proprietary systems which can be installed safely from the slab side. These wall panels interlock together to create a solid, fire-resistant wall to the lift shaft.

Crucially, the lift shafts need to be able to fit within the structural grid, i.e. between the beams that connect the columns. Lift shafts are significantly bigger than the lift cars to allow room for the guidance rails, the counterweight mechanism and the door opening mechanism, and also to allow for air to move past the lift (refer to Figure 9.1).

Advances in lift engineering mean that for small lifts in smaller buildings, the motor is now simply fitted to the wall inside the shaft itself. Modern lift motors are able to regenerate energy on 50 per cent of their trips, so running costs have come down significantly. Lifts in large buildings will still require a lift room above the lift shaft (larger than the shaft itself) in order to accommodate the lift motor and cable drum: the cable will run down the shaft through a slot in the slab of the lift motor room floor.

Regardless of size, the lift will need a 'lift pit' below the lowest floor served (1.5m deep or more) and a lift 'over-run' space above the top of the lift car (refer to table).

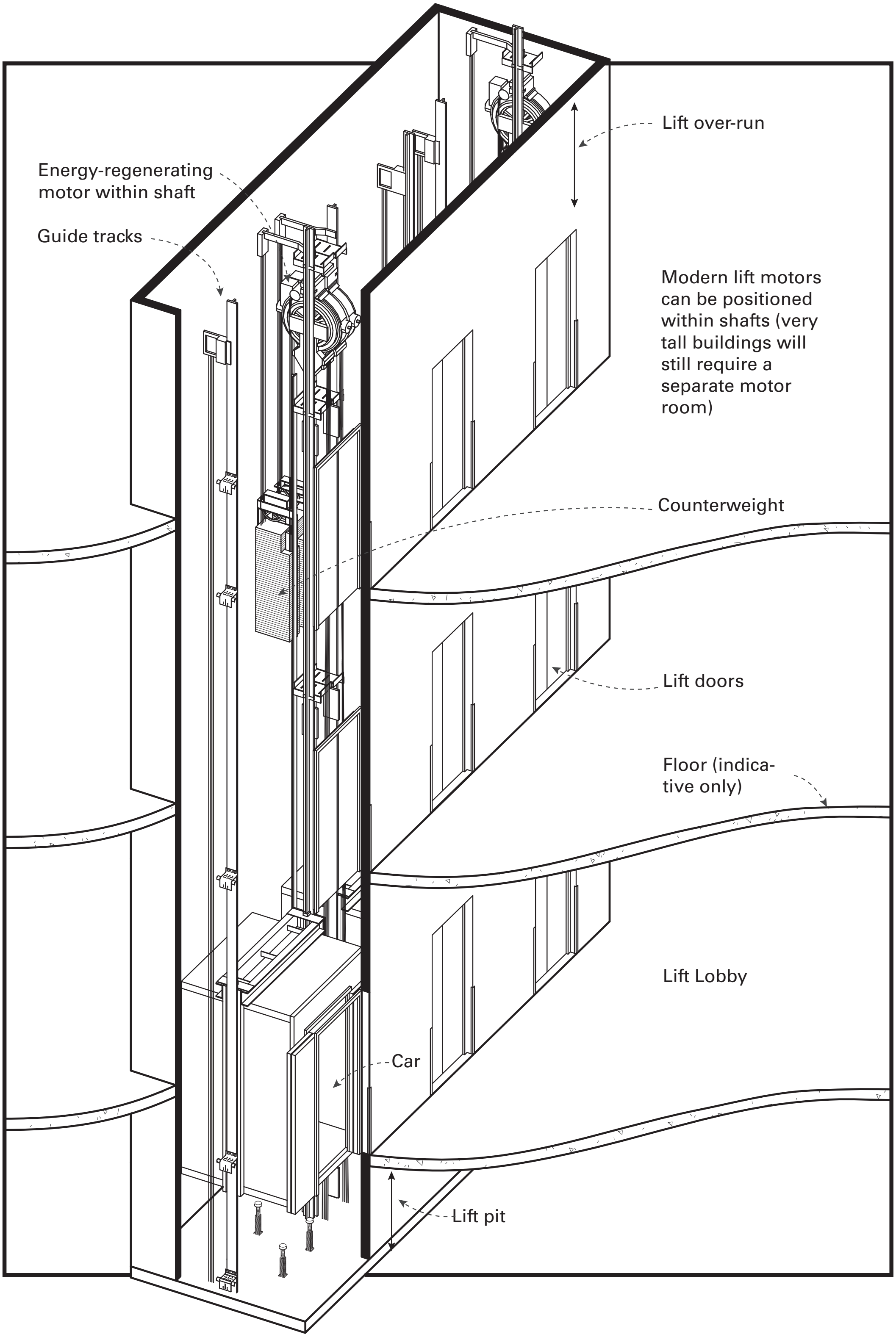

Figure 9.2 Lift cutaway section

9.5 Lift cars (elevator cabs)

A lift car's capacity depends on its size and load; refer to Table 9.2. Lift shaft dimensions are clear open *minimum* dimensions.

Table 9.2 Lift / elevator sizing

	Very small (residential only)	**Standard (office minimum)**	**Bigger (offices)**
Capacity: people	8	13	24
Capacity: weight – kg (lb)	630 kg (1389 lb)	1000 kg (2204 lb)	1800 kg (3968 lb)
Car size: width × depth – m (feet)	1.1 × 1.4m (3′ 7″ × 4′ 7″)	1.4 × 1.6m (4′ 7″ × 5′ 3″)	1.8 × 1.4m (5′ 11″ × 6′ 10″)
Car height: – m (feet)	2.2m (typical) (7′ 3″)	2.4m (typical) (7′ 11″)	2.5m (typical) (8′ 3″)
Shaft size: width × depth – m (feet)	1.7 × 1.8m (5′ 7″ × 5′ 11″)	1.8 × 2.2m (5′ 11″ × 7′ 2″)	2.2 × 2.8m (7′ 2″ × 9′ 2″)
Lift over-run	Minimum 3.5m (11′ 6″) above FFL of highest floor served	Minimum 3.7m (12′ 2″) above FFL of highest floor served	Minimum 3.7m (12′ 2″) above FFL of highest floor served
Lift pit	Minimum 1.5m (4′ 11″) below FFL of lowest floor served	Minimum 1.5m (4′ 11″) below FFL of lowest floor served	Minimum 1.5m (4′ 11″) below FFL of lowest floor served
Lift machine room needed?	No. Motor can be included in shaft.	Usually not. Only needed in tallest towers	Only needed in tallest towers

* Indicative dimensions only. This information is taken from Schindler Lifts data and Kone Elevators data; other lift companies will have similar data available. Check with manufacturer for Lift Room requirements and dimensions.

9.6 Lift car construction

Despite the feeling of the lift being a strong, solid box, modern lift cars are actually very thin lightweight structures. Any extra weight is unnecessary dead weight which would just slow the car down and wear the motor out. The lift car is therefore typically a collection of very thin metal panels with lightweight finishes applied internally to make it appear more solid than it really is. Materials may include thin skins of metal, glass, tiles, timber veneer or stone – sometimes applied to a thin aluminium sandwich panel for maximum strength but minimal weight. Floors can rack (twist) so lift manufacturers recommend floor finishes like carpet or hard-wearing vinyl surfaces. Thick stone floors are out, due to weight issues.

A steel cradle like a sturdy picture frame wraps around two sides of the lift car and supports the floor of the car from below, with the beam overhead providing a sturdy mounting that the whole lift car hangs from. The lift car is suspended at this mounting point by a strong cable (now mostly a high-strength nylon band) which in turn is connected to the motor. The weight of the lift is balanced by counter-weights: a set of heavy steel weights that weigh about half of the indicated payload. Both the lift and the counter-weights run up and down the shaft on a series of perfectly vertical guide rails, with wheels and rollers running smoothly on their tracks to ensure the car does not rock from side to side.

The braking mechanism works on those guide rails also, with the lift motor now electronically controlled so that passengers always arrive perfectly level, safe and sound at their floor. That takes quite a bit of clever technology, with the most important part being the smooth opening of the doors. You can have doors at one end or both ends, but not at the front and the side simultaneously. Doors are expensive, so to keep the cost down, keep the doors at one end only if you can.

9.7 Glass lifts

Lifts do not always have to be solid-walled boxes travelling within solid shafts. If the core is sited on the external wall of the building or next to an internal atrium, some lifts are planned to make the most of stunning views. At the Lloyds building in London (1986), Richard Rogers used glass lifts to great effect (refer to Figure 16.4). The lifts were created with three sides built from toughened, laminated glass, as was the roof to the cab. The stainless steel-clad underside of the lift holds all the services to each lift (such as lift door machinery and air-conditioning to the lift car itself), with a blue light that flashed as the lift climbed up the building.

In America, architect John Portman used glass lifts to great advantage many times in his tall atrium designs for hotels and office buildings. Portman's buildings can be seen all over America in Hyatt hotels, but his creation at the Hyatt Peachtree Plaza, Atlanta is always a favourite. Portman's lifts within an indoor atrium have one great advantage over Rogers' external lifts: the weather. The need for all lift doors to be 100 per cent weathertight on all floors of buildings like Lloyds pushes the cost of the glass lift system up considerably.

9.8 Lift doors

Lift doors are made from steel (often stainless steel) so that they can resist fire. A minimum opening size will ensure comfortable access for the disabled and easy access for large objects. There are always two sets of doors: one set is fixed to the lift car and the other set remains on each floor and are fixed to the wall of the lift shaft (refer to Figure 9.1). The lift has an intricate mechanism so that both doors close seamlessly with each other, and the doors are fire-rated and self-closing. The lift cannot move while the doors are open. Those Hollywood movies where people ride around on top of lift cars inside lift shafts? Very dangerous – and obviously, very false!

Lifts are, in fact, a very safe way to travel. Far safer than traveling in a car or on a motorbike. But if you don't like lifts, you can always take the stairs.

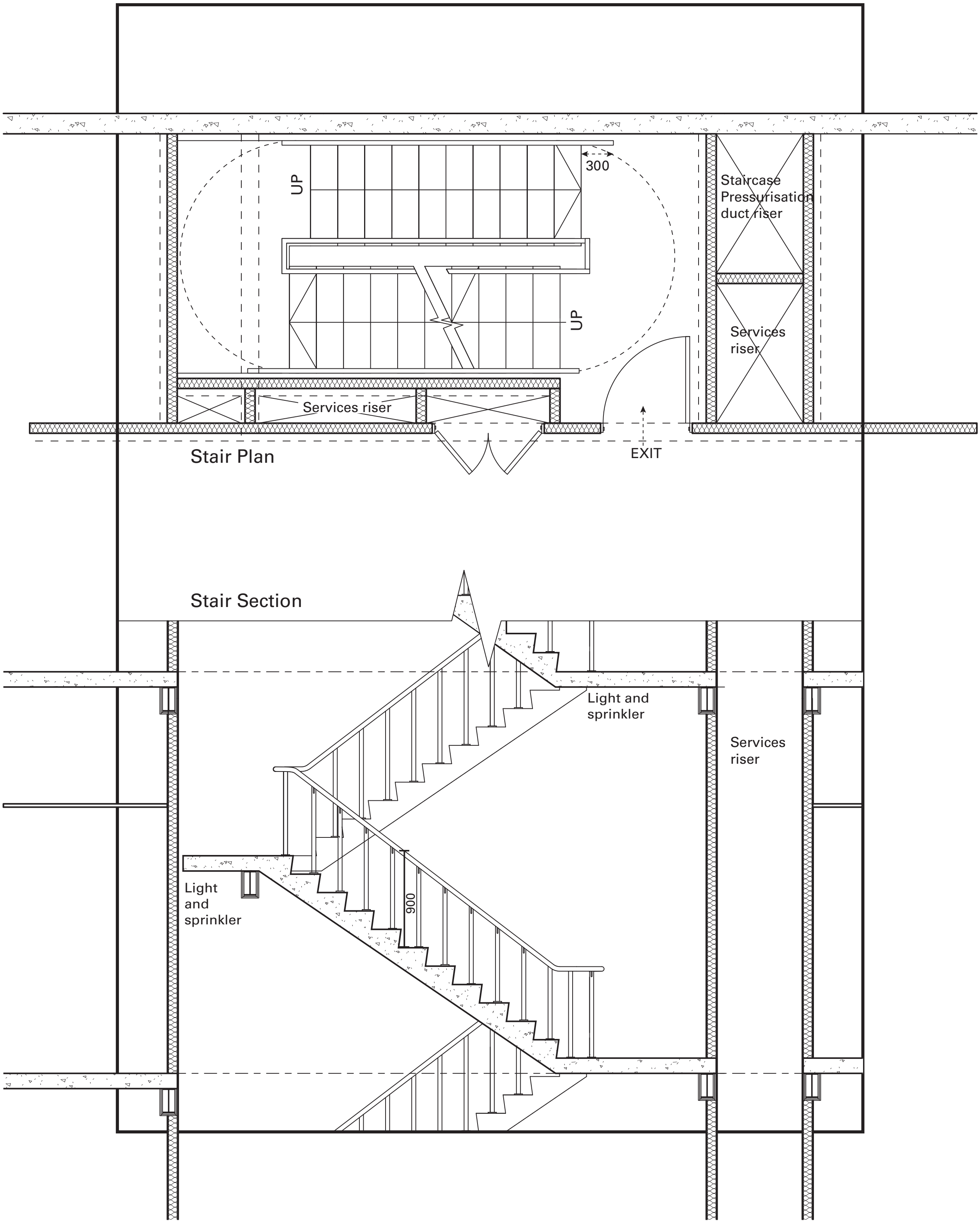

Figure 9.3 Stair plan and section

9.9 Stair design

Any multi-storey building should have at least two sets of escape / egress stairs to help the occupants escape from fire or other emergency. If a fire should break out on an office floor, any people on that floor should be able to get their way safely to one of the stairs, and so for that reason the stair entries are spaced as far apart as possible. A good place to start is to ensure that no one has more than 24m (72′) to walk to a fire exit stair. This distance will be prescribed by the Building Code in your country, which calculates the length of time and walking distance it would take to get people out of a building safely and may be doubled if the building is fully sprinklered. Every Building Code is different (but similar), so exact dimensions and distances will vary.

In the same way that lifts travel in a fire-protected lift shaft, stairs need similar fire protection too. Each separate stair must be contained in a separate stair shaft, composed of two-way fire resistance rating (FRR) walls, which must remain intact as long as the building is standing. The key thing is that the construction achieves the FRR necessary – this may mean that the stair shaft walls are constructed of concrete (mandatory in some countries) or lined with FRR plasterboard. Stairs can criss-cross each other in the same structural void, but if they do, they must still be encased in two separate FRR enclosures. This is called a scissor stair and can sometimes save space in the core.

An important part of designing a building for fire safety is the fire doors to stop the spread of smoke and flames. In an emergency, people in a building will be moving swiftly towards the exit stairs, so any door they encounter must open away from them in the direction of travel. They don't want to have to stop and pull open a door towards them – they just need to push it to open it and keep going down the stairs. That means that doors will always open *into* a fire egress stair on each floor – except for the ground floor. On the ground floor, the door on the stair must open *outwards* in the direction of escape towards the street. 'Crash bars' or 'panic bars' can be fitted to the final ground floor fire doors which will automatically unlock and open the fire doors outwards, merely by pushing against the bar.

9.10 Size of stairs

Staircase sizes always end up being bigger than you may first think: allow a space of at least 6m × 2.4m (18′ × 8′) to plan each stair within (refer to Figure 9.3). Each length of stairs between landings is called a flight of stairs, and every riser in that flight *must* be the same height. Try to position the flights so that one flight is offset from the other flight by a whole single stair tread, as that will make detailing the handrail to the stair so much easier and using the stairs so much more comfortable. Trust me on this – just do it. Never have the two flights align.

While staircases for some buildings may be allowed to be less than 900mm wide, my recommendation is that a more suitable width for stairs should be, if possible, a minimum of 1100mm for any office building. Actual minimum width will relate to the occupancy of the floors. The width normally remains the same all the way down the building, with no obstructions. Doors must never impede the width of the escape route, so position the doors to avoid cutting into the flow of people escaping. The dotted semi-circular line on the plans indicates the escaping pedestrian traffic flow.

Make sure that there is at least 100mm of space between flights that are next to each other to help your handrails work smoothly and another 50mm to each wall to enable a prefabricated stair to be lowered in (refer to Figure 9.4).

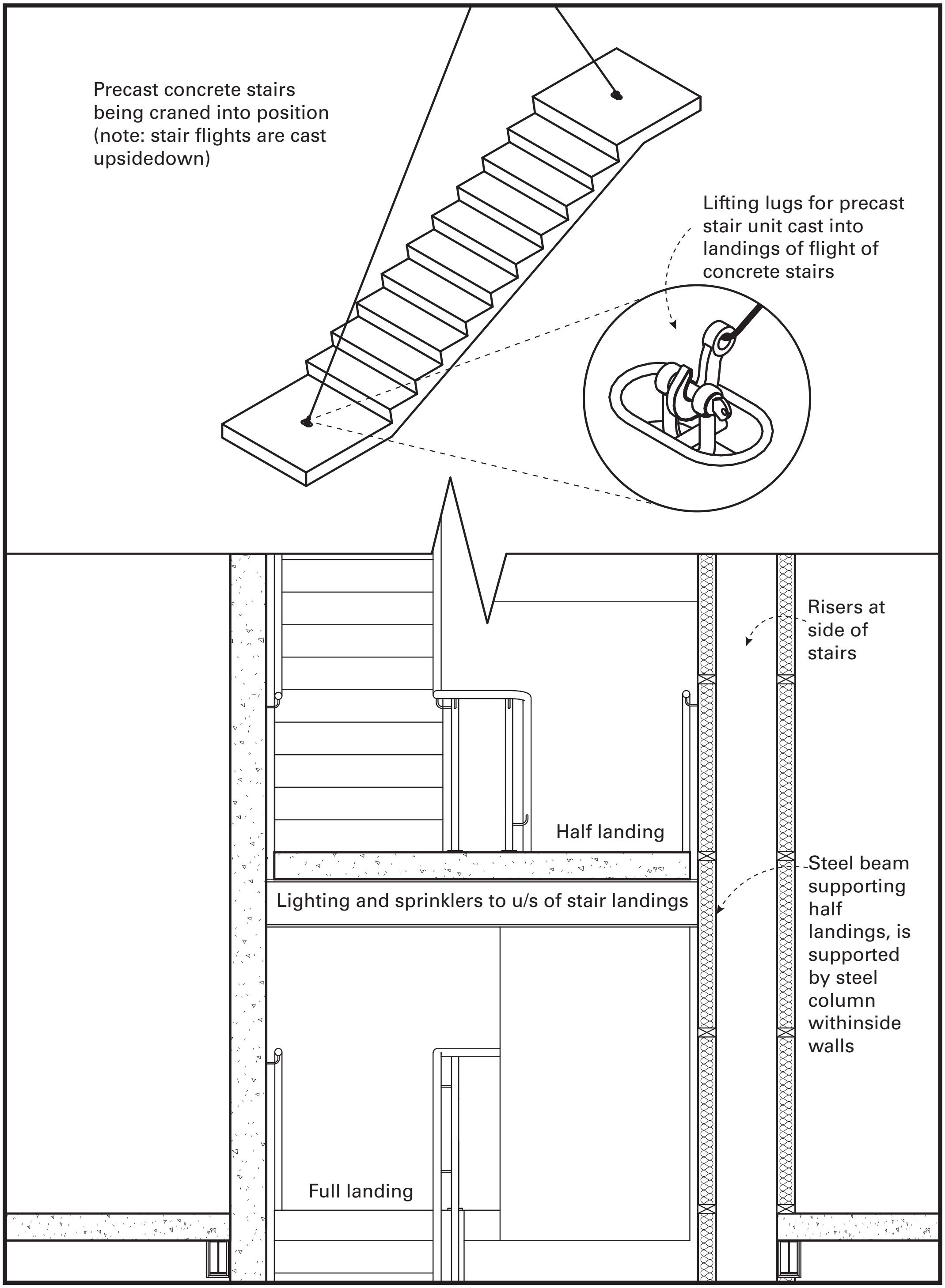

Figure 9.4 Precast stair installation

Table 9.3 Stair width build-up (internally). Wall thicknesses still to be added

	Gap at wall	Flight of stairs	Gap in middle	Flight of stairs	Gap at wall	Total
Stair width	50mm (2″)	1100 (or more) (3′ 7.3″)	100 (4″)	1100 (or more) (3′ 7.3″)	50 (2″)	**2400mm** (7′ 10.5″)
Half landing depth	50mm (2″)	Same width as flight, i.e. 1100 (or more) (3′ 7.3″)	None	Plus one tread offset	None	
Top / Full landing depth	None	Same width as flight, i.e. 1100 (or more) (3′ 7.3″)	None	Plus one tread offset, plus enough room for door swing to avoid clash	None	Also consider disabled refuge area, plus fire-fighting hydrant

* Indicative only. All dimensions subject to change to comply with your local Building Code and your individual building. Refer to plans for clarification.

Table 9.4 Stair riser heights and tread depths

Stair type	Height (riser) max	Depth (going / tread) min	Comment
MH M2.21 Disabled stair	170 max	250 min	Max 12 risers recommended per flight
MH B2.30 Common	190 max	250 min	
MH K1.3 Institutional	180 max	280 min	
NZBC: Common stair	190 max	280 min	
NZBC: Accessible stair	180 max	310 min	
NZBC: Service stair	220 max	220 min	

* Sources: from NZBC D1: Table 6 (New Zealand Building Code); Ministry of Housing (UK)

9.11 Stair construction

Escape stairs need to be fireproof and extremely strong to be able to cater for the rare occasion when hundreds of frightened people are rushing down them on their way out to safety. While your CAD program may automatically create them as a solid block of concrete cast in the shape of a flight of stairs, you can use this as a starting point, but it is *not* an end point. You should design the stair structure and handrail yourself. It can be steel or concrete, be cast in place or prefabricated and brought out to site. The structure can be integral to the stair or can be completely separate. The design is up to you. On one project I worked on, I had to detail 64 different staircases, each with several flights of stairs, and all the floor slabs, landings, doors, door handles and handrails. That's enough stairs to last me half a lifetime – yet I still enjoy designing simple things like stairs.

Often on a multi-storey building, these fire stairs are all the same and are made in a factory and craned down the stairwell into place. Fun fact: precast concrete stairs are cast in an upside-down mould to gain a good clean finish to the exposed stairs, usually with the landings integrated into the mould as well. Once the concrete has set, the flights of stairs are flipped over, transported to site and craned into position down the stair shaft. It is a pretty tight fit. Often they will build the walls around the stairs afterwards so they do not get damaged by the precast flights crashing into the wall. Stairs should be fitted with contrasting non-slip covings at the exposed edge to make them safe to use in emergency conditions.

Sometimes stairs may even have steel handrails attached in the factory so there is a minimum of work needed on site. As they typically arrive with a landing built in as well, your design task is how that prefabricated stair is going to sit within the stairwell and stay in place. During severe seismic events, precast elements not fixed securely can come loose; stair flights have, on rare occasions, come loose and fallen down the stairwell (catastrophic to anyone using the stair at the time). Precast stairs need a minimum of 100mm seating at each end so that if there is any movement in the building, the stair can stay in place. The stair could rest on a beam fixed between the walls or rest on a projecting corbel, or the end of the stair could sit in a rebate at slab edge.

Remember to allow some room for tolerance – the crane driver will be high up and will have to lower this section of stair down a tiny narrow slot that they cannot even see, so a good 50mm gap on each side will be the minimum to aim for (refer to Figure 9.4).

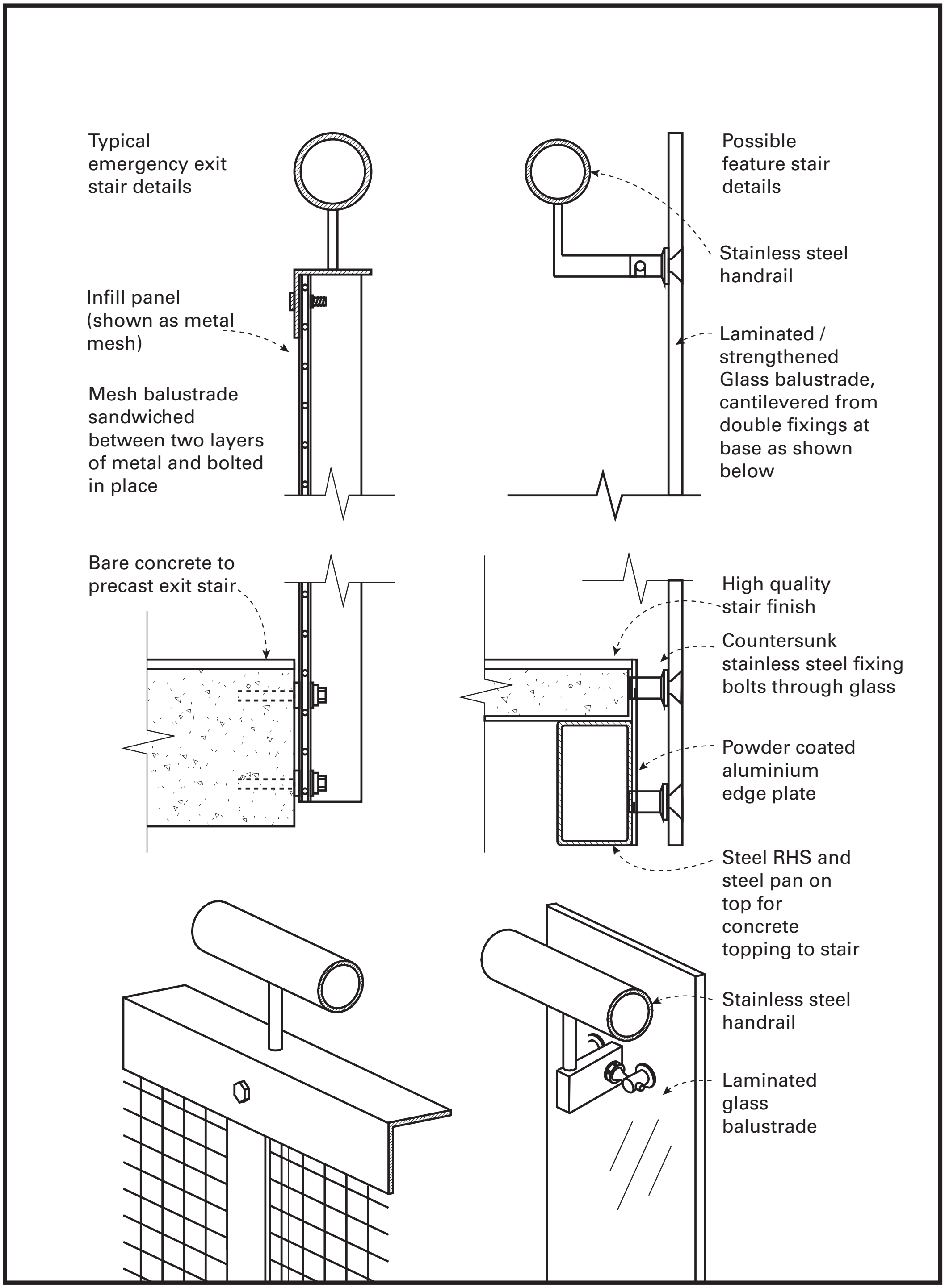

Figure 9.5 Stair balustrade details

9.12 Staircase pressurisation

It is crucial that in an emergency, no smoke or flame can enter the emergency exit stair. Every tall building staircase should therefore have a duct next to the stair for staircase pressurisation to pump a small but steady amount of air every one or two floors into the stair shaft. This way the stair is always at a positive air pressure – slightly higher than the office floor and smoke cannot seep into the stair shaft. If the Grenfell Tower in London had been provided with staircase pressurisation, many lives would have been saved; if the building had been sprinklered, everyone would have lived. So always remember these three main things: always have a second means of escape, always pressurise your stair shafts and always have sprinklers in your tower.

9.13 Feature stair

You may also install a nice stair in a more public location so that people feel comfortable using stairs to climb the building. It is also an extremely good way to meet other people in the building, so designers are often now deliberately designing in one special stair, out in the open (not enclosed in a shaft), so that employees in a building can 'accidentally' meet each other. This is known as the 'bump' factor (seriously, it really is!) and has been proven to have a beneficial effect on productivity and workplace happiness. This is sometimes termed a 'vertical gym', as it is healthy for people to climb stairs – it tones your legs and bum and gets your heart pumping.

Use this chance to design a unique stair that is perfect just for your building. Be aware that Fire Engineers really don't like you doing this, as it may create a nasty fire problem for them: like a route for smoke and flames. Awkward. The Fire Engineer will help advise on specific methods of combating any spread of flame up through that special social stair you have created.

The feature stair, if you have one, should be a much higher spec than the concrete or steel fire stairs. While some aspects may be more luxurious (timber treads perhaps, rubber or granite, or even glass?) and the balustrades may be glass or timber instead of just steel posts, other aspects are universal no matter what the function of the stair: you need a handrail, both sides, the top of which should be 900mm above the pitch line, and 1000 or 1100 at the landings (depending on your country's Building Code – refer to Figure 9.5).

The riser heights of the stairs may be a little lower, the tread depths a little bigger, the width of the flights certainly a lot wider. This is not an emergency Exit stair, but an everyday Access stair. Make it a joy to climb. The construction details are all yours. Think about the tactile pleasure of holding onto a nice smooth handrail. Perhaps it is made from stainless steel? You can have the stainless steel polished or brush finished or even bead-blasted. Stroke it – what do you like to feel? How would you connect it to the stair? What do you want the user to see? And importantly: what do you *not* want them to see?

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10

Chapter Ten

Core: facilities

Guy Marriage

Core: facilities

10.0 Toilet facilities

Called a bathroom or restroom in the USA, the WC in the UK, a washroom in Canada, a powder room in some estate agent's brochures and the dunny in outback Australia; none of these names are really an accurate description. Let's just call it what it really is: toilet facilities. People need intensely private personal space to use a toilet, to wash hands after and to freshen up. One of the key functions of the core is to provide a discrete space for these private ablutions to take place in relative comfort and anonymity. High-quality toilet facilities are always desirable in high-spec modern office buildings. Quality fixtures and fittings are needed: but first, the plan must be right.

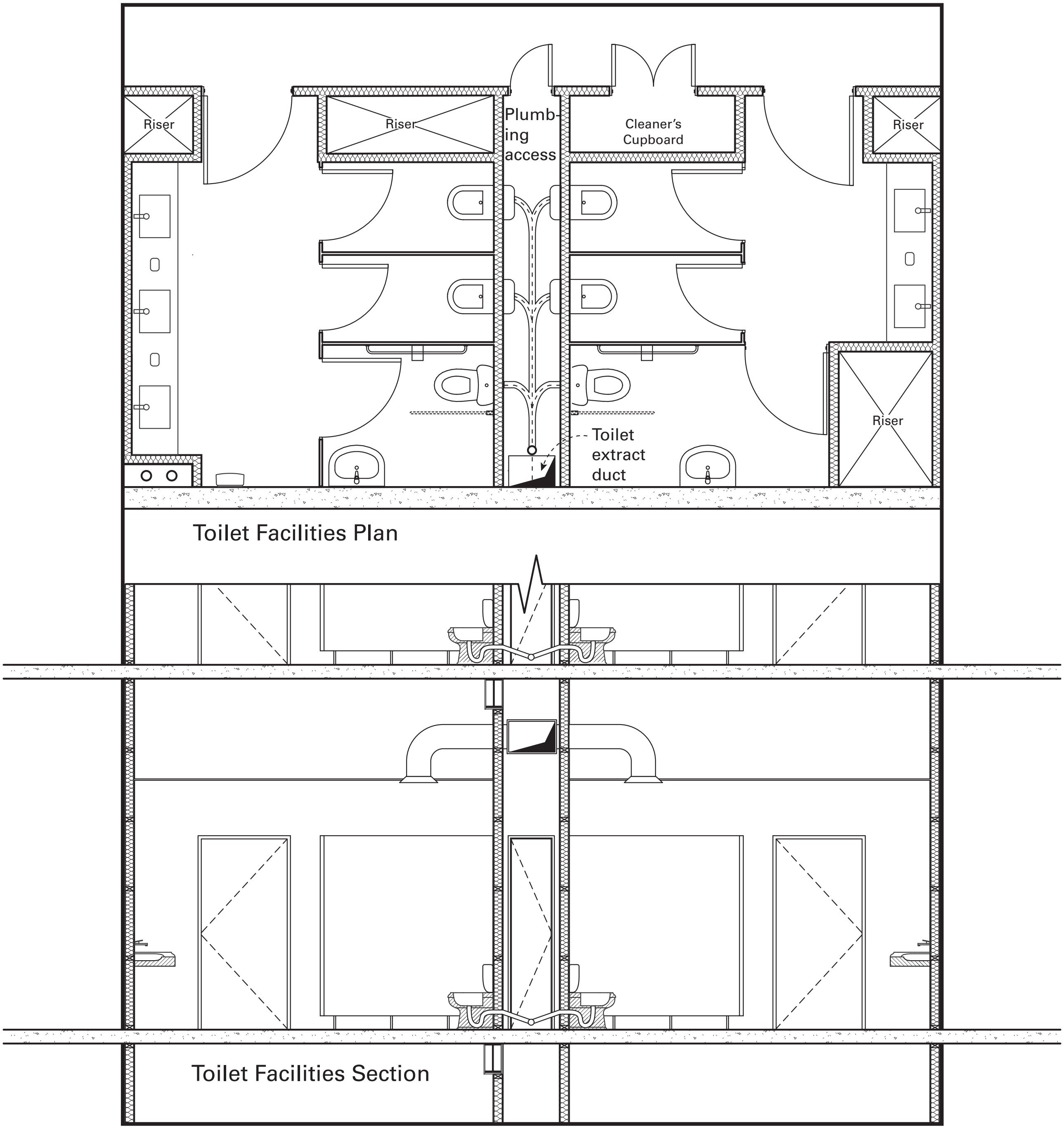

Figure 10.1 Toilet facilities plan and section

10.1 Toilets and washrooms

If you can, try to ensure that access to toilet facilities are flexible – easily accessible from both sides of the core, allowing the floor to be leased to multiple tenants. It is often best for access to the facilities to come via the lift lobby so as to avoid using up valuable floor space for corridors. While once toilets were commonly situated off the stairwell, up or down a flight of stairs, that's pretty unusual in modern office design. All toilet facilities must be easily accessible by all.

Toilet facilities are highly important to the tenant, but also use up a lot of the landlord's valuable floor space. There is therefore often a conflict between the desire of the tenants for comfortable, luxurious, spacious toilet facilities and a contrasting desire from the landlord to provide toilet facilities that are small in area and low cost to build. A purpose-built-for-tenant office building may therefore supply a different quality of facilities than that which a speculative-built office building may deliver. As the designer, you have a crucial design job to do: to plan the most appropriate response. Minimum plan dimensions are presented in volumes such as the Metric Handbook, Neuferts Architectural Data, or AIA Standards, but these should be checked against real-life dimensions. Try and be generous with dimensions, as minimum sizes are not enjoyable by all, nor usable by many.

10.2 Privacy and design

Bathrooms need to be spotlessly clean and to function well. The design of toilet facilities is often taken as a measure of quality for the entire building. Excellent design of toilet facilities is often a sign that the architect has considered the design of the whole building as one coherent design concept. Conversely, great design elsewhere can be let down by poor consideration of ablutions. That means consideration of function, materials, privacy and servicing, all executed to the same high standard.

There are two key aspects to the design of toilet facilities: the seen and the unseen. Both are equally important.

The seen: what is visible and how well it works. Try and put yourself in the space to consider how the layout would feel like. As privacy protection is a big part of the design, careful placement of cubicles is fundamental. Cubicle doors should not be visible directly opposite the entrance door, whereas it is OK for the hand-basins and hand-driers to be visible. Don't design facilities where you have to squeeze past other users to get to the toilet – not a nice experience for either person. Try to avoid placing lines of cubicles down narrow dead-end corridors and think carefully about the placement of urinals: privacy at the toilet is as highly important to men as it is to women.

The unseen: the ability to service the facilities is also highly important: to clean the spaces, to fix the broken fittings, to unplug blocked pipes or malfunctioning cisterns without inconveniencing users. A plumbing riser is often provided behind the WC pans, between 600–900mm wide (2–3'), where the plumber can access the cisterns and fix any plumbing issues, without having to disrupt the entire WC facility. Soil waste pipes from the WC pans can discharge into a central waste pipe, which will then join the main soil stack descending down the core (refer to Figure 10.1). As part of the servicing design, always include a cleaner's cupboard in a central area near the toilets: a lockable small room for cleaning supplies and a sink for washing of mops.

10.3 Male, female, unisex, disabled

Toilet facilities have typically been offered only in a binary formation: male or female, but people do not all fall neatly into just two different genders. There are intersex and trans persons who may want to use a toilet space where they feel comfortable. Aim to provide bathroom spaces that are as gender neutral and non-discriminatory as possible, able to be used by tenants as they see fit.

You will also need to consider that at least some of the staff will be differently abled and may need the more generous space of a disabled toilet (Figure 10.2). In many ways, therefore, a row of individual, unisex, disabled-friendly toilet cubicles may be the best, most modern solution: at least some toilet facilities should always be offered as unisex facilities, able to be used by all people.

There is another vital function of the bathroom: that of a 'third space', a place where people can escape to for a few minutes, away from the pressures of the office. Design in a comfortable, quality 'vanity' bench top. Hand basins and mirrors are key facilities, but so are waste bins, hand-driers, soap dispensers, fresh air, clean water, good lighting and, of course, super-clean floors and walls (refer to Figure 10.2).

10.4 Showers and changing rooms

Modern office buildings also need to provide washing/showering facilities. With more people spending longer at work and more people cycling to work or exercising at gyms near work, many office workers prefer to shower and change at their place of work. Twenty years ago, it was highly unusual to provide showers in office buildings, whereas now it is almost mandatory, as no one wants to sit next to a smelly lunchtime jogger or sweaty commuter cyclist. These changing room spaces definitely need to be segregated by gender, and storage should be provided for cycling clothes or work clothes.

One option is to provide a shower in the disabled WC room on each floor, but a better option may be to provide purpose-built shower facilities somewhere near where the bicycles are parked. As the designer of the office space and shower facilities, a decision needs to be made on number and size of showers and changing rooms provided, as these factors affect the developer's profit margin and is part of the net to gross calculations. A likely result is that the base build design will offer certain minimal shower facilities and the fit-out team may decide to install additional facilities. If you can, allow for this possible future retrofit in the planning of the core at a lower level of the building so you can include bicycle storage and shower facilities nearby where it is most useful.

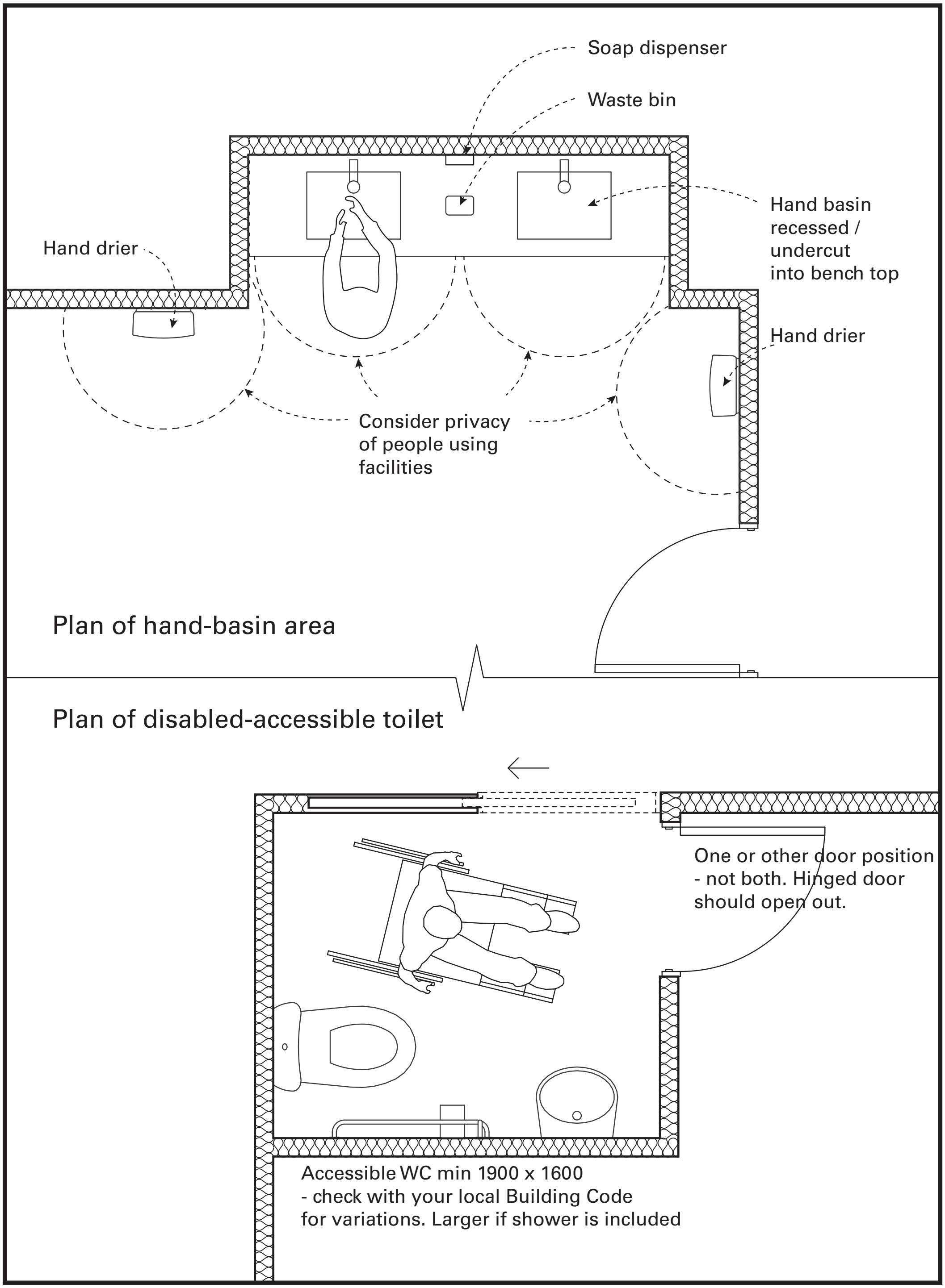

Figure 10.2 Washing and drying near hand basins

10.5 How many toilets to provide?

Each country has their own methods of calculating the right number of possible toilet facilities. Much of the time, for unknown reasons, there are never enough toilets for women, even if they have been provided according to their Building Code. As long as you can show that you have met the minimum requirements of the Building Code, you can provide more cubicles or a different configuration that meets the needs of your client, but remember that bathroom facilities are expensive to build. The client may not want to provide more than the bare legal minimum in their country. Regardless, we are all human and all need to use the toilet as much as any other person in any other country, so the results should all be much the same wherever you are in the world. However, they are not – they do vary from country to country, as shown below.

Toilet provision tables

The table for toilet provision is often hidden in your Building Code where you least expect it. In New Zealand, it is in part G1 of the NZBC (on the fourth page of Table 1, under Commercial: 'staff facilities for offices'). In the UK, these provisions are in a completely separate document: BS 6465-2:2017 Sanitary Installations Code of Practice. In the USA, it is in the 'International Building Code' under Section 1210 Toilet and Bathroom Requirements, Table 2902.

How to calculate toilet numbers required

First, calculate how many people will be working on each floor. For example, let us assume that the floor is net 1000m^2 (10,764 sq ft) in size, and that each person will occupy a minimum of 10m^2 (107.6 sq ft) of space. That allows us to easily calculate that there may be a maximum of about 100 people working on each floor of the building. As the designer, you have no way of knowing whether these 100 people will be all women or all men: most probably, there will be a mixture of the two.

So: how many WC to provide for each sex? If we assume that the office floor will be split equally, 50/50 between men and women, you will almost certainly be wrong. On some floors there may be more men, on other floors there may be more women. It is best to assume that out of 100 possible staff, it is possible that on any given floor 60 of them could be male, but also 60 of the staff could be female. You should plan, therefore, to adequately provide for the possibility of both 60 men and 60 women at the same time.

Using table 10.1 to meet the requirements of the New Zealand Building Code, those 60 men and 60 women would require between them a minimum of:

Female: 3 × WC, 2 × hand basins,
Male: either 3 × WC and 2 × hand basins, or 2 × WC, 1 × urinal and 2 × hand basins
Disabled: 1 × WC and 1 × hand basin

Table 10.1 Toilet facilities – New Zealand

	WC pans	**Hand basins**	**Urinals**	**Unisex facilities**
Staff: female	1–10 women = 1 WC 11–50 = 2 WC 51–90 = 3 WC >90 = add 1 per 60	1–70 women = 1 hb 71–250 = 2 hb >250 = add 1 per 200	–	1–5 staff = 1 unisex 6–30 = 2 unisex >30 = add 1 per 40
Staff: male (if WC pans only)	1–10 men = 1 WC 11–50 = 2 WC 51–110 = 3 WC >110 = add 1 per 70	1–70 men = 1 hb 71–250 = 2 hb >250 = add 1 per 200	–	
Staff: male (if both urinals and WC pans are present)	1–10 men = 1 WC 11–60 = 2 WC 61–120 = 3 WC >120 = add 1 per 80	1–70 men = 1 hb 71–250 = 2 hb >250 = add 1 per 200	1–150 men = 1 uri 151–550 = 2 uri >550 = add 1 per 450	
Staff: with disabilities	1 for first 300 staff, 1 more if over 300	1 for first 300 staff, 1 more if over 300		

Source: NZBC Clause G1

Alternatively, provide a Unisex solution of 4 × Unisex WCs, each with a hand basin, of which at least 1 cubicle must be suitable for the Disabled.

Table 10.2 Toilet facilities – USA (IBC)

	WC pans	**'Lavatories' (basins)**	**Urinals (separate calc)**	**Unisex facilities (not specified)**
Staff: female	1–50 women = 1 WC >50 = add 1 per 50	1–40 women = 1 hb 41–80 = 2 hb >80 = add 1 per 80	–	
Staff: male (if WC pans only)	1–50 men = 1 WC >50 = add 1 per 50	1–40 men = 1 hb 41–80 = 2 hb >80 = add 1 per 80	–	

Source: International Building Code

By the International Building Code (IBC – really just North American), WCs = 1 per 25 for the first 50, 1 per 50 thereafter.

Lavatories = 1 per 40 for the first 80, 1 per 80 thereafter (in IBC, lavatory means hand basin).

Using the example (Table 2902) of the requirements to meet the International Building Code, those 60 men and 60 women would require between them a minimum of:

> Female: 3 × WC, 2 × lavatories (hand basins).
> Male: 3 × WC, 2 × lavatories (hand basins), Urinals specified separately.
> Disabled: Not specified.

You can see therefore that even though NZ and the USA calculate numbers in different ways, the outcomes here are similar.

Table 10.3 Toilet facilities – UK

	WC pans	**Wash basins**	**Urinals**	**Unisex facilities**
Staff: female	1–5 women = 1 WC 5–15 = 2 WC 16–30 = 3 WC 31–45 = 4 WC 46–60 = 5 WC 61–75 = 6 WC 76–90 = 7 WC 91–100 = 8 WC >100 = add 1 per 25	1–5 women = 1 wb 5–15 = 2 wb 16–30 = 3 wb 31–45 = 4 wb 46–60 = 5 wb 61–75 = 6 wb 76–90 = 7 wb 91–100 = 8 wb >100 = add 1 per 25	–	Minimum of 1 fully accessible (disabled-usable) unisex WC must be provided per floor
Staff: male (if WC pans only)	Same as per women	Same as per women	–	
Staff: male (if both urinals and WC pans are present)	1–15 men = 1 WC 16–30 = 2 WC 31–45 = 2 WC 46–60 = 3 WC 61–75 = 3 WC 76–90 = 4 WC 91–100 = 4 WC >100 = add 1 per 25	1–15 men = 1 wb 16–30 = 2 wb 31–45 = 2 wb 46–60 = 3 wb 61–75 = 3 wb 76–90 = 4 wb 91–100 = 4 wb >100 = add 1 per 25	1–15 men = 1 uri 16–30 = 1 uri 31–45 = 2 uri 46–60 = 2 uri 61–75 = 3 uri 76–90 = 3 uri 91–100 = 4 uri >100 = add 1 per 25	
Staff: with disabilities	Minimum of 1 per group	1 with each accessible WC.		

Source: BS 4685-1:2006

The new British Standard, however, has increased the number of fittings required substantially (refer to Table 10.3). For 60 women, you would need five to six toilets and five to six washbasins, with the same for males, or if urinals are provided, then three toilets, two urinals and two hand-basins (known as washbasins in the UK). Other countries will be different again.

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11

Chapter Eleven

Designing for deconstruction

Designing for deconstruction

Gerard Finch

11.0 Design detailing for end-of-life material recovery

High-rise buildings consume a large amount of natural resources and energy in their construction. In fact, more than half of all the raw materials that we harvest on the planet go towards the creation of new buildings. It is therefore essential that the architect take responsibility to ensure deployed materials can retain their value for as long as possible. This is best achieved at the time of design and means breaking the building down into separate layers, all of which have different design lifespans, and ensuring that each layer can be easily separated when required. Considering the end-of-life of your building design may only require changes to minor architectural details; however, it can sometimes also require you to rethink the entire structural and finishing systems of the building. This design focus mirrors 'design for serviceability and maintenance' ideas that are vital in the design of modern buildings. Designing for material recovery is also commonly referred to as 'designing for deconstruction' or 'circular economy design'. Under these concepts, the five layers of a building are 'stuff, space, services, skin and structure' (Brand, 1994). Design requirements for each layer are discussed in this chapter.

11.1 A note on 'high-value' recovery

Before you try and design a building for material recovery, it is important to understand what is required to prevent materials being sent to landfill or contaminated. The type of recovery required is call 'high-value recovery'. This means that the building will either be designed in such a way that allows materials to be efficiently removed without damage and directly reused or allow for contaminant-free material remanufacturing with minimal losses in material quality. Remanufacturing will require stripping the material from the building, separating it from any contaminants and sending it to a remanufacturing factory, or if it is a natural material, sending it to be composted. Direct reuse is typically the preferable option, as it reduces the cost of recovering and reusing building materials. Often, however, it is cost prohibitive to design for full reuse recovery at the outset. Therefore, simply ensuring that materials deployed in buildings do not become contaminated when they are fixed and finished is a vital step towards effective material stewardship. This means using reversible fasteners, avoiding adhesives and secondary finishes and ensuring that no specialist tools are required to separate built elements.

11.2 Stuff

Wall finishes

'Stuff' refers to all of the things that we put inside a building to make it habitable and useful. This includes furniture, floor and wall coverings and window coverings (blinds/curtains). Of particular concern for the architect in respect to end-of-life material management are the surface finishes. In most cases, any internal wall surface will be finished with a polymethyl methacrylate 'acrylic' paint product. While this is an exceptionally durable and easy to maintain finish, it often contaminates the materials it is applied to in such a way that additional processing is required before the materials can be remanufactured. Paint finishes also have the additional disadvantage of hiding fixing points which makes separation significantly more time consuming.

Flooring finishes

In most medium and high-rise construction, the structural element of the floor is reinforced concrete. This will typically be a thin layer (around 100mm in depth). Above this sits the desired flooring finish, which depends on the function of the given space and the building's architectural design. The way in which this material is both modulated and adhered to the concrete deck below is an important consideration in terms of maintenance and high-value recovery. One of the lowest impact solutions is to polish the top of the concrete slab and coat it with a natural polymer, such as linseed oil. This oil finish will seal the concrete and prevent it from becoming stained over time. The combined materials (concrete and linseed oil) are both inert natural materials with the potential to be used as aggregate at the end of their useful life.

However, aggregation of concrete at the end of its first life is not considered a high-value recovery option, and the monolithic concrete deck itself should be substituted for a modular timber solution (see 11.6). Also, note that a polished concrete flooring finish is inappropriate for most office situations due to its inability to dissipate noise. When a soft flooring finish is required, the recommended solution is a modulated floor covering, such as carpet tiles. In a conventional setting, this is a nylon-based carpet tile with vinyl backing that is adhered directly to the concrete floor (refer to Chapter 13). If recovered and separated, these tiles can be directly remanufactured into new carpet tiles (Interface: 2019). To make this process easier, it is recommended that the regular flooring adhesive is replaced with small adhesive pads in the corner of each tile (TacTiles: 2019). These create a floating flooring finish that leaves no residue on the subfloor and speeds up the disassembly process.

Ceiling finishes

Ceiling finishes are perhaps the easiest elements of a building in which high-value material recovery can be achieved. This is largely because a ceiling is

not required to be load bearing or resistant to moisture. In fact, many architects incidentally eliminate the possibility of waste in this area altogether by leaving the underside of the overhead structure exposed and neatly detailing the articulation of services. From a maintenance and resource conservation standpoint, this is excellent. Alternatively, the other popular ceiling finish in high-rise buildings is suspended ceiling tiles. These tiles (generally, 1200mm by 600mm or 600mm by 600mm) sit in an inverted 'T' aluminium channel suspended by a thin steel cable off the structure above (refer to Chapter 14). The consistent modular nature of the grid and the way the tiles sit in the metal track without any fixings means that tiles and the metal grid itself can typically be effortlessly reused or remanufactured.

11.3 Space

Partitions

In the context of end-of-life material recovery, the 'space' layer refers to the systems and methods used to divide up the internal spaces of a building. In medium and high-rise construction, these are typically non-load-bearing partition walls using lightweight steel stud and track systems or lightweight dressed timber framing. Internationally, steel stud systems are the more popular option and, in principle, have the potential for high-value recycling. These systems are either pop-riveted or screwed together in-situ and have plasterboard sheets glued and screwed to both faces. At end-of-life, plasterboard sheets must be destructively removed, leaving glue, screw and plasterboard residue on the steel studs which must then be removed if the system is to be reused. Such contaminants are, however, easily removed during remanufacturing, and it is therefore common for steel studs to be separated at the end of a building's life and sent to a metal recycling facility. Timber partition walls face similar end-of-life recovery challenges as their steel competition. Adhesive, plasterboard and fixing residue remain on the timber elements when the plasterboard is destructively removed, requiring further work by the contractor to enable reuse. But because these contaminants cannot be removed easily from the timber without causing irreversible damage, the most common end-of-life option is low-value recycling – such as being processed in wood chips for garden mulch or for use as biofuel – or landfill.

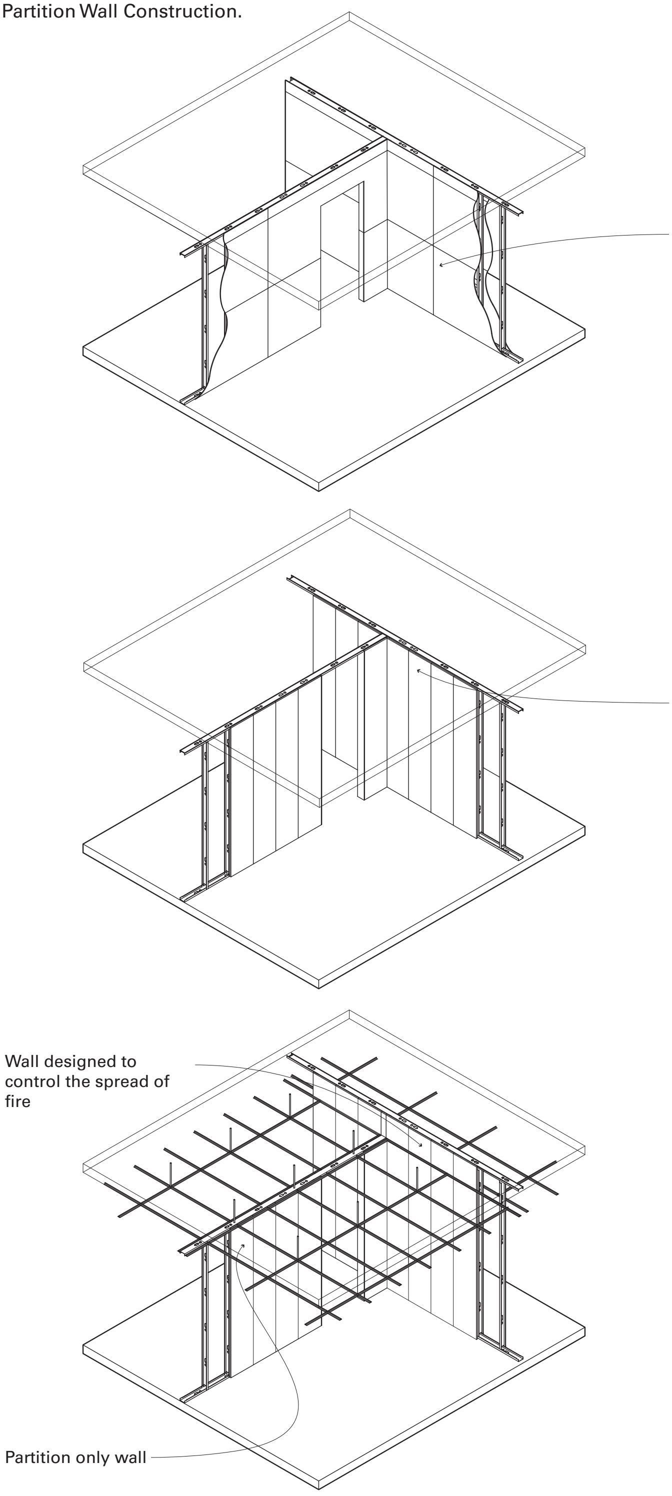
The advantage that steel has over timber is that it is more likely to be remanufactured into a high-value 'life-for-like' product. However, this remanufacturing advantage does not necessarily mean that steel is the better ecological choice. It is very important to be aware of the embodied energy costs and carbon potential of both systems. For example, in the production of one raw tonne of materials, steel requires 24 times more energy than timber (Bribián et al: 2011). This translates into the production of 1.9 tonnes of carbon dioxide (CO_2) per tonne of steel (Kundak et al: 2009). Alternatively, for the same weight of timber, 1.7 tonnes of CO_2 have been sequestered (absorbed) (Hollinger et al: 1993). Other pollutants from the steel manufacturing process, such as sulphur dioxide emissions, further limit the ecological advantages that steel is perceived to have over timber (Pour et al: 2016). From a long-term sustainability standpoint, timber remains the recommended mainstream solution (Bejo: 2017; Edwards et al: 1994).

Conventional timber partition systems may be a better holistic sustainable solution than steel track options, but ultimately neither approach is an ideal high-value recovery approach. An alternative and more purposeful step towards waste-free solutions is the adoption of adaptable and reusable partitioning systems. Although these can be more expensive than conventional options, they offer the advantage of being designed specifically for removal and reconfiguration. An example is the

JuuNoo Wall System that uses height-adjustable structural elements and flat timber panels with hidden fixings. Another approach is to use conventional dressed timber studs that bolt or screw into a steel track at their base and top. This cuts down on the amount of steel used and ensures an easily reversible connection between each stud at the ‘bottom plate’. Then, instead of adopting a monolithic finish, use a panelised wall lining product with hidden and reversible fixings. To exceed the minimum fire safety requirements in medium- and high-rise buildings, this will need to be a non-combustible product such as gypsum or metal. One option is the use of square edged 600mm wide plasterboard sheets positioned vertically between studs and fixed using a visible ‘T’ track or hidden *‘Fastmount Panel Clip System’* (Fastmount: 2018).

It is also important to consider how the bottom/top plate (or track) is fixed to the structure. Most timber partitions fixed over a concrete floor will use Dynabolts that thread through the bottom plate and expand in the concrete as they are tightened. Steel tracks on concrete will often use a 2.6 by 35mm gas gun fired carbon steel pin (at 600mm centres) (Ramset: 2018). These solutions do not prohibit material recovery, but they do make the process more labour intensive.

Partition Wall Construction.



Traditional Construction Partition:

Zinc coated rolled steel C-channel partition frame members with plasterboard linings screwed and glued to each face. Bottom channel dyna-bolted to floor. Top channel mounted to suspended ceiling tiles or to underside of floor structure.

On Recovery:

Plasterboard torn away and clean-filled. If some care is taken the steel studs are separated, mixed with virgin steel and recycled.

Reusable Construction Partition:

Zinc coated rolled steel C-channel partition frame with punched holes for clip-on panels. Full height panels with a square edge or ship-lap edge finish. Note full height opening.

On Recovery:

Directly reused, any damaged frame members mixed with virgin steel and recycled. Damaged panel members refinished and reused.

Other Details

Mass standardisation of wall framing components increases the likelihood of material reuse and, therefore, custom elements should be integrated carefully.

For example, when walls are required to prevent/slow the spread of fire they must be full height (i.e. finish at the underside of floor structure). Partition-only walls can finish at the level of the suspended ceiling. This makes running services more straightforward. The result is two different stud heights. To retain reuse value it is recommended that when fire control is required, a secondary element that spans from the top of the wall to the underside of the structural floor is adopted - rather than walls of a different stud height.

Figure 11.1 Partition wall construction

11.4 Services

The design of services for high-value recovery can be implemented at two different levels: material selection and design of the service solutions themselves, and the way the services are deployed in the building. In this section, we will only discuss how to better articulate and deploy building services to promote end-of-life material recovery. It is important to note that many of the fixing details for services are standardised and will be managed by a specialist building services engineer. However, it remains important for the architect to communicate the need for simplified and non-specialist fixing solutions to other consultants. It is therefore important to be aware of effective ways to fix services to the buildings structure in a way that facilitates high-value material recovery. The most efficient way to do this is to congregate many fixings onto a single element that is then itself fixed to the structure. This reduces the number of fixing points to the main architectural elements, reducing damage and making disassembly faster. Many medium- and high-rise buildings already use this strategy and achieve it using a modular support structure made up of steel 'U' channels with integrated fastening capabilities called '*Unistrut*' (Atkore: 2018). Although costly and carbon intensive, this product is natively recoverable and already an industry standard. You will most commonly find it in service risers supporting heating, ventilation and cooling (HVAC) ducts, as well as pipes carrying liquids.

11.5 Skin

When designing the façade of a high-rise building for potential material recovery, it is important to consider the materials you have specified, what additional finishes they required, the geometry of the façade itself and the way in which the façade system is fixed to the superstructure.

Façade materials

Curtain walls are an effective 'skin' system for enabling high-value material recovery (Kim: 2013). The use of exclusively technical materials with dry jointing details means that very little contamination takes place. There are drawbacks, however, if direct reuse cannot be achieved and remanufacturing is required. With current technology float glass, the type of glass most commonly used in buildings for glazing cannot be remanufactured into new glazing units 'for the sake of quality' (Kim: 2013). Instead, this material is recovered and then processed into low-value products such as additives for asphalt production and foamed insulation products. The best action that a designer can take in this instance is to ensure that the geometry of the glazing is standardised. This improves the likelihood of a future architect being interested and able to reuse the glazing units (Jaillon & Poon, 2014). To achieve standardisation and retain a dynamic articulated façade design, consider secondary elements rather than changes to the shape of the glazing units. Secondary elements can include adjustable louvers, shutters and suspended screens connected to the transom sections of the curtain wall. Furthermore, in curtain wall systems where deconstruction was considered in the design phase façade, components will be able to be dismantled from the inside. This alleviates the need for scaffolding or external lifts, making deconstruction safer and more cost effective (Kim: 2013).

Geometry for disassembly and reuse

For glazing units to be able to be dismantled from the inside requires consideration of the overall size of individual glazing sections. How these components are going to be brought back into the building and then transported to ground level should be understood. Weight of the glazing unit in this instance is not a concern, as there are tools available to support the glass from inside the building as it is removed. Further, it is not a requirement that all glazing elements in the curtain wall are exactly the same size. Modular variation in which smaller segments add together to be the same size of larger sections is also likely to result in elements that are attractive to reuse. Note, however, that a higher number of unique components in a given assembly decreases the likelihood of reuse. This rule also applies for non-glazed sections of a multi-storey building façade. If direct reuse of materials is an aim, ensure that there are as few variations in size and fixing of components as possible. Consider, when specifying unique and one-off façade

elements, switching to a material that has the potential for remanufacturing at end-of-life without any losses. This could be a sustainably sourced hardwood product, a thermally stabilised softwood product (such as *Accoya* or *Abodo*), a natural plastic polymer (i.e. polylactic acid-based plastics) or an already reconstituted product (such as *KLP's Plastic Cladding*).

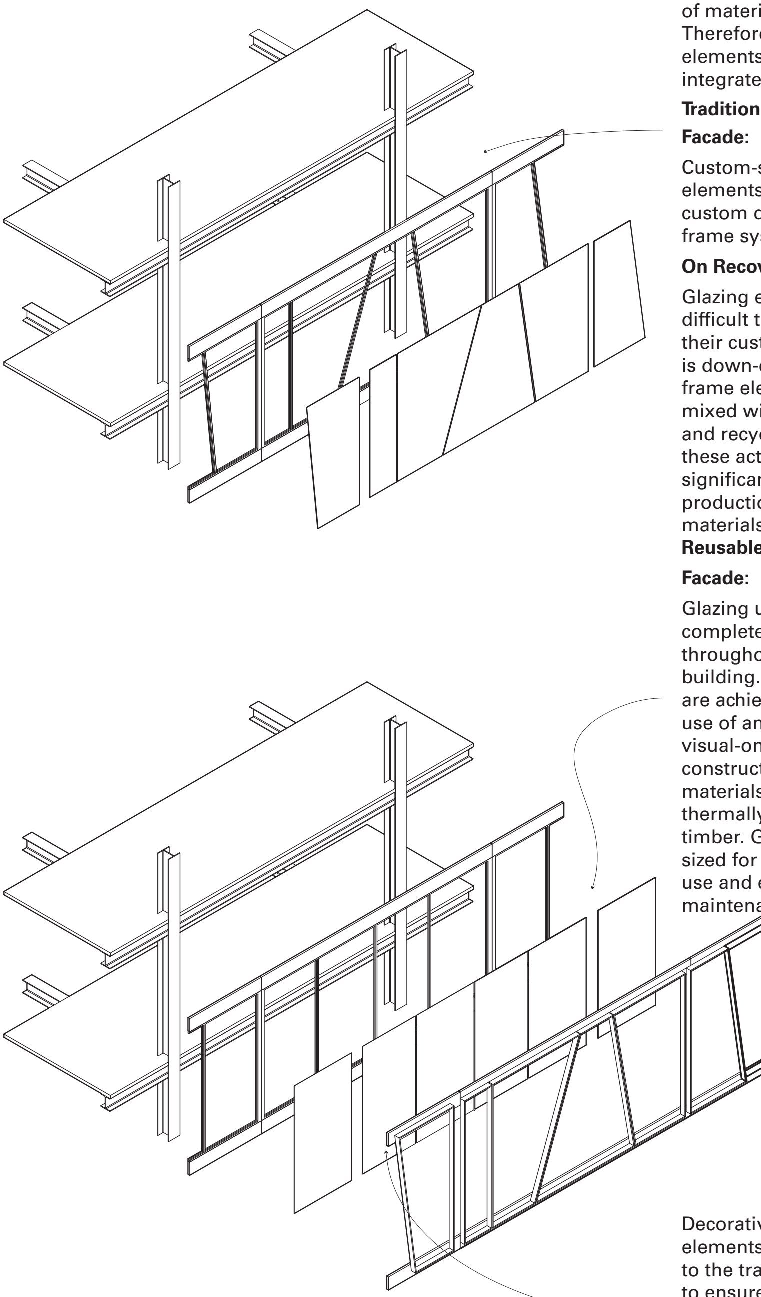


Figure 11.2 Façade construction

11.6 Structure

The structural elements of a building are responsible for consuming up to 50 per cent of all the materials used in construction. It is therefore vital that design features allowing for high-value material recovery are included in the structural design. It is up to you as the architect to advocate for such design features and ensure specialist consultants, such as structural engineers, understand these design ambitions.

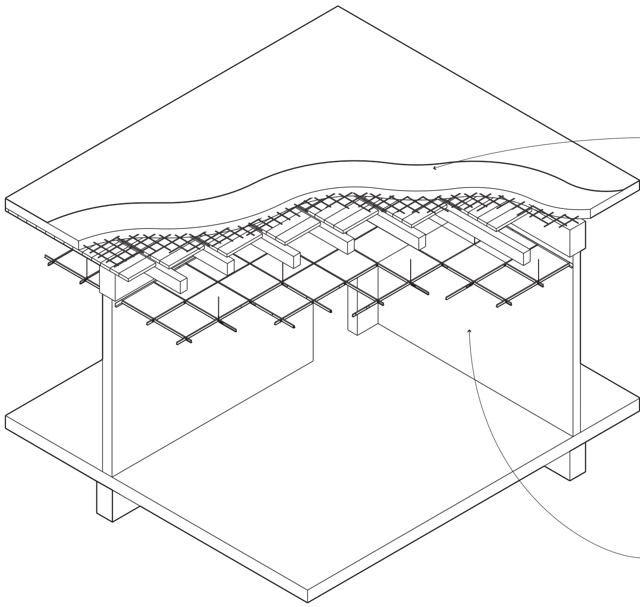
Materials

A major factor to consider when designing for material recovery is the ultimate end limitations of the materials. For example, although precast concrete elements can be reused directly, if they become damaged or unwanted, any reprocessing of the material will result in an irreversible devaluation of the material. This is because there is no way to recover the Portland cement from crushed concrete aggregate. Therefore, to create a new concrete element, virgin Portland cement must be acquired. Based on this issue, it is recommended that concrete be only used when absolutely necessary, such as in the foundation of the building. Cross laminated timber (CLT) panels can be used to replace concrete shear-walls and even flooring elements. Careful detailing of the CLT at its perimeter will ensure that these mass timber elements can be easily recovered at the end of their useful life.

Geometry

Again, a key part of making materials attractive to reuse depends on the geometric configuration of the structure itself. It is important to design for spatial characteristics that use massively similar elements. This will decrease the cost of materials, save on detailed design drawings, make construction faster and make the structural elements significantly more likely to be reused. In this context, use square structural bays as much as possible, as the same beam design can be used in four instances rather than two. Likewise, ensure that all of the connections between these beams and the columns are completely reversible. For steel and mass timber, this means bolted connections; for concrete, this might mean the use of corbels on columns and additional steel ties (Salama: 2017; Storey: 2005). And even though designing for recovery does call for a significant degree of standardisation, note that it is possible to express the original architectural language and design for recovery. One way to achieve this is to work backwards, first specifying the architectural plan, and then examining the maximum level of standardisation that is possible without compromising the design.

Floor Assembly Construction.



Traditional Construction

Floor:

Conventional concrete frame construction with rib and infill floor deck assembly, including 100mm reinforced concrete slab and carpeted finish.

On Recovery:

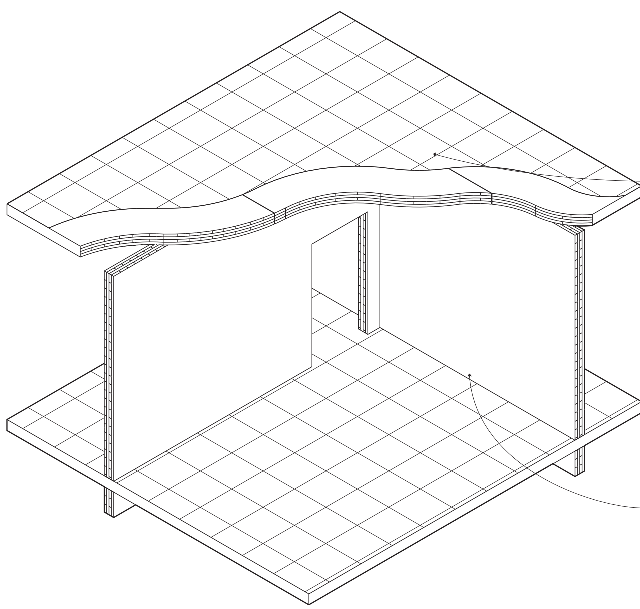
Concrete broken up and downcycled to aggregate. Steel reinforcement mesh separated from crushed concrete, mixed with virgin steel and recycled. Timber infill landfilled, clean-filled or downcycled into fuel. Carpet landfilled.

Ceiling:

Suspended ceiling tile grid hanging by cables from underside of concrete rib and timber infill floor.

On Recovery:

Directly reused, damaged ceiling tiles landfilled, aged ceiling tiles painted or cleaned. Damaged frame members mixed with virgin steel and recycled.



Reusable Construction

Floor:

Standardised Cross Laminated Timber (CLT) panels bolted at all junctions with steel plates at major joints with an adhesive backed floating modulated carpet tile floor covering.

On Recovery:

Floating carpet tiles fully reusable, or recycled if worn. Deconstruction economical with adhesive fixings. Full size CLT panels directly reusable via unbolting.

Ceiling:

Not applicable - exposed CLT acts as ceiling. Services fixed directly to underside of CLT and left exposed.

On Recovery:

N/A

Figure 11.3 Floor assembly construction

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12

Chapter Twelve

Services

Services

Guy Marriage

12.0 Services

The core also is a place for services to rise through the building so they can be distributed on different floors. These services include fresh water going up through the building and foul water such as sewerage and stormwater coming down. The core takes electrical wiring and telephone / internet data cabling up to each floor, as well as specialised cabling for fire alarms and water services such as sprinkler pipes, heating water pipes, and chilled water pipes. The core also, in most buildings, takes air up and down the building, including both fresh air being ducted into the office floors and stale air (exhaust air or return air) being ducted out (refer to Figure 12.1). Good core design and good services provision is essential to having a good building design.

12.1 Risers: holes in slab

A lot of the services going into a core will travel in what is called a services 'riser' (in America: a 'chase'). A riser starts with a series of holes or voids through the slab that typically align vertically through the building (refer to Figure 12.2). These voids are denoted with an X on the drawing (meaning that there is no slab at this point). When walls are built around these voids, the resulting space is a riser: a space that rises from one floor to another. Inside the riser, we can install services, and if they are moving air around the building, then the air is put into long thin steel boxes or tubes called ducts. Ducts rising vertically through the core typically do so in a riser. Risers can also carry pipes or wires.

There are a lot of things that move up and down in the core, apart from people in lifts and stairs. Essentially, these services can be broken down into three main groups. These include:

Power and data

- Electrical wiring – for power and lights – will end in an electrical distribution board (DB), or switchboard in a cupboard (a whole small room) at each floor. While power for lights will stay at a high level in the ceiling (on cable trays), power for appliances needs to be available at floor level, circulating to the floor especially at columns and around the perimeter (in cable trunking).
- Emergency lighting. A separate wiring network will supply the emergency lighting.
- Data wiring – telephone / computer – will often also end in a small communications room or cupboard at each floor, often with a network server complete with many data cables in and out. There can be quite significant amounts of wiring in a 'wireless' building.
- Building Management System (BMS) – if elements of your sophisticated modern building are computer controlled by a BMS, then there will be additional power and data cables to all controlled items.
- Security cabling – There may be a separate small network for security cabling, connecting alarm sensors.
- Fire alarm cabling – another separate set of wiring, often in red cables. Connects to the fire alarm sensors and to the fire warning sound system – which may be alarm bells or a recorded message.

Note: wiring risers should always be separated from liquids. The power and data wiring can be threaded through holes cored in each floor slab but should also be fire sealed at each floor with fire collars (refer to Figure 13.4). Piped liquids can be carried through holes cored in the slab, but when allocating room for pipes, allow extra room for fixing and a thick layer of insulation.

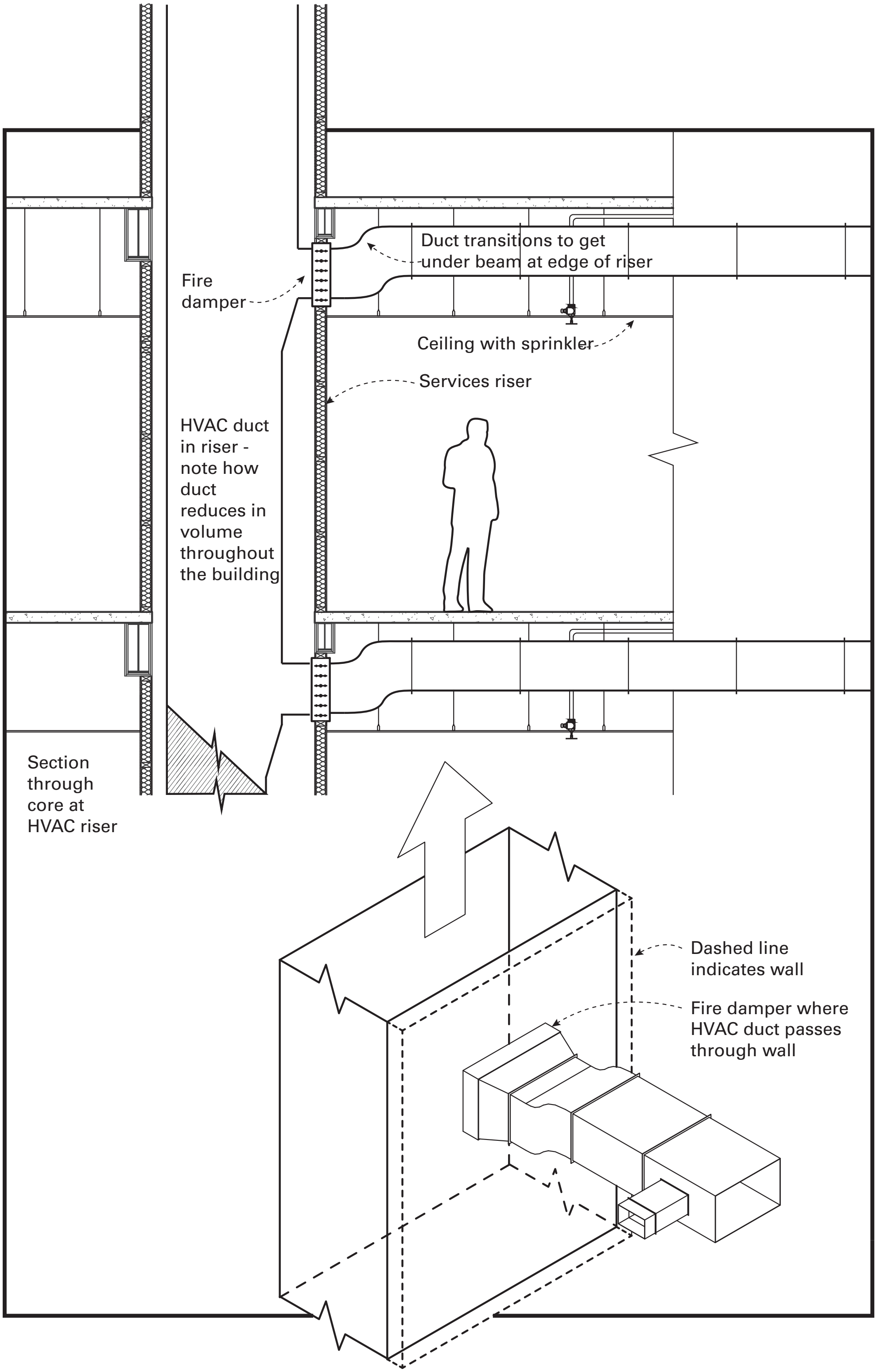

Figure 12.1 HVAC duct in riser

Piped liquids

- Liquid services – there are lots of pipes, which will typically include:
    - Fresh cold water – supply to kitchens and bathrooms etc.
    - Fresh hot water – supply to bathrooms and kitchens.
- Heating pipes – these will circulate warm or hot water, often from a central boiler in the basement, to warm you up via radiators. Common in northern Europe and other cold climates.
- Cooling pipes – to cool you down and cool the building down, on a completely separate circuit from the fresh cold water. In some cases, the heating or cooling source may be from deep underground, accessed via heat exchangers.

Fire protection

- Sprinkler supply – sprinklers work by having the piping always full of water; therefore, it has to remain primed, ready to go off. This is on a completely separate circuit to another water supply.
- Dry riser / wet riser – pipes for the Fire Brigade to connect to in the case of a fire, with riser outlets on each floor in the fire stairs. If it is a 'dry riser', the pipe remains empty until the Fire Brigade comes and fills it with water from street level. Here the word 'riser' refers to the pipe, not the vertical shaft.

Plumbing and drainage

- Grey water – slightly dirty used water from handbasins and showers. Not drinking quality, but these can be used for supplying cisterns in the toilets. Now increasingly common in Green Star buildings.
- Black water – the sewer pipe or soil stack going down and out. This connects at ground level to the public sewer. Toilet facilities may be self-contained composting toilets, but this is still highly uncommon in office buildings.

Other pipes

- Gas piping – not in all countries, but some offices may require natural gas for cooking, etc., or more commonly, to fire the boiler in the basement for space heating.
- Oil piping – common in the USA for domestic heating to fire the boiler in the basement.

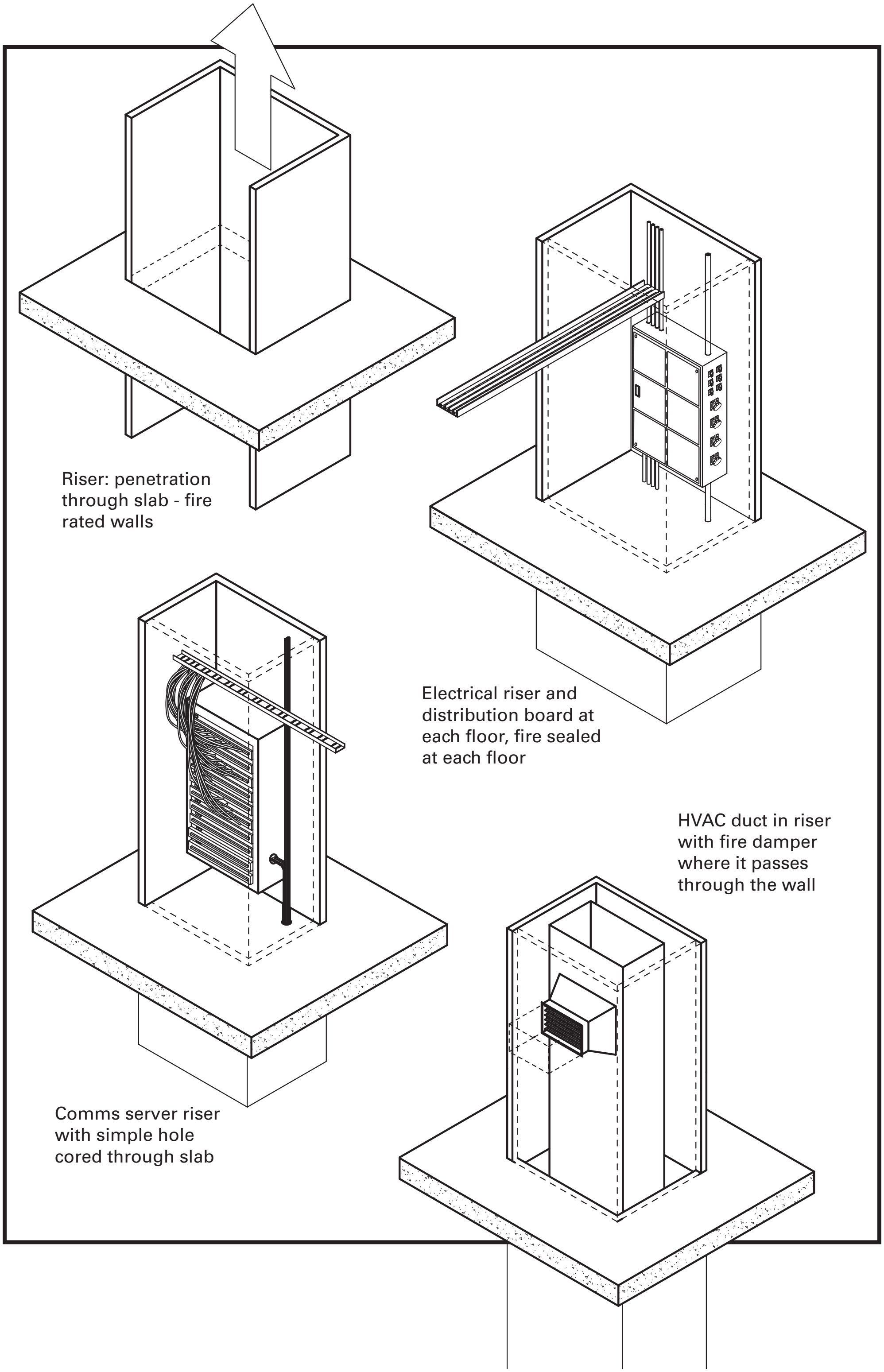

Figure 12.2 Comms riser, electrical riser, HVAC riser

General air handling

- Air ducting – if the building is not 100 per cent naturally ventilated, then air must be transported around in ducts. These include three main functions:
  - Fresh air supply – from outside mainly, around the whole office space.
  - Stale air extract – either discharged outside or mixed 50/50 with the fresh air and returned to the offices.
  - Exhaust air – smelly stale air, from the toilets or kitchens, etc., venting out to the external city air.

Note: Air handling is the most prominent use of space in the services floor, often found at the very top of the building or halfway up in a dedicated floor space. Make sure the fresh air intake is not anywhere near the exhaust. Often the fresh air will come in on one side of the building and go out on the opposite side or enter at roof level and exit at ground level. For the really bad toilet smells, the discharge must be high – above the last office floor.

Targeted air handling

- Staircase pressurisation duct (SPD) – ensures air pressure in the stair is always positive to stop any smoke infiltration as people are trying to evacuate. One SPD for every staircase.
- Toilet extract – no one wants to smell those smells – out they go!
- Kitchen extract – old tuna sandwiches and fried egg smells – out!
- Retail extract – shops downstairs and especially restaurants need large ventilation extracts too.
- Car park extract – cars produce particulates, carbon monoxide, and smelly fumes – extraction needed.
- Extra extracts – always allow some room for more ducts to be added in later.

Note: Ducting and associated pipework, along with cable trays for power and data, etc., usually rises vertically through the core and then traverses horizontally through each office space in the ceiling plenum (discussed further in Chapter 14). Since the Seddon earthquakes in 2013 and the Kaikoura earthquakes in 2016, more thought is being given to the stability of all these ceiling-mounted items to stop them moving, breaking loose, and collapsing all over the people on the desks below (Baird and Ferner, 2018). Answer: securely restrain all services from swinging and breaking loose.

Let's examine some of these services further, starting with the one that may well be described as the most important service of all in a tall building.

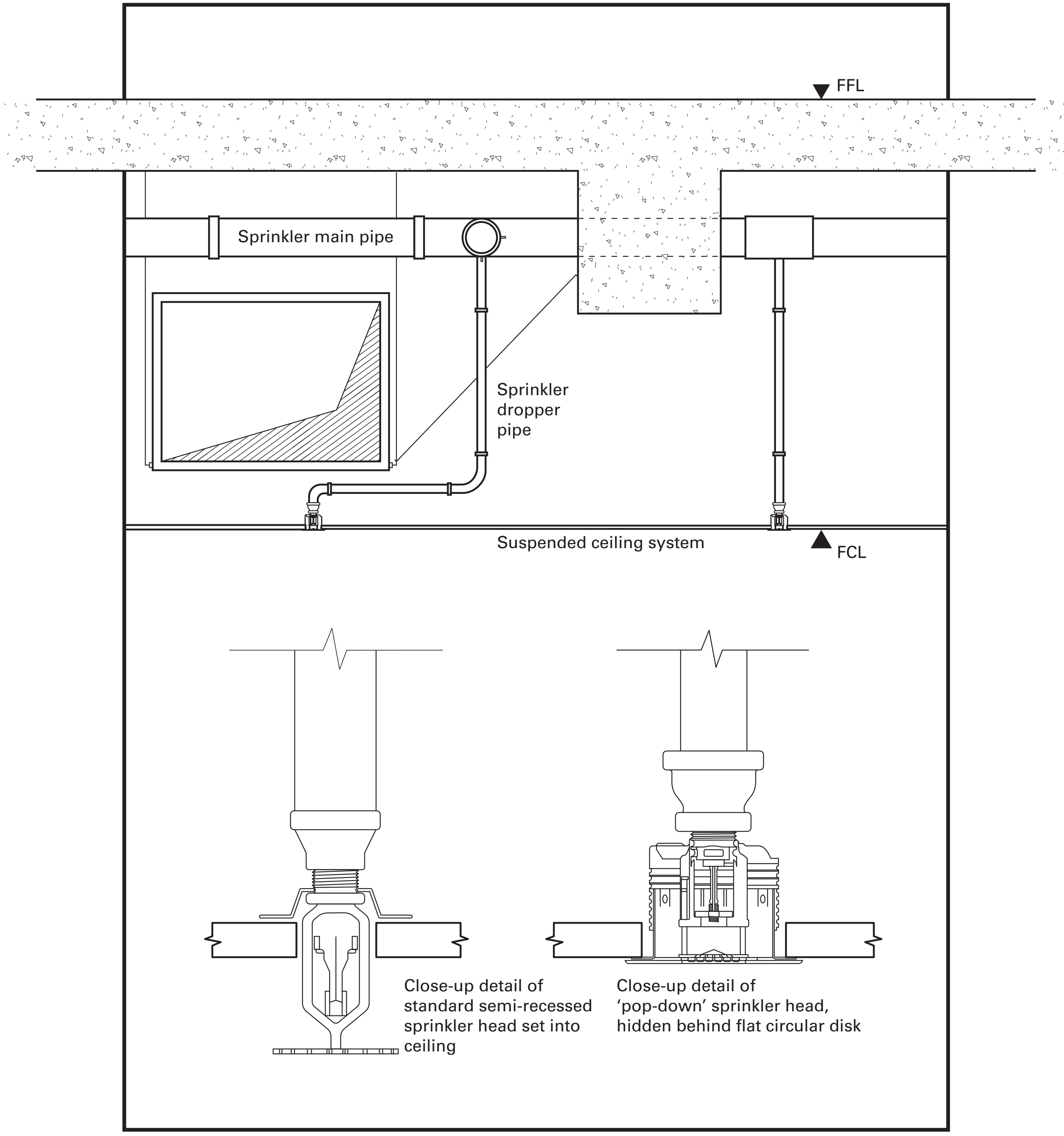

Figure 12.3 Sprinklers

12.2 Sprinklers

The advent of the automatic sprinkler system since 1874 has led to a huge reduction in the number of people killed in building fires throughout the world. Until the horrific 2001 attacks on the World Trade Centre twin towers in New York, there had not been any major fatalities in office buildings fitted with sprinklers. The simple fact is: sprinklers save lives. Following the disastrous tragedy of the Grenfell House apartment building fire in London in 2017, where 79 or more people died due to some horribly simple reasons: no sprinklers, only one exit stair, highly flammable cladding, and an inept disaster management strategy, expect there to be a further strong push for sprinklers in apartment buildings as well. Sprinklers are already common / effectively mandatory in large office buildings in the USA and Canada, but not necessarily all countries.

The system is simple: a sprinkler head contains a small fragile glass bulb filled with a coloured liquid: if the temperature rises, the coloured liquid expands and thus the glass is broken, the sprinkler is set off, and large volumes of water flows out through the nozzle (refer to Figure 12.3). Please note that unlike every Hollywood film you have ever seen, setting off one sprinkler does not set them all off – only that one sprinkler directly above the fire will be set off. The glass breaks only when temperatures are high enough that there is obviously a fire – and the amount of water coming out of the sprinkler head is more than enough to contain the blaze. If the fire grows larger, more sprinklers will be set off until the blaze is extinguished.

The greatest damage from fires in a sprinklered building therefore is the water damage to the interior. The inside of the steel sprinkler pipes may have some rust, and so the water that comes out may be brown and rusty. . . regardless, carpets, desks, computers and all paperwork below the sprinkler will be ruined and will need to be replaced. Water will seep down cracks or shafts into the floors below, etc. – water damage from sprinklers and fire-fighters can be substantial. Still, a sprinklered building is far safer for human life and every building should be sprinklered, not just offices. Churches, heritage buildings, school buildings all too often are not sprinklered due to lack of funds or lack of forethought, yet they are where it is needed most. Houses can also be sprinklered, but this does not yet happen widely at all, yet housing is the place where most deaths from fire occur.

Sprinkler heads are laid out to a frequency set by a Building Code Standard, but often the actual layout of the sprinkler pipe network is left entirely up to the sprinkler contractor. Their desire is to get the pipes installed quickly and move onto the next project (margins in the business are tight and there is little time or room to muck around). That is why it is important for the designer of the building to have thought about the position of sprinkler heads beforehand and produce a co-ordinated plan and section.

Broadly speaking, sprinklers should be positioned in the middle of a room and in the middle of a ceiling tile (not through the actual ceiling grid), at a spacing of between 4m and 4.5m in every direction. They should not be closer to a wall than about 2m if possible (i.e. a radius of spread of 2m will give you a 4m spacing). The key thing to do is to think about where the sprinkler might fit in an office space, as well as how this might fit in with the lights in the room as well. You cannot have a light fixture in the same physical tile as a sprinkler head. Electricity and water do not mix well.

The position of the sprinkler head is set at the ceiling height (it is possible to get pop-down sprinkler heads that sit flush with the ceiling for a more aesthetically pleasing look), but the sprinkler pipe will typically be set much higher, possibly even right up under the floor slab above, with flexible dropper branches of the sprinkler pipe joining the two (refer to Figure 12.7). The position of that high-level sprinkler pipe is not of so much concern to you in the plan, but it is common to dictate where this may occur in the section so that you can work with the sprinkler contractor, having a mutually agreed zone in which they can install their pipework.

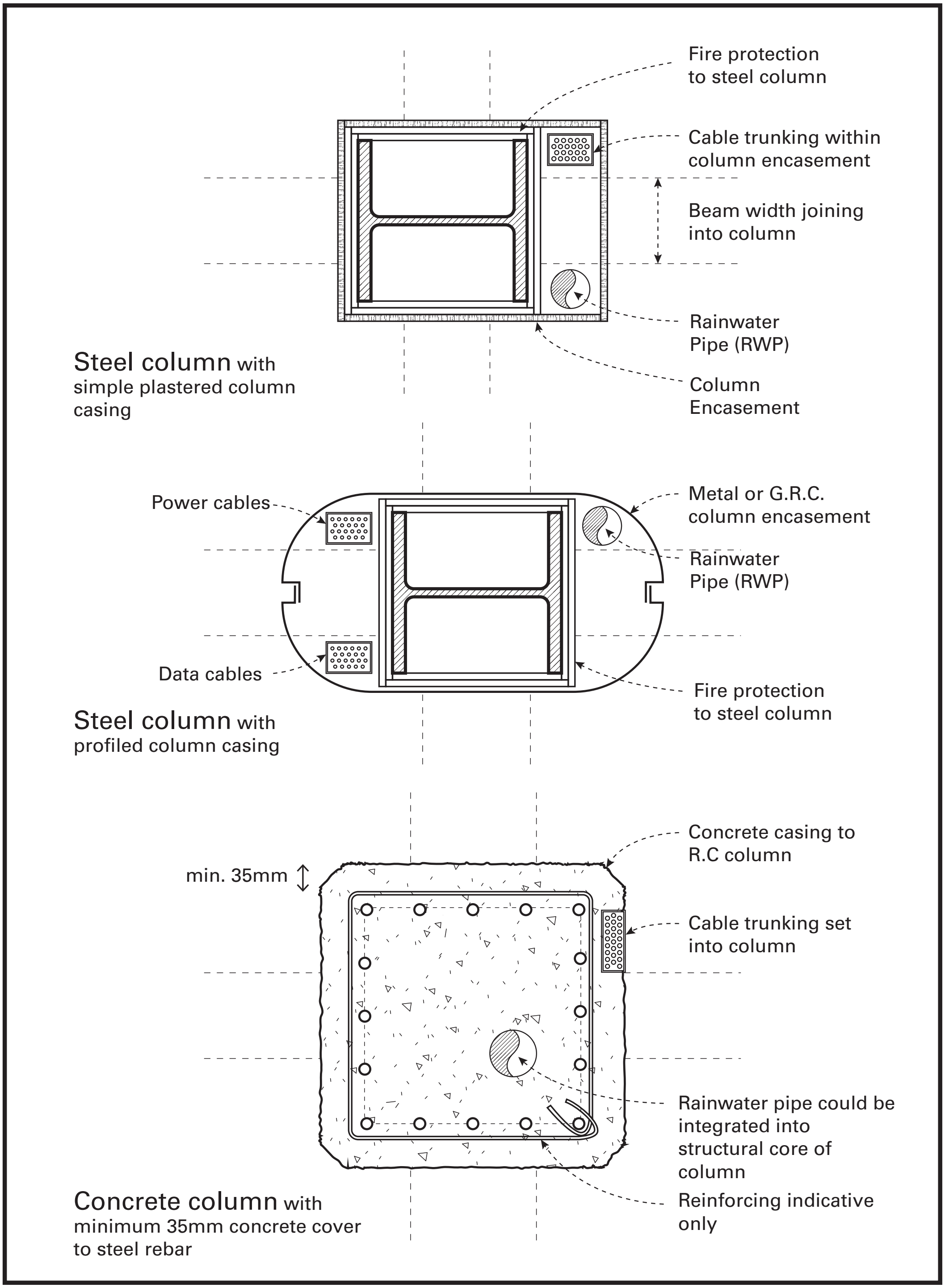

Figure 12.4 Hidden services in columns

12.3 Cable trays

The considerable amount of lighting in an office building needs connecting to a considerable amount of electrical power cables, and these are typically carried on cable trays: a system of light perforated steel trays that are arranged to give solid support to the wiring. When fully loaded with copper wires, they can be extremely heavy. The cable tray is supported by steel angles or Unistrut channels below and hung from steel rods drilled into the underside of the slab above. On some occasions where only a few wires need to be carried, a system known as a catenary wire is used, where a strong steel wire is stretched and hung from the underside of the slab, and the cables simply cable-tied to the steel wire. There is also fire alarm wiring, which may often run in another separate tray or catenary.

To get those cables in the ceiling down to the desks below, the layout of the cable trays should go from the electrical riser and circle round the building, connecting every column, including the external perimeter columns. Data cables (for computers and telephones) should be kept at least 300mm away from power cables at all times and should have a separate cable tray network from the power cables. Electrical cables can be routed down the columns and from the base of the columns into any perimeter cable trunking around the edge of the office floor (refer to Figure 12.4). Desks will often be pushed up against columns and so computers, etc. can be simply plugged into power points situated at the base of each column.

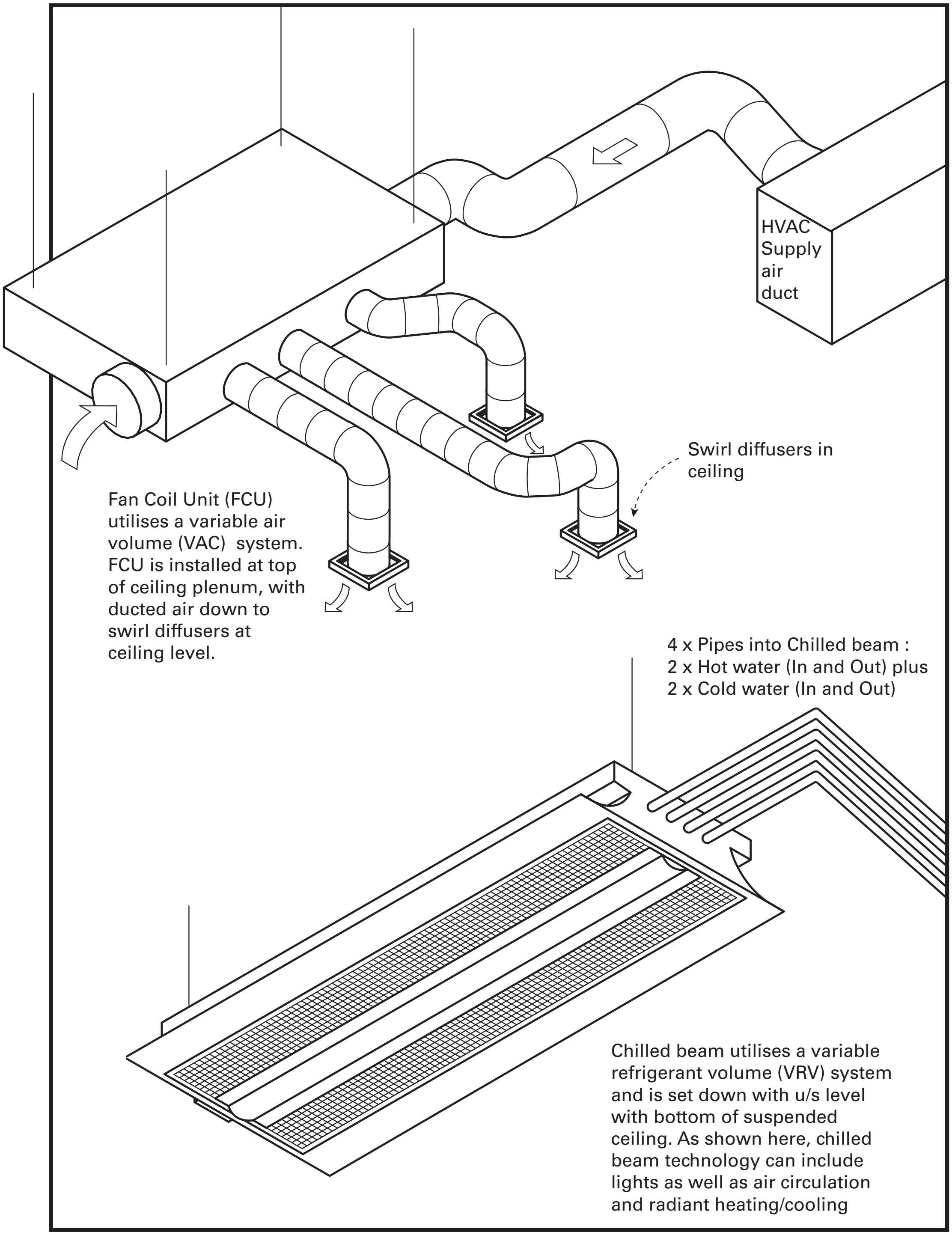

Figure 12.5 Chilled beam vs fan coil unit

12.4 Heating, ventilation, and air-conditioning: HVAC

There are many books on HVAC aimed at the budding HVAC engineer, but few aimed at the Architect, with Baird (2001) a rare exception on how to integrate environmental HVAC systems into architecture.

Air-conditioning, when required, is because human beings (and their computer equipment) emit heat. A floor of 100 people walking around or sitting working is like having 100 portable heaters, all on at the same time. Computers and lights all also emit heat. Combined with that, human beings breathe in oxygen and breathe out carbon dioxide and water vapour. Buildings therefore need a method of reducing excess heat and getting rid of excess CO_2 and moisture, while introducing a steady supply of fresh air full of fresh oxygen. How do they do this?

First, obviously, we could just open a window and utilise natural ventilation. With the strong push towards green buildings and lower energy costs, this is an increasingly desirable solution, but it does not work for every client or every tenant or every building. In a tower 30 floors up, the wind is quite strong, and opening a window to get fresh air means papers on your desk go flying and the cold wind whistles in. In windy cities like Chicago and Wellington, this issue arises on much lower levels too.

In Germany, there is a movement towards double-skin façades (DSF) where windows open into a void before connecting to the open air. It is twice as expensive but does allow naturally tempered air and saves on the cost of air-conditioning machinery (Heusler et al, 2001). Slowly, buildings in other countries are also adopting DSF systems, such as Meridian in Wellington (Barbour and Marriage, 2007), or the new Christchurch City Council building further south in NZ.

In hot and humid climates where they haven't planned for full air-conditioning, you will often see air-conditioning units outside, bolted to the window ledge. Here they just take the air direct from outside and blow it inside once it has been cooled down a little by running the air over cold water. This is extremely energy inefficient and therefore costly. In some residential homes, you may use a slightly more sophisticated version of this called a heat pump. For an office building, we need something a lot more sophisticated.

The most common system of air handling is to suck fresh air in (typically on the roof, away from the traffic fumes) and blow it through a system of ducts down to supply grilles throughout each ceiling. This involves a giant machine on the roof known as an Air Handling Unit (AHU) and a lot of ductwork. The duct starts off large at the top, blowing air at high speed as it moves down through the building, with ducts reducing in size until by the time the fresh air reaches the office desks, it is just a gentle breeze. The air can also be tempered (i.e. made warmer or

colder or more or less humid) by more expensive equipment (also, typically on the roof or sometimes in the basement) so that it arrives at your desk in a comfortable state. It is not 100 per cent fresh outside air, however – it is mixed with 'return' air from your office space at a ratio of about 50/50 (varies dependent on CO_2). The return air seeps up into the ceiling 'plenum' (the area above the suspended ceiling), and the temperature of the outside air is tempered in combination with the portion of return air.

The typical means of tempering the air within the ceiling space is via a Fan Coil Unit (FCU) distributing heated or cooled air by convection, working in conjunction with the AHU (Watts: 2001). The FCUs are small, relatively inexpensive boxes that are installed up in the ceiling void, which have an air intake from the piped air from the AHU on the roof and another open valve for the return air from the plenum. Each FCU will have three or four flexible supply ducts splaying out to 'swirl diffusers' (or grilles) set into the ceiling (refer to Figure 12.5). The FCU will mix the fresh air from the AHU in with the return air within the ceiling to deliver this air to the people in the office. If you have lots of air supply grilles, you may need lots of FCUs. Because FCUs recirculate a high proportion of the air they move, they tend to end up reconditioning (warming up or cooling down) the same air several times over, which can be wasteful in terms of energy efficiency.

A better system of air handling is gaining traction around the world over the last couple of decades, with the use of 'chilled beams' (refer to Figure 12.5). This is not an actual structural beam, but instead it is a system which is supplied with some fresh air and hot and cold water, and it tempers the air locally. It is more expensive to buy than an FCU and is integrated into the ceiling partially exposed to view. It requires far less air volume to be supplied and uses less energy. Chilled beams work by 'entraining' the return air into the fresh air: fresh air is blown into the space and the reticulated component is carried along for the ride, rather than actively moved about with fans. Occupants of buildings like it more too, as it is much quieter than the muffled roaring of an FCU. Fresh air still needs to be supplied to the chilled beam, but not in such great volumes, so duct supply sizes are much reduced. No supply grilles are needed, as the entire chilled beam is a supply mechanism. Because chilled beams do not move as much air as an FCU, they will not have as high an output, so a chilled beam building may still have some FCUs in intensively used areas like meeting rooms.

Sophisticated green buildings use a mixture of natural ventilation through features like double-skinned façades and ceiling-mounted chilled beams. Unsophisticated buildings that you see just about everywhere else use FCUs and big AHUs. There are many other systems, but for our purposes those two extremes can suffice to illustrate the issues at stake. Regardless of the HVAC system used, ducting systems are still needed to move the air. For this reason, you need to understand a bit more about ducting.

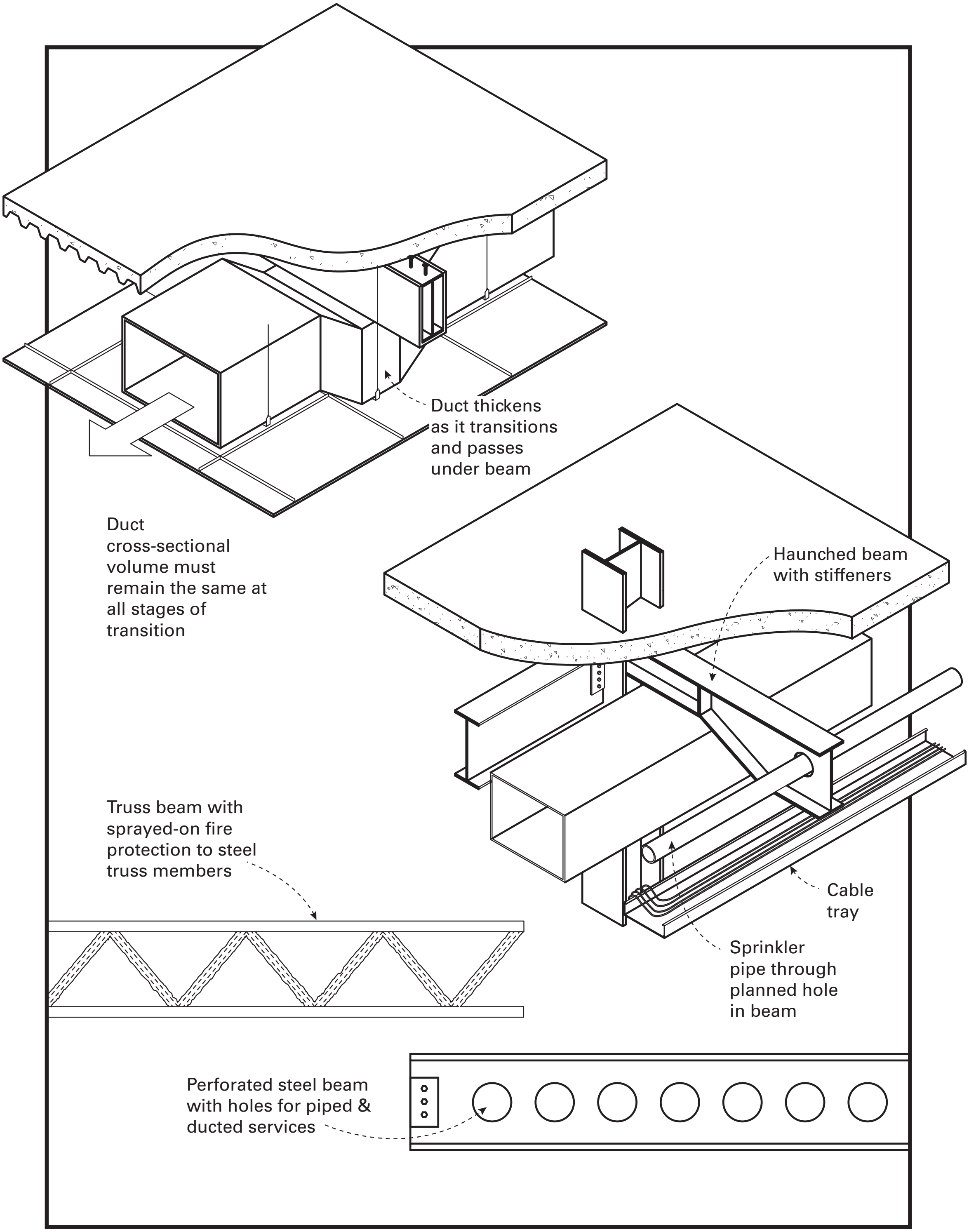

Figure 12.6 Beams vs ducts in ceiling zone

12.5 Ducting

Ducting is typically either square, rectangular, or round (in cross section), made from lengths of thin galvanised steel sheet metal, joined together to make continuous lengths. Where needed, crinkly flexible ducts can connect from the rigid duct to the ceiling grilles. The most efficient shape for any duct is a circular profile, as it has no corners in which air can drag and cause eddies. In practice, rectangular ducts are more typically used, as they fit better into the inevitable space constraints (see Figures 12.6 and 12.7).

The architect or designer of the office space does not normally get involved with the design of the ducting that supplies air and takes air away, but it is the lack of this involvement that causes so many issues on-site. On some specialised buildings, such as a hospital or a museum, up to a third of the entire budget can be spent on the services, and if you get this wrong, rework is even more expensive. Better to get it right the first time.

There are two broad principles here. First, fresh air needs to be ducted to the office floor, and second, stale air needs to be ducted away. This therefore requires two completely separate ducting systems.

The size of the ducting will change as it goes along, with the main duct gradually reducing in size as each part branches off to another supply grille or to an FCU. Therefore, you will need to allow for the ducting to be largest where it exits from the core duct riser, and it will be at the smallest diameter far away from the core. The key thing to remember here is to allow room for the large ducts to get out away from the core and past any beams on the way. This is the role of the HVAC engineer or the HVAC contractor, but it helps if you have figured out some possible routes for this to happily occur.

Sheet metal ducts are not all that heavy, but still require struts to suspend them from the underside of the slab above. As air can be pushed along the ducting at high(ish) speeds, the ducting is often covered with an acoustic / thermal wrap which covers over both the duct and its support bars below. This helps to keep the noise down and the conditioned air within the duct at the right temperature to heat or cool the building (refer to Figure 12.4).

All of this work will be done by the specialist contractors on the project, but what you need to remember as the designer of the space below is that if the HVAC designer indicates that there is a, say, 300 × 600 duct passing under a beam, you should allow at least 50mm extra on each side for the wrap. This takes the effective size of the duct to at least 400 × 700, and the requirement for brackets to hold this duct up in place take even more room below the duct. Your remaining available 'under-beam' space is now getting very tight and cramped.

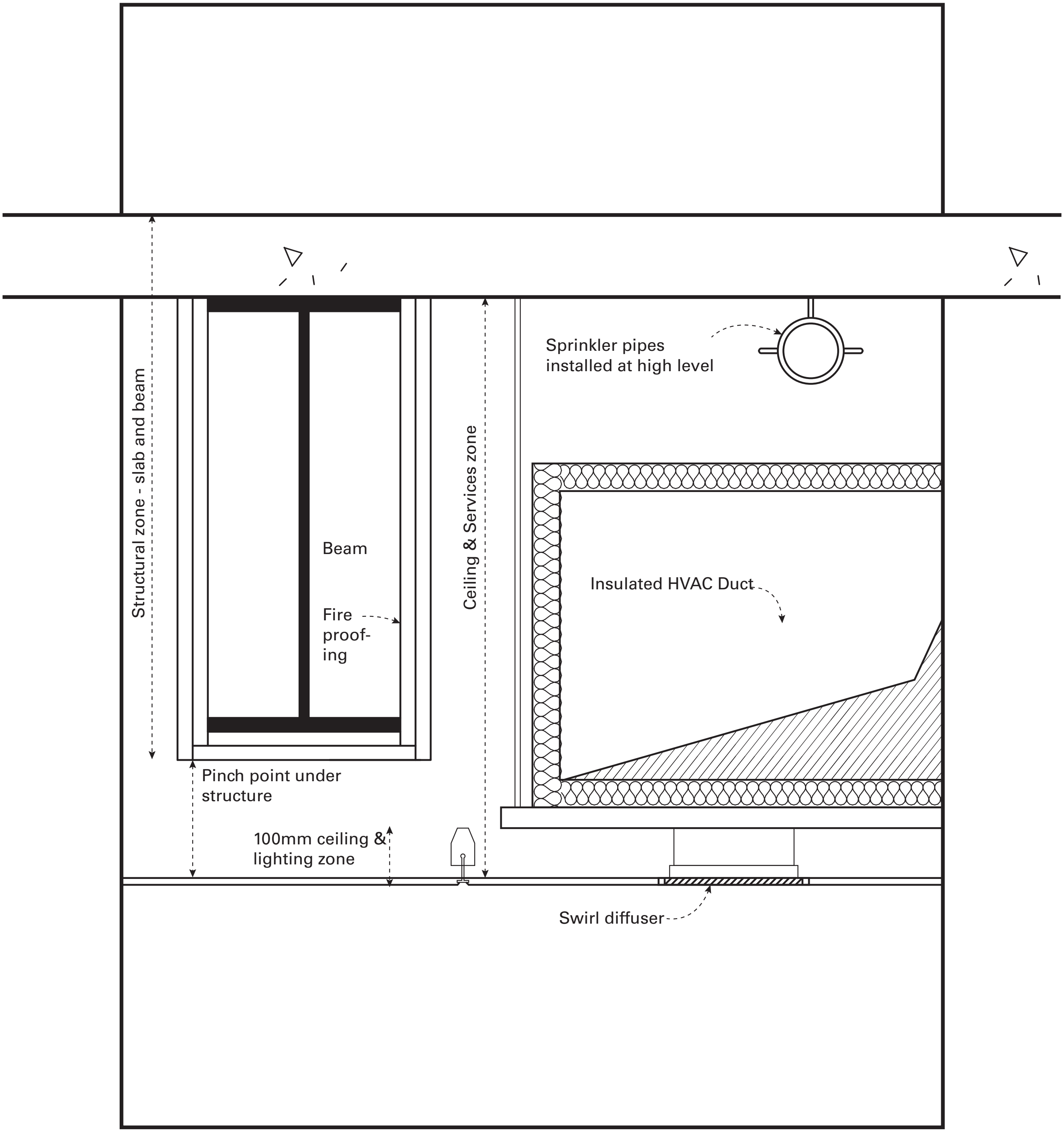

Figure 12.7 HVAC duct in ceiling zone

While a circular duct of diameter 480mm has the same cross-sectional area of 0.18m^2 as the previously quoted 300 × 600 duct, the air will flow more smoothly and hence use less energy to move along the duct. However, it will probably be easier to find room in the ceiling void for a duct only 300mm high than one 480mm high.

Carrying this onto a further extreme, a duct could be sized at only 100mm high and 1.8m wide, which would have the same cross-sectional area, but would be severely constrained in its layout flexibility, and would convey air with considerable drag, owing to the low profile. The drag of the air manifests as acoustic noise and generally you should not want to hear anything more from your air handling more than a quiet murmur. Quiet is good. Squashed ducts are not good (aim for a max ratio of 1:4), as they are noisy (fans working hard to overcome the drag), and noise means inefficiency.

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13

Chapter Thirteen

Floors and penetrations

Floors and penetrations

Guy Marriage

13.0 The office floor space

Structural solutions for floor slabs have already been discussed in an earlier chapter (Chapter 4: Structure: concrete). But what happens to that exposed floor slab surface?

In the planning of an office floor, once structural grid and core position have been set, the planning grid should then extend to the edge of the building to inform the layout of the façade. It should by now become obvious to you that the planning grid and the proposed repeating module of the internal office floor should, if at all possible, coincide with the façade grid. If your planning grid module is set at, say, 1500, then this should tie in directly with the façade module, with mullions set out either at 1500 centres or a division/multiple of that. This means that should any future tenant decide to subdivide your open-plan office floors later on, the internal notional divisions that you have installed in the ceiling will tie in seamlessly with the external façade.

If you have carefully planned out your floors and ceilings in the way that we have described, you will not suffer the nasty problem of an office wall dissecting a window pane, nor will your window layout force you to build offices that clash with the internal lighting and HVAC. Use the planning grid to plan out and position possible future office layouts for the building, including any possible perimeter office spaces. This is known as 'space planning'. For a start on office space planning, consult the works of Francis Duffy (Duffy 1976).

There are also other things to consider when planning out office floors.

13.1 Finished slab

Depending on the quality, budget and servicing requirements of your building, the floor slab may be used as the finished floor, or there may be a raised floor. If it is to stay as a slab (discussed in Chapter 11), then the first thing that will need doing is to make sure it is completely level, as a concrete floor slab can often contain substantial rises and falls as the concrete slab bows under its own dead load and any new live loads.

Architects think that slabs will be poured perfectly flat and stay that way, but in reality, they often have a small downwards sag in the middle of each floor span. Some imperfection in levels is acceptable, but too much is unwelcome and must be addressed.

Realistically, there are only two ways of coping with this: either a small amount of grinding down the high points on the raised surface or to build the slab up a little in the middle of the slumped areas with a ‘floor levelling compound’ (FLC). This is an expensive, quality product that is largely self-levelling: once poured onto a (cleanly swept, dust-free) floor it will spread evenly, bond rigidly to the concrete slab and fill any cracks or depressions. Once it has set hard, the surface finishes can be applied. But once a FLC has been applied, the bare slab will never look as good again.

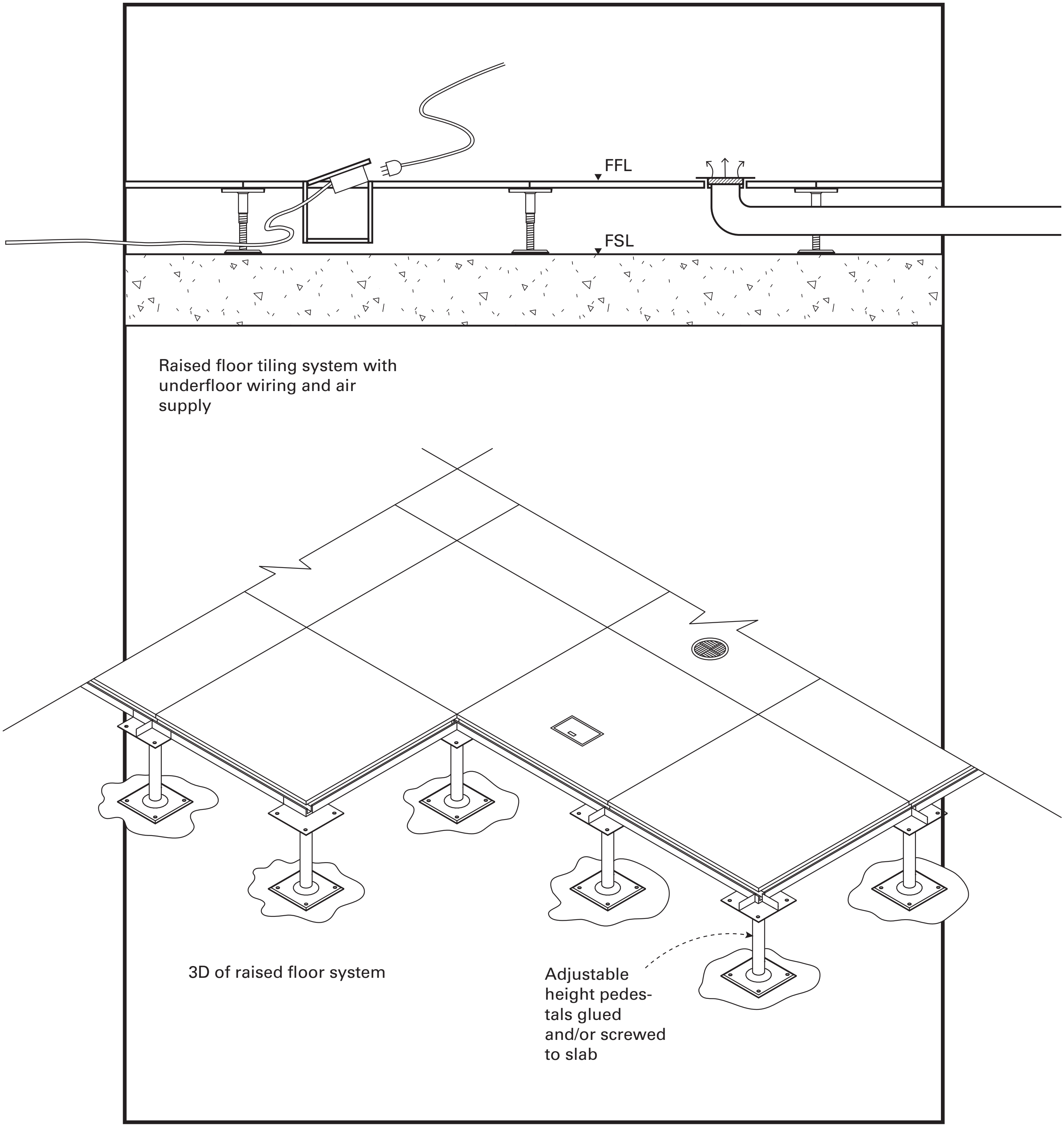

Figure 13.1 Raised floor system

13.2 Raised floors

A 'raised floor' is a system of creating a void above the floor slab for the purposes of running power and data wiring, and in some instances, reticulation of air supply as well (refer to Figure 13.1). This requires a regular grid of small adjustable metal pedestals, on which sit a series of strong, thick floor tiles (timber, steel or plaster composites), with carpet tiles over the top. Raised floor tiles are typically 500 × 500 (1′ 8″ sq) in size and should relate to the planning grid in the building. Typically, the entire height of the raised floor is 150mm (6″), so with a 50mm (2″) thick floor tile, there is a gap remaining underneath about 100mm (4″) in height.

A raised floor permits an extremely flexible approach to office layout, so items like power outlets can be placed with no restrictions and desks do not need to be directly adjacent to the columns or the external façade (via perimeter cable trunking). In some countries, raised floors are common in quality office buildings and it is an almost mandatory feature in big wealthy cities like London, Frankfurt and New York.

If a raised floor is intended, it needs to be allowed for very early on in the build, as this will affect the position and height of stairs, doors, windowsills, lifts: in short, everything. It is exceptionally hard to retrofit in a raised floor later on within a building, as elements like stair landings will need to be adjusted to meet the new floor level.

It is also possible to have taller raised floors in high-use areas (such as share trading floors at the Stock Exchange), where the raised floor may be 300–600mm (1′–2′) in height, to allow room not only for wiring, but also some ventilation ducting as well. Air supply grilles at floor level are a sensible, comfortable place to locate fresh air inlets, as the most comfortable place for fresh air to enter is actually from below, not above. Sadly, this is not common.

Heights are easily adjusted via the screw pedestals to bring the floor back up to one common height, with pedestals typically both glued and screwed in place to ensure no squeaking or toppling. The floor tiles are not fixed in place, so that they can be simply removed for access to the wiring and ducting below. One certain advantage with a raised floor is that if the floor slab has been laid badly or the slab has slumped a little, a raised floor can hide any imperfections in the floor slab and get the tenant a fully flexible, dead flat floor in their office, ready for carpeting.

13.3 Floor finishes

Floor finishes in office buildings are another fiercely competitive marketplace. Areas of flooring are large, and margins of profit are tight, so different suppliers will be keen for you to supply their product. The following list is a guide to possible flooring solutions.

Carpet

Residential carpets may be wool in 'broadloom' strips about 3.6m wide (wool is a traditional carpet material for NZ and Australia), while commercial carpets are usually carpet tiles, now nearly always plastic-based (with nylon fibres and an impermeable resin backing). In theory, the carpet tiles are fully recyclable: in practice, I'm not so sure. Carpet tiles typically come in 18″ × 18″ size in the USA and a 500 × 500 size in metric nations.

Carpet tiles are normally 'direct stick', i.e. glued straight to the slab (or the raised floor if you have one), as opposed to residential carpet which may be 'double stick', i.e. an underlay layer is glued down to the slab first and the broadloom carpet is fixed over the top after. Carpet tiles are laid across the top of the slab or raised floor, with joints between the tiles landing on the centre of the tiles, not on the joint of the tiles themselves. This keeps the floor feeling smooth and level. Carpet tiles are glued in place with a tacky glue (that never quite sets), so the tiles can be easily peeled off and reapplied again later. This makes it easy to replace worn tiles and also to access the wiring below the floor. As Finch notes in Chapter 11, design with deconstruction in mind.

Polished concrete

To grind concrete flat is an extremely dusty, messy industrial process: to 'polish' it is even more so. In reality, to polish the concrete means to grind it with a watery slurry, and depending how long and how deep you grind, the finished result will vary. The 'industrial' look is popular with some people but is seldom found in high-quality office buildings as it is a harsh floor, both acoustically and recreationally. It is possible in New York warehouse-style lofts, but only on floors: realistically *you cannot have polished concrete walls*. The grinding process requires hours of work with a very heavy machine, not something that is possible on a vertical surface.

Hard flooring rolls and tiles

Once FLC has been applied, one possible flooring product is a hard, plastic-based floor covering such as square tiles or rolls of linoleum (naturally based materials), or a roll of 'vinyl' (petroleum-based polyvinyl chloride, or PVC). These are waterproof, extremely durable solutions, but the use of PVC should be banned due to

unsustainable chemical use. Research your product choice carefully to avoid further harm to the environment but also know that any hard surface will have poor acoustic qualities and is not recommended except in wet areas. The tiles or rolls are available in an enormously wide range of products and finishes, and they will be adhesively stuck to the concrete substrate.

Ceramic or porcelain tiles

Harder, higher quality and thicker than a PVC tile, ceramic tiles are reserved for harsh wet environments such as bathrooms. Wet areas such as showers should be waterproofed first with a liquid or sheet membrane and then the selected tiles laid on top in a highly adhesive mortar. An application of a waterproof grout is washed over the top to infill the gaps between tiles, which then sets hard. A 6mm ceramic tile floor may mean a total build-up of 10mm or more in thickness.

Stone tiles

Natural stone such as marble or granite can also be laid in tile form, usually only in extremely high-quality office facilities. Stone tiles are thicker, so a greater build-up is to be expected. Again, careful research is needed by you as the architect to find the right sort of stone. As a natural product, it will wear, and it will have natural imperfections. Sandstone will wear out faster than slate. Limestone will wear out faster than marble. Granite will be the hardest, longest lasting material of all.

Timber finishes

Timber is a popular look, easy to keep clean and environmentally friendly, but it is thicker than PVC timber-look slats that many people use. Real timber has a warmth and character that is hard to replicate, but the biggest issue is how to make it stay down on the floor: you can’t nail into concrete. One possible solution is to glue 18mm thick plywood squares down to the slab first, and then nail fix the timber boarding into the ply. Another option is to ‘float’ the floor above the concrete, but this may mean that the floor ‘pops’ and forms large raised bubbles as the humidity levels change throughout the year.

13.4 Penetrations through floor slabs

Broadly speaking, the floor slab of your building is acting as a structural diaphragm at each floor level. Penetrations through the floor slab are possible but need to be planned. Within the core itself, a lot of the floor will be penetrated by voids such as lifts, stairs, ducts and risers. Holes can be ‘cored’, i.e. drilled through the concrete slab for smaller piped services, as discussed in Chapter 12. These small penetrations are sealed against fire at each floor with intumescent fire seals or fire collars (refer to Figure 13.2).

For large penetrations, like stair shafts, lift shafts and HVAC risers, unless the slab has been designed to support itself in both directions (called a two-way slab), the cut edge of the slab at the void will normally need a beam under each edge. These voids are sealed vertically with fire-rated walls from floor to ceiling.

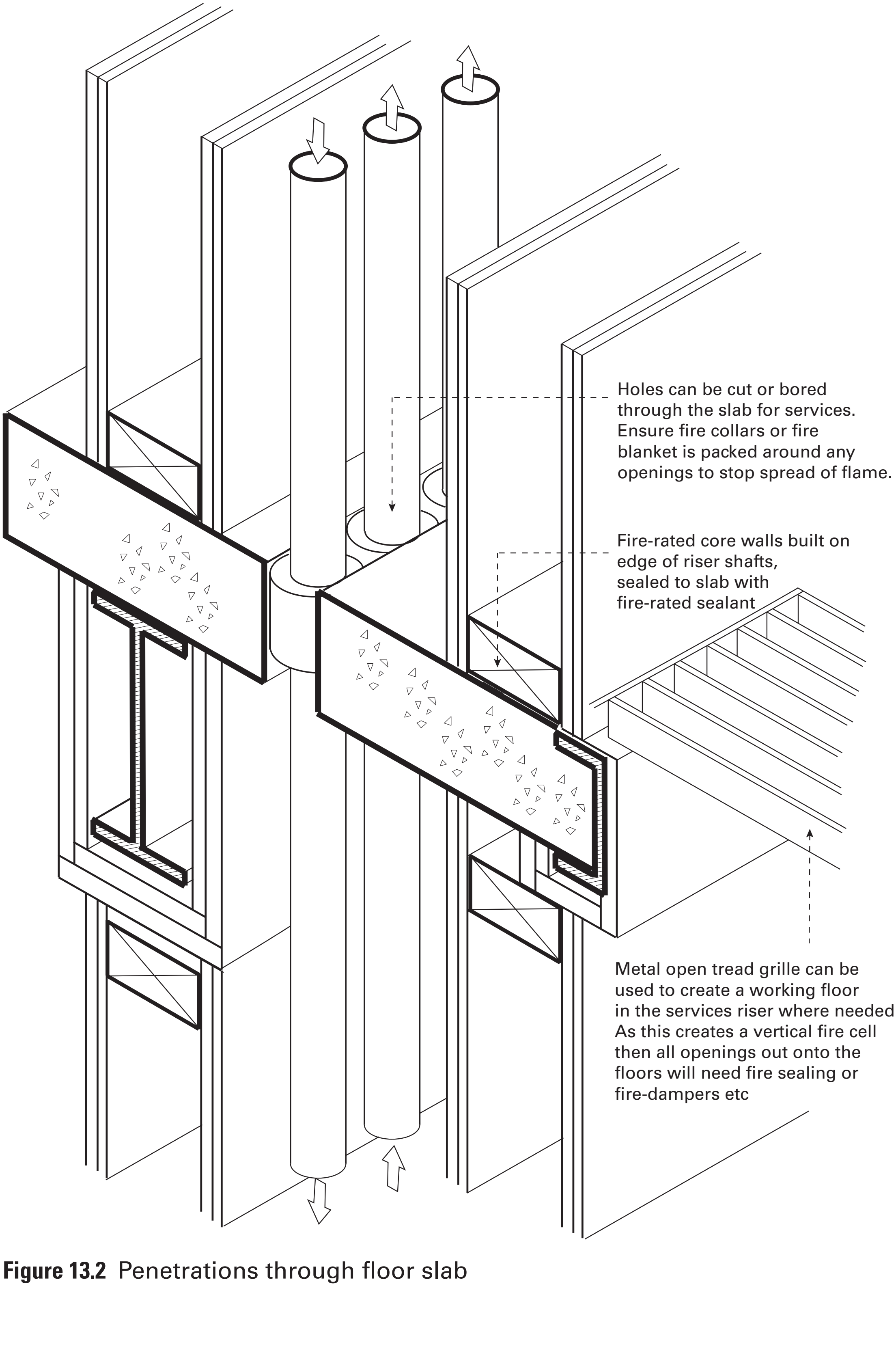

Figure 13.2 Penetrations through floor slab

13.5 Penetrations through beams

There are some quick rules of thumb for penetrations through beams:

- Only in the middle third of the length of the beam,
- Only in the middle third of the height of the beam, and
- Only if the engineer has given permission.

This allows the vitally important lower flange of the beam to continue to take the load. Some buildings have beams predesigned for penetrations through. A castellated beam has hexagonal holes through it, cleverly cut out to save material. Beams with rows of circular cut-outs (known as cell beams in NZ) are becoming increasingly more common (refer to Figure 12.6). Regardless, it is far simpler and cheaper to design and cut *any* openings into a beam when it is in the factory than to have to try and install extra penetrations after the beam is installed on-site! So, always try and design in all and any penetrations early in the design phase.

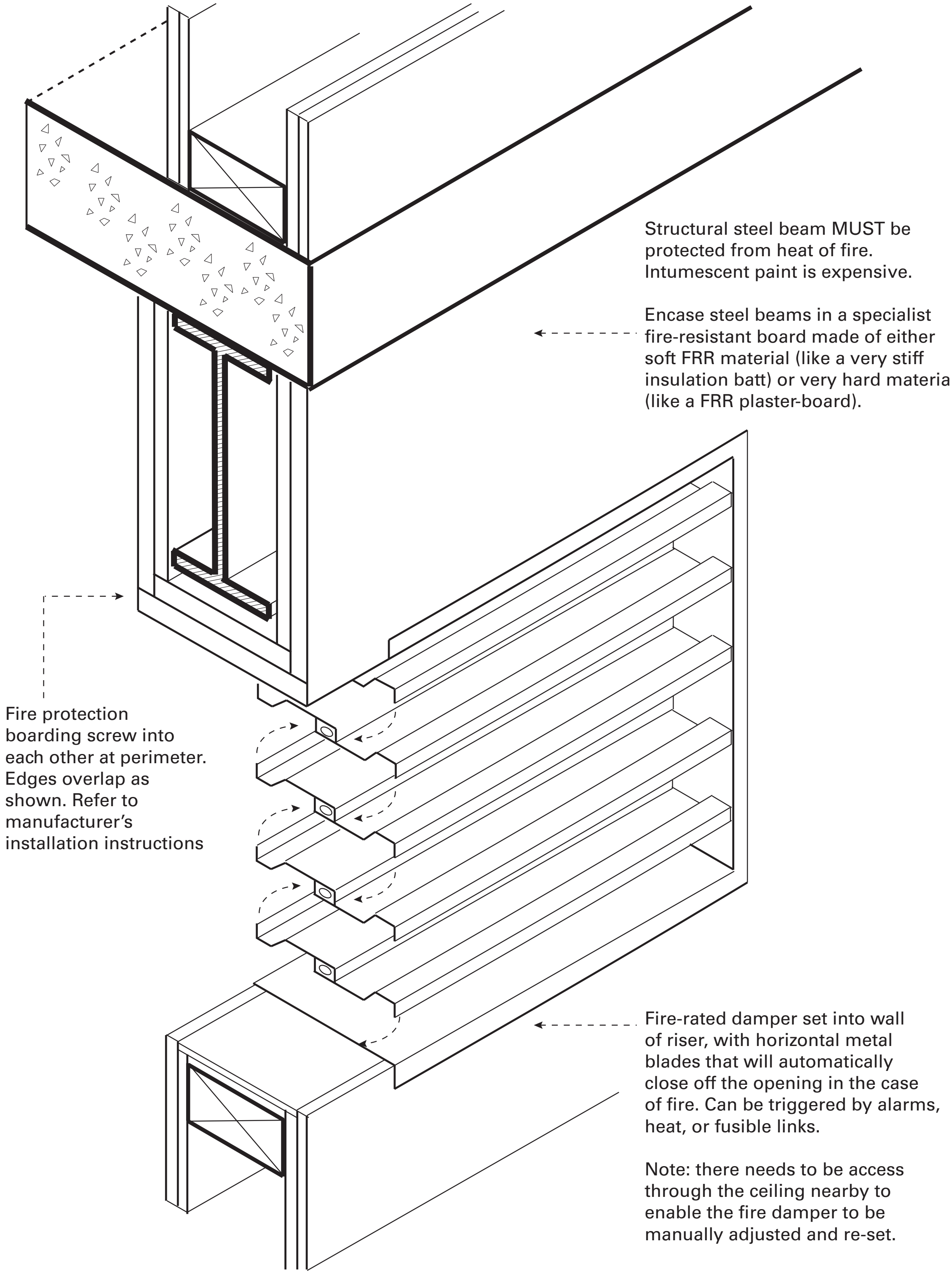

Figure 13.3 Fire damper set into riser wall

13.6 Penetrations through walls

Penetrations through walls are different: refer to Chapter 6 regarding shear wall systems. If the wall is a shear wall, then the engineer will want either very small or very few openings through it. This makes it tricky if you have a lot of penetrations that you want to get through the wall. Items like doors for the lifts can reduce the bracing capability of the shear wall greatly, so penetrations through the shear wall must be kept to an absolute minimum. If you are planning for a shear wall to be a wall at the back of the lifts, with no penetrations, that is fine. If you are planning a shear wall at the front of the lifts, with lots of lift doors, don't! Too many holes mean not enough shear action. The next thing to do may be to move the shear wall elsewhere, where it can be much more solid and suffer less interruptions.

Openings in the walls of any fire-rated riser are fitted with large closable metal flaps, or 'fire dampers', that will automatically clamp shut in the case of a fire (refer to Figures 13.2 and 13.3).

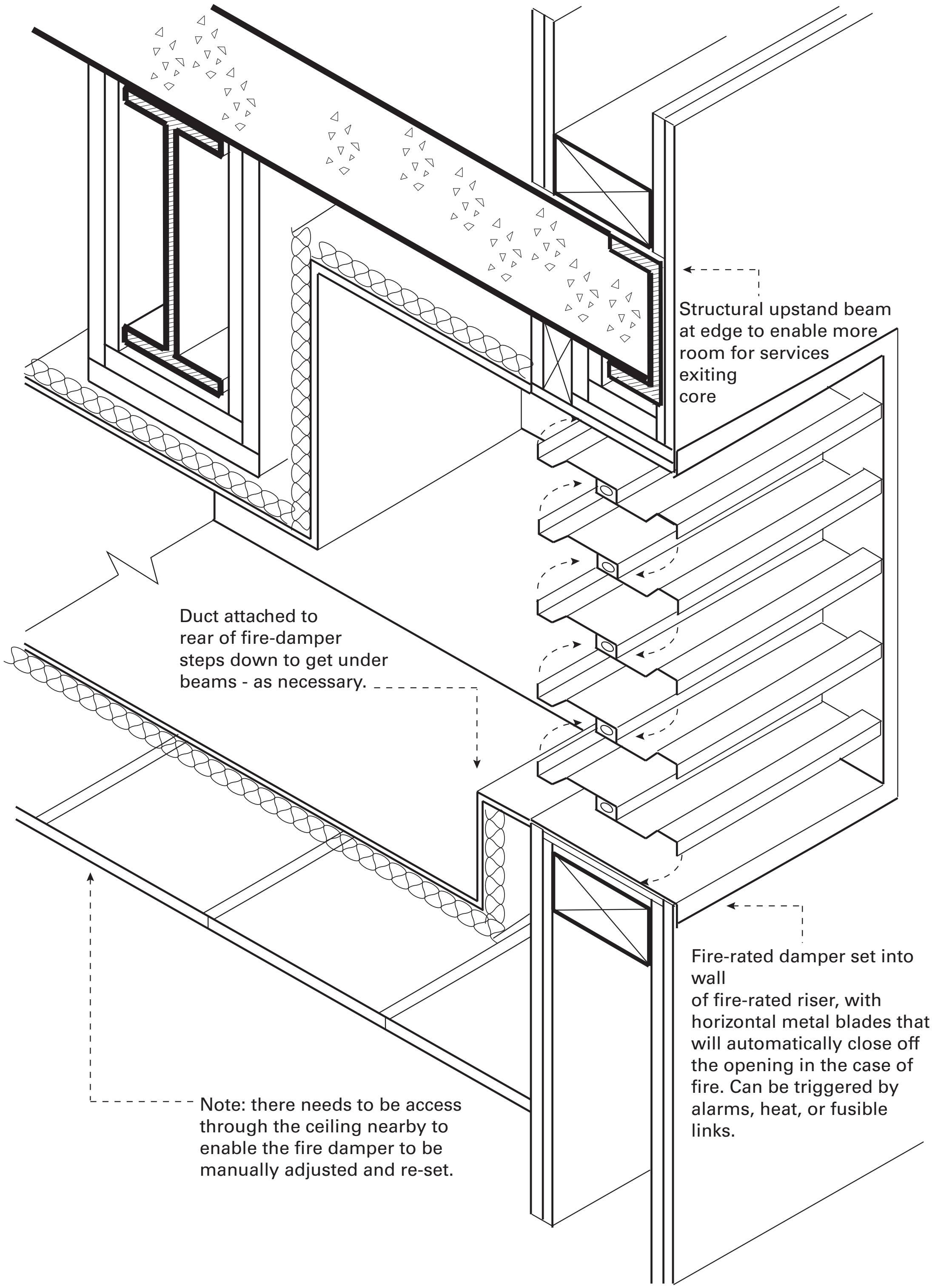

Figure 13.4 Fire damper in wall connected to duct

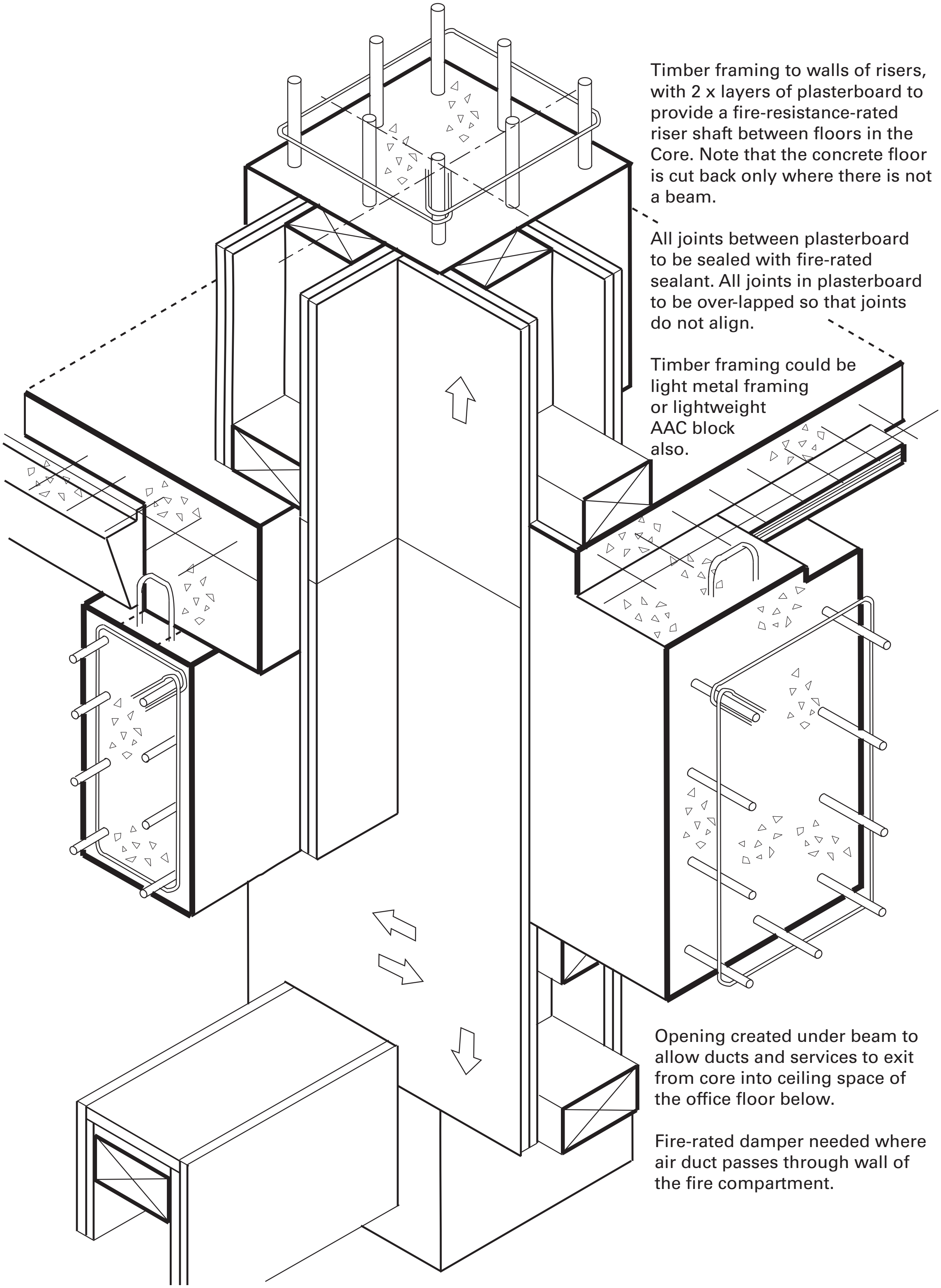

Figure 13.5 Junction at column with risers

13.7 Integrating openings and services

A fresh air duct discharging a large volume of air at each floor presents the designer with a difficult problem: where to bring the air up the building, and also how to take the air out horizontally onto each floor: normally at high level, just under the floor slab of the floor above.

There are a few different ways of resolving this problem. The best option, perhaps counter-intuitively, is to locate the duct vertically on the outside of the structural core, which then resolves the problem of having to penetrate the actual structural core wall itself. The ducts can then be hidden behind a non-structural wall.

Another way is to break the duct down into a couple of smaller ducts and take them out different places through the core wall. Another is to split the air intake and the air exhaust into two separate ducts but combine them within the same riser so that as one reduces in size, the other duct can increase in volume. There are many tricks which you will be able to work through with your services engineer on a real live project, but it is important to know that there are options available and to try some of these out on your building design. You may want to consult Baird (2001) for more ideas on integration of environmental control systems into your building.

The best single thing you can do is to create at least one area next to the HVAC riser that has the smallest possible beam to allow as large a duct as possible to exit the core. Avoid clashes between HVAC and beams – your services contractor will thank you.

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14

Chapter Fourteen

Ceilings

Ceilings

Guy Marriage

14.0 The suspended ceiling

Depending on who you talk to, the suspended ceiling is either deathly dull or the greatest thing since sliced bread. In a way, it looks quite similar to sliced bread: smooth, flat, white, and rather boring. Why is it there and what is it doing? Indeed, why should architects be concerned about what is going on in the ceiling, unseen? Is this something that architects even do – or is this just left to the ceiling and services contractors to install?

Architects undertake Reflected Ceiling Plan (RCP) drawings – usually one for each floor – where the lights, air grilles, ceiling tiles, sprinklers and other fittings, etc. are set out. It is vitally important for architects to be involved not just in the planning of the ceiling, but also of the services above the ceiling. Architects need to work from very early on with the services engineers to ensure a clear understanding of the services strategy. The various different ceiling contractors may have no particular interest in ensuring that everything lines up in neat straight lines on the completed ceiling, but you sure will! A badly coordinated ceiling indicates poor design and looks awful.

Modern office ceilings typically consist of a regular grid of ceiling tiles set into a regular grid of lightweight metal tracks, laid out at one consistent height above the floor. This array of tiles extends to the perimeter of the building on every side and is usually white to assist in maximising light levels. Most importantly, the ceiling creates a level surface plane in which to fix services and expose them to view or hide services that do not need to be seen.

Into this ceiling are set a regular array of light fittings, sprinkler heads, smoke detectors, speakers for any audio warning system and the air-conditioning grilles for both supply of fresh air supply and extract of stale air. All of these items need to finish as flush as possible with the underside of the ceiling, which is set at between 2.5m and 3.0m above the finished floor level (FFL): typically the finished ceiling level (FCL) for an office floor is set at around 2.7m (9’) above the FFL. All of the ceiling tiles, the lights and the air handling grilles must be capable of being easily moved for maximum flexibility to suit new office layouts.

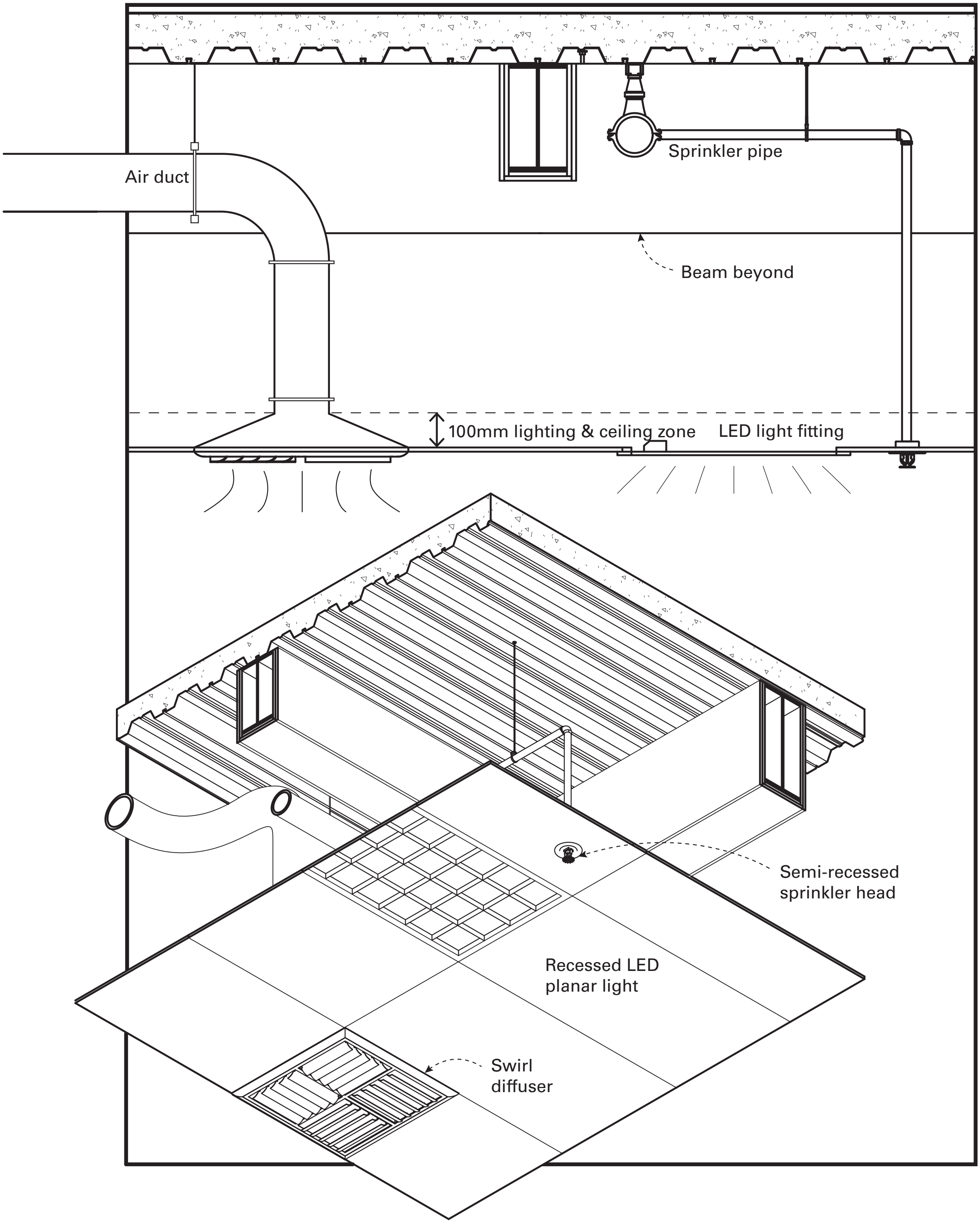


Figure 14.1 Ceiling zone and suspended ceiling tiles

14.1 The ceiling plenum

If an office space has a suspended ceiling, then the space above the ceiling is known as the ‘plenum’. The plenum has two chief functions. One is that it provides a cavity to draw in return air, while the other is that it provides a useful screen for a lot of ceiling-based services.

In terms of construction, the layout is theoretically simple. At the very top of the plenum is the underside of the floor slab above, with beams projecting down. Suspended just below the underside of the floor slab are the main sprinkler pipes. Galvanised steel pipe ‘droppers’ (with flexible hoses to accommodate seismic movement in earthquake-prone countries) will descend from the main sprinkler pipes down to the ceiling so that on completion all that can be seen below is the sprinkler head. Sprinkler heads can also be set flush, with a ‘pop-down’ sprinkler head (refer to Figure 12.3).

The lowest 100mm of the ceiling will contain the ceiling grid, ceiling tiles, lighting and fixing points for anything on the underside of the ceiling (refer to Figure 12.7).

Above that is the ‘free zone’ to enable services flexibility: primarily a zone for ducting, which needs to be coordinated with the structural beams that support the floor slab above. This includes HVAC, sprinkler droppers, fire proofing, cable trays and a whole lot of wiring. Understandably, space can get quite congested up there in the plenum, so it needs to be carefully planned (refer to Figure 14.1).

The task is to plan out potential routes for the largest services first, taking care to avoid clashes with the structural beams supporting the floor above. You really do need to know where every beam is, even quite early on in design to avoid ugly clashes later. On any ceiling plan that you work on, start by showing (in dashed lines) the width of the structural beams supporting the floor above, as these beams will have a major effect on the possible layout of services. This is where the true power of the BIM model comes in: to lay out structure and services virtually and avoid a physical clash between the two. It is a lot better and cheaper to resolve these potential clashes in pixels before they occur for real on site. Due to seismic requirements in NZ, every element in the plenum now needs to be separated by a minimum 50mm between two seismically restrained elements.

14.2 Ceiling grid

The ceiling grid is not a conceptual grid of lines, but an actual physical/structural thing. It consists of a two-way array of thin lightweight steel or aluminium profiles, suspended dead level or raked by wires and/or struts from the underside of the slab above. It will be installed later in the construction timeline, after the majority of the services have been installed in the ceiling. Lightweight grid is OK for non-seismic countries, but heavy-duty seismic grid is now required in seismic regions in NZ. While the ceiling grid is only 38mm high, the overall zone should be 100mm to allow for the insertion of ceiling tiles. So, if the underside of the ceiling is at 2.7m above the FFL, the effective top of the ceiling is at 2.8m above the FFL.

The grid itself is made up of main tees and cross tees. Main tees are the structural elements that are physically supported by the structure above, and they run the length of the space. They're generally about 1200 apart and are run perpendicular to the structure above in order for them to be suspended easily. Cross tees are then generally 1200 long and are clicked into pre-punched holes in the main tee to create a ladder-like formation. For a 600 × 600 tile configuration, secondary cross tees are then clicked into place to further split up the module. Unlike main tees, cross tees are not suspended by wires or steel struts from above.

Ceiling grids can be visually expressed, with a thin flat strip visible between every tile, or occasionally the grid is hidden with just the tile visible. The ceiling grid should coordinate with the planning grid, as all large areas of ceiling will need back bracing, particularly where partition walls will be needed. The bracing may take the form of two steel stud arms at 45 degree angles, fixed from the grid to the underside of the slab above, every 1m to 1.2m, and so, before you know it, your ceiling is going to be filled with a veritable minefield of bracing, particularly in seismic areas. The most important factor is that your ceiling grid works with your lighting layout so that lights are not positioned where a wall may be built in the future. It is useful, therefore, to have an idea where the possible internal office partitions may be going to happen in the future.

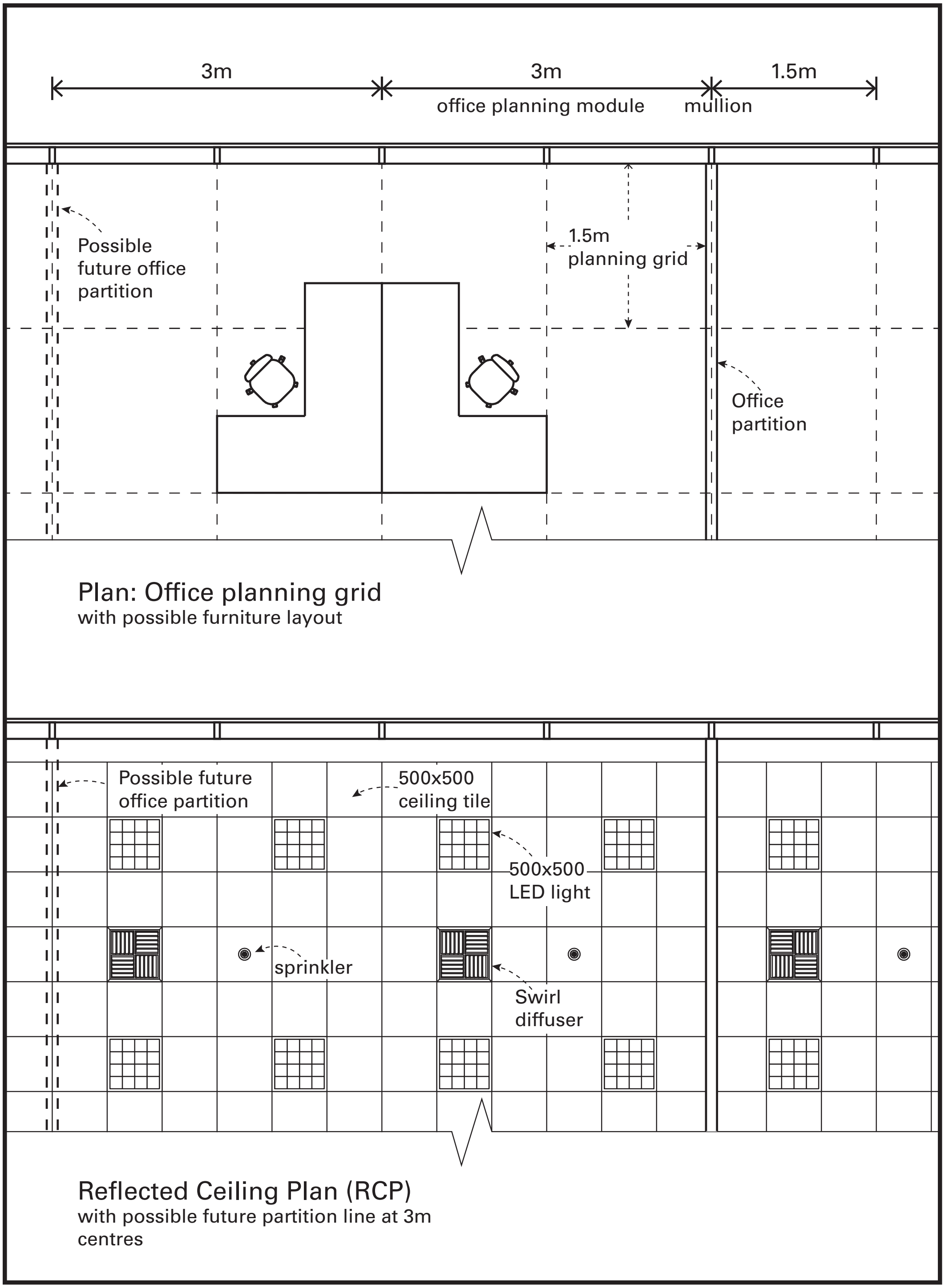


Figure 14.2 Reflected ceiling plan relationship to planning grid below

14.3 Ceiling tiles

A ceiling tile has a number of main functional purposes. One is to separate – visually and physically – the inhabitable space from the services needed. Second, it can be utilised very effectively as an absorptive acoustic surface. The selection of the ceiling tile can have a huge effect on the acoustic comfort and overall feeling within the space. Whether or not sound will travel (be amplified) and transfer into adjoining spaces is determined by the type of ceiling tile selection, related to the activities below. A bar, for instance, has very different acoustic needs to that of an open plan office. Acoustics are such an invisible variable and are only usually noticed when they don't work! Ceiling tiles also create an even surface for light and a level plane at which to end the height of office partitions.

Ceiling grids relate to the ceiling tile size, based around a strict module. Ceiling tiles are commonly rectangular at 1200 × 600 (4′ × 2′) or square at 600 × 600 (2′ x 2′). Less common are other sizes such as 1200 × 300 (4′ × 1′) or 1500 × 600 (5′ × 2′). Tiles normally have a laminated white tissue face to reflect a maximum amount of light, with acoustic properties to deaden the spread of sound and to ensure a good level of privacy between adjacent rooms. They may have extensive surface patterns or 3D textures to break down the sound and must be made of sturdy materials to support their own weight. Anything over 7.5kg needs to be tied back to the structure above, but if it is lightweight, it can be fixed to the ceiling grid. Tiles should be easily removable so that services can be accessed, serviced and changed. There are a wide range of ceiling tiles and the product range is closely fought over for market share on both cost and performance.

For many years, ceiling tiles have been heavy, with many made from solid gypsum plaster, complete with elaborate surface patterns cast into them for acoustic absorption and visual detail. The Canterbury, Seddon and Kaikoura quakes in New Zealand (2011, 2013 and 2016) proved that heavy tiles suspended in a lightweight ceiling grid are not a good idea in seismic areas: damage caused by collapsing ceilings was extensive and expensive. Non-structural building elements need to be restrained just as much as structural elements. Revised building codes will make it clear that in the future, ceiling grids will need to be stronger and better restrained against both movement and collapse, while ceiling tiles will need to be made lighter and cause less damage if they do fall. New Zealand has already taken this step. Other countries will surely follow.

The most common ceiling tiles available in New Zealand are made of glass-wool or mineral fibre. The real workhorse, everyday tiles are the mineral fibre tiles (also known as mineral wool), as they have a medium weight, have some absorption performance due to the engineered face and so are able to attenuate (stop) some sound from passing through. Due to its wide-ranging performance, it is often used as a base-building tile.

Glass-wool is a lightweight and very acoustically absorptive material, so tiles made from glass-wool are ideal in larger spaces such as open plan offices. Their weak point, however, is that they cannot be used by themselves if sound transmission between adjacent spaces will be an issue. One way to combat this is to put vertical barriers within the plenum or to use a tile with an attenuating backer. Other materials often used for ceiling tiles are polyester fibre (which may have flammability issues), plywood, aluminium and, more recently, some natural options such as sheep's wool and coconut fibre. These options can provide visual appeal but are not standard and may incur extra cost. Regardless of the material used, ceiling tiles still need to accommodate lights, sprinklers, ventilation grills, speakers, smoke alarms, exit signs and connections to wall partitions for offices.

Basic standards for ceiling tiles have either a square edge (SE) or a rebated edge (RE), which alludes to the way the tile sits in the grid. An SE tile sits with the tile face at the same FCL as the ceiling grid, while with a RE tile, the visible face is about 6mm (0.25") lower than the grid and creates a negative detail around the tile.

Custom-made sizes of ceiling tiles are not impossible but are more expensive. Custom-made materials for ceilings also vary: large flat sheets of plasterboard can be used, but their very permanence makes them difficult to locate services above, so they are not typically used in commercial office spaces except perhaps for high-quality prestige areas requiring less flexibility. Plywood veneered panels with acoustic cutouts are great for a different appearance and good sound control, but are heavier and more expensive, so perhaps are also best kept reserved just for prestige areas.

Battens and baffle ceilings (made from timber slats, aluminium sections, fabric-covered glass-wool or polyester) can also be useful to direct the eye but allow only limited access to services, and this will also mean the ceiling is no longer a separate sealed space. There is also the option of having no ceiling at all as in loft-style or studio spaces, where air volumes and an open understanding of the building are important and visible structure is desired. Highly flexible for services – but impossible to control the acoustics. And remember: if you want to have exposed services, they need to be impeccably designed and installed, as anything less than awesome will look like a dog's breakfast. . .

14.4 Lighting

Lighting in commercial office buildings is substantially different from lighting in small domestic spaces. In a house, light will often be from daylight, with small and thoughtfully placed windows allowing sunlight and daylight to stream into bedrooms and living rooms alike. Household inhabitants will be there both by day and by night, so a mixture of light sources is needed, i.e. both daylight and artificial (electric) light, accomplished by a mixture of pendant (hanging) ceiling lights, inset (recessed) ceiling lights and more personal task lights, such as table lamps. A house is poorly served if all it has is a single overhead light bulb in the centre of a room. Lighting in a house should be planned to create warm, comforting, special spaces, and the use of indirect lighting is common – with electric light sources bouncing light off a wall or a ceiling, as well as more direct lighting such as an angle-poise lamp for your drawing board or your laptop.

In a commercial office building, lighting is, sadly, often very different. Office spaces in the past tended to situate lighting exclusively overhead in a continuous array, shining a uniform amount of light down to every desk. This is what has been designed and incorporated into nearly every office building throughout the western world for the last several decades. A more inhospitable and inhumane lighting system is hard to imagine. Office lighting can be and should be better than that to make a more comfortable space for the occupants. Let’s try to change that! For a start, occupants will normally be there mainly during the day, so daylight is an important consideration, especially at the perimeter. Yet, for most deep-plan office buildings, daylight is not enough for people to do their desk-based work.

14.5 Lighting design

The initial lighting design for an office space must allow for a constant, equal glow of light down onto the common desk height of 750mm above floor level. This requires a set amount of light, normally a minimum of 320 lux at desk height, to be output from an array of lights set flush into the ceiling. Lighting manufacturers make their lights to seamlessly fit into the standard size ceiling grid tile modules. If you have a 600 × 600 (2′ × 2′) ceiling grid, you will be able to get a light fitting that will fit comfortably into that 600 × 600 module (refer to Figure 14.2). Similarly, if you wish to have a different ceiling tile size, perhaps 1200 × 300 (4′ × 1′), then there are lights for that module size as well. Older style light fittings often dictate the 1200 or 1500 ceiling modules.

For the last 50 years, the lamp in these light fittings has been almost exclusively the preserve of fluorescent batten lamps: long, thin tubes filled with gas that glows when an electric current is passed through it. Please note the spelling of the word: it is not a *flour* lamp (indicating something based on wheat?) but a *fluor*escent lamp, i.e. a lamp that fluoresces, or glows. Nearly all students spell this wrong – I will be so happy if I can stop even just that one spelling mistake! However, fluorescent lamps are disliked by many, as they can flicker, and in some people this causes irritation. Older style lamps did flicker often, while modern lamps with fresh new electronic ballasts are unlikely to cause issues like that, but regardless, few people really enjoy the effect of the fluorescent light itself. Often perceived as cold and harsh, sometimes with a slight greenish tinge, the lamps are cheap to buy and cheap to run, and when you have a thousand such lights in a building, cheap counts.

There is no doubt that we will see more and more ceiling lights based entirely on LED (light emitting diode) bulbs, which are more expensive to buy, but also very low energy consumption and so they are much cheaper to run. Fluorescent lamps are already being phased out in commercial buildings – new office buildings are now installing all LED lamps. The LED light fitting will also fit within the ceiling tile module and is thinner and flatter – so much so it is unbelievable. The direction of light output is important – fluorescent lamps tend to emit light generally everywhere, including down, up and sideways, so reflectors are incorporated behind the lamp to redirect light downwards. LED lamps can be far more directional and emit light powerfully downwards but often next to nothing out the side or upwards (which can be a bad thing – if there is no light out to the side, the white ceiling can look grey, dark and cavernous). The lighting designer's manual will show the 'metrics' or characteristics of how the light performs. Lights need to be positioned approximately every 2–3m (6′ – 9′) in each direction in order to get an even spread of light over the entire office floor (refer to Figure 14.2). Software can be used to perform an analysis of the space to see what lighting type will be suitable for the office floor.

Luckily for you and occupants of your future office space, attitudes are now changing. Systems such as Digitally Addressable Lighting Interface (DALI) will allow individual control of brightness of lights within the ceiling, in some cases even altering light levels direct from your iPhone. Skilled lighting designers will also look at ceilings more inventively, varying lighting levels around certain building uses – more informal pendant lamps for instance, hanging near the lunch area or reception desk perhaps, bouncing light upwards off the ceiling, as well as straight down. Don’t accept banal uniform lighting solutions as the only response.

14.6 Ceiling ventilation grilles

There are really only two different types of ceiling grilles: either for supplying air or for extracting air. The first blows and the second one sucks. Obviously, they need to be set apart from each other so that the air gets to mix and ventilate the office space in between. In some areas with bad smells, everything sucks.

Similar to the layout of lights, supply grilles need to integrate with the ceiling tile layout, and they need to be a regular array to ensure a continuous even flow of fresh air throughout the office floor. It is slightly different with the extract or 'return' air grilles – it is important also for the stale air to be extracted, but these can be arranged to encourage air movement across a space. Normally, all this will be done by the HVAC engineer, but again, your job is to make sure that a system can work and not cause conflict with other ceiling fixtures or future room layouts (refer to Figure 14.2).

The supply air grille is often a 'swirl' diffuser, i.e. a grille in which the air comes out in four different sideways directions and will encourage a gentle eddy of air across the room, rather than just one continuous blast of air downwards in one direction. The extract grille is simpler and just sucks air in. If there are opening windows in a building façade, then it is normal to have the extract grilles on the opposite side of the room from the opening windows so that the fresh air can flow across the room. In areas such as toilets and kitchenettes, it is common for there to be extract grilles but no supply air so that generally air will flow into those rooms but not flow out, thus keeping all odours trapped inside and expelled out the building. As tasty as your toasted cheese and tuna sandwich may be, others may not want to smell it!

14.7 Other elements in the ceiling

Apart from lights and ventilation diffusers, there are a few other services commonly found in commercial suspended ceilings. Sprinkler heads are the most difficult to design around, as their positioning is much harder to shift later on (as the sprinkler pipe network is full of water). Sprinklers are covered in more depth in Chapter 12. Speakers and fire sensors are also ceiling mounted, and again, need to be as discreet as possible. Sensors like smoke detectors and heat detectors are vital to the functioning of the office space, and these are hard-wired into the wiring system above the ceiling. Lastly, the design of the ceiling is intimately joined to the design of the services running above the ceiling and all the seismic bracing and clearance that is required within the ceiling void.

15

Chapter Fifteen

Residential

Residential

Guy Marriage

15.0 Living

Buildings for high-rise residential are very different from high-rise offices and really deserve a book entirely to themselves – a good reference guide is Heckmann and Schneider's *Floor Plan Manual Housing* (2011). The purpose, planning, form and function are all completely different from that of commercial buildings and often the construction is too. There are, of course, similarities as well, as the building is doing essentially the same thing – reaching up to the sky – via a mix of floor plates and supporting structure. There will be a core, but the scope of the core will be substantially different: there are far less services for a start. The structural grid will likely be different, not trying to maximise the spans for open-plan office space, but instead trying to integrate with layouts of apartment floor plans. Structural column centres can be closer together as well. There will also be a much greater desire to connect with the outdoor environment via balconies and windows needed to almost every room, so the façade articulation will be different as well. Figure 15.1 sets out the key differences between the various types of apartment circulation systems.

Since the year 2000, there has been a worldwide boom in urbanisation and an ensuing huge number of new apartment buildings – many of them badly built and badly designed. In New York, there is currently a very curious boom in super-tall, super-skinny, super-expensive apartment buildings that appear most reminiscent of the Italian hill town of San Gimignano. The most recent super-skinny tower is 111 West 57th St (refer to Figure 15.5), being completed in 2019 (architects: SHoP). While occupant loads are far lower in residential towers than in a commercial tower, privacy is of paramount importance in apartment design both visually and acoustically, so super-skinny buildings permit one apartment per floor. Fire separation is also approached differently, with many separate tenancies in the same building and even on the same floors, all filled with sleeping people. Let's examine these issues individually.

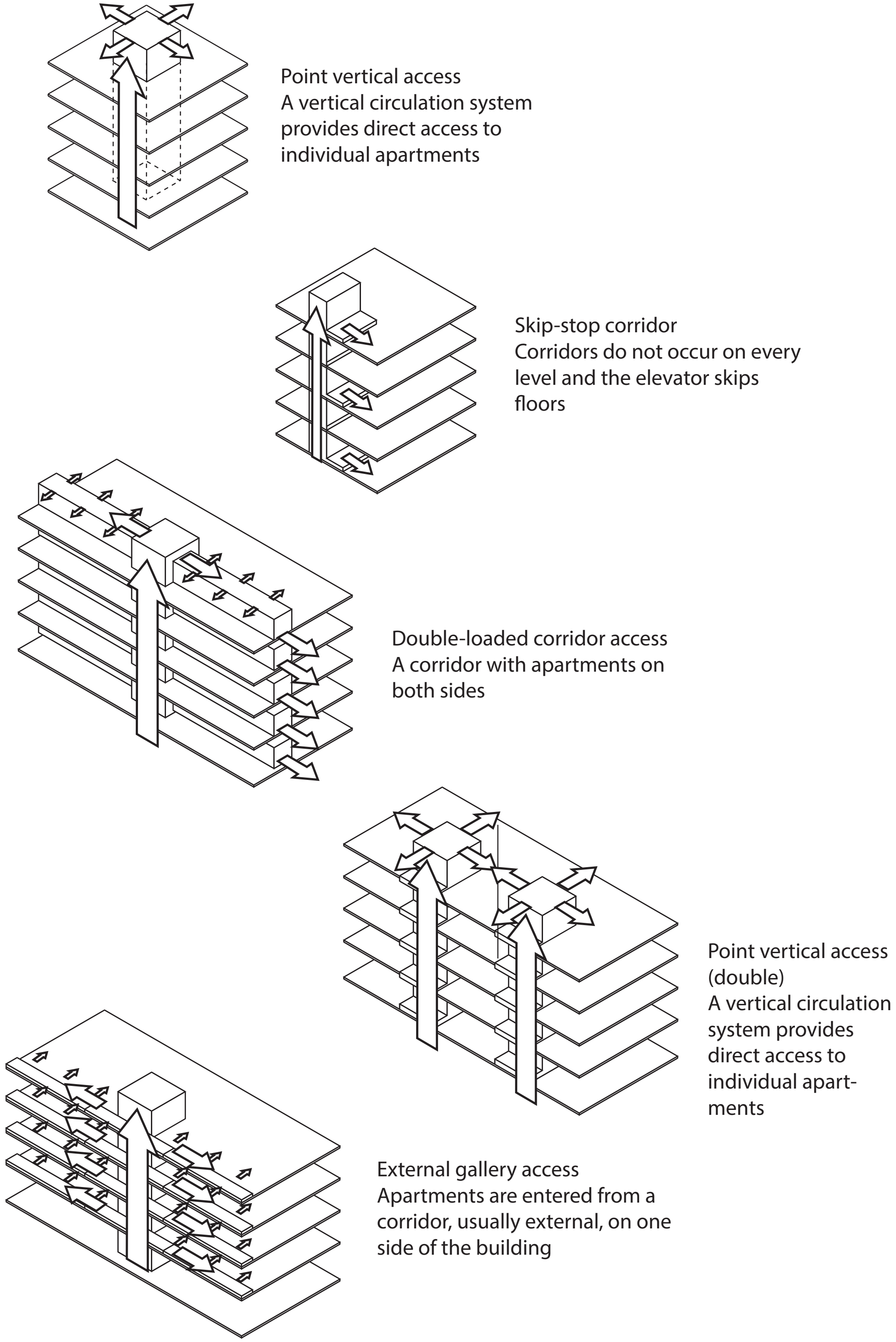


Figure 15.1 Apartment planning – basic circulation schemes

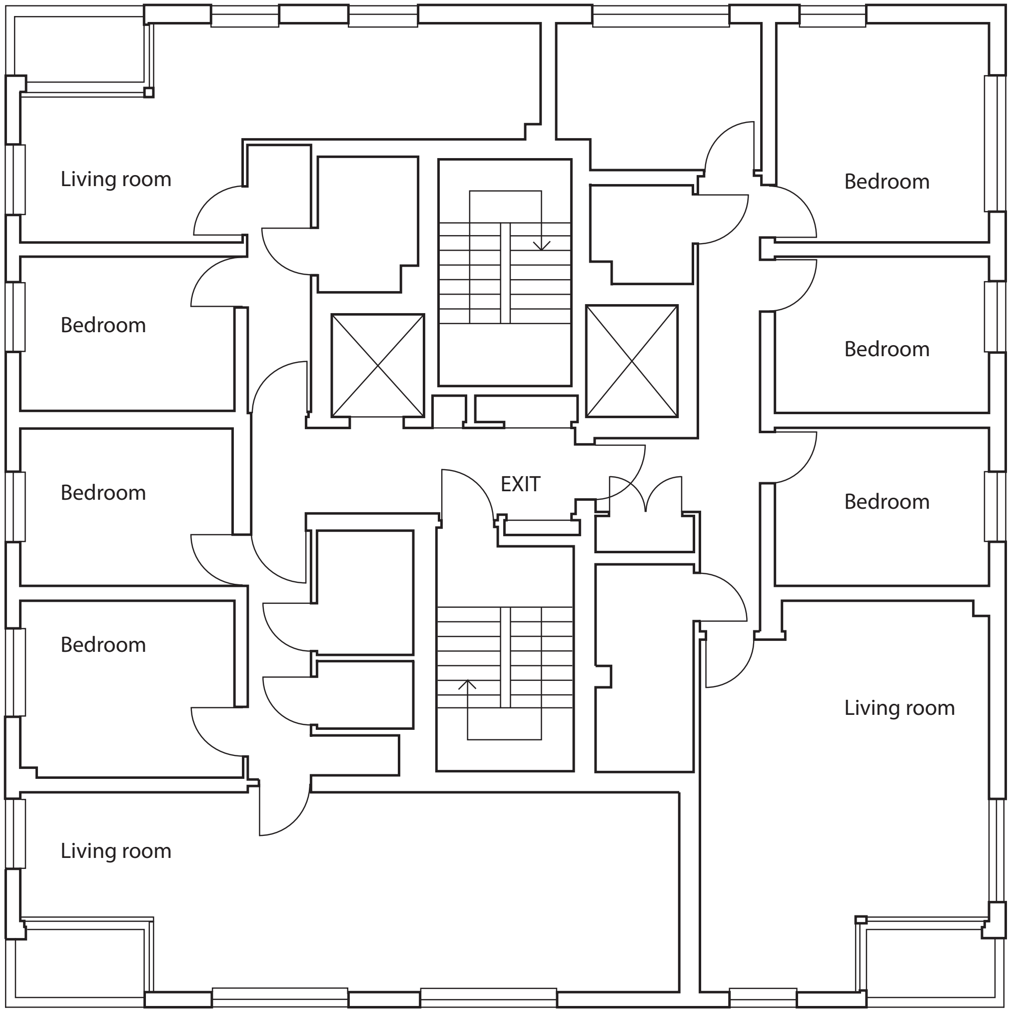
15.1 Structural frame

All of the issues that occur with the structural framework of an office building are present in an apartment building also. The structural frame may again be a concrete frame, steel frame or massive timber construction, but the wonderful advantages of a steel frame in an office building – flexibility and large spans – are not so appreciated in a residential building. Different factors rule the design decision process. Apartment inter-tenancy walls must be strictly fire-proof and sound-proof, generally remaining in place for the life of the building.

In some developments, the use of precast concrete wall panels has been a major step forward, permitting apartments to have a single dividing precast concrete wall between tenancies. Solid concrete mass has both thermal and acoustic advantages, so it is great at impeding sound waves and is highly desirable in high-rise apartment developments. The building structure may then be designed as a series of flat plates making up cells in a box-like structure for stability and ease of assembly. This places considerable onus on the designers to get the joints between panels right, as the ghosts of Ronan Point still haunt those that get it wrong (Ronan Point was a disaster in British post-war housing: a lesson in how not to construct precast concrete buildings).

The biggest and most exciting changes to the way that we design and build apartments are only just taking place now. The invention of CLT along with the ability to model it accurately in CAD and machine it via CNC technology has unleashed possibilities of prefabricated multi-storey apartment construction that can be erected quickly, in a material that many people appreciate for its warmth and natural feel. The smaller spans of the residential apartment are perfectly suited for using CLT to construct the structural box, and the CLT has a reasonable acoustic rating. CLT apartment buildings are often associated with concrete topping slabs for density and the use of plasterboard linings to walls and ceilings to lessen possible fire spread and acoustics. Figures 15.2, 15.3 and 15.4 all refer to the example of CLT construction in London at Murray Grove in Hackney, designed by Waugh Thistleton Architects and constructed in 2009.

Steel-framed structures can function well as apartment buildings too, but the deciding factors for success will be on what the inter-tenancy walls are made of and how they are detailed. Inserting concrete tilt-slab walls or CLT walls is not feasible in a steel structure, so walls are more likely to be twin walls of light steel frame or light timber frame, all clad with multiple layers of plasterboard (drywall). Steel construction is not the first choice for apartment towers when built from new. This is perhaps demonstrated best in Agrawal's book *Built* (2018), where she notes that in the Shard tower in London, the structural system starts off in steel for the commercial floors, is changed to concrete for the residential floors above, and then reverts back to steel for the final pointed tower.



Small central core, no wasted space with corridors.
Three apartments on this floor:
One 3-bed apartment,
One 2-bed apartment,
One 1-bed apartment.
Small external balcony to each apartment.
Single stair and single lift to this floor (low-rise).
Upper floors have two stairs and express lift.

Murray Grove apartments, Hackney, London

Core: very small amount of space for services Risers - just Electrical Cbd and small Data Riser, no HVAC riser.

Structure all CLT slabs and CLT wall panels Externally clad to protect timber from exposure to weather conditions.

9 floors residential accomodation.

Architects: Waugh Thistleton Architects

Figure 15.2 Residential building with CLT walls

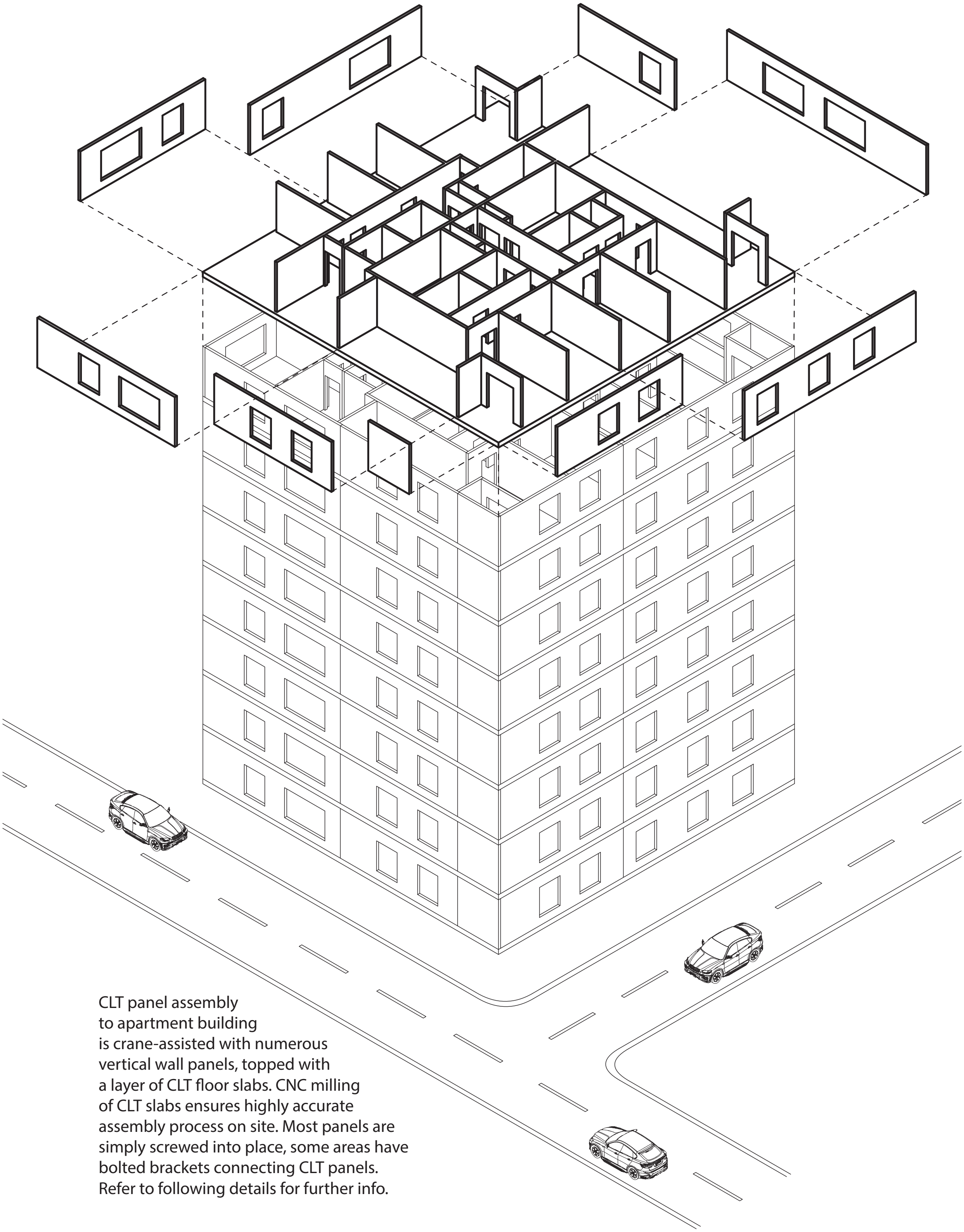


Figure 15.3 Assembly of CLT panels

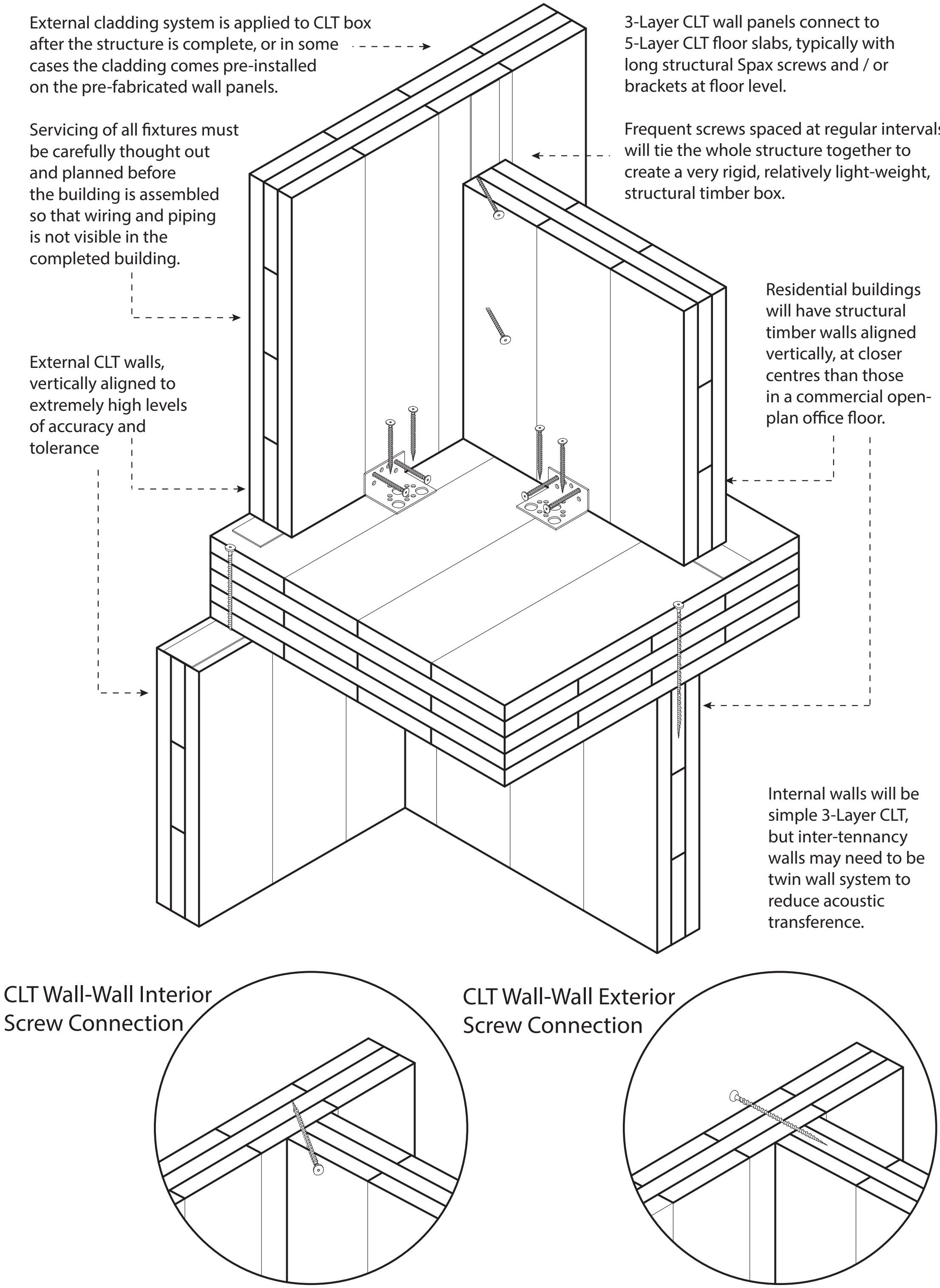


Figure 15.4 CLT wall to floor connection details

15.2 Planning grid

What drives the planning of an apartment building? Although prices and construction methods may vary hugely, one thing stays the same: the size of people. Apartment buildings, above all, are based on room sizes, and one of the crucial coordinating dimensions is the size of a bedroom. Architects all over the world aim for a main bedroom size of around 3m (9′ 11″) wide – a little smaller for lower-cost apartments, slightly larger for higher-cost apartments, as generally, housing costs relate to floor area (Marriage, 2003; Marriage 2010). The need for bathrooms, corridors and other circulation mean that a 4m spacing is a bare minimum between centres of party walls, while 4.2m or 4.8m is a much more comfortable dimension. If you are designing apartment buildings, refer to Auckland City's *Good Design Manual (n.d.), the London Housing Design Guide* (2009) and Heckmann and Schneider's *Floor Plan Manual Housing* (2011).

15.3 Core

Vertical circulation of the occupants of the apartment building is a key feature of a core in apartment buildings, so lifts (elevators) and emergency exit stairs (at least one, preferably two) are always needed. Other services are needed in vastly smaller quantities. Electrical and data risers are required, but the electrical load of apartments is far less than that of commercial offices, so distribution boards on each floor will be smaller and easier to manage. Piping for sprinklers and fresh and foul water is also required, but the large requirement for central provision of HVAC in an office tower is just simply not needed in an apartment building. Neither are features like communal toilet facilities, communications room, kitchenette or other features often found in a commercial building core.

Generally speaking, each apartment is responsible for its own fresh air and air conditioning, with only toilet vent pipes likely to be linked upwards through risers. Features such as common access rubbish chutes are no longer routinely installed in high-rises, due to the mess that results from lack of maintenance. Air intake and exhaust is likely to be taken care of on an apartment-by-apartment basis, without a common air supply. In Europe, it is very common for apartment buildings to have a common heating solution, with a basement boiler circulating hot water round all the apartments, whereas in places like New Zealand it is unheard of.

While cores are likely to be considerably smaller, there may be more of them. The days of building massive apartment buildings with only one central core and long inter-connecting walkways to the apartments are hopefully gone for good. Numerous studies of public housing projects in the United States and United Kingdom have shown that having public space with little public oversight leads to severe crime outputs, so extensive external walkways are no longer recommended for designs. Apartment designs are now frequently aimed at the upper end of the market rather than just publicly funded social housing, as was the case in the 1960s. Smaller, more frequent cores are preferred for up-market apartment buildings, with short internal corridors leading to only a select few apartments per floor. Less communal space has the added effect of permitting more external windows per apartment, and hence more privacy for occupants (Figure 15.1).

There may also be a requirement for several small services risers, often combined between just two or three apartments per floor, for handling waste water – both from toilets in apartments but also as a route for storm-water downpipes. These mini risers may only be 300–600 (1′ to 2′) wide and are often hidden unobtrusively in the boundary walls between units, but they are vital to avoid long pipe runs across ceilings of apartment units. They need to be planned to be able to descend vertically straight down the building and into a common collector pipe system at ground or basement level, but also to have accessible service panels on each floor in case of blockage or maintenance.

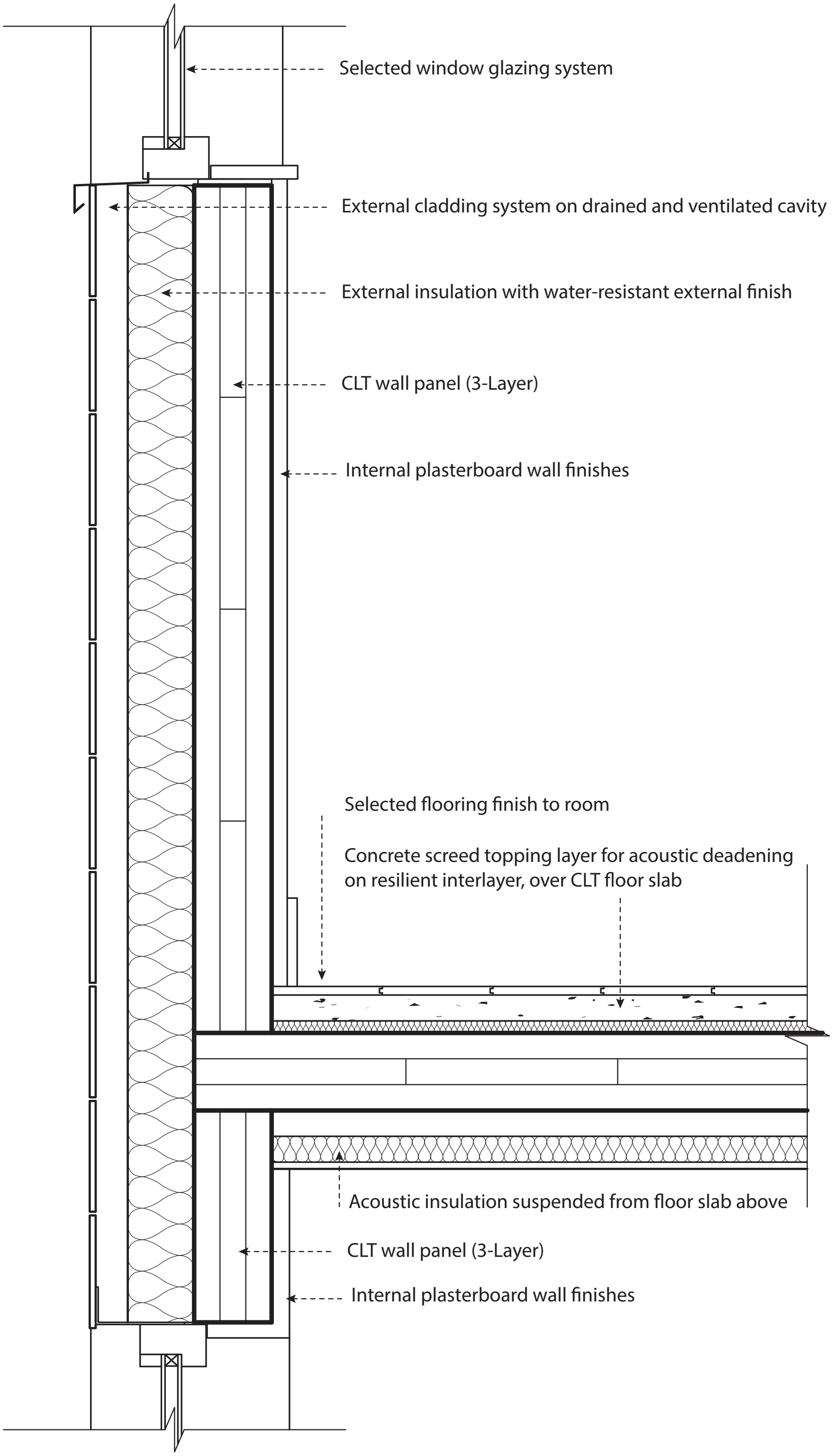


Figure 15.5 Section: CLT wall to floor junction

15.4 Acoustic issues

One of the best things about living in an apartment building is that you can live in the heart of the city – as I do – but one of the worst parts is the noise. A city never sleeps. Rubbish trucks at 3 a.m., road sweepers at 5 a.m. and drunken revellers at any time after midnight mean that external noise is a frequent visitor. But the worst type of noise of all is internal noises, such as a mysterious tapping sound from somewhere unexplained, somewhere in the building. Is my neighbour really dropping knives and forks on a tiled floor in the middle of the night? How can a ballerina who looks so small and dainty make all that noise as if she is wearing boots? Who is drilling holes in the wall at 2 a.m. and on which floor and why won't they stop?! And woe beside anyone who lives in a building with uninsulated plumbing risers – flushing toilets late at night is no joke at all. Luckily, I live in an apartment building I designed myself, so I don't suffer from that particular problem! Some people living in old converted warehouses with cast-iron columns and beams, channelling that 'New York loft-style' look, have found that the metal structure is excellent at conducting sound from one floor to the next – or on occasions hearing music from the ground floor right up on the top floor. Not at all what you want in a residential building where acoustic privacy is paramount.

The issues arise because there are two main ways that sound waves can travel from the source to our ears: either through the air (airborne sound) or through direct transmission with another material first (impact sound). An example of the first is when someone speaks to us in the same room or plays their stereo loud in a neighbouring room, while an example of the second is when someone is walking in stiletto-heeled shoes on a bare concrete floor above you (like my neighbour does), late at night. It is as irritating as hell.

15.5 Acoustic solutions

Airborne sound is fairly easily treated if you do not want to hear the sound: build a solid wall between you and the source. The more dense and massive the wall, the more sound it will cut out, so apartment walls made of solid concrete are an excellent solution. Mass and density stops the transmission of many airborne frequencies, so this is a key reason why we are seeing more apartment buildings made from concrete: it is the most solid, dense material we can use. It is brilliant at acoustic deadening, but is also the heaviest solution, so experiments continue with other material solutions and detailing at junctions to try and control noise, while still retaining seismic integrity. Extra layers of plasterboard, fixed with the joints staggered between layers, are also useful solutions, as are plasterboard layers fixed on 'resilient' (i.e. slightly bouncy) framing.

Impact sound is far harder to control. The easiest way is to control at source – if the neighbour wore socks or rubber-soled shoes inside their apartment instead of stilettoes, the actual impact noise would be instantly lessened. The sound would also be less if there was a good thick carpet on a thick rubber underlay instead of trendy, bare concrete 'industrial' flooring. But if you can't control it at source, then the only option is to control it after that. Insulation between floor and ceiling, and suspended ceilings hung off resilient channels all help reduce the effect of impact sounds from one floor down to another. Impact sounds travelling through walls are less common – neighbours do not usually tend to physically tap on the wall – but it is amazing how audible the click of a light switch or the slamming of a door can be late at night when nothing else is stirring.

The answer to all these issues is isolation: twin walls, with a fluffy insulating batt in between to soak up the acoustic vibrations. Twin horizontal layers too: a thick insulating ceiling suspended below a solid floor, with any path for direct transmission of noises to be designed out at source. Compulsory carpet and underlay in all rooms except kitchen and bathroom will help hugely, with additional acoustic deadening layers installed under any tiles or linoleum in the kitchen and bathroom. This could take the form of a layer of cork or other rubbery material to deaden the sound before it gets firmly transmitted into the concrete floor. At all times, think of ways to break up the direct transmission path of sound waves.

CLT has some inherent mass as a material but being a resonant substance, it can also pass on certain frequencies quite well, i.e. it can resonate like a drum. Many CLT residential buildings are therefore composed of twin CLT walls between apartments, which has a great deadening effect on acoustics. In direct transmission acoustic tests on floors, however, CLT requires a concrete topping to help deaden the sound, or a ceiling lining to the underside that can assist in stopping

the acoustic transmission or a double layer with rubber mountings between to reduce the acoustic transmissions.

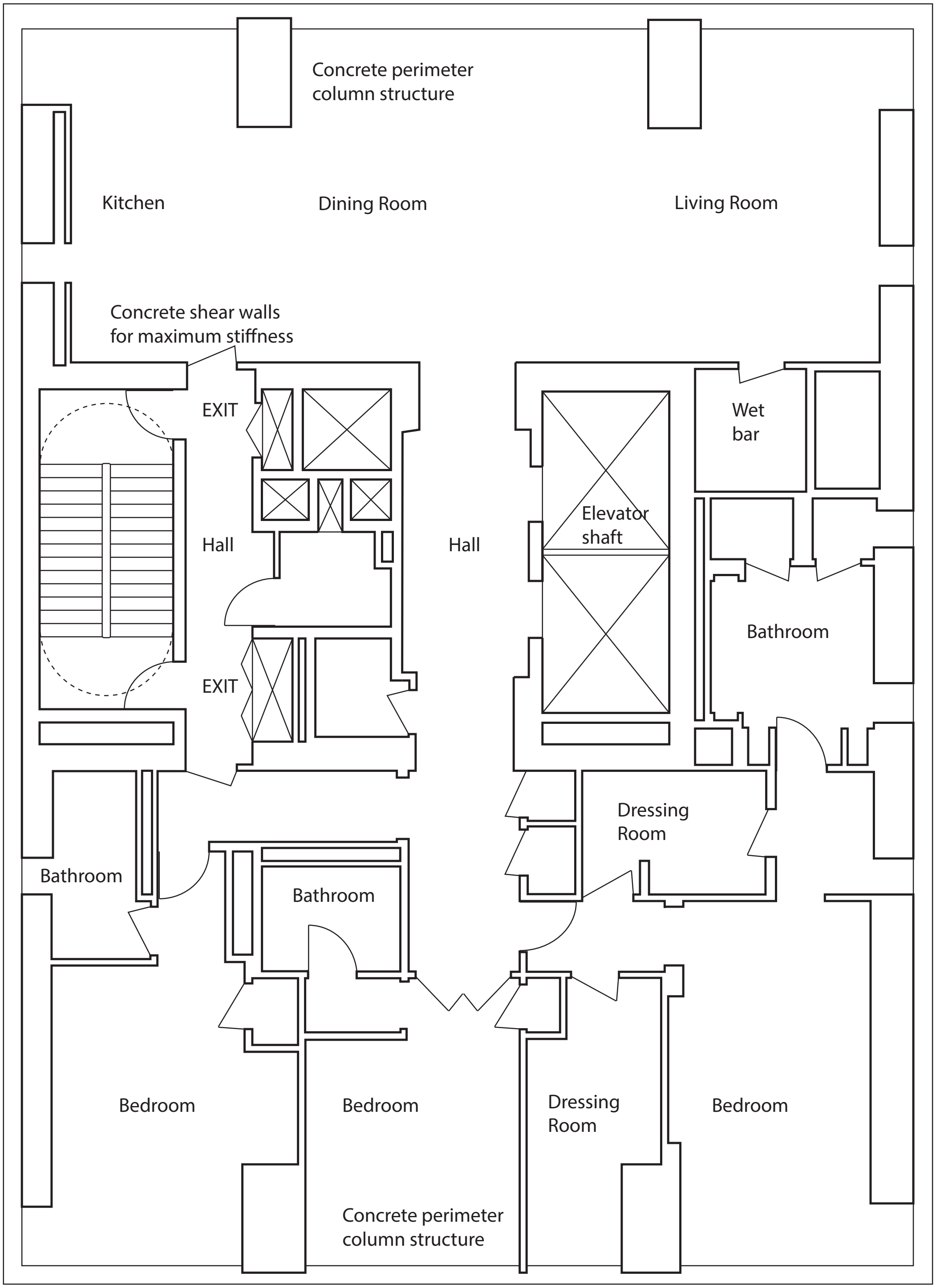
Noise transmission can also happen when steel columns and beams are bolted together, as the New York loft-style dwellers will have found out, but this can be mostly overcome by isolating steel structures within apartment walls. Of course, there is another reason for isolating steel structures within apartment walls: fire.

15.6 Fire separation

Spread of flames and smoke is one of the biggest issues with an apartment building, and it is your duty to design this out at the source. Every apartment building must have clear and unimpeded access to the emergency exit staircase via a short safe and non-flammable corridor. As with any multi-storey building, there should be two means of escape, unless the Fire Code in your region permits otherwise. The enclosure of the apartment means that this is a separate fire compartment from neighbouring units adjoining on the same floor, as well as above and below. Not only does no one else want to smell the neighbour's cooking, no one wants to have a small fire in the neighbouring apartment spread any further either.

Probably the biggest shake-up in recent times has been the case of the fire in Grenfell Tower in London, with 79 people killed by smoke and flames in a Council-owned social housing tower block – all totally unnecessary and all totally preventable deaths, if the correct design and construction decisions had been made, correct building procedures followed, and a sensible evacuation procedure had been in place. A small fire broke out in one apartment on one lower floor and the story should have ended there. Instead, the flames spread externally up the building, as well as sideways behind the newly installed cladding, and then the cladding itself caught fire, leaping floor after floor, up the building and breaking in through windows as it rose. Tenants were told to stay put, instead of being ordered to evacuate. There was only one means of escape – a single staircase with no pressurisation against smoke – and there were no sprinklers installed in the entire building. The building was engulfed by flame and burned like a torch.

The demise of Grenfell Tower and the subsequent public enquiry will have an ongoing effect on tall apartment buildings all around the world (Grenfell Tower Inquiry, n.d.). Flammable composite aluminium cladding panels are being banned and removed worldwide after the belated realisation by some that the plastic core between the thin aluminium outer shells is, in effect, akin to a solid form of petroleum. Firestop material between floors will be far more highly inspected in the future to ensure it is correctly installed. Sprinklers will, hopefully, be made mandatory for all high-rise apartments, both for new builds and retrofit to existing buildings. Secondary means of escape should be mandated for all apartment buildings. Staircase pressurisation should be absolutely mandatory, especially if a building has only one staircase. And lastly, dividing walls and floors between tenancies must be constructed carefully and competently to ensure they not only achieve the fire-rated-resistance for the desired time, but must also be smoke-proof as well.



Note: just one apartment per floor

Based on Apartment building at 111 West 57th St, New York (completion 2019).

Figure 15.6 Residential tower building

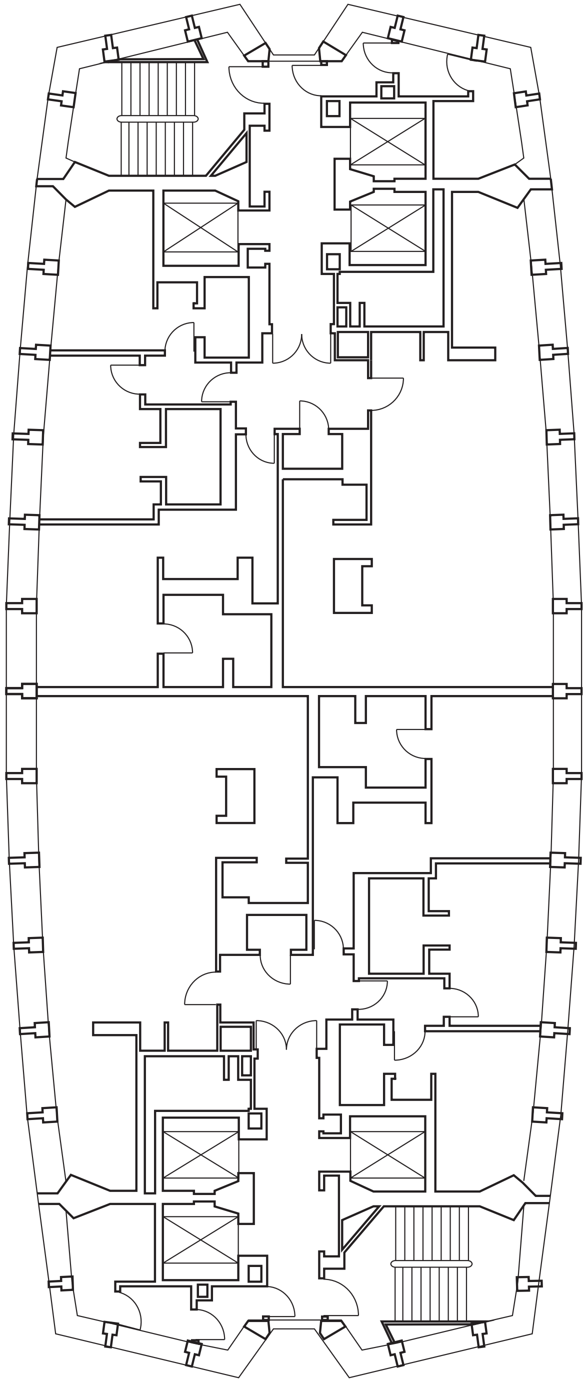
15.7 Façades

All of the issues that are presented in the chapters on façades are present here for residential buildings as well, with the added complication of numerous opening panels on the outside for fresh air. Generally, people living in apartments want access to the outside environment and so having opening windows and usable balconies are a design necessity. Balconies can be designed to clip on to the external face of the building but will then be beset by wind, and the connection details are difficult. Balconies may also be inset into the building to preserve the lines of the architecture and lessen the effect of wind, but this then has ongoing effects on waterproofing and insulation to floors above and below. There is no simple, easy answer except for careful detailing, flashings and layers of waterproofing.

Materials of the external skin of apartment buildings may also tend to be more solid than those of commercial offices. Much as the view out from tall buildings may encourage you to design all glass façades on an office building, with a residential tower the need for visual and acoustic privacy means that solid wall panels may well be more appropriate. External wall cladding with materials such as precast concrete and (in some countries) brick may be far more appropriate than unitised glass and aluminium façades. The detailing of junctions between external and internal walls needs to be carefully thought through to ensure that seismic events do not have a detrimental effect on building movement tolerances, and all openings must be detailed and inspected for fire-stopping wraps and collars around all services penetrations.

There is also a worldwide trend underway for the conversion of older, out-of-date office buildings into developments full of residential living opportunities: some better than others. The Centre Point Tower in London is a prime example: one of the UK's most notoriously famous office buildings of the 1960s. The office floors (refer to Figure 8.5) were converted into apartments in 2015, increasing in size and levels of luxury, the further up the building you climb. It was always an exciting looking building but was perhaps rather poorly suited to offices, although it yet remains to be seen how well it adapts to residential (refer to Figure 15.6).

Materials like brick and concrete block are alright for small-scale developments but simply are not suitable for multi-storey housing towers in new buildings today. Concrete block is far too brittle to be used in any seismic zone, although precast concrete panels should be able to be used at will. While vast urban estates in Europe and North America have been built from brick in the past (refer to Figure 18.7), the continued need for brick walls to be carefully tied back to the structure means that future maintenance issues are too high. It is far more likely that small, thin brick 'slips' are used, incorporated onto the face of the precast concrete



Split Core residential tower

Escape stair and 3 lifts
at each end of tower

Drawing based on plan of Centre Point Tower, London.

Architect: Seifert and Partners, 1966.

Converted to Residential
(4 apartments per floor to lower floors,
3 apartments per floor to middle floors,
2 luxury apartments per floor at top.

Architect: Conran and Partners, 2015.

Figure 15.7 Plan: Centre Point apartments

panels (refer to Figure 18.5). These issues, and more, are discussed in the final chapters, on façades.

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16

Chapter Sixteen

Façade principles

Façade principles

John Sutherland

16.0 The narrative

A façade is generally the first thing one sees when looking at a building. Exploration of the façade continues as one moves around it. The façades of a building may not all be the same. Or should not be the same!

Façades are usually either 'heavy' – as they were in times past – or 'light' – as they are more and more today and have been ever since at least the early days of the Bauhaus. The development of elevators and steel structures allowed buildings to become taller, so building solid structures at height became both uneconomic and structurally limiting. But even 'light' is relative, as lightweight façades can be anything from panels of thin dimension stone (heavy-ish) to very thin aluminium (very light) through faience and terracotta to multi-pane glass of substantial weight and thickness all in metal, more often than not aluminium, frames supported and cantilevered off floor edges on brackets.

Façades have come tumbling down from time to time, usually when attacked by seismic activity: both 'heavy' façades as in San Francisco (USA) in 1906, or Napier (NZ) in 1931 and Christchurch (NZ) eighty years later, being largely unreinforced stone or brick. Poorly designed 'lightweight' façades have suffered, caused by the same, but more recent, earthquakes in Wellington and Christchurch. Heavy façades are seldom built these days, although the porcelain tiles glued and the polished dimensioned stone pinned onto precast concrete panels, as used on the Majestic Centre in Wellington (architects: Manning Mitchell – refer to Figure 16.1) might rate as heavy – more about both later. Some of the heaviest façade panels these days are precast concrete, some of which include insulation in a sandwich.

Façades are very often known as 'building enclosures', which is fair enough and implies there is an enclosing function going on. Enclosing what? Generally, interior space of many and various kinds. For the purpose of this text, we will take it as everything outward beyond the line of the structure. Buildings must have one kind of structure or another to hold themselves up. Other chapters of this book describe these. Structures are usually framed objects formed from concrete in any of its many forms or mild steel or, increasingly now, laminated timber in panel or structural section forms. These objects are roofs, columns, beams, shear walls, bracing and monolithic slabs. Together these elements form a chosen structural system which transmits an aggregated series of well understood loads to foundation systems and then into the ground and down to bedrock or something like it by a variety of types recommended by the geotechnical engineer in conjunction with the project structural engineer. These loads are basically dead loads (weights, the mass of the materials themselves working as gravity loads), but on the way down they will have to contend with, collect and transform eccentric loads, with their own wind and seismic actions which create movements which must be considered and allowed for in the façade design.

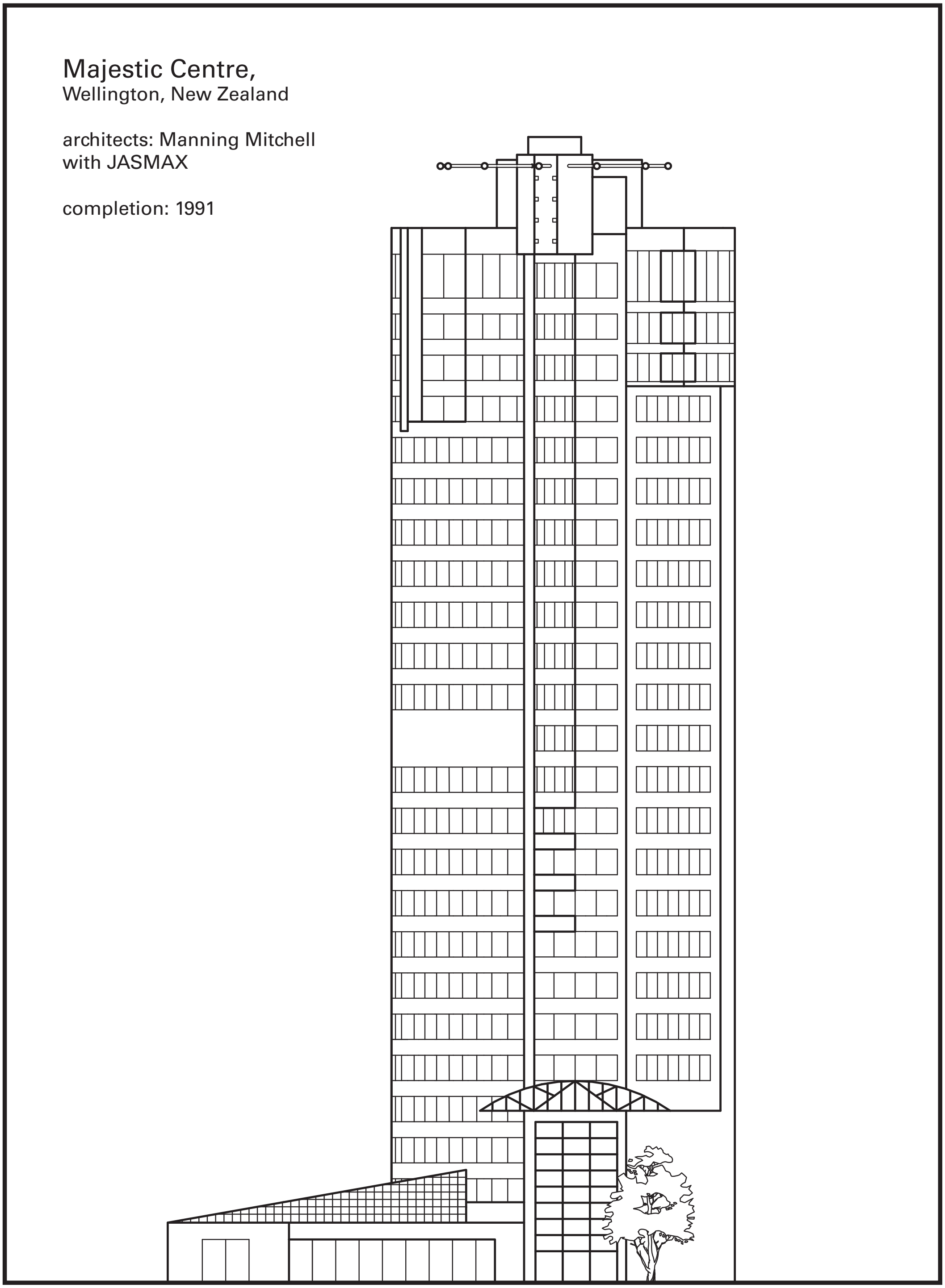

Figure 16.1 Majestic Centre

And then the structure has to cope with forces which act on it created by the building enclosure itself – The Façade. All movements, however eccentric above ground, are generated by building form: for example, the GLA 'Egg' designed by Foster & Partners and Arup in London with its outrageous (refer to Figure 16.2) overbalancing form – the gravity loads must be calculated to arrive vertically onto its foundations, no matter how idiosyncratic the steel structure and cladding might be.

All in all, façades are complex beasts.

Thomas Hertzog et al. (2017) talk about a building being a 'large technical object' and its façade being a 'structural sub-system' of that, a system which requires consideration of and solutions to bioclimatic factors involving high-level performance design criteria for functional/technical/aesthetic matters. In the late 1960s, American architects and engineers were trying to work out how to go really high without framed structures and arrived at combined structural/enclosure façade systems sometimes in tube forms, sometimes rectangular, as were the Twin Towers of New York, which had a tube-in-tube system (refer to Chapter 6) with large trusses that supported the floor's steel/concrete construction from the façade back to the building's core. Fly a fuel-laden modern aircraft into it and as we now know, catastrophic implosion and tragic collapse. While the combination façade/structure was designed to cope with an airplane crash, the designer's worst-case scenario was for a low-on-fuel Boeing 707, not the events of September 2001.

But this chapter is not aiming just at buildings that high, although some of the same height, for example Petronas Towers in Kuala Lumpur, have been basically framed structures hung about with stainless steel.

The common phrase 'It's all just a façade', when used for/against a person, implies that the person is often not quite what they would appear to be on the outside. So it is with buildings: the façade sometimes disguising or not representing at all what goes on beneath the skin. This has become a characteristic of much contemporary architectural design, as computer design facilitates the modelling and creation of unusual shapes and forms which architects then need others to add both flesh and bones. Enter the façade consultant – but this book is meant to reduce some of this need.

The structure is likely to be the skeleton on which a façade is hung, placed within or is directly supportive of. The skeleton can be behind, in plane with or external to the façade. External structure generally limits itself to diagonal bracing external to the façade face, which creates problems for that face related to breaking through and making weather-tight the façade to find the primary structure behind. There are many examples of this. A very complete exoskeletal façade (structure and services) is Piano and Rogers' Centre Pompidou (1977) in Paris, although this is a horizontal building (refer to 16.3). Rogers' (on his own this time) Lloyds Bank (1986), a tall building in London's financial centre, has a similarly complex exoskeleton (refer to 16.4), as does Foster and Partners HSBC (1986) in Hong Kong (refer to Figure 16.5) and the same firm's diagrid façade for the Gherkin (2003) in London.

City Hall,
Greater London Authority,
London

architects: Foster and Partners

engineers: ARUP

completed: 2002

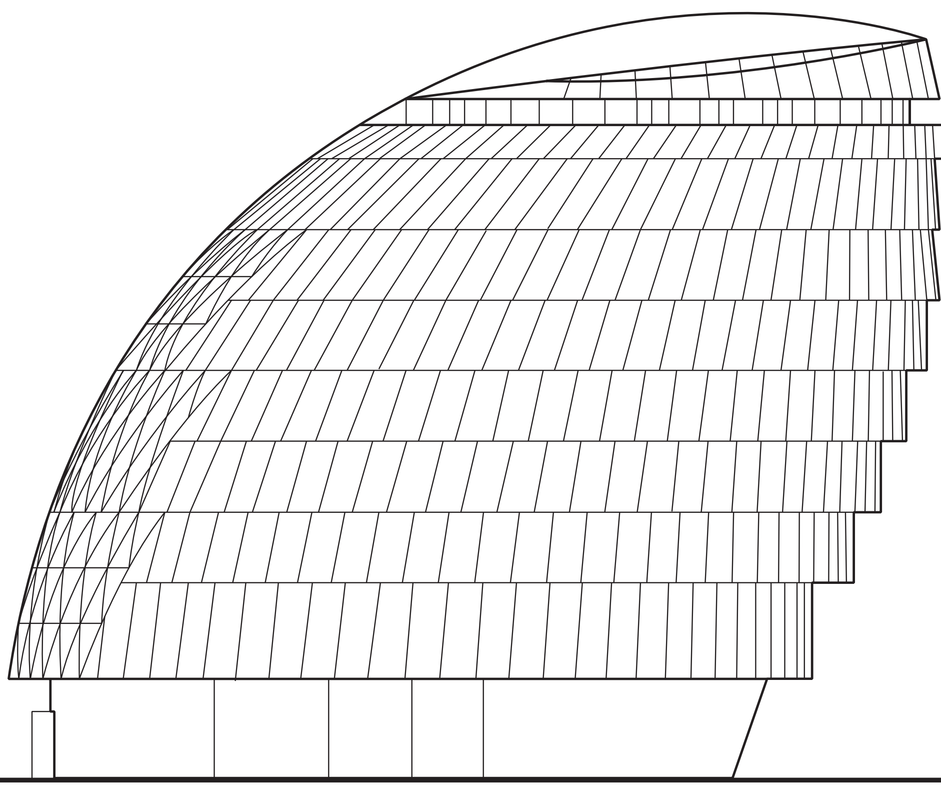

Figure 16.2 City Hall, Greater London Authority

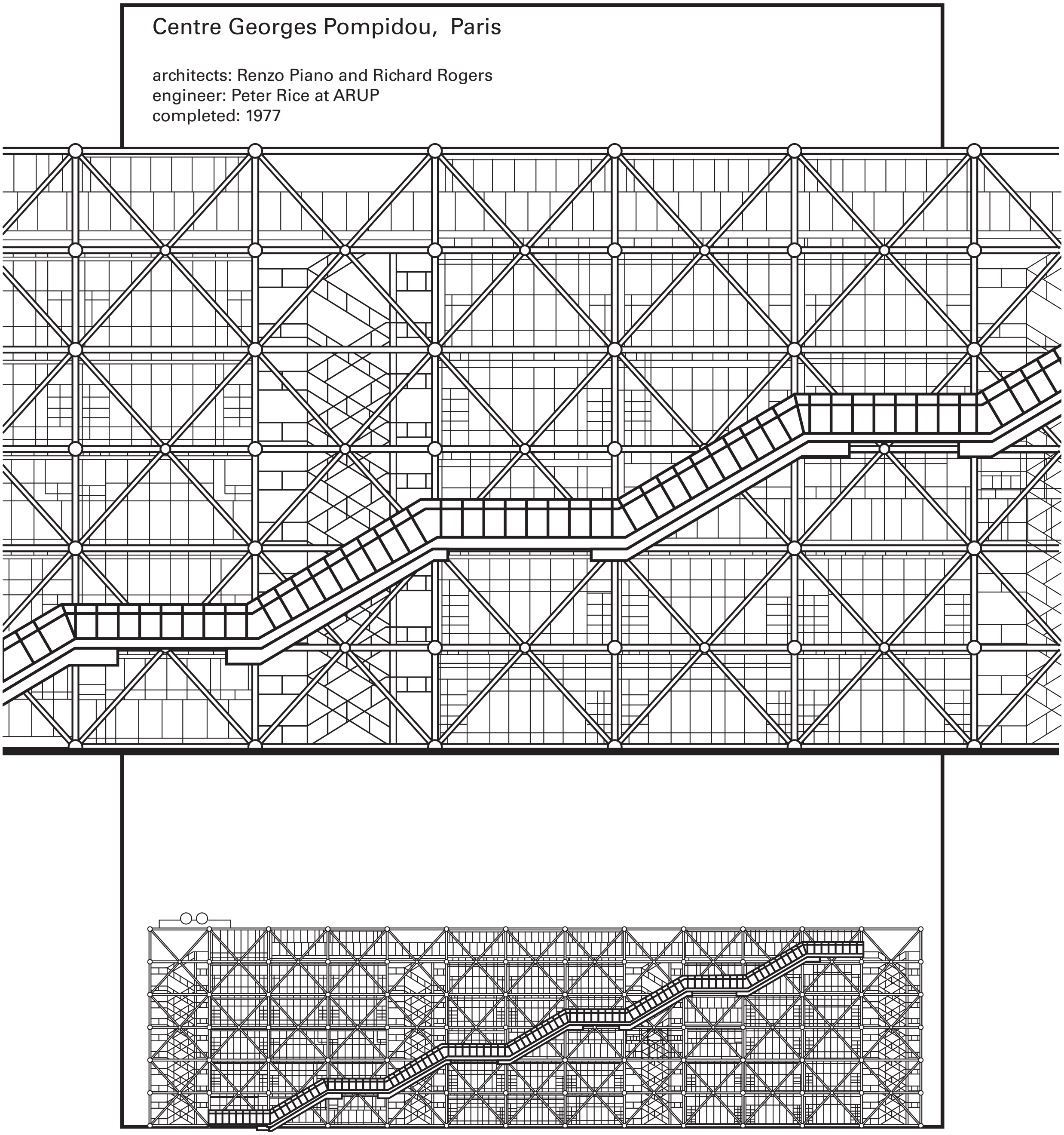

Figure 16.3 Centre Pompidou

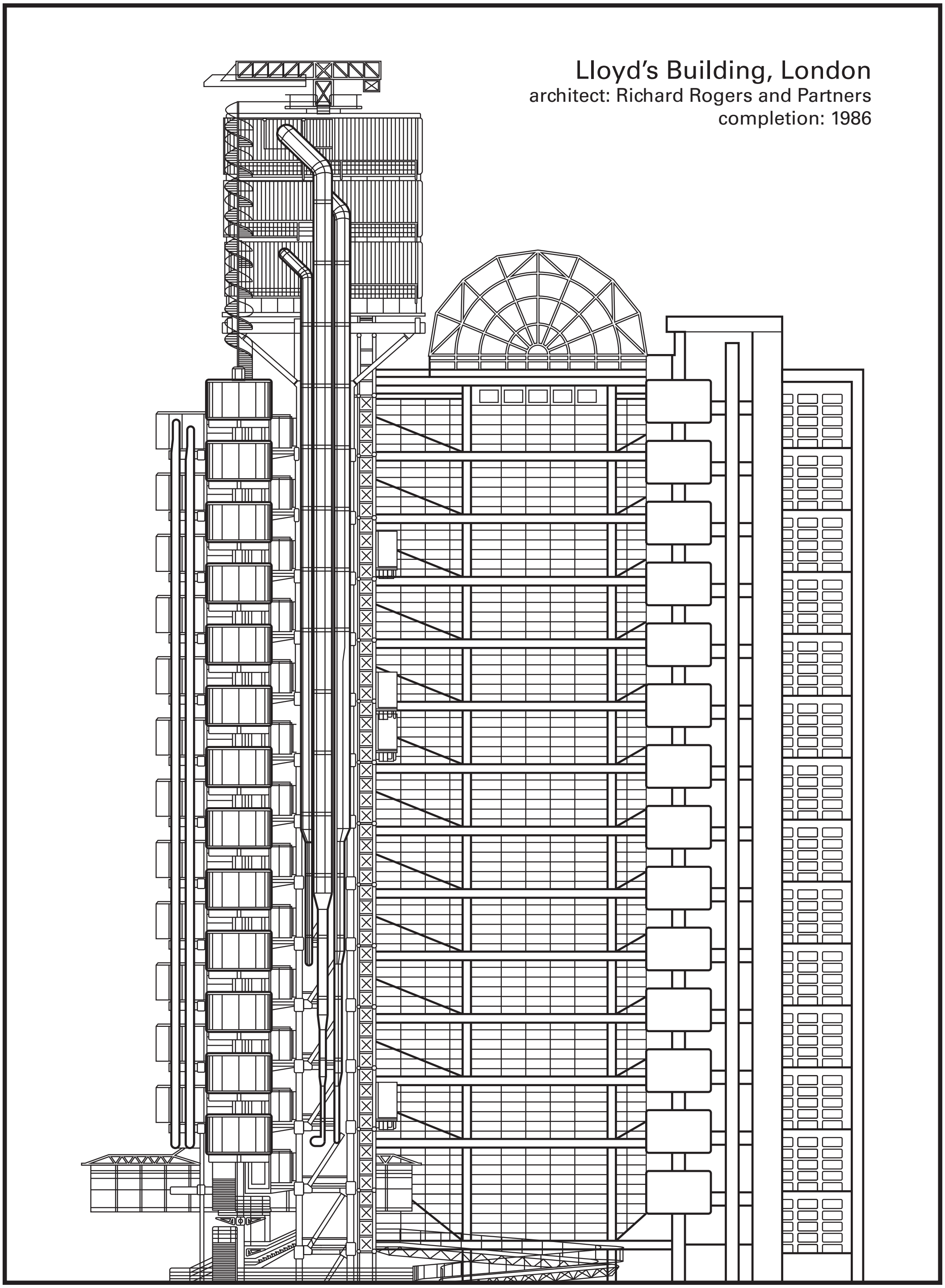

Figure 16.4 Lloyds Building

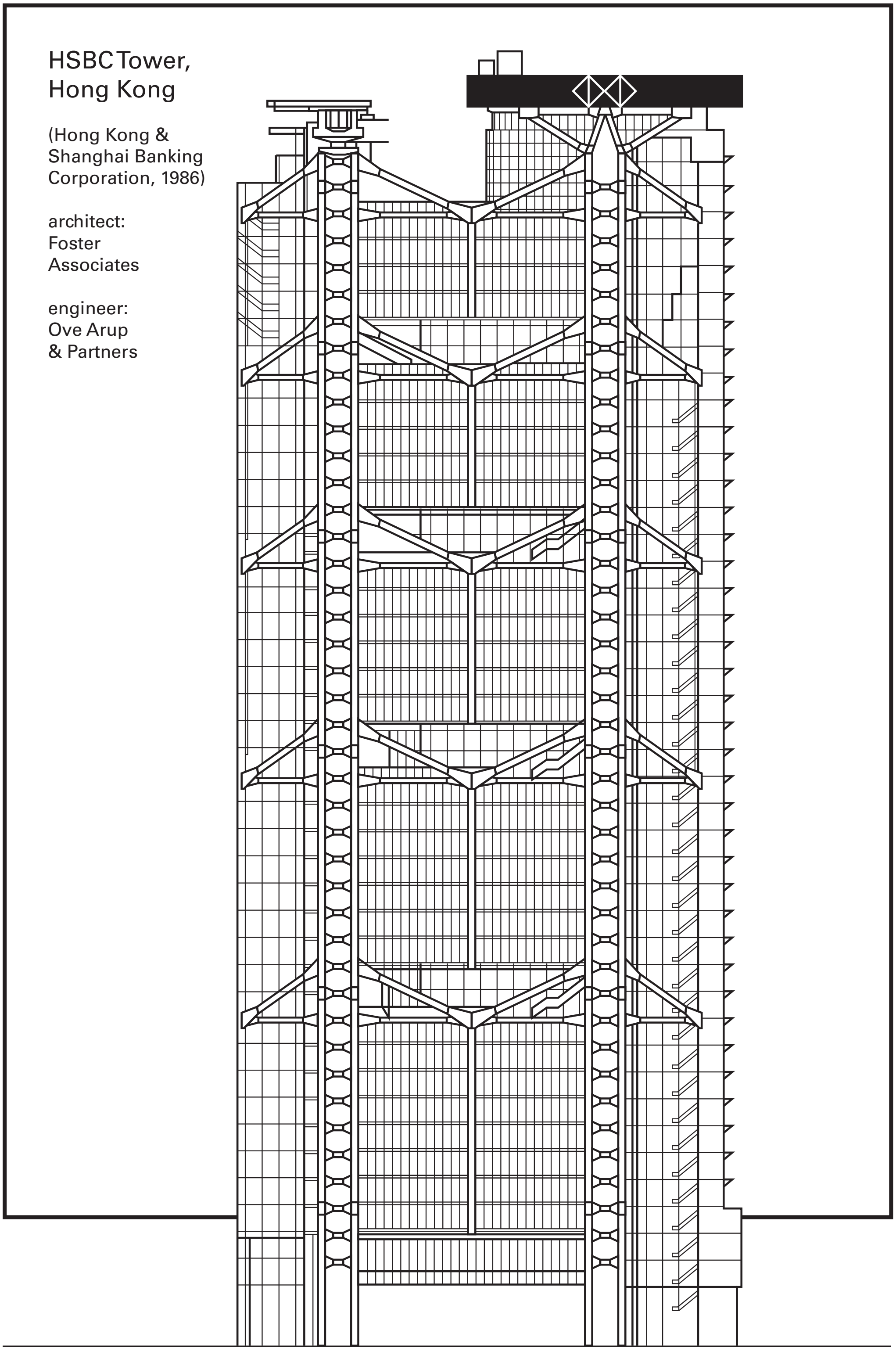

Figure 16.5 HSBC Tower

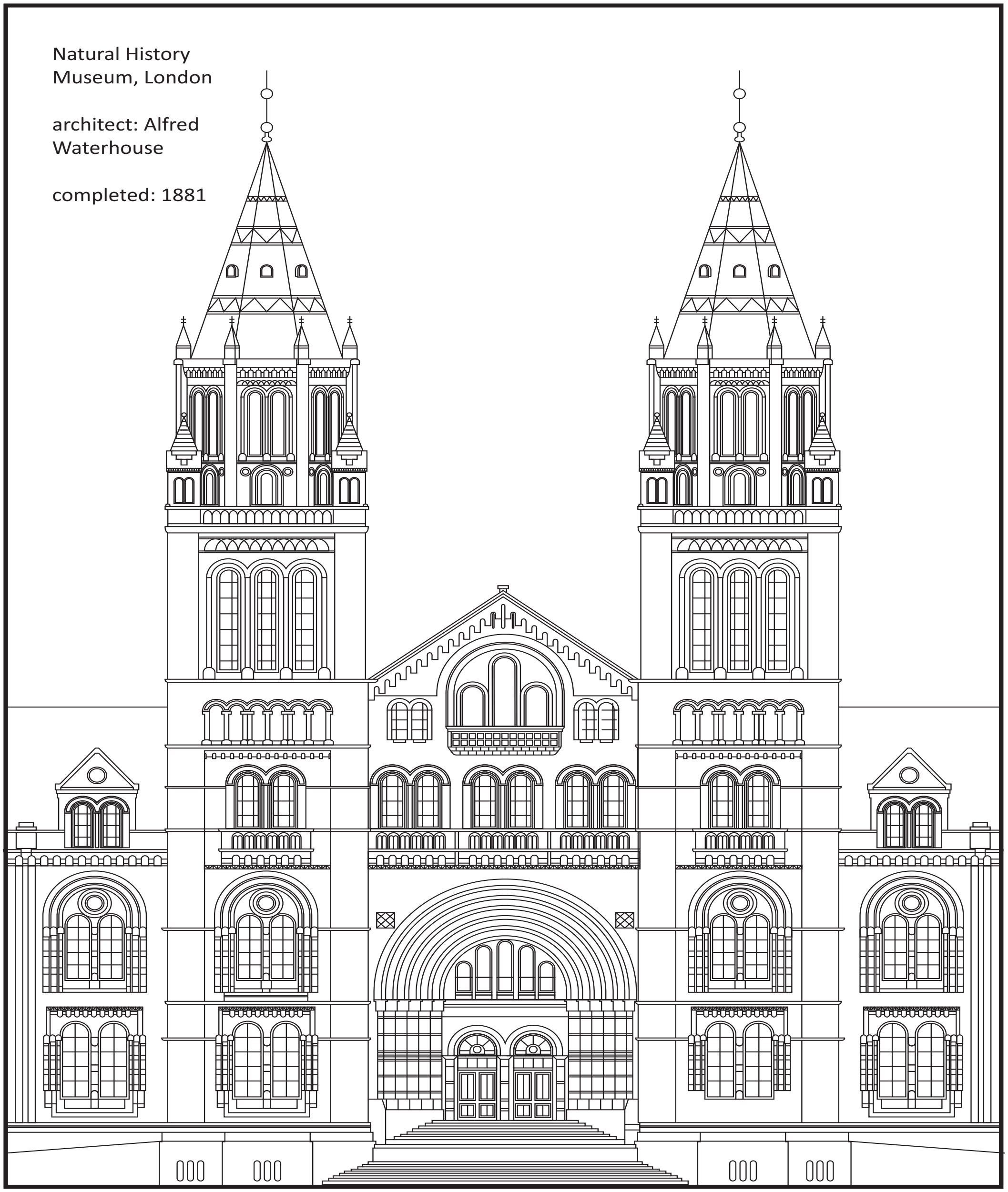

Figure 16.6 Natural History Museum

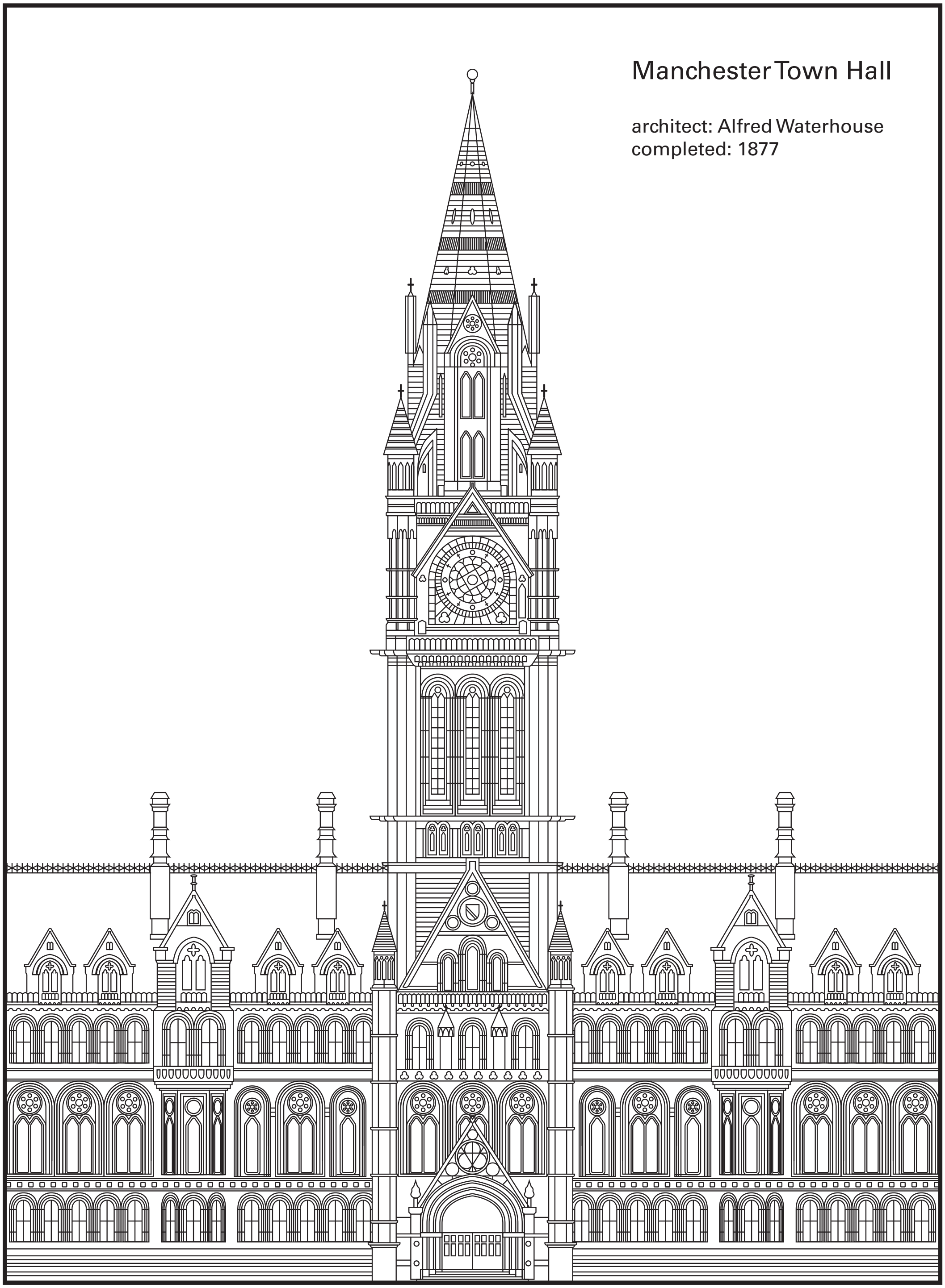

Figure 16.7 Manchester Town Hall

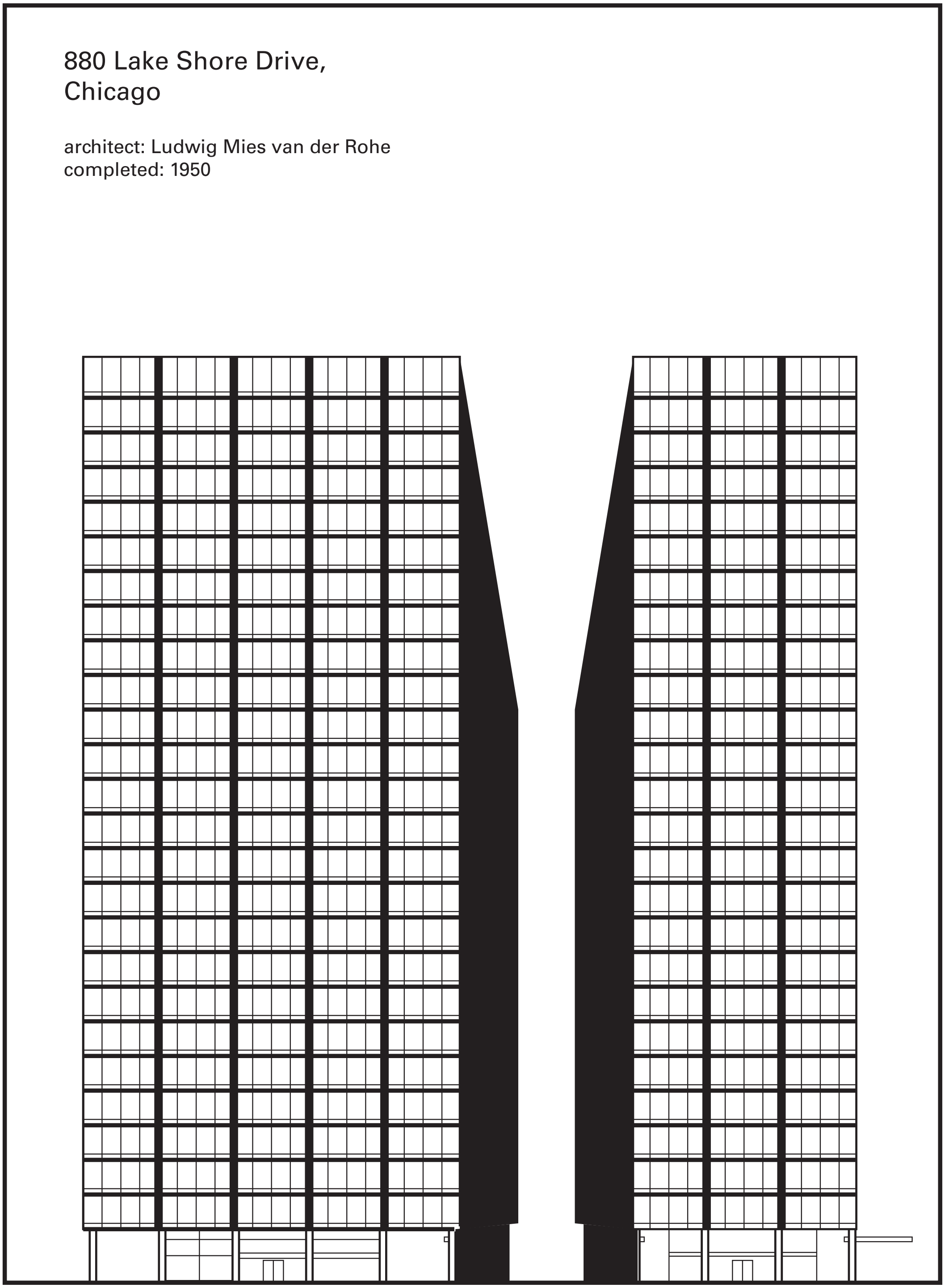

Figure 16.8 Lake Shore Drive apartments

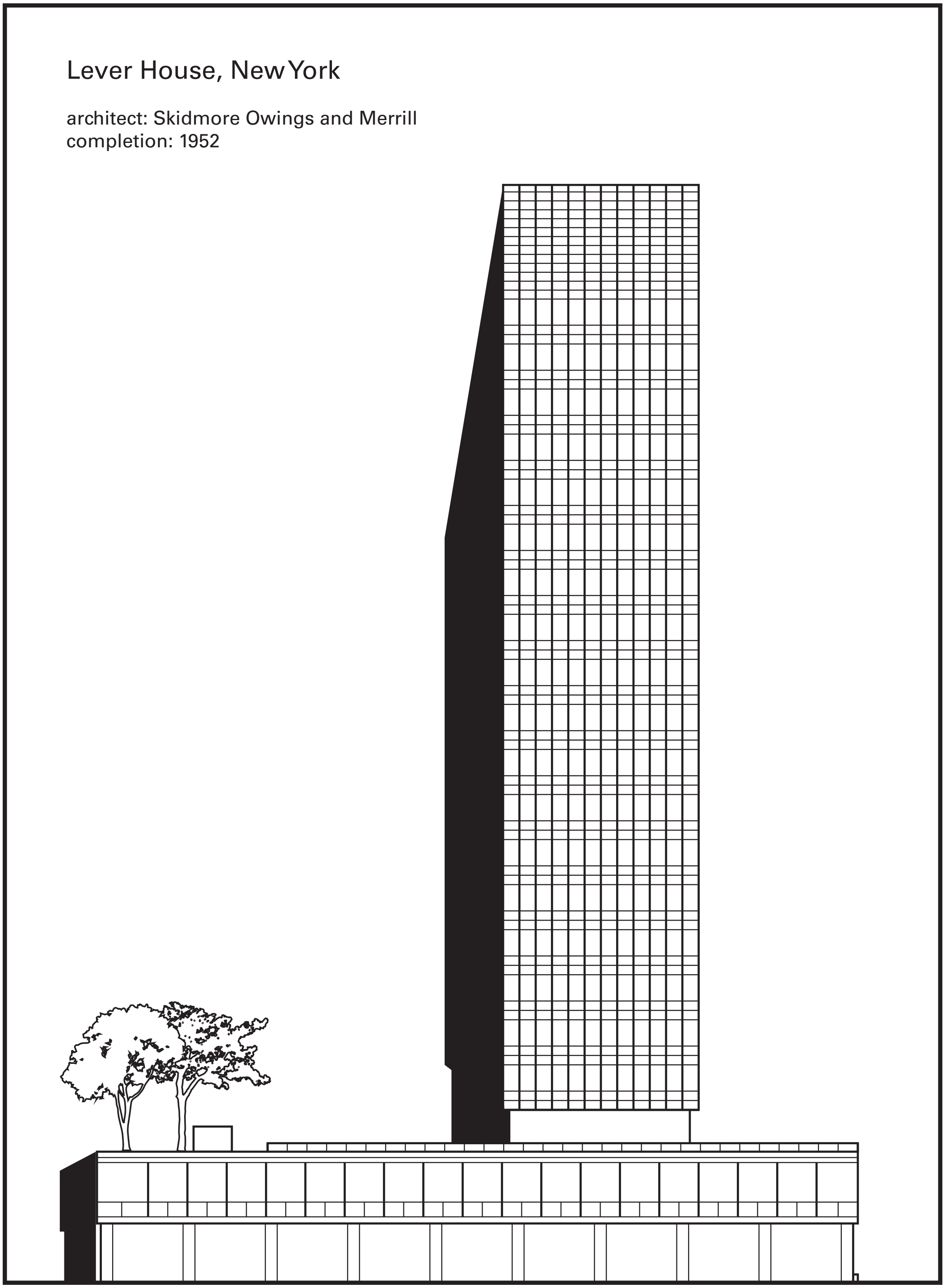

Figure 16.9 Lever House

Typically, because of weathering problems caused by penetration of the enclosure, most primary structure is internal to the façade where it is best protected. In this case, façades either sit within the structure or external to it, supported by brackets off the floor slabs or edge beams (Figure 17.2).

As I write this, I am looking at construction drawings for two highly regarded English Victorian buildings. On the one hand, London's Natural History Museum (refer to Figure 16.6) in Romanesque Revival style has a façade of thin stone and faience (tin-glazed terra-cotta cladding panels, shapes and forms) hung on a cast iron structure of columns and beams; thus, an early lightweight façade. On the other hand, the Manchester Town Hall (refer to Figure 16.7) in neo-Gothic style discloses a load-bearing brick and bonded-in stone structure. Built within five years of each other by the same architect – Waterhouse designed both – which represented the battle of the styles and the predilection of the client, sometimes religiosity based – Gothic was good. Conspicuously, the façade types are different. Built in the 1880s, the Natural History Museum presages the future of lightweight claddings. Not that the Great Exhibition Building (The Crystal Palace) of 1851 designed by Paxton – a gardener to the rich and famous of the day – hadn't already set an amazingly high standard thirty years before. These are British examples and not tall but all groundbreaking in their time.

Similar clashes of style and façade type were occurring in the USA at the same time on really tall, generally cast iron or steel buildings. For some examples of the different genres Peter Gossel offers for consideration (Gossel 1991) Jenney's Leiter Building (1879) in Chicago, the 'Tacoma Building', also in Chicago (1889), the 'Flatiron' Fuller building (1902) and Flagg's 'Singer Building' (1908) in New York. Look them up. There are many others of similar vintage.

In 1931, the Empire State Building was completed in record on-site time. It is a 103-floor steel-framed structure with dimension stone cladding. After WW2, a burgeoning American economy threw up a large number of tall buildings which have been the architypes for most glass and aluminium (sometimes bronze or stainless steel) framed curtain walls since. Iconic glass boxes include Mies' Lake Shore Drive Apartments Chicago (1950) (refer to Figure 16.8), the Harrison/Abramovitz + Corbusier UN Secretariat New York (1950), SOM/Bunshaft's Lever House in New York (1952) (refer to Figure 16.9) and Mies' Seagram Building in New York (1958). It goes on and on. London now has The Gherkin, the GLA Egg (both Foster and Partners) and The Shard by Renzo Piano. Sydney has Aurora Place, also by Renzo Piano, and many others by Harry Seidler.

To study the art of the possible or the impossible, look no further than Dubai or China.

Massey House, Wellington

architect: Ernst Plischke and Cedric Firth
completion: 1957

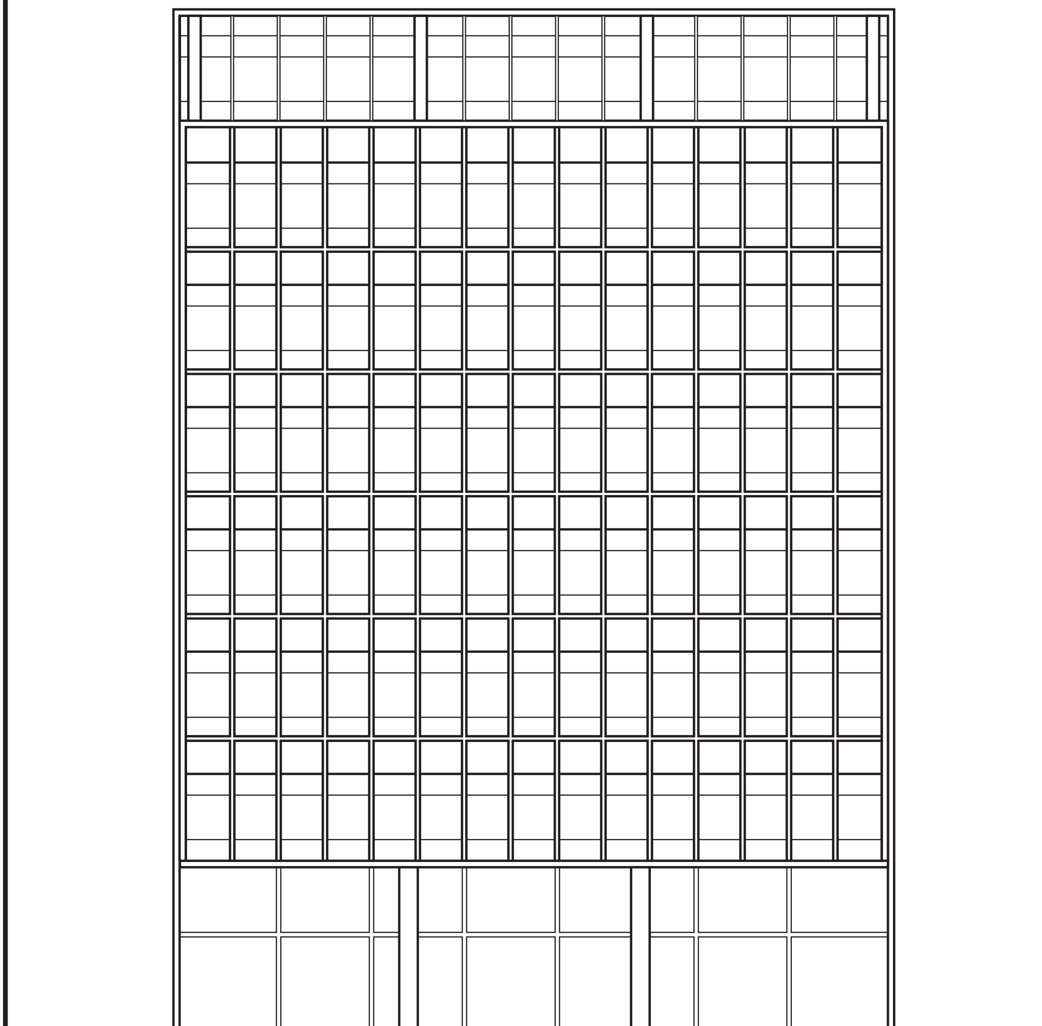

Figure 16.10 Massey House

By comparison and in the same period, New Zealand's tiny and cash-strapped economy delivered lightweight clad buildings such as Firth & Plishke's Massey House (1957) in Wellington (refer to Figure 16.10), Tibor Donner's Auckland City Council Administration Centre (1961–1966) and Thorpe, Cutter, Pickmere and Douglas' AMP Building (1962) in Auckland. Both cities have done better, or perhaps worse, since. Each is described by Shaw (1998). They all have external curtain walls which would have been designed to some extent by their architects and structural engineers without the benefit of specialist curtain wall suppliers and consultants, as neither of whom existed at the time. It is likely that the window frame and glass suites would have come from Australia, as their major cities were building tall at the time.

What is interesting about the New Zealand examples is that their architects, like Waterhouse, must have felt they knew what a façade was and were prepared to be responsible for the design and some of the detail. This ability is seldom likely to be the situation today unless the architect's training has had a large component of engineering, both structural and building services with a good understanding of building physics because, as Herzog has said earlier, façade design is a 'structural sub-system' which requires consideration of and solutions to bioclimatic factors involving high-level performance design criteria for functional/technical/aesthetic matters. We know now that there are many more things that should be considered (although Massey House is said to have been designed to cope with a 450mm seismic sway). Architects can handle the aesthetic component but are likely to need help to be provided by others – structural/façade/building services/fire engineers – on the functional/technical matters.

In today's context, there may be nothing wrong with this (and lost ground can seldom be regained), but it is important that architects understand what is involved and know the strategic questions to ask of their consultants to get the best results. One can't think of Fosters or Rogers' offices not being heavily involved in achieving their façades.

An inability to know what questions to ask is a matter of some concern and the intention of this book and the next chapter in particular is to provide a 101 Primer on façade issues that will enable better-informed conversations to be possible with all those involved in the design of façades for mid-rise tall buildings. Ledbetter (2001) wrote that:

> The façade is indeed one of the most complex parts of the building in terms of design and design conflicts . . . [especially] when performance requirements are expanded to include [an] appearance that is prescribed before detailed design... It provides the weather surface, is the principal controller of the internal environmental conditions, [and] carries wind loading and applied loads . . . all within a zone no more than 300mm from outside to inside face.

Add in Durability, Green Building Council sustainability and energy transfer and note:

> . . . it gives the building its appearance . . . The global move away from traditional forms of building, both in style and materials, creates a universal need to know **why** façades are constructed in a particular way and not simply how they are built.

Ledbetter goes on to say:

> The façade is a major part of the building . . . For commercial buildings the cost of the façade is governed by the materials used and the complexity of the wall [which normally] costs between fifteen and thirty percent of the cost of the building.

This is quite a lot really, but not much when it is considered what an average façade could/should do and the matters of performance that need to be considered. Ledbetter (2001) sets out the scope of façade performance (and added to by the author) carefully, and this constitutes the basis of the next chapter.

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Hertzog, T. et al. 2017. *Facade construction manual* (2nd edition) Edition DETAIL 2017 'A1 External and Internal Conditions' pp19–45.

Ledbetter, S. R. 2001. 'Facade Engineering – where are we now?' in *Proceedings – ICBEST conference 2001* – ICBEST: Ottawa. Keynote address pp1–10

Shaw, P. 1998. *A History of New Zealand Architecture* (2nd edition). Wellington: Hodder Moa Beckett. 'Plishke's Massey House' pp151–152

17

Chapter Seventeen

Façade: performance

Façade performance

John Sutherland

17.0 Performance

This chapter continues from the previous chapter by expanding on Ledbetter's statement:

> The façade is a major part of the building . . . For commercial buildings the cost of the façade is governed by the materials used and the complexity of the wall [which normally] costs between fifteen and thirty percent of the cost of the building.
>
> (Ledbetter 2001)

This may seem considerable, but when it is considered what an average façade could/should do and the matters of performance that need to be considered for human habitation to be possible, it becomes more reasonable. In the table below, Ledbetter sets out the range and scope of façade performances (expanded on by the author) carefully and in detail. This constitutes the basis of the chapter, as each of the tabular issues is discussed in more detail.

Table 17.1 Issues for consideration in Façade Performance (after Ledbetter). The columns must be read separately. Horizontal connections are not necessarily meaningful

Material	Performance	Quality	Appearance	Cost
Glass Annealed; Toughened; Heat soaked; Laminated; Multi-pane [IGU]; Environmental e.g. low-e; Electro- chromatic;	***Weather*** Watertight; Airtight; Wind loading [DWP (Pa)]; Daylighting; Ventilation	***Workmanship*** In- factory; On site; Normal standard of finish; Better than normal standard of finish; Quality [QA] ISO 9000	***Finishes*** Self colour [anodised]; Applied colour [powder coat]; Texture; Gloss levels; Fading tendencies; Galvanised; Zinc thermal spray	**Capital costs** [Capex]; Materials; Components; Elements; Systems; High Capex/low Opex; Low Capex/high Opex
Metals –panels/frames Solid aluminium ACM Bronze Corten steels MS Coated steels Titanium Extrusions, sections panels	***Seismic*** Horizontal movements; Vertical movements; Inter-storey drifts.	***Durability*** What the code requires; What is reasonable for building's whole- of- life; Owners expectations; Maintenance cycle and other issues.	***Fit*** Tolerances; Deviations; Flatness; Alignment; Size; Tolerance accommodation;	**Operating costs** [Opex]; Materials; Systems; Cleaning and inspection; Inspection cycle; Repairs/replacement cycle for materials; Maintenance/ access
	Thermal U-values; R- values; Solar gain; Heat loss/ heat gain; Thermally broken frames; Junction details.			**Whole of life costs**; Capex vs Opex; Energy; Maintenance; Design Life cycle;

(*Continued*)

Table 17.1 (Continued)

Material	Performance	Quality	Appearance	Cost
	Wind effects Wind load on building face; Effect of wind speeds on face on surrounding spaces; Testing – wind tunnel			
Sealants Silicones; Polyurethanes; Hybrids;	***Moisture*** Aggravated thermal bridging [ATB]; Condensation; Mould etc.		***Materials*** Texture; Consistency; Production and installation QA/QC.	**Environmental costs**; Value added; Offsets to costs
Gaskets/setting blocks PVC; Silicone; Santoprene	***Acoustics*** Inside to outside; Outside to inside; Inside to inside; Frame effect			
	Fire Resistance to fire; FRRs Reaction to fire; Replacement Protection from fire			
	Security Blast; Entry control; Invasion; Intrusion; Wilful damage; Civil unrest; Impact			

Finishes Anodising; Powder coat; Wet coats (paints); Waterproofing coats: incl Silicone/Silane Anti-graffiti coats See also **Appearance**	***Light*** Too much light; Not enough light; Control of light; Nature of light- contrasts			
Stone Granite; Marble; Limestone; Sandstone; Lab analysis of nature of stone to be used				
Pre-cast concrete panels Natural; Textured or patterned; Insulated (embedded); Applied finishes; Thru' coloured; Absorption; Water resistance				
GRC Natural; Textured or patterned; Applied finishes; Coloured; Fixings.				

(*Continued*)

Table 17.1 (Continued)

Material	Performance	Quality	Appearance	Cost
GRP Texture/shape; Colour- thru' or applied coatings; Colourfastness; Moulds; Boat building techniques; Fixings				
Bricks Colour; Texture; Size; Thickness; Face patterns; Veneers				
Insulation External; Internal; Embedded				

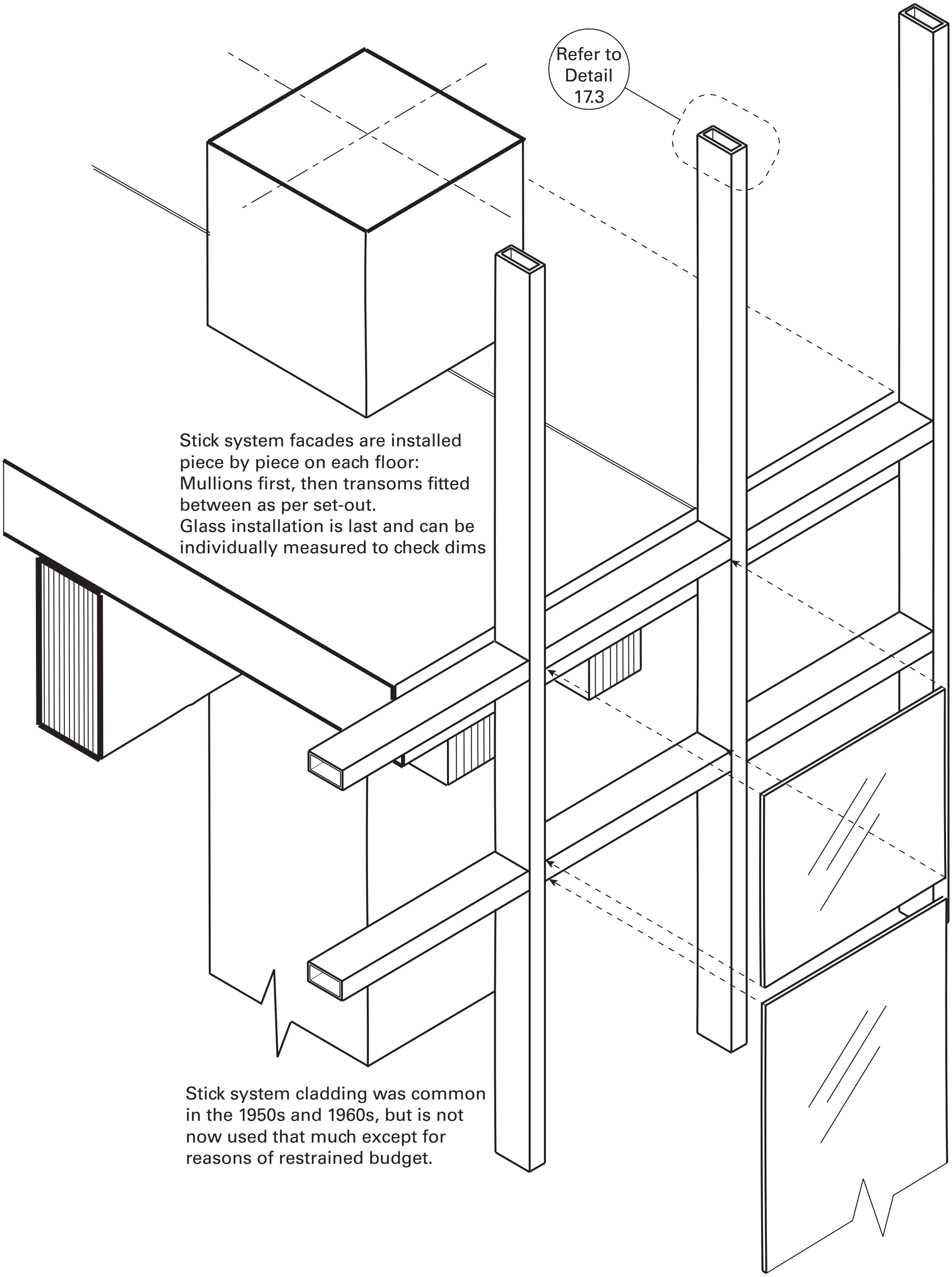


Figure 17.1 Façade – onsite assembly of stick system

17.1 Buildability

Overlaying many of these matters are issues of buildability, durability and life cycle. As to actual construction, the different achieved tolerances vary widely and affect matters of buildability, weather-tightness and construction sequence. The off-site cladding component manufacture has tight tolerances (often 3–5mm), while the permitted tolerances stated in various documents for the building frame itself depend on the material used: concrete has very large tolerances (10–20mm), while steel has small to medium (5–10mm). Designers must take these into account.

While there are many cladding types that can be used, and taking a glazed curtain wall as an example, two main options exist:

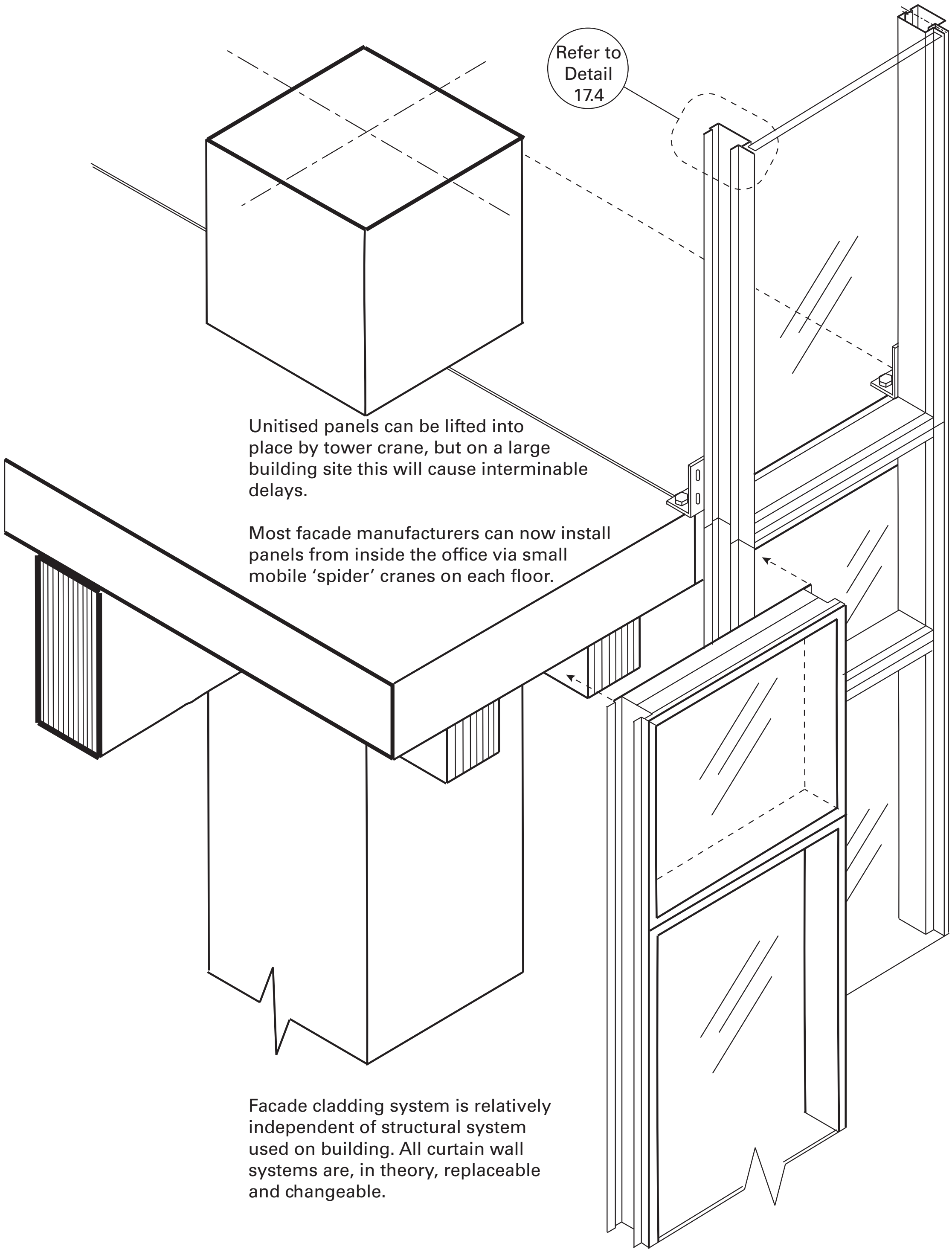
1. Factory prepping of extruded and panel components for the weather-exposed, on-site assembly of a **'stick system'** (refer to Figure 17.1 and 17.3) off special scaffolding versus
2. Factory-manufactured fully framed **'unitised/glazed'** units (refer to Figure 17.2 and 17.4) that can be taken to site to meet a programme, off-loaded from the delivery vehicle, direct, via crane, onto completed floors, flat stacked and then installed externally by mechanical devices, set vertically and bracketed to the structure. All this is carried out from inside the completing frame structure. Unitised curtain wall panels can be installed generally about five floors behind structure.

This is the very obvious difference between prefabrication (protected manufacturing activities) and site (climate exposed) assembly. Both methods are used – almost culturally dependent – around the world to designer and/or contractor choice or necessity. Most unitised systems are installed progressively on a floor by floor basis with male and female interlocking jamb extrusions, while stick systems are installed and jointed continuously on any one or more floors depending on the height of the mullion members. The introduction of horizontal (transom) members is by factory-prepped spigot and on-site sealant jointing, followed often by on-site structural silicone glazing.

There are other designs that use sophisticated mullion to mullion compressed gasket jointing systems retreating inwards from the face to create multi-chamber lines of defence within the depth of the mullions.

As with other unitised systems, these drain to horizontal, probably-split (refer to Figure 17.4) transoms at each floor level.

There are not many other cladding systems, while factory made (for instance precast concrete or GRC/GRP units), that can be installed from the inside in the same



Unitized system being installed, showing panel coming onto site with IGU already installed

Figure 17.2 Façade – unitised glazing system

way. These are delivered to site, to a programme, and require crane availability so as to hoist them externally into place on arrival. All are bracketed to the structure from the inside. **Tilt slabs** got their name originally from being poured on the project concrete floor, allowed to cure and then tilted up, propped and jointed. However, to introduce beneficial off-site manufacture, most precast concrete panels are now plant-manufactured, cured and trucked to site according to programme and craned into place to be secured by internal brackets in order to maintain programmes. Precast concrete panels are not rebated vertically but usually jointed with a mid-panel width baffle (refer to Figure 17.5) in matching grooves and an inside soft (wet) air seal. An external seal is not necessary, and its omission saves later maintenance costs. Four-way joint intersections need particular care, as the effect of tolerances at the intersection of horizontal and vertical joints can create weak spots in the cladding: always flash horizontally at this point. If an external sealant is used, then the cavity that is formed must be drained to the outside above adjoining external finished levels.

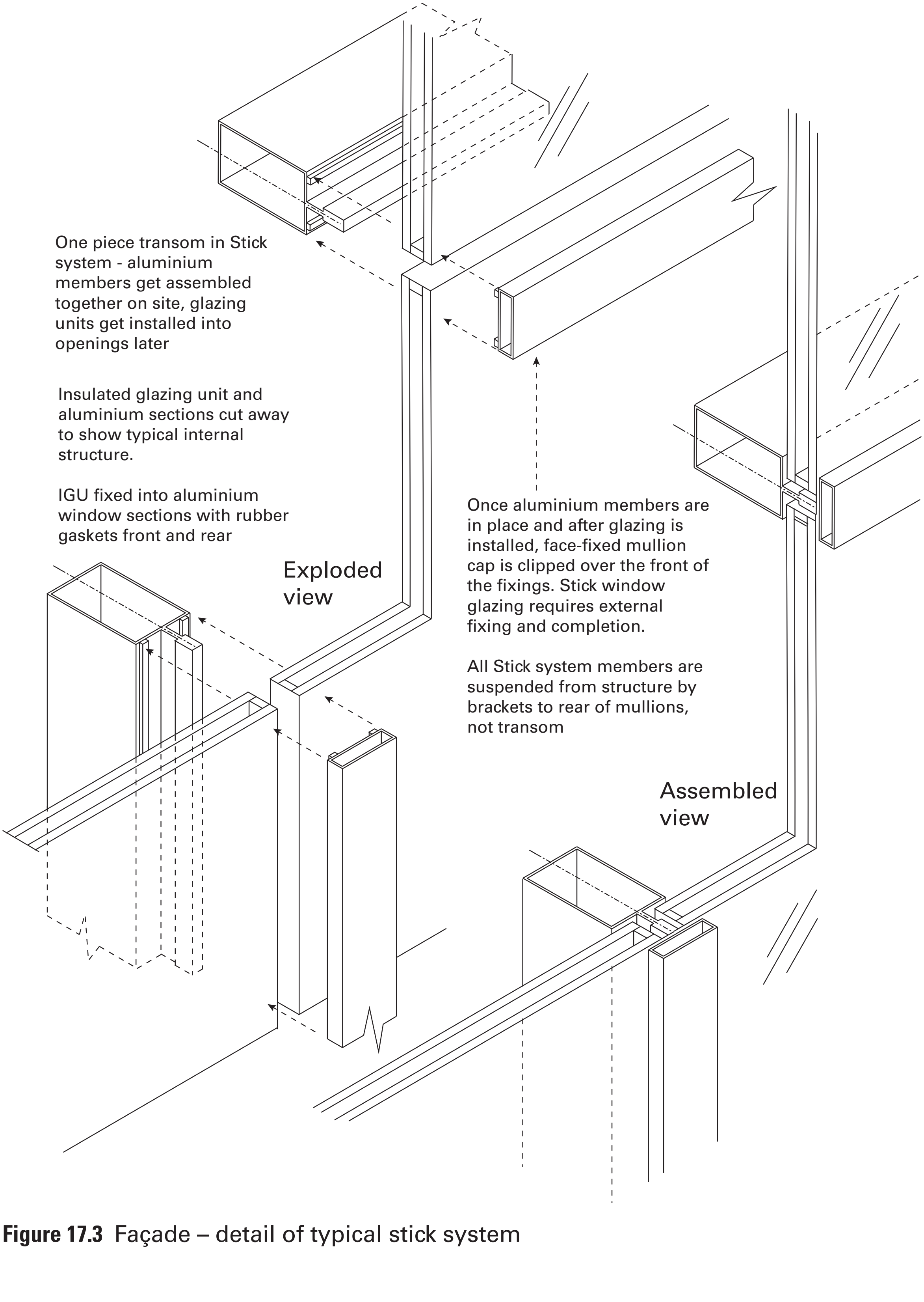


Figure 17.3 Façade – detail of typical stick system

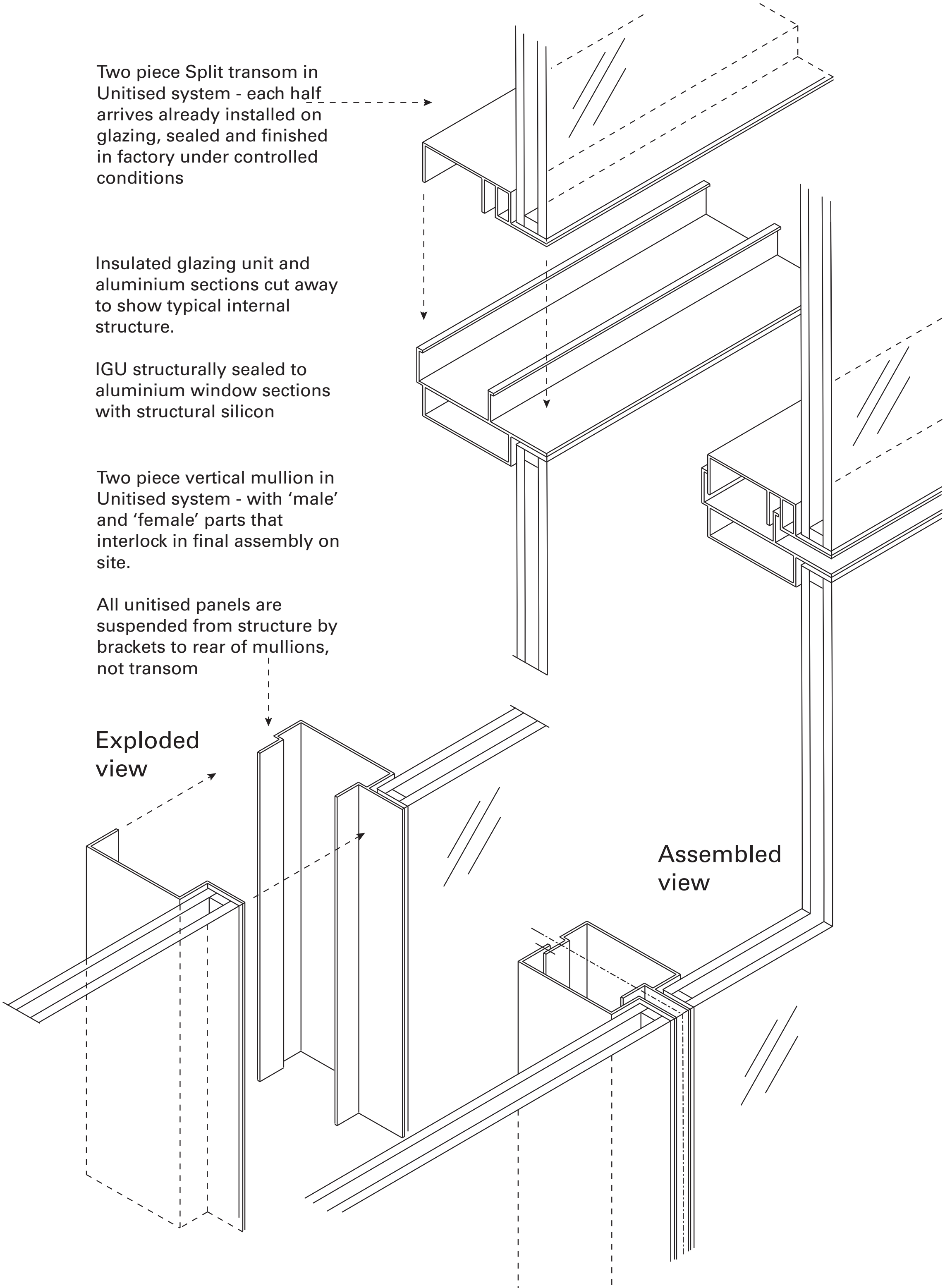


Figure 17.4 Façade – detail of typical unitised system

17.2 Testing

The general intention of all these variants is to create a weather-tight pressure-equalised drained-joint system. To show that they comply before installation, there are national norm-provided **test methods** available to proof-test prototypes of all these systems. Unitised systems can be tested to meet stated performance design requirements in an in-house rig, while stick systems are more likely to be tested on an external rig, often using an aeroplane engine to match design wind pressures for structural performance and with water in the wind to test for weather-tightness. Different test methods will be used in different regulatory jurisdictions, but test methods are such an international commodity that tests are interchangeable depending on regulatory permissions. For instance, the several **AAMA** (US) and **AS/NZS** (Australasian) test methods could be used in New Zealand. Other regulatory jurisdictions would undoubtedly vary that. Testing can be very much mix-and-match depending on regulatory permissions. In fact, test methods seem to be converging in their similarity and methods of test, which brings ISO documents into consideration.

Systems are increasingly being tested to cope with seismic movements of the structure, although at extreme heights, wind action movement dominates. As structures become lighter, movements become larger and more significant and weather-tightness more difficult to achieve because of the gaps that must be bridged.

17.3 Durability

The following issues taken from Table 17.1 above affect the necessary thinking about durability.

Compliance:

Some building codes require durability standards for building work. They carry the idea that durability statements are required to ensure that buildings are sufficiently durable so that all other objectives of a building code are satisfied throughout the (code) life of the building without needing re-construction or major renovation. To do this, durability must be included in the mandatory performance part of the national code. Other building codes rely on standards or other kinds of norm documents to support the importance of durability.

Such codes introduce the concept of time of continuing compliance related to normal maintenance. For instance:

- The life of a building being **not less than 50 years** for those parts of the building that provide structural stability or are difficult to access or replace or where a failure could go unnoticed (50 years is a common design life for the structure of a building);
- The life of a building being not less than **15 years** for building elements moderately difficult to access or replace where failure to comply would go undetected until normal maintenance was carried out (this could be applied to the materials of a façade of a building);
- The life of a building being not less than **5 years** for building elements easy to access and replace. Failure to comply would be easily detected in normal use (aesthetic coatings).

The façade's whole-of-life

One of the problems with any code is that it very rapidly becomes the lowest common expectation, where the building product manufacturing and marketing side of the industry and their legal advisors directly couple warrantees with the code-required durability of product and system.

This makes it very difficult to devise and quantify what the appropriate whole-of-life of any building will be. It may also be possible to state and design for a 'life of a building' less (temporary) or more (special) than 50 years by specific design. To achieve longer periods, maintenance cycles must change and be part of the design process and structural design perhaps modified to less, or more, stringent design on the basis of statistical probability and return periods. For instance, a briefed longer than basic code design life can attract higher wind speeds or

escalated Richter scale seismic return periods. The satisfaction of this additional design life would require additional construction costs.

Owner or community expectations or matters of national importance relate directly to these matters and should always be an important part of the brief, as are any resulting maintenance issues. Many otherwise elegant façades cause their owners to expend very large sums of money maintaining or at least cleaning them, particularly all-glass façades.

In the main, aluminium extrusions and glass together create durable whole-of-life façades. So too will precast concrete panels of adequate thickness, although exposed sealant jointing, however or whenever used, will require replacement at best every 25 years.

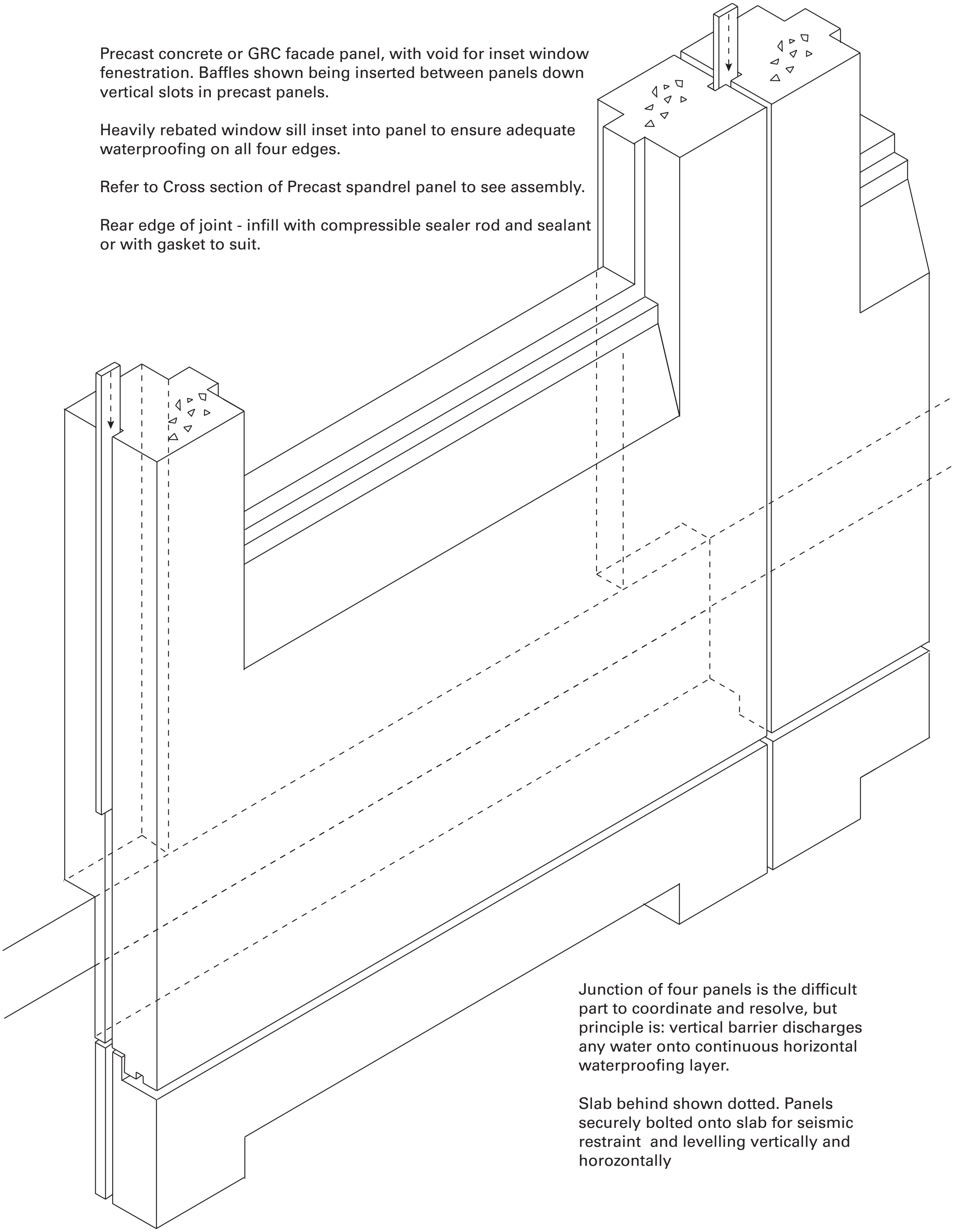
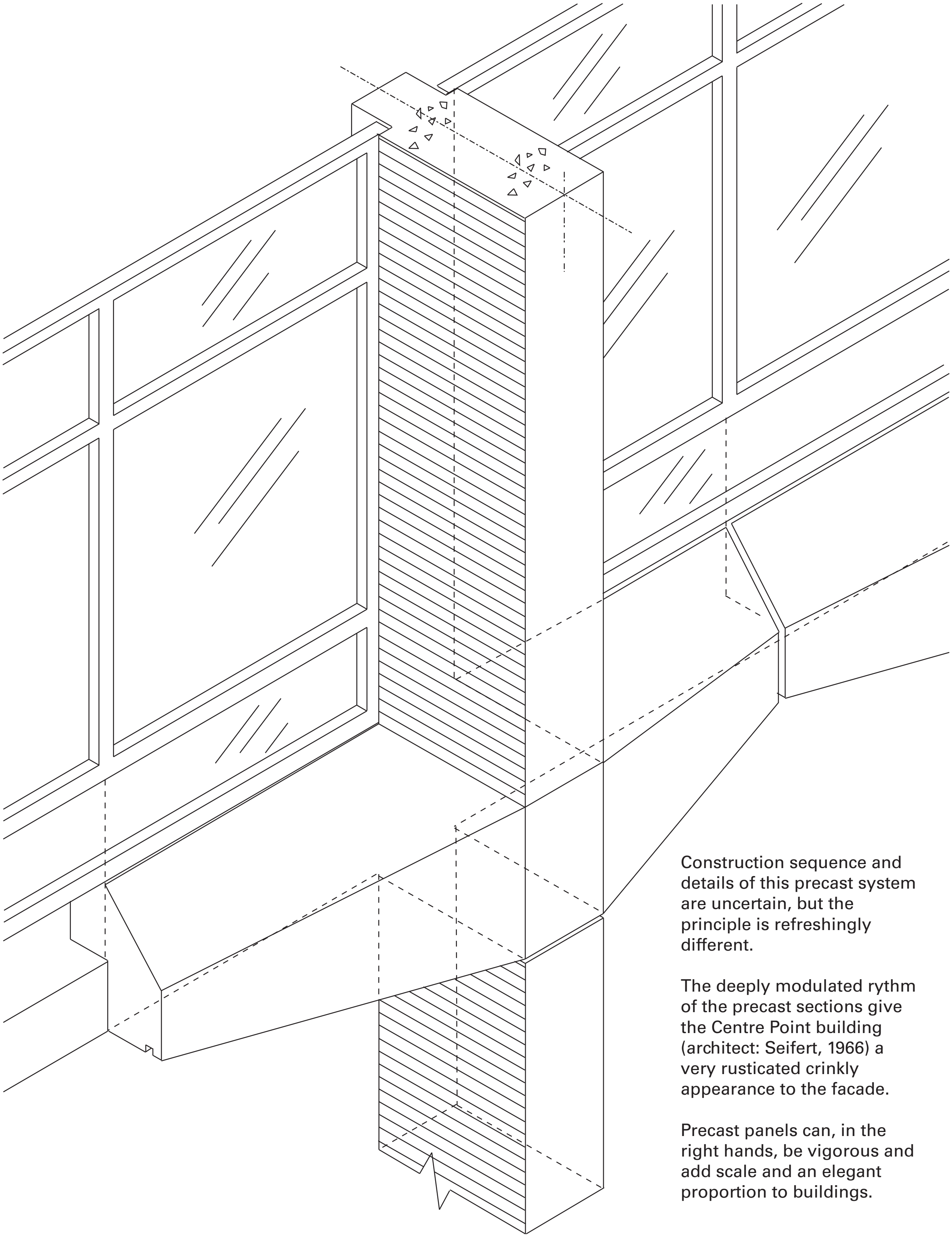


Figure 17.5 Precast panel for typical spandrel



Construction sequence and details of this precast system are uncertain, but the principle is refreshingly different.

The deeply modulated rythm of the precast sections give the Centre Point building (architect: Seifert, 1966) a very rusticated crinkly appearance to the facade.

Precast panels can, in the right hands, be vigorous and add scale and an elegant proportion to buildings.

Figure 17.6 Precast concrete façade Centre Point

17.4 Bits and pieces (components)

Both of the two curtain wall systems discussed above, depending on the design, will use mostly similar 'bits and pieces' (refer to Figures 17.3 and 17.4):

- **Head frames** – top of panel horizontal members (which may also be the lower member of a split transom in panelised construction);
- **Sill frames** – bottom horizontal members (which may form split transoms with upper sill frame members in panelised construction). Split transoms usually occur at or just above structural floor levels.
- **Side frames (jambs) –** vertical members usually occurring against solid construction where the window or curtain wall forms an intersection with other cladding and flashing systems. All intersections are danger points. Excellent flashing design is vital to weatherproof the intersection detail.
- **Transoms** – generally, but not always, horizontal members placed between head and sill frames if required for aesthetic or functional purposes;
- **Mullions** – vertical members which visually subdivide a curtain wall. In a unitised curtain wall, they are usually split (using male and female extrusions – refer to Figure 17.4), where they are the joining means of one panel to another. In a stick system, they will usually be full box section (refer to Figure 17.3), prepped to receive transoms. Split mullions provide the means for introducing brackets for mounting projecting vertical or horizontal sun control louvres, signage or design features. Depending on loading, the brackets can be side fixed to a mullion or taken back to primary structure. Careful design will not prejudice the pressure-equalised drained-joint nature of the façade.
- **Note** – The use of multi-pane glazed vision panels (for example triple glazing) with high R-values has made it imperative to use thermally broken extrusions for all the above frame members and to align all insulated façade components horizontally and vertically.
- **Spandrels** – are the panel forms created between transoms and mullions or jambs. They can be made from glass (clear or back painted) or metal and are usually insulated to create an R-value similar to the multiple pane vision glazing used elsewhere. Metal claddings and spandrels must be considered carefully to understand their compliance with spread of flame- and fire-resistant design requirements (refer to Figure 17.5).
- **Glass** generally – Glass is a specialist topic in its own right and too convoluted to be tackled in a text of this kind. Performance glasses come from a limited number of producers. A design which emphasises glass must be specified to provide excellent internal comfort performance for the building's occupants. This means solar and temperature control in two directions, both inwards and outwards. Glass buildings are usually sealed and air-conditioned and provide little ability for occupants to control their own environment.

Extrusions are available that enable a total glass look, where the glass is structural silicone glazed to the frames with structure behind blanked out as in most modern automobiles. Structural glazing, once of concern to both designers and regulators, has been around for more than 30 years and can reach high levels of performance and longevity (Yu, 2014).

- **Double skin façades** – One means of providing a measure of personal control of internal climate is by designing double skin façades (refer to Figure 17.7), where the inside glazed wall can include opening (probably sliding) windows (airtight and weather-tight when closed) and the outside glazed wall does not have to be weather-tight. The space between inside and outside glazed walls provides stack ventilation and a means of maintaining and cleaning glass with grid floors at floor level. Early German examples were very complex in moving air vertically by introducing it at every floor. It is understood that labour regulations need to provide physical adjacency to an openable window were the driving force behind double façades in Germany. Such façades are expensive because they are in effect two façades. Life cycle analysis is likely to be required to convince sceptical clients of the substantial benefits of double skin façades (Heusler et al, 2001).

The benefits are considerable, but it is necessary to address the interaction of the façade with the building services. It must lead to an integrated approach between the architect, the building services engineer and the façade engineer which will probably, in turn, require different conditions of employment for each to ensure the necessary very good communication between them.

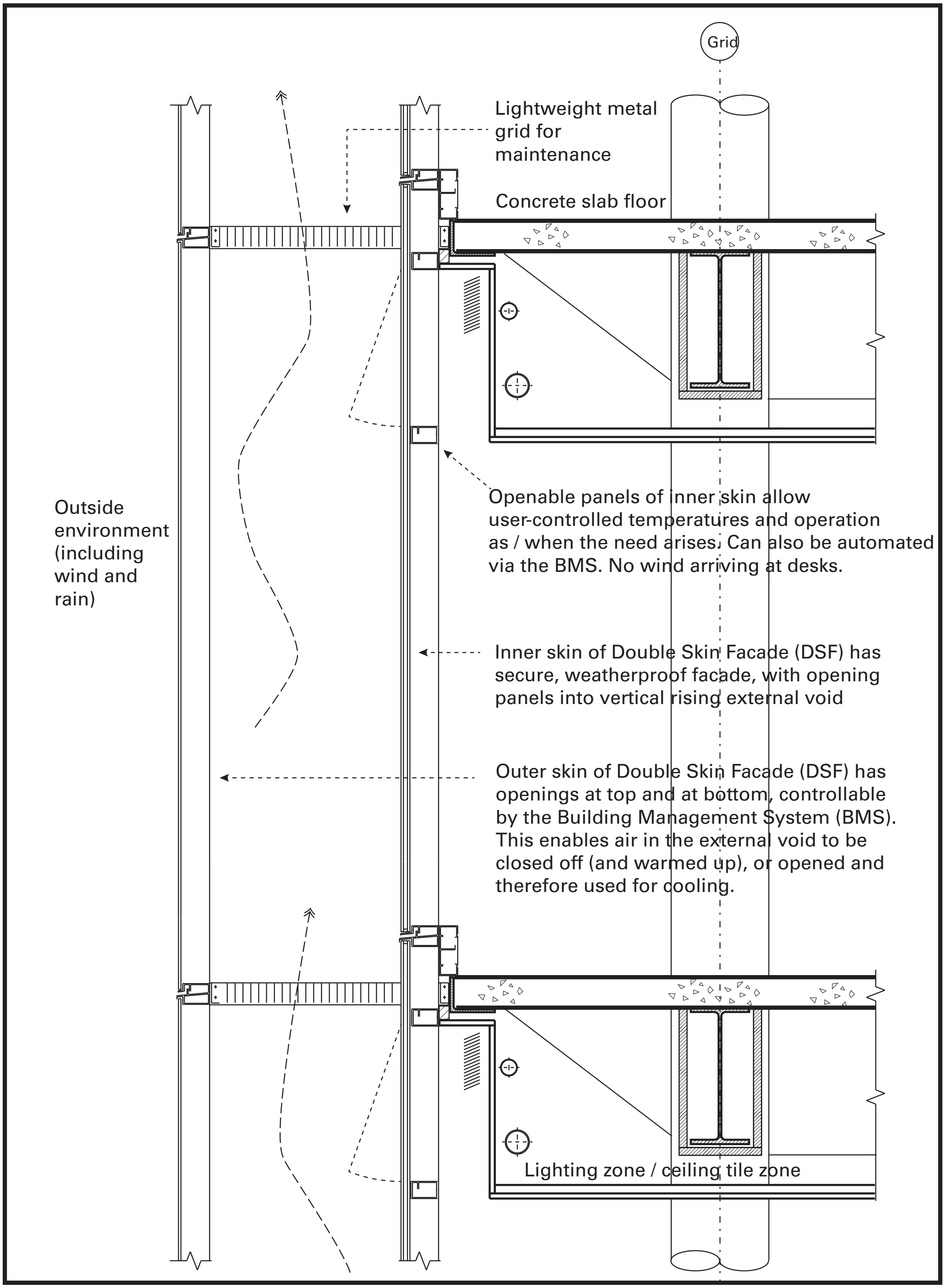


Figure 17.7 Section: double skin façade with access walkway

17.5 Specification of façades by performance

Today most façade specification is by a mixture of performance and prescription. It involves the issues of **seeking** performance/**stating** performance/**securing** performance.

Seeking performance

The extent to which this can be done by performance relative to prescription will depend on understanding:

- the level of **maturity** of the contractor/ subcontractor/ manufacturer/supplier parts of the façade industry;
- the **skill** levels available to interpret the specification;
- proper allocation of **risk;**
- the **technology/design capacity** of the industry;
- the t**esting** capability – availability of rigs;
- availability of good **norm documents;**
- how **water behaves** in the air and on surfaces (weather attack).

It is necessary to sort out the priority factors, which include the following four key points:

1. **Structura**l – the means of coping with the many forces/loads/actions stated (in Table 17.1) but particularly seismic actions which govern up to xx metres high before the wind loads particular to the site take over. Wind loads are stated as ULS and SLS design wind pressures at the site for each façade elevation. This information comes from the project's structural or façade engineer by calculation or can be obtained from boundary layer test results. These can tighten up and make calculated pressures on the face more precise and sometimes more economical as to glass thicknesses. They can also be used to predict wind conditions at ground level around the building.
2. **Weather-tightness** – control of water entering from the outside to comply with NZBC Clause E2. This is a feature of the extrusion shapes, joint labyrinths, drainage means, seals and gasket shapes. All these provide the pressure equalisation system that makes windows, curtain walls and their joints and junctions weather-tight (refer to Figures 17.3 and 17.4). Panel systems rely on other jointing/coating methods for their weather-tightness and are usually sealant or baffle jointed (refer to Figure 18.3).
3. **Gas (air)** – air-tightness of the envelope, inwards and outwards, is often either forgotten or taken for granted. This tends to depend upon climate but Passivhaus techniques require it more generally. Poor performance in this matter

can seriously prejudice the performance of the building in general. Techniques and test methods are available for checking that performance statements have been met and are included in CIBSE Technical Memoranda. Buildings should be tested to positive and negative pressure of 50Pa to meet a specification of XX $m^3/hr/m^2$ permissible leakage. Leakage figures can be a requirement of regulatory control. The important thing for the designer is to decide where the air-seal line indicating the surface at which air-tightness will be maintained should be.

4. **Energy** control – **thermal** design. Required minimum R-values are provided in building regulatory documents. These are often too low for use in tall buildings and it is a matter of judgement and briefing as to what is actually required for occupant comfort and good energy economy. This is the stuff of building services engineering and requires best possible coordination techniques from all project consultants. The optimum position for insulation – and shading – is outside the structure which can require new methods of construction to be used (refer to Figure 17.8). We have already read a brief discussion of the knock-on effect of using multi-pane glazing on the need for enhanced insulation elsewhere in one of the façade's layers. Refer to **Note** in 17.4 Bits and pieces above.
5. **Other factors –** might, on a project basis, involve:
   Maintenance costs
   Operational
   Security issues

Stating performance

Involves specifying the various performances required for the priority factors above and listed in Table 17.1. Most countries have national project specification systems. The UK has NBS, New Zealand has CIL Masterspec, Canada and USA have CSI documents. All can be used to specify prescriptively or by performance or an appropriate mix and match of both. To a large extent, this depends on how a façade contractor is to be selected and the façade is to be designed, procured and installed.

Method 1 – **Architect nominates** by brand or company after establishing brand conformance with wind zone. Architect provides elevations, some sections and some details. Nomination may be positive and allow no alternatives or provide multi-choice of equivalent brands for the main contractor to choose from and might involve early subcontractor involvement (ECI). Applicable norm standards are listed for basic compliance.

Method 2 – **Main Contractor chooses** on basis of designer's performance specification and own preferences in a novated design/build arrangement.

Method 3 – **Façade Contractor designs,** engaged by means of early contractor involvement contract, from the provision of complex and detailed performance specifications and indicative design drawings by architect or façade consultant. The chosen façade contractor is nominated and contracted to the project main contractor.

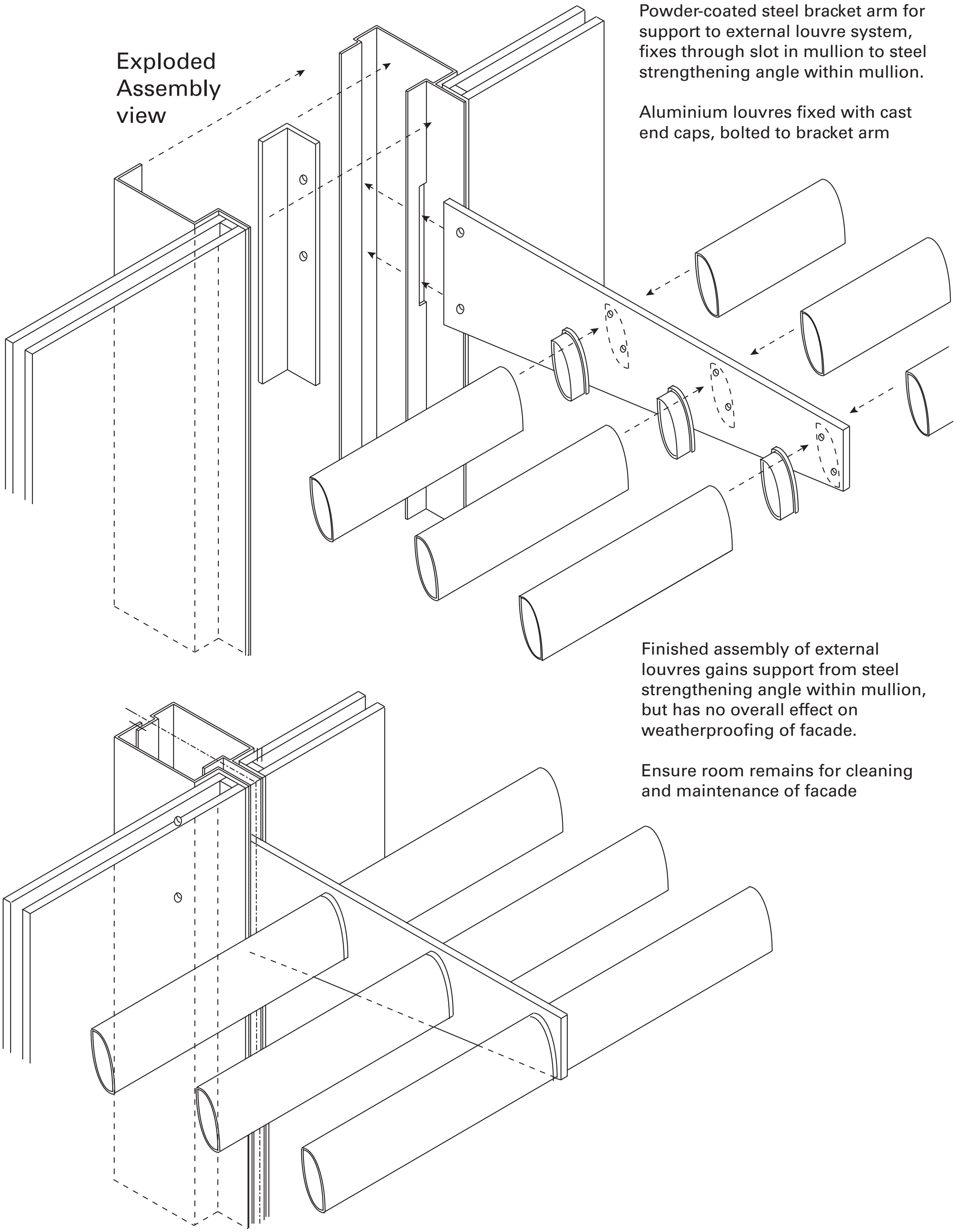


Figure 17.8 Unitised system with inserted bracket for external louvres

Securing performance

Involves the thoughtful and careful selection of the façade contractor to be entrusted with the design of the façade as set out in Methods 2&3 on a rational basis of skill/competence/trade knowledge/sound financials/site control and the ability to deliver the required quality. Involvement includes stating the proofs of compliance that will be necessary and confirmation of the Quality Assurance that will be delivered to conform with ISO 9001, including testing during manufacture and on site when in place. The provision of shop drawings is reviewed by third parties and prepared to a particular, specified quality standard. Prototypes manufactured and tested are important parts of securing performance. And over it all are the agreed levels of the on- and off-site observation to be provided by the designer, the façade consultant and the contractor.

All this diligence is required to secure the contracted performance.

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18

Chapter Eighteen

Façade detailing

Façade detailing

Guy Marriage

18.0 External façade

In the previous two chapters, we have examined the history, the principles, and the performance criteria that your façade has to meet. In this final chapter, we bring the whole building together in the illustrations included here, with drawings that integrate the façade with the underlying structure and internal servicing. We also recap on some of the water-proofing detailing devices that you need to know, in particular around the design of complex elements of the building such as the façade.

Façade engineers

The actual final detailing of the façade is now getting so specialised, especially on large and tall buildings, that your local Council is unlikely to have the specialist knowledge on how to evaluate the weathertightness of the proposal. Increasingly, therefore, 'façade engineers' are being brought onto projects to design, to help, or to peer-review the façade designs. The façade engineers will have an experienced understanding of the issues that need to be looked out for on a high-rise construction project and will advise the architectural team on the issues that need to be resolved. You have seen the range of issues that need to be considered when addressing façade performance in Table 17.1.

Façade contractors

While contractors are becoming more and more involved at running the project in general, this reaches a peak with the involvement of the façade contractors. Often one single contractor is asked to provide a price for the cladding package to cover the entire external part of the building – walls, roof, all the railings, glazing, and any penetrations through the façade into the structure. That way, the entire responsibility for water-proofing a façade can be assigned to just one single contractor and that can easily add up to 10–25% of the entire cost of any large building project.

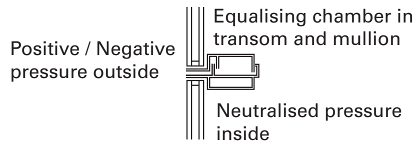
Understandably, therefore, these specialist façade contractors are extremely sought after, with often only one major contractor per country. In Europe, there is Permasteelisa in Italy; Lindner (who absorbed Schmidlin), Seele, Gotz, and Schuco in Germany; Kawneer in the USA; while in New Zealand there is only Thermosash. Much of the technical expertise and manufacturing of these advanced façades is done in Europe, specifically Germany, while most other countries lag behind.

Unlike the General Arrangement drawings where the Architect may still take the lead in the documentation phase, because of the importance of the façade drawing package, the industry is increasingly seeing a majority of the façade

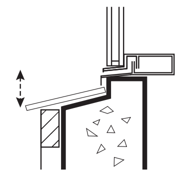
documentation actually being done by the façade contractors themselves. The architects and engineers may have some input into the design of these drawings to ensure the appearance and performance of the façade is as they want, but because the Council no longer has the ability to vet the drawings correctly, the alternative is that they may bring in an experienced practitioner – a 'peer reviewer'. In order for you to have as smooth a process through the peer review process as possible, you need to know more about how the water-proofing systems work.

P.R.O.B.L.E.M

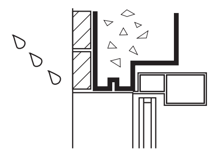
Pressure :
create a chamber in your façade design to allow the pressure to equalise



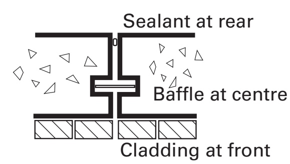
Rebates :
don't let water drive straight in, form a physical step in the slab and the walls



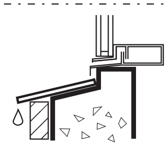
Overlap :
the lower member should always be protected by the upper member



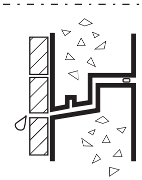
Baffle :
provide a second or third line of defence with an internal barrier



Lips :
rebate the slab edge to form a lip that protrudes out



Exit :
always allow the water to find a way out and exit the building façade



Membrane :
always lay a waterproof membrane (DPM or DPC) on your base material

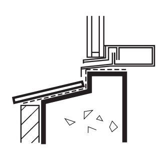


Figure 18.1 P.R.O.B.L.E.M.

18.1 Water-proofing

The greatest life-giving force in nature, which we all need to survive, is water. Unfortunately, when it comes to buildings, the biggest problem is that same thing: water. To make your building survive, you need to make sure that water does not get into your building. In theory, this is easy: water is easily affected by gravity and likes to go downhill, so make sure there is always a route for water to track *down and out* of your building, avoiding the possibility of the water going *down and in*. But if it is so easy, then how come so many buildings all over the world suffer from leaks?

Part of the problem is that low-rise, simple, residential design details are used by some designers and contractors on the much harder problem of commercial multi-storey buildings. To be frank: those details are not good enough. In many cases, the materials used are not suitable either.

Modern commercial office buildings are now usually built to incredibly high standards, as well as being very rigorously tested via full-scale prototypes. Large test rigs belonging to all the major cladding installers all over the world can test a full-scale section of your wall, using the actual products that will be used on the final completed façade. By blasting air and water at the façade at enormous pressures, often with the help of an aeroplane engine or similar, any faults in the building design can be ironed out before the whole building appears on-site. In cities like Dubai and Abu Dhabi, the issues are likely to also involve the incredible heat on the façade, as well as the fine sand of the desert dust storms. The high temperatures that the façade will reach may cause materials to expand beyond the range of what otherwise may be considered normal.

Some of the outcomes of the façade testing is that a more in-depth understanding of the issues around water-proofing is evolving. Some of these water-proofing issues are already well known. We know that water always responds to gravity, usually flowing downhill. The first issue is that under extreme weather conditions, water is able to be driven *uphill* by peaks in wind pressure. If you live in a windy city like Wellington or Chicago or actually any city with tall buildings, then watch out for water not following the laws of gravity and working its way uphill. In Wellington, where I work, on one particularly crazy weather day, I actually saw hail being blown *up* the side of a building (that's not normal by the way!).

By creating a façade detail with a pressure-equalising chamber in it (as most quality façade systems have), water droplets may be driven momentarily as far as the first chamber, and once the wind gust is over, the water can then once more continue down and outwards, free from the façade. That's one important principle right there: allow the pressure outside to be lessened before it comes inside. We include for you here some important detailing 'cheat sheets' that spell out, in

drawn form and in words, the ways for you to make sure your **problem** has gone away, and have been **changed** into an opportunity for good solid weatherproof detailing (refer to Figures 18.1 and 18.2). Study these and implement them in your design. Print them out and pin them next to your desk so that you see them every day.

Water does not just need wind for it to move – it is quite happy moving along by itself. The curious phenomenon known as capillary action can have serious water-proofing effects – water will track *up* a small thin crack with amazing rapidity in any gap up to 5mm wide. So, a building with a bigger gap (say, 6–10mm) is less likely to have problems than a building with a fine, almost un-noticeable 2mm gap. That 2mm gap will mean that any moisture, even without the encouragement of wind, will work its way inside. So too will water work its way in with an even tinier 0.5mm gap – any moisture on the surface will get actively sucked right up into the gap. Again, the extra width of the pressure-equalising chamber can help here as well, providing a clean, clear break from the curious effects of the capillary gap.

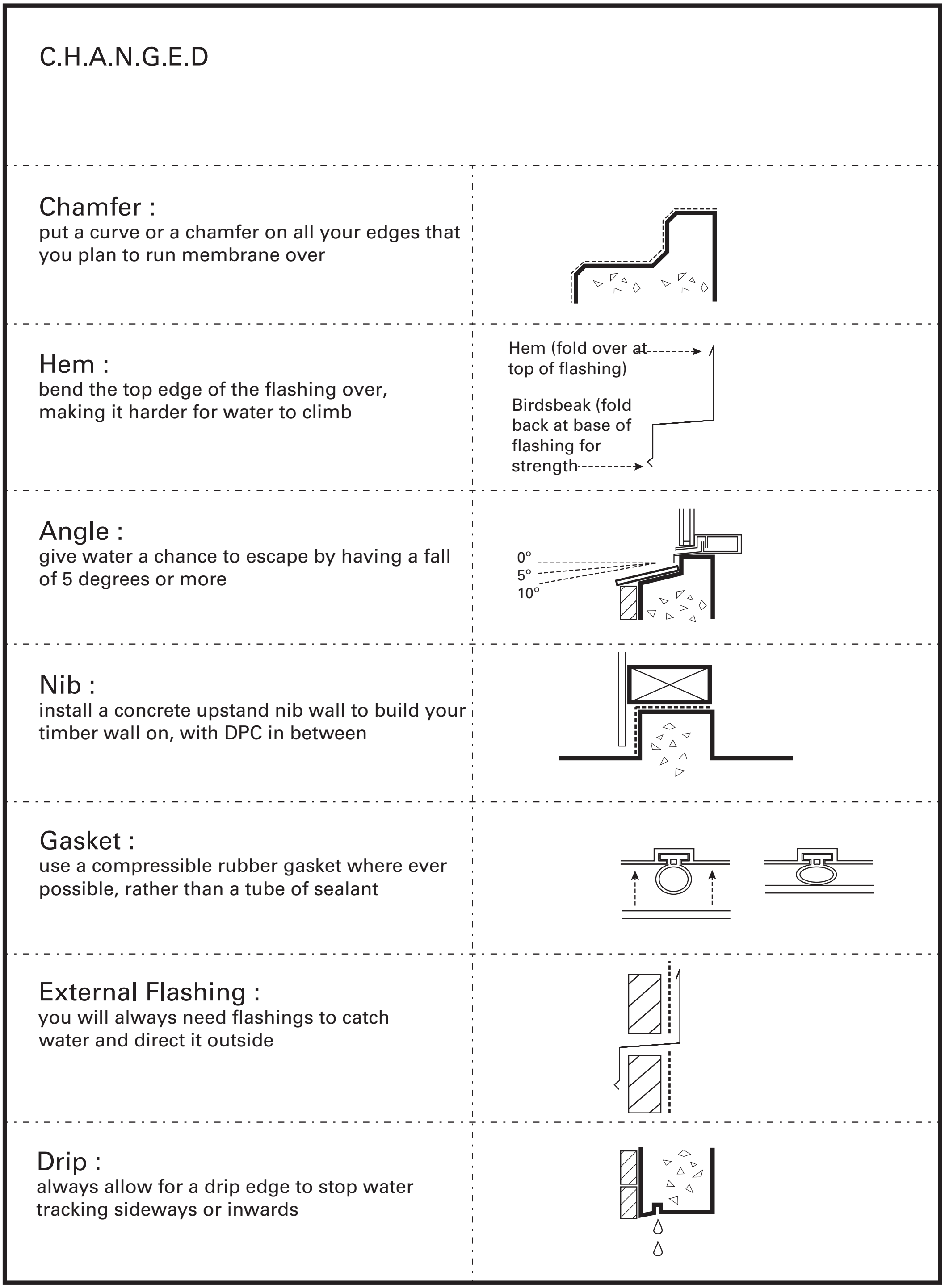


Figure 18.2 C.H.A.N.G.E.D.

18.2 Water-proofing mantras

Let us start with some basics for water-proofing that will work on any size of building and deal broadly with any problem. BRANZ, the Building Research Association of New Zealand, states that for water-proofing of housing you always need to think about the four Ds (Weathertight, 2017):

Deflection – deflect rain away from walls.
Drainage – design wall assemblies to incorporate drainage to allow water to escape.
Drying – allow ventilation into cavities to permit air movement and assist drying.
Durability – all materials must meet the durability requirements of the Building Code.

These four basic guidelines were developed by BRANZ and modelled after the Canadian system (which had, from memory, six Ds – I'm not sure where the other two Ds went). The principles still hold true, both for small residential buildings, as well as the bigger, taller buildings we have been discussing.

In addition, we need to establish some further design principles that all good façade designers understand and keep to. These are shown in the form of two handy little mnemonics (refer to Figures 18.1 and 18.2). There are many more detailing tips we could give, but these basic moves will help you understand the issues and put in place solutions to solve the problems. We've also included a summary of the basics on external material cladding connections (refer to Figure 18.3).

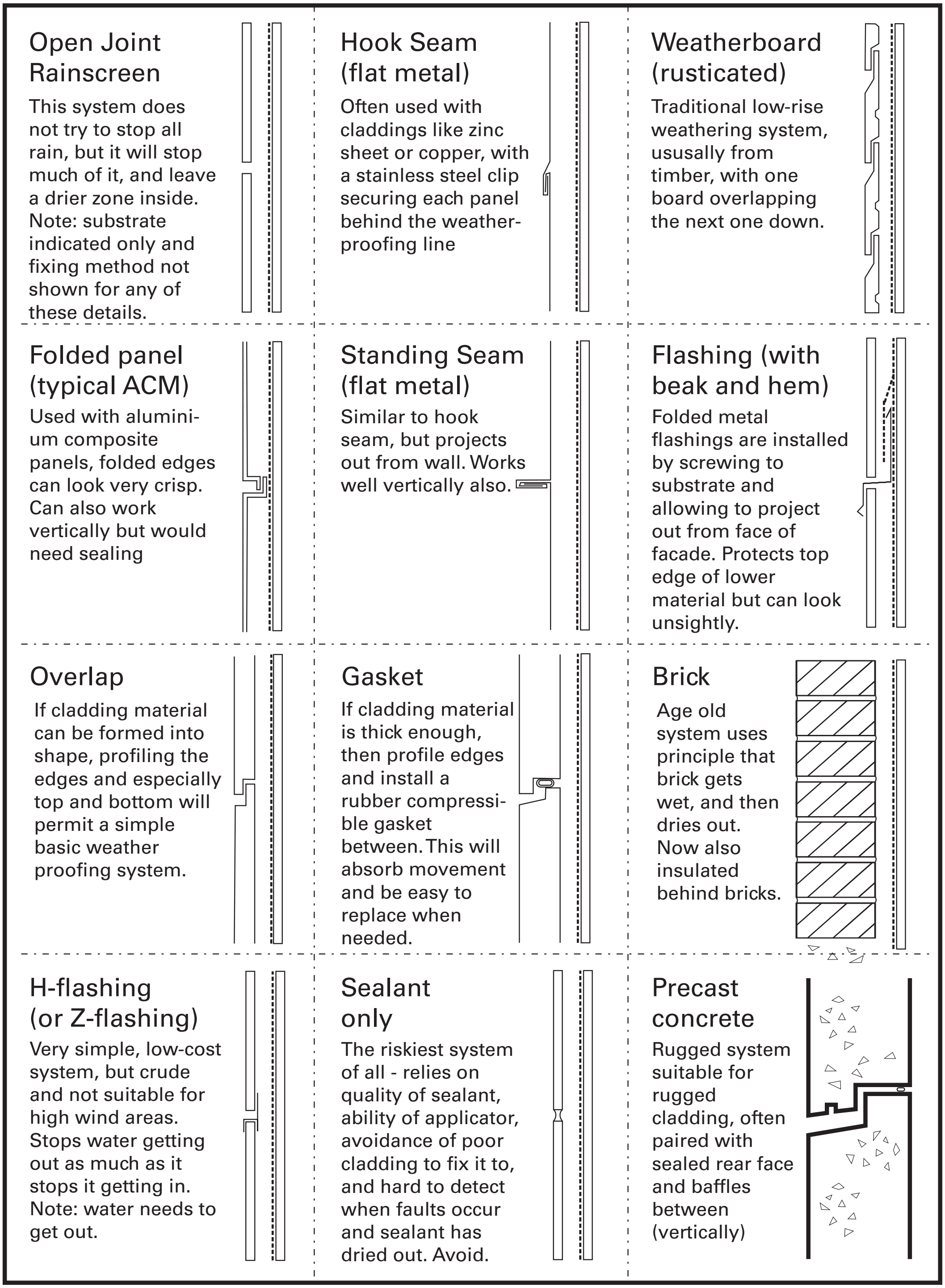


Figure 18.3 Cladding joints

18.3 Modern construction issues

Many students of architecture reading this text will find that some parts of this book have introduced new information to them that they may not have been fully aware of before. Other students may be being taught outdated and outmoded means of construction such as brick detailing, still highly popular in small residential developments in places like England (refer to Figure 18.4). This is a perfectly valid material system for the construction of housing similar to those we have seen for the last few hundred years, but as humankind moves more and more into living in highly urbanised situations like our modern metropolis, there is an undeniable reality to face. We cannot build our way out of our current housing predicament by continuing to build small houses all over the land and driving to work in fossil-fuelled cars with internal combustion engines. Nor can we expect to build the modern metropolis using the same methods of construction involving application of cement mortar to rectangles of kiln-dried clay.

The future of our cities worldwide, but especially in the developed world, is already well established in the modern construction idiom. It is not perfect, but it is the way that we build now, as well as in the foreseeable future. There are serious concerns over the use of concrete due to the extensive production of cement and the CO_2 this produces. A report in the Guardian newspaper notes, 'perhaps the most astonishing statistic of the modern age: since 2003, China has poured more cement every three years than the US managed in the entire 20th century'. (Watts, 2019 and Gates, 2014). Clearly, the present rate of use of this material is unsustainable and urgently needs to be changed, but there is no denying that at present there are no viable alternatives to its use in building foundations.

Similarly, the use of steel, while highly recyclable and admirably recycled, is still highly problematic. Production of steel is one of the materials that still requires the intense heat from the burning of coking coal to get the furnaces to a high enough temperature in the first place. Solar-powered photovoltaic (PV) panels are great at trickle-generating electricity in an environmentally sustainable manner (if we ignore the damage caused by the creation of the PV panels in the first place), but they cannot generate enough heat to run a steel smelter. The cruel blunt fact remains that the continued use of fossilised plant remains from hundreds of millions of years ago (coal, in case you haven't been paying attention) is, at this stage, still necessary for the creation of steel.

There are other materials, barely discussed in this book, including the production of aluminium (or aluminum to our American readers). Aluminium is used extensively for window systems in New Zealand, while other countries may prefer to use PVC, with varying levels of success (but not on high-rise buildings). Aluminium has some good points: it is both highly recyclable and highly recycled in many parts of the world, but the unpleasant truth is that it is monstrously energy intensive to process bauxite into

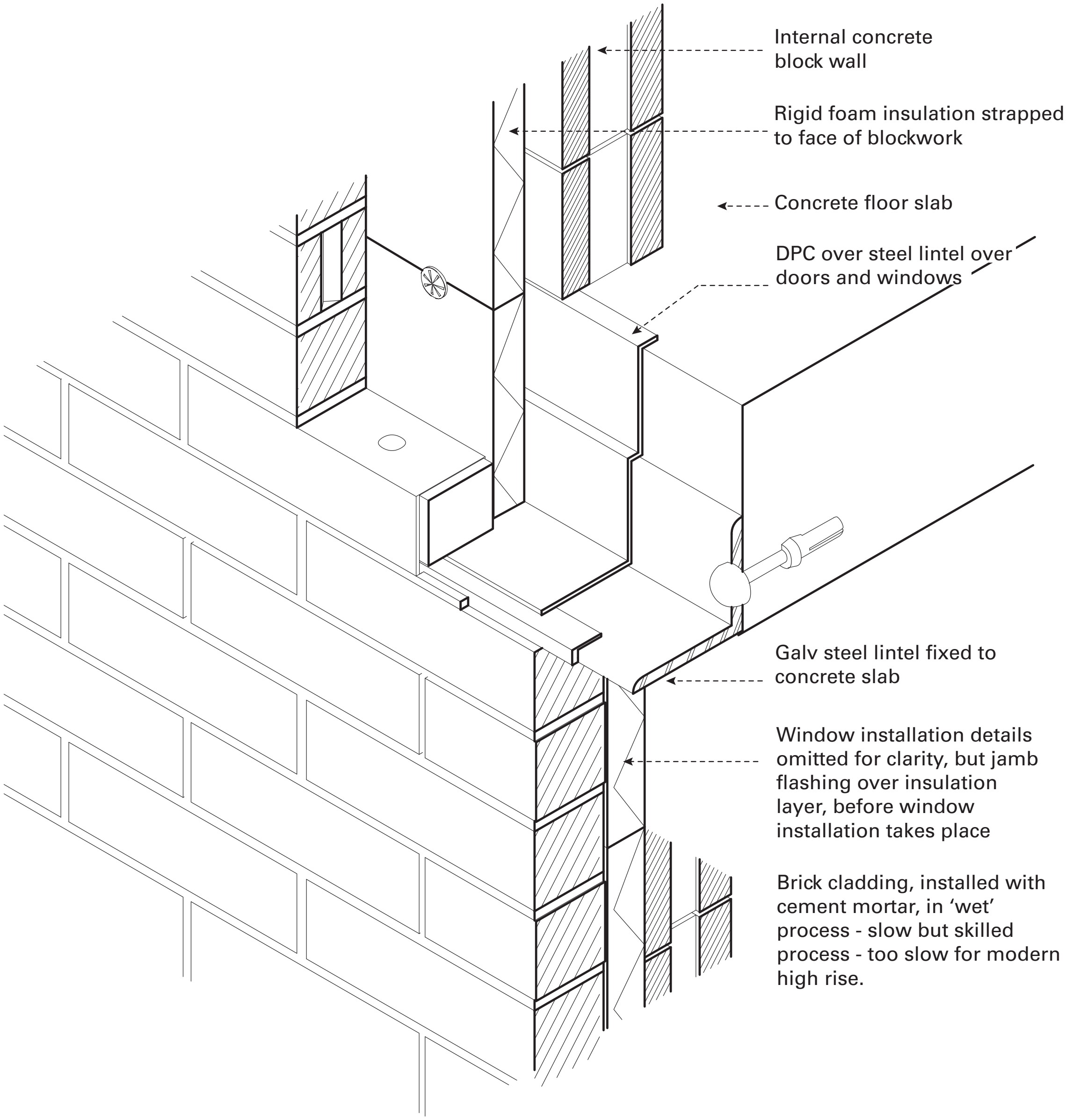


Figure 18.4 Brick detail

alumina in the first place, before the final smelting into ingots of aluminium. New Zealand is one of the few places in the world where aluminium is produced using no fossil fuels, by utilising the massive power of the Manapouri hydro-electric dam to power the turbines that produce our aluminium. The rest of the country pays for this feature through ridiculously high electrical power prices, in the process producing some of the purest aluminium in the world, used for things like the body of your Apple iBook. Please don't mention it – there is nothing I enjoy more than paying through the nose for electricity just to help support the massive profits of one of the wealthiest companies on the planet. . .

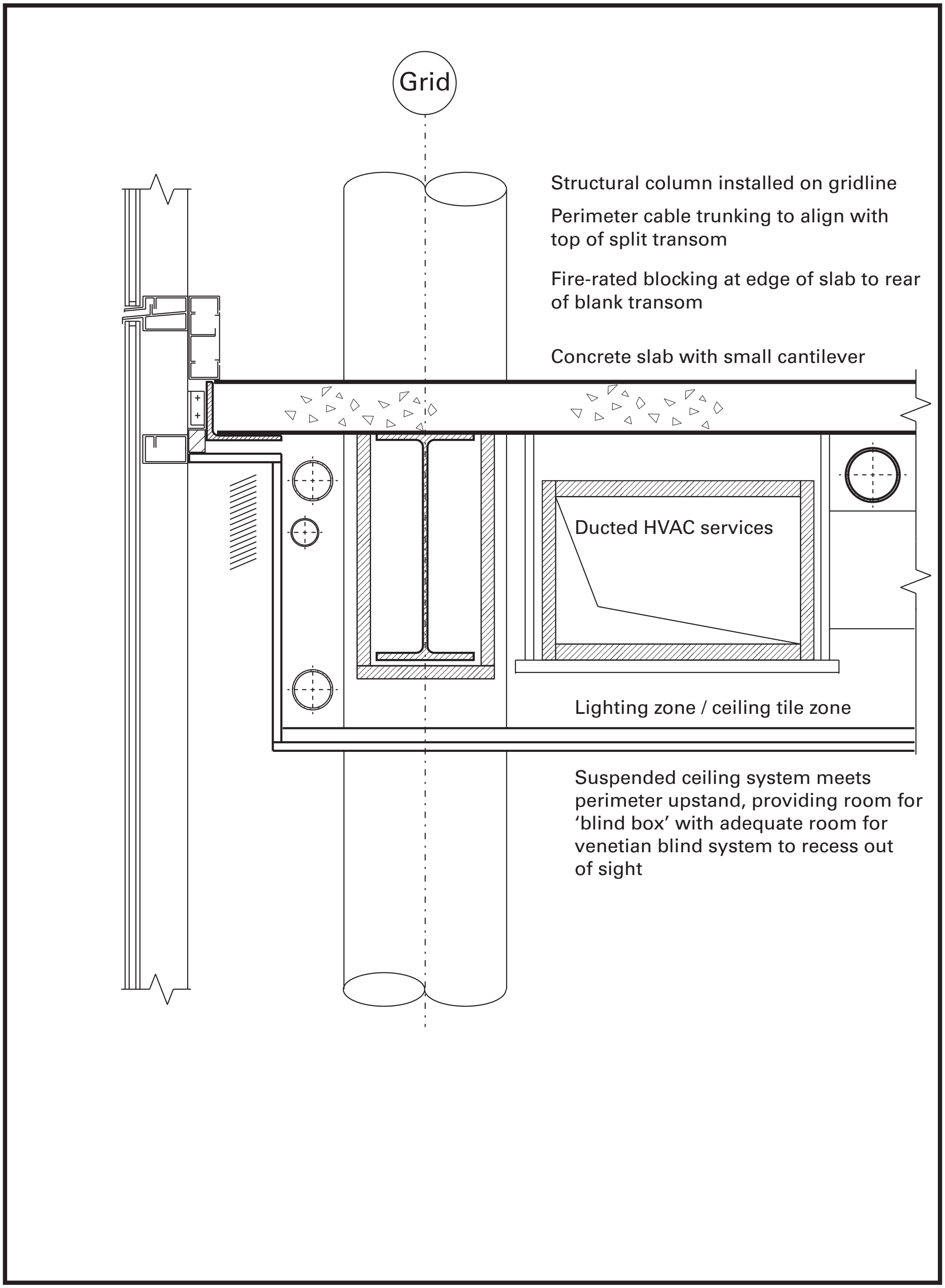


Figure 18.5 Section: glazed curtain wall / ceiling junction

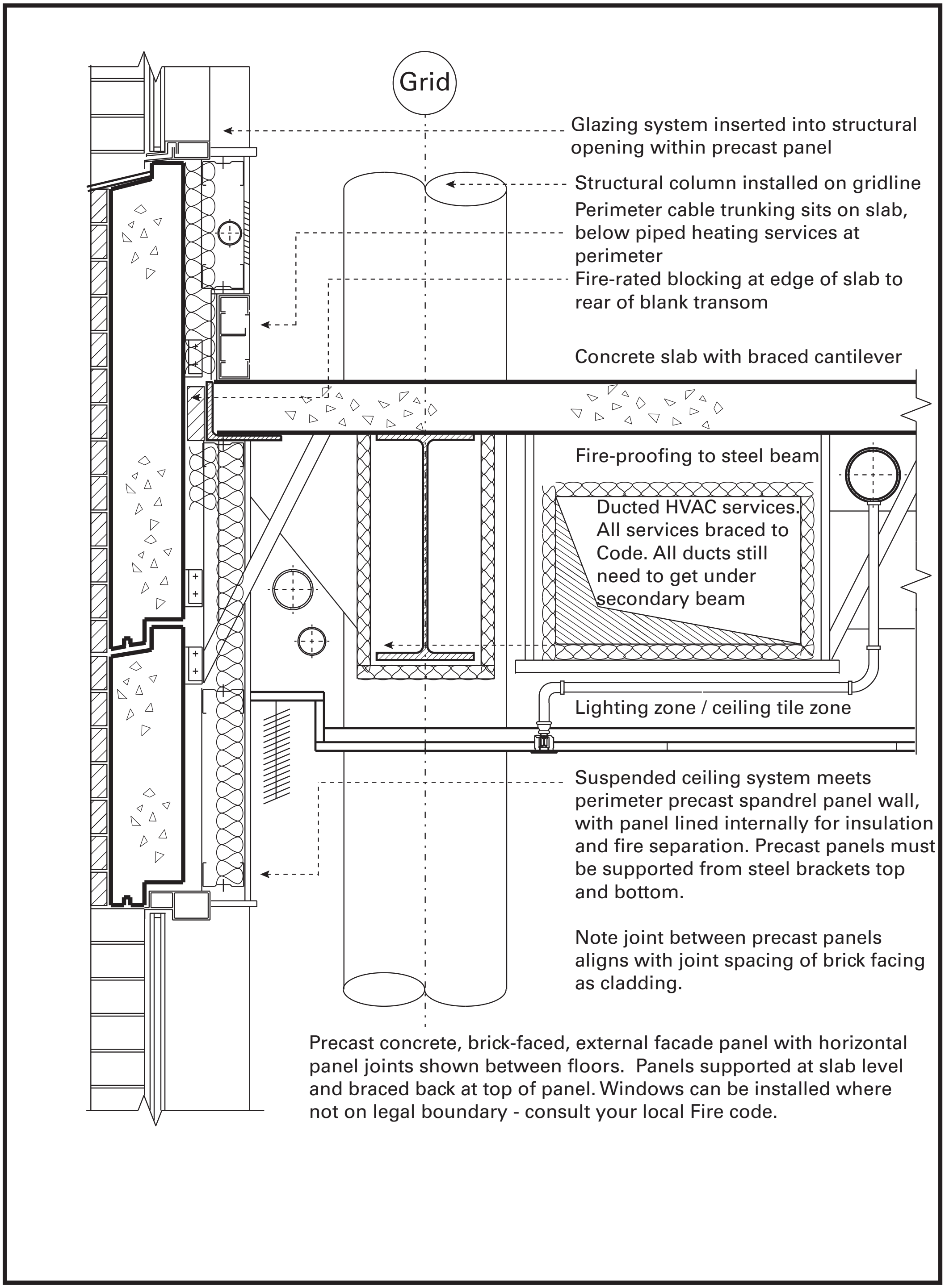


Figure 18.6 Section: precast concrete panels / ceiling junction

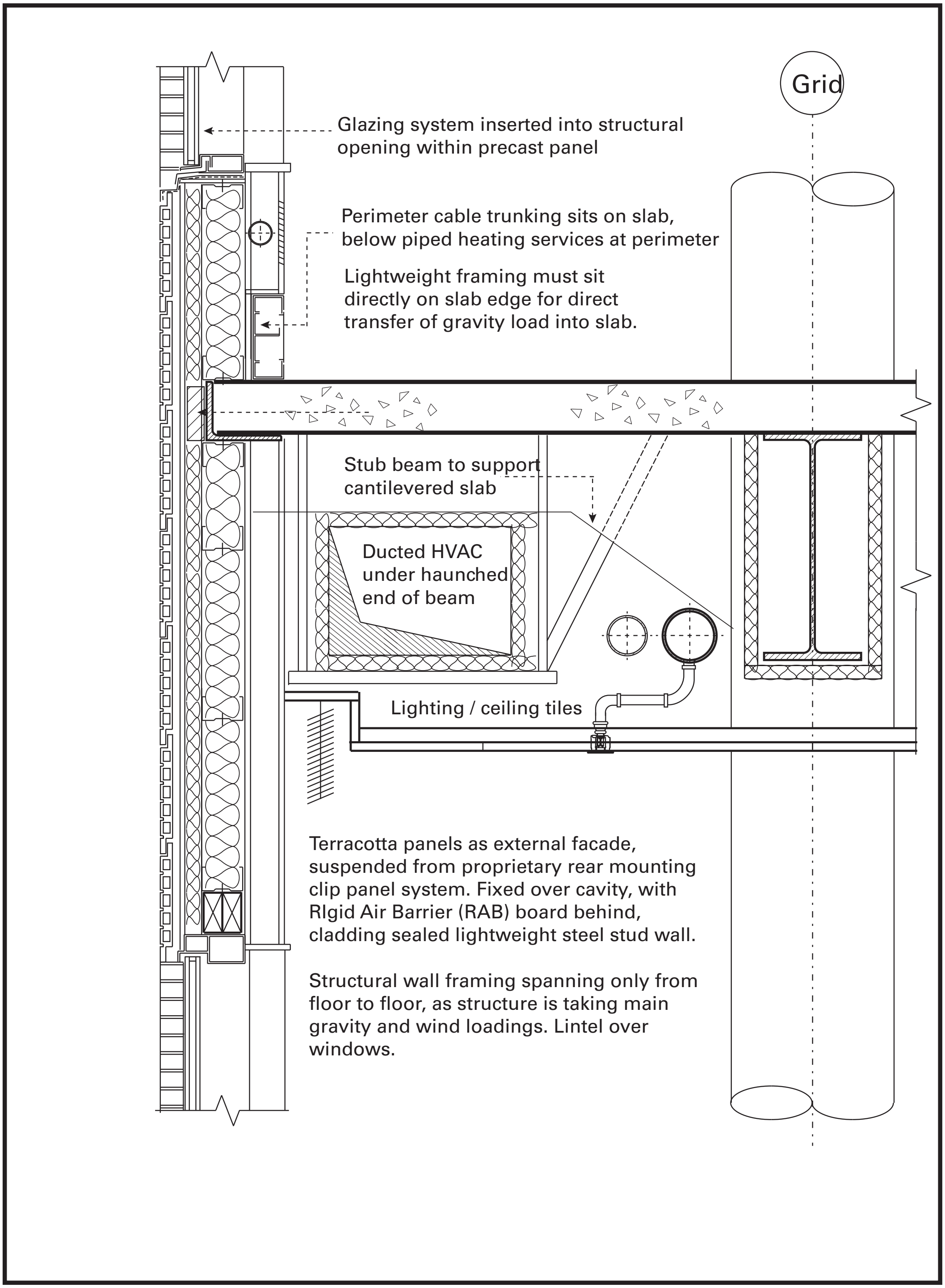


Figure 18.7 Section: terracotta cladding / ceiling junction

18.4 Construction in the future

The author of this chapter firmly believes that the future needs to change, and the answer is in your hands. Continued massive consumption of steel and concrete is clearly out of the question for the health and future of humankind on this planet. Continuing on-site construction of complicated building systems is also clearly not the way forward if we want to build quickly, reliably, and on a large scale. The real future of the world's construction industry lies in two key changes to our methods of construction: off-site construction (prefabrication) and engineered timber production. The high cost of labour in developed countries and the poor safety record of construction companies worldwide will inevitably mean a continued move to constructing larger and larger parts of buildings in controlled factory conditions. Unitised façade components are an obvious shining example of the advantages to constructing offsite and just assembling on-site.

The continued developments in engineered timber buildings are, to me, undoubtedly the way forward for the construction industry in many countries around the world, an area that my students and I, as well as my work colleagues at the incredible First Light Studio, are busy exploring – both on paper and in real life. One of my former students, Ben Sutherland, constructed a completely digitally fabricated CLT house (New Zealand's first) as part of his Master of Architecture thesis and then set up a company (Makers of Architecture) to continue to do the same for other people (Marriage and Sutherland, 2014). The future of construction is clearly growing in forests all around us as we speak. Timber products are lightweight, incredibly strong, and flexible, and lock away large amounts of CO_2 that we have otherwise not yet figured out what to do with.

The time will come – perhaps shortly, but more likely in a long time period – where the information in this book is no longer relevant and all it does is describe methods of construction that belong in a museum. But I suspect this book will still be relevant for many years yet. Congratulations. You have got to the end of this book and I hope you found it useful, informative, and entertaining. Even more importantly, I hope that you have found it so useful that you have gone out and bought your own copy and have it near your desk as you work on your assignments or your first multi-storey high-rise office building. The future of the world is in your hands. Make the best of it that you can.

Guy Marriage, 1 March 2019.

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