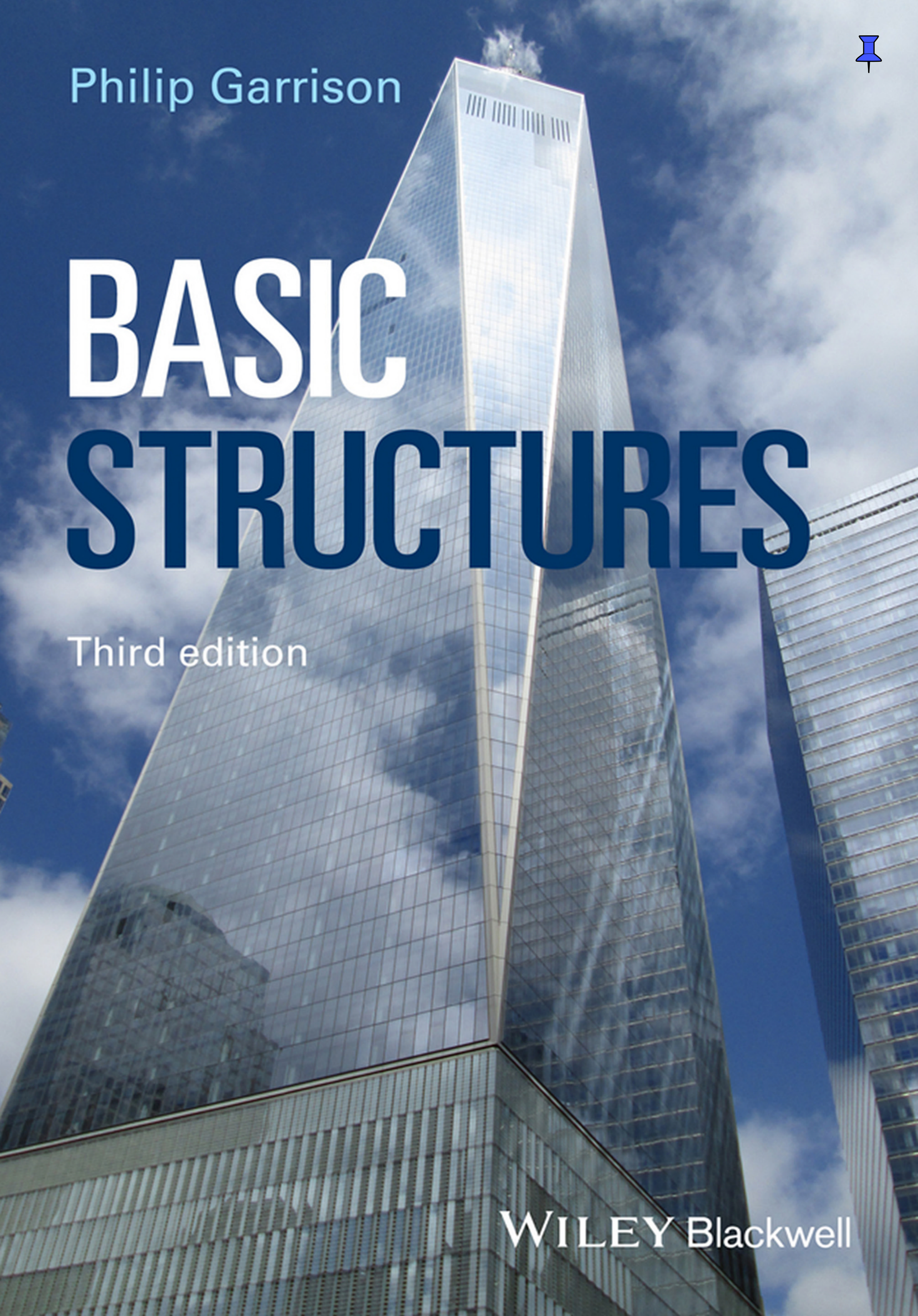
Philip Garrison

BASIC STRUCTURES

Third edition



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Basic Structures

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3rd Edition

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To my father and late mother, Fred & Jean Garrison

Contents

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- Colleagues Matt Peat and Dave Roberts who diligently read the first edition of this book and pointed out the several errors that I, the reviewers and proofreaders had all overlooked.
- Brian Walker, who patiently and with great humour taught mathematics to me and my fellow adolescents at Aberdeen Grammar School back in the early 1970s. (If you ever read this Brian do get in touch. Chapter 27 is down to you.)
- Last but not least Jim Adams, without his inspiration there would have been no book.

And, to parrot that hackneyed catch-all used by all authors at this point, my thanks go to all the others I haven't mentioned, without whom, etc. – they know who they are!

Last but not least, my thanks go to you, the reader, for buying this book. I understand that textbooks are expensive and student resources are stretched to the limit, so thank you for your faith in me and I trust you will not be disappointed.

And thanks to those who bought the previous editions of the book. In the 11 years since this book first appeared I've received countless emails from readers all over the world. It is always gratifying to hear that I've managed to help a complete stranger who I almost certainly will never meet. Keep them coming!

Introduction

When I was 16 years I had a Saturday job as a shelf-stacker at a local supermarket. One day, during a tea break, a co-worker asked me what I did the rest of the week. I explained that I had just done O levels and was going on to do A levels. I told him how many and in which subjects. He then asked me about my career aspirations (not his exact words). I explained that I wanted to become an engineer. His aghast response was: 'What! With all those qualifications?'

Engineers suffer from a lack of public perception of what their profession entails – many people think we spend our days in the suburbs, mending washing machines and televisions. Architects are more fortunate in this respect – the public have a better grasp of their profession: 'They design buildings, don't they?'

Public perceptions aside, careers in both civil engineering and architecture can be extremely rewarding. There are few other careers where individuals can be truly creative, often on a massive scale. The civil engineering profession offers a variety of working environments and a large number of specialisms within civil engineering. Civil engineers have opportunities to work all over the world, on projects large and small, and could come into contact with a wide variety of people, from the lowest worker on a construction site to government officials and heads of state.

In the 21st century there is a huge demand for civil engineers and many young people (and some not so young!) are realising that this is a profession well worth entering.

Traditionally, students embarking on university courses in civil engineering would have A levels in subjects such as mathematics, physics and chemistry. However, for a variety of reasons, many of today's potential students have A levels (or similar) in non-numerate and non-scientific subjects. Moreover, a sizeable number of 'mature' people are entering the profession following a first career in something completely different. As a university admissions tutor, I speak to such people everyday. It is possible, depending on the specialism eventually chosen, to enjoy a successful career in civil engineering without an in-depth mathematical knowledge. However, it is extremely difficult to obtain a degree or Higher National Diploma (HND) in civil engineering without some mathematical proficiency.

Turning to architects – these are creative people! Every building they design has a structure, without which the building would not stand up. Architects, like civil engineers, have to understand the mechanisms which lead to successful structures.

This book is about Structures. Structures is a subject studied as part of all civil engineering degree, HND and Ordinary National Diploma (OND) courses, as well as architecture degree courses, and also on some degree courses in related subjects (e.g. quantity surveying, building surveying, construction management and architecture).

The purpose of this book

I have taught structures to undergraduate civil engineers and architects since 1992. During that time I have noticed that many students find the basic concept of structures difficult to grasp and apply.

This book aims to do the following:

- to explain structural concepts clearly, using analogies and examples to illustrate the points
- to express the mathematical aspects of the subject in a straightforward manner that can be understood by mathematically weak students and placed in context with the concepts involved
- to maintain reader interest by incorporating into the text real-life examples and case histories to underline the relevance of the material that the student is learning.

This book presumes no previous knowledge of structures on the part of the reader. It does, however, presume that the reader has a good general education and a mathematical ability up to at least GCSE standard.

The intended readership

This book is aimed at:

- Ordinary National Certificate (ONC), Ordinary National Diploma (OND), Higher National Certificate (HNC), Higher National Diploma (HND) or first-year degree (BSc, BEng or MEng) students on a civil engineering (or similar) course, who will study a module called structures, structural mechanics, mechanics or structural analysis
- students on a BA degree course in architecture.

The following will also find this book useful:

- students on courses in subjects related to civil engineering and architecture – e.g. quantity surveying, building surveying, construction management or architectural technology – who have to do a structures module as part of their studies
- those studying technology at GCE A level, GNVQ or similar
- people working in the construction industry in any capacity.

The following will find the book a useful revision tool:

- a second (or subsequent)-year student on a civil engineering or architecture degree
- a professional in the civil engineering or building industry, and practising architects.

A word about computers

Computer packages are available for every specialism, and structural engineering is no exception. Certainly, some of the problems in this book could be solved more quickly using computer software. However, I do not mention specific computer packages in this book and where I mention computers at all, it is in general terms. There are two reasons for this.

1) The purpose of this book is to acquaint the reader with the basic principles of structures. Whereas a computer is a useful tool for solving specific problems, it is no substitute for a thorough grounding in the basics of the subject.
2) Computer software is being improved and updated all the time. The most popular and up-to-date computer package for structural engineering as I write these words may be dated (at best) or obsolete (at worst) by the time you read this. If you are interested in the

latest software, look at specialist computer magazines or articles and advertisements in the civil and structural engineering and architecture press, or if you are a student, consult your lecturers.

I have set my students assignments where they have to solve a structural problem by hand then check their results by analysing the same problem using appropriate computer software. If the answers obtained by the two approaches differ, it is always instructive to find out whether the error is in the student's hand calculations (most frequently the case) or in the computer analysis (occurs less frequently, but does happen sometimes when the student has input incorrect or incomplete data – the old 'rubbish in, rubbish out'!).

The website

You will find worked solutions to some of the problems in this book at a website maintained by the publishers: www.blackwellpublishing.com/garrison. In addition, all readers can contact me via the website – your suggestions, comments and criticisms are welcome.

An overview of this book

If you are a student studying a module called structures, structural mechanics or similar, the chapter headings in this book will tie in – more or less – with the lecture topics presented by your lecturer or tutor. I suggest that you read each chapter of this book soon after the relevant lecture or class to reinforce your knowledge and skills in the topic concerned. I advise all readers to have a pen and paper beside them to jot down notes as they go through the book – particularly the numerical examples. In my experience, this greatly aids understanding.

- Chapters 1–5 introduce the fundamental concepts, terms and language of structures.
- Chapters 6–10 build on the basic concepts and show how they can be used, mathematically, to solve simple structural problems.
- Chapter 11 deals with the very important concept of stability and discusses how to ensure structures are stable – and recognise when they're not!
- Chapters 12–15 deal with the analysis of pin-jointed frames, a topic that some students find difficult.
- Chapter 16 covers shear force and bending moment diagrams – an extremely important topic.
- Chapters 17–20 deal with stress in its various guises.
- Structural materials are dealt with more fully in other texts, but Chapter 21 provides an introduction to this topic.
- Chapter 22 has more on materials, and a word on design standards.
- Chapters 23 and 24 deal, respectively, with the conceptual design of structures and the calculation of loads.
- Chapter 25 is a descriptive introduction to structural design, which should be read before embarking on a structural design module.
- Chapter 26 discusses more unusual types of structures.
- Chapter 27 deals with deflection, and outlines a method whereby deflections can be calculated.
- Chapters 28–34 serve as an easy introduction to several slightly harder topics that students will encounter on the second or third year of a civil engineering degree course.

How to use this book

It is not necessary for all readers to read this book from cover to cover. However, the book has been designed to follow the subject matter in the order usually adopted by teachers and lecturers teaching structures to students on degree and HND courses in civil engineering. If you are a student on such a course, I suggest that you read the book in stages in parallel with your lectures.

- All readers should read Chapters 1–5 as these lay down the fundamentals of the subject.
- Civil engineering students should read all chapters in the book, with the possible exception of Chapters 14 and 15 if these topics are not taught on your course.
- Students of architecture should concentrate on Chapters 1–9, 21–24 and 26, but read certain other chapters as directed by your tutor.
- If you're studying civil engineering and want to know how to get more out of the profession whilst you are a student, see Appendix 6 for inspiration.

Let's keep it simple

James Dyson, the inventor of the dual cyclone vacuum cleaner that bears his name, discusses one of its design features – the transparent plastic cylinder within which the rubbish collects – in his autobiography:

> A journalist who came to interview me once asked, 'The area where the dirt collects is transparent, thus parading all our detritus on the outside, and turning the classic design inside out. Is this some post-modernist nod to the architectural style pioneered by Richard Rodgers at the Pompidou Centre, where the air-conditioning and escalators, the very guts, are made into a self-referential design feature?
>
> 'No,' I replied. 'It's so you can see when it's full.'
>
> (From *Against the Odds* by James Dyson and Giles Coren (Texere 2001))

It is my aim to keep this book as simple, straightforward and jargon-free as possible.

Worked solutions to the tutorial questions can be found at

www.wiley.com/go/garrison/basicstructures

1 What is structural engineering?

Introduction

In this chapter you, the reader, are introduced to structures. We will discuss what a structure actually is. The professional concerned with structures is the structural engineer. We will look at the role of the structural engineer in the context of other construction professionals. We will also examine the structural requirements of a building and will review the various individual parts of a structure and the way they interrelate. Finally you will receive some direction on how to use this book depending on the course you are studying or the nature of your interest in structures.

Structures in the context of everyday life

There is a new confidence evident in major British cities. Redundant Victorian industrial structures are being converted to luxury apartments. Tired old 1960s shopping centres are being razed to the ground, and attractive and contemporary replacements are appearing. Public housing estates built over 40 years ago are being demolished and replaced with more suitable housing. Social shifts are occurring: young professional people are starting to live in city centres and new services such as cafés, bars and restaurants are springing up to serve them. All these new uses require new buildings or converted old buildings. Every building has to have a structure. In some of these new buildings the structure will be 'extrovert' – in other words the structural frame of the building will be clearly visible to passers-by. In many others, the structure will be concealed. But, whether seen or not, the structure is an essential part of any building. Without it, there would be no building.

What is a structure?

The structure of a building (or other object) is the part which is responsible for maintaining the shape of the building under the influence of the forces, loads and other environmental factors to which it is subjected. It is important that the structure as a whole (or any part of it) does not fall down, break or deform to an unacceptable degree when subjected to such forces or loads.

The study of structures involves the analysis of the forces and stresses occurring within a structure and the design of suitable components to cater for such forces and stresses.

As an analogy, consider the human body, which comprises a skeleton of 206 bones. If any of the bones in your body were to break, or if any of the joints between those bones were to disconnect or seize up, your injured body would 'fail' structurally (and cause you a great deal of pain).

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Fig. 1.1 **Lower Manhattan skyline, New York City.**
This is one of the largest concentrations of high-rise buildings in the world: space limitations on the island of Manhattan meant that building construction had to proceed upwards rather than outwards, and the presence of solid rock made foundations for these soaring structures feasible.

Examples of structural components (or 'members', as structural engineers call them) include the following:

- steel beams, columns, roof trusses and space frames
- reinforced concrete beams, columns, slabs, retaining walls and foundations
- timber joists, columns, glulam beams and roof trusses
- masonry walls and columns.

For an example of a densely packed collection of structures, see Fig. 1.1.

What is an engineer?

As mentioned in the introduction, the general public is poorly informed about what an engineer is and what he or she does. 'Engineer' is not the correct word for the person who comes round to repair your ailing tumble dryer or office photocopier – nor does it have much to do with engines! In fact, the word 'engineer' comes from the French word *ingénieur*, which refers to someone who uses their ingenuity to solve problems. An engineer, therefore, is a problem-solver.

When we buy a product – for example, a bottle-opener, a bicycle or a loaf of bread – we are really buying a solution to a problem. For instance, you would buy a car not because you wish to have a tonne of metal parked outside your house but rather because of the service it can offer you: a car solves a transportation problem. You could probably think of numerous other examples:

- A can of baked beans solves a hunger problem.
- Scaffolding solves an access problem.
- Furniture polish solves a cleaning problem.
- A house or flat solves an accommodation problem.
- A university course solves an education problem.

A structural engineer solves the problem of ensuring that a building – or other structure – is adequate (in terms of strength, stability, cost, etc.) for its intended use. We shall expand on this later in the chapter. A structural engineer does not usually work alone: he is part of a team of professionals, as we shall see.

The structural engineer in the context of related professions

If I were to ask you to name some of the professionals involved in the design of buildings, the list you would come up with would probably include the following:

- architect
- structural engineer
- quantity surveyor.

Of course, this is not an exhaustive list. There are many other professionals involved in building design (e.g., building surveyors and project managers) and many more trades and professions involved in the actual construction of buildings, but for simplicity we will confine our discussion to the three named earlier.

The architect is responsible for the design of a building with particular regard to its appearance and environmental qualities such as light levels and noise insulation. His starting point is the client's brief. (The client is usually the person or organisation that is paying for the work to be done.)

The structural engineer is responsible for ensuring that the building can safely withstand all the forces to which it is likely to be subjected, and that it will not deflect or crack unduly in use.

The quantity surveyor is responsible for measuring and pricing the work to be undertaken – and for keeping track of costs as the work proceeds.

So, in short:

1) The architect makes sure the building looks good.
2) The (structural) engineer ensures that it will stand up.
3) The quantity surveyor ensures that its construction is economical.

Of course, these are very simplistic definitions, but they'll do for our purposes.

Now I'm not an architect and I'm not a quantity surveyor. (My father is a quantity surveyor, but he's not writing this book.) However, I am a structural engineer and this book is about structural engineering, so in the remainder of this chapter we're going to explore the role of the structural engineer in a little more detail.

Structural understanding

The basic function of a structure is to transmit loads from the point at which the load is applied to the point of support and thus to the foundations in the ground. (We'll be looking at the meaning of the word 'load' more fully in Chapter 5, but for the time being consider a load as being any force acting externally on a structure.)

Any structure must satisfy the following criteria:

1) Aesthetics – it must look nice.
2) Economy – it mustn't cost more than the client can afford; and less if possible.
3) Ease of maintenance.
4) Durability – this means that the materials used must be resistant to corrosion, spalling (pieces falling off), chemical attack, rot and insect attack.

5) Fire resistance – while few materials can completely resist the effects of fire, it is important for a building to resist fire long enough for its occupants to be safely evacuated.

In order to ensure that a structure behaves in this way, we need to develop an understanding and awareness of how the structure works.

Safety and serviceability

There are two main requirements of any structure: it must be **safe** and it must be **serviceable**. 'Safe' means that the structure should not collapse – either in whole or in part. 'Serviceable' means that the structure should not deform unduly under the effects of deflection, cracking or vibration. Let's discuss these two points in more detail.

Safety

A structure must carry the expected loads without collapsing – either as a whole or even just a part of it. Safety in this respect depends on two factors:

1) The **loading** that the structure is designed to carry has been correctly assessed.
2) The strength of the **materials** that are used in the structure has not deteriorated.

From this it is evident that we need to know how to determine the load on any part of a structure. We will learn how to do this later in the book. Furthermore, we also know that materials deteriorate over time if they are not properly maintained: steel corrodes, concrete may spall or suffer carbonation, and timber will rot. The structural engineer must consider this when designing any particular building.

Serviceability

A structure must be designed in such a way that it doesn't deflect or crack unduly in use. It is difficult or impossible to completely eliminate these things – the important thing is that the deflection and cracking are kept within certain limits. It must also be ensured that vibration does not have an adverse effect on the structure – this is particularly important in parts of buildings containing plant or machinery.

If, when you walk across the floor of a building, you feel the floor deflect or 'give' underneath your feet, it may lead you to be concerned about the integrity of the structure. Excessive deflection does not necessarily mean that the floor is about to collapse, but because it may make people feel unsafe, deflection must be 'controlled'; in other words, it must be kept within certain limits. To take another example, if a lintel above a doorway deflects too much, it may cause warping of the door frame below it and, consequently, the door itself may not open or close properly.

Cracking is ugly and may or may not be indicative of a structural problem. But it may, in itself, lead to problems. For example, if cracking occurs on the outside face of a reinforced concrete wall, then rain may penetrate and cause corrosion of the steel reinforcement within the concrete, which in turn leads to spalling of the concrete.

The composition of a building structure

A building structure contains various elements, the adequacy of each of which is the responsibility of the structural engineer. In this section we briefly consider the form and function of each. These elements will be considered in more detail in Chapter 3.

Fig. 1.2 Roof structure of Quartier 206 shopping mall, Berlin. Quite a 'muscular' roof structure!

A roof protects people and equipment in a building from weather. An example of a roof structure is shown in Fig. 1.2.

If you plan on buying a house in the United Kingdom, be wary of buying one which has a flat roof. Some roofing systems used for waterproofing flat roofs deteriorate over time, leading to leaking and potentially expensive repairs. The same warning applies to flat-roofed additions to houses, such as porches or extensions.

Walls can have one or more of several functions. The most obvious one is **load-bearing** – in other words, supporting any walls, floors or roofs above it. But not all walls are load-bearing. Other functions of a wall include the following:

- partitioning, or dividing, rooms within a building – and thus defining their shape and extent
- weatherproofing
- thermal insulation – keeping heat in (or out)
- noise insulation – keeping noise out (or in)
- fire resistance
- security and privacy
- resisting lateral (horizontal) loads such as those due to retained earth, wind or water.

Consider the wall closest to you as you read these words. Is it likely to be load-bearing? What other functions does this wall perform?

A ***floor*** provides support for the occupants, furniture and equipment in a building. Floors on an upper level of a building are always ***suspended***, which means that they span between supporting walls or beams. Ground floor slabs may sit directly on the ground beneath.

Staircases provide for vertical movement between different levels in a building. Figure 1.3 shows a concrete staircase in a multi-storey building. Unusually, the staircase is fully visible from outside the building. How is this staircase supported structurally?

Fig. 1.3 **A very visible staircase. How is it supported? You'll learn more about cantilevers later in the book.**

Foundations represent the interface between the building's structure and the ground beneath it. A foundation transmits all the loads from a building into the ground in such a way that settlement (particularly uneven settlement) of the building is limited, and failure of the underlying soil is avoided.

On a small sandy island in the Caribbean, a low-rise hotel was being constructed as part of a larger leisure resort. The contractor for the hotel (a somewhat maverick individual) thought he could save money by not constructing foundations. He might have got away with it were it not for an alert supervising engineer, who spotted that the blockwork walls did not appear to be founded on anything more rigid than sand.

A furious argument ensued between the design team and the contractor, who not only readily admitted that no foundations had been built but also asserted that, in his opinion, none were required. In a developed country the contractor would have been dismissed instantly and probably prosecuted, but things were a little more free and easy in this corner of the Caribbean.

But nature exacted its own retribution. That night, a tropical storm blew up, the sea washed over the island … and the partly built structure was entirely washed away.

In a building it is frequently necessary to support floors or walls without any interruption or division of the space below. In this case, a horizontal element called a ***beam*** will be used. A beam transmits the loads it supports to columns or walls at the beam's ends.

Fig. 1.4 **A conventional building enclosed in a glazed outer structure. The two structures appear to be completely independent of each other.**

A ***column*** is a vertical load-bearing element which usually supports beams and/or other columns above. Laymen often call them pillars or poles or posts. Individual elements of a structure, such as beams or columns, are often referred to as ***members***.

See Fig. 1.4 for an unusual pairing of two separate structures.

A few words for students on architecture courses

If you are studying architecture, you may be wondering why you need to study structures at all. It is not the purpose of this book to make you a fully qualified structural engineer, but, as an architect, it is important that you understand the principles of structural behaviour. Moreover, with some basic training there is no reason why architects cannot design simple structural members (e.g. timber joists supporting floors) themselves. On larger projects architects work in inter-disciplinary teams which usually include structural engineers. It is therefore important to understand the role of the structural engineer and the language and terms that the structural engineer uses.

How does the study of structures impinge on the training of an architect?

If you are on a degree course in architecture, you will have formal lectures in structures throughout your course. You will also be assigned projects involving the architectural design of buildings to satisfy given requirements. It is essential to realise that all parts of the building need to be supported. Always ask yourself the question: ‘How will my building stand up?’ Remember – if you have difficulty in getting a model of your building to stand up, it is unlikely that the real thing will stand up either!

2 Learn the language: a simple explanation of terms used by structural engineers

Introduction

Structural engineers use the following words (amongst others, of course) in technical discussions:

- force
- reaction
- stress
- moment

None of these words is new to you; they are all common English words that are used in everyday speech. However, in structural engineering each of these words has a particular meaning. In this chapter we shall have a brief look at the specific meanings of the aforementioned words before exploring them in more detail in later chapters.

Force

A force is an ***influence*** on an object (for example, part of a building) that may cause movement. For example, the weight of people and furniture within a building causes a vertically downwards force on the floor, and wind blowing against a building causes a horizontal (or near-horizontal) force on the external wall of the building.

Force is discussed more fully in Chapter 4, together with related terms such as mass and weight. Forces are also sometimes referred to as ***loads*** – the different types of load are reviewed in Chapter 5.

Reaction

If you stand on a floor (or a roof! – see Fig. 2.1), the weight of your body will produce a downward force into the floor. The floor reacts to this by pushing upwards with a force of the same magnitude as the downward force due to your body weight. This upward force is called a ***reaction***, as its very presence is a response to the downward force of your body. Similarly, a wall or a column supporting a beam will produce an upward reaction as a response to the downward forces the beam transmits to the wall (or column) and a foundation will produce an upward reaction to the downward force in the column or wall that the foundation is supporting.

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Fig. 2.1 **Oslo Opera House.**
Floors don't always have to be flat! At Oslo's new opera house the public is encouraged to walk all over its sloping roof.

The same is true of horizontal forces and reactions. If you push horizontally against a wall, your body is applying a horizontal force to the wall – which the wall will oppose with a horizontal reaction.

The concept of a reaction is discussed in more detail in Chapter 6 and you will learn how to calculate reactions in Chapter 9.

Stress

Stress is internal pressure. A heavy vehicle parked on a road is applying pressure to the road surface – the heavier the vehicle and the smaller the contact area between the vehicle's tyres and the road, the greater the pressure. As a consequence of this pressure on the road surface, the parts of the road below the surface will experience a pressure which, because it is within an object (in this case, the road) is termed a ***stress***. Because the effect of the vehicle's weight is likely to be spread, or dispersed, as it is transmitted downwards within the road structure, the stress (internal pressure at a point) will decrease the further down you go within the road's construction.

So, stress is ***internal pressure*** at a given point within, for example, a beam, slab or column. It is likely that the intensity of the stress will vary from point to point within the object.

Stress is a very important concept in structural engineering. In Chapters 17–20, you will learn more about how to calculate stresses.

Moment

A moment is a turning effect. When you use a spanner to tighten a nut, mechanically wind up a clock or turn the steering wheel on your car, you are applying a moment. The concept and calculation of moments is discussed in Chapter 8.

The importance of ‘speaking the language’ correctly

A major American bank planned changes to its London headquarters building that entailed the removal of substantial internal walls. Although a well-known firm of structural engineers was used for the design, the work itself was entrusted to a firm of shopfitters who clearly had no experience whatsoever in this type of work.

The client issued the structural engineer’s drawings to the shopfitting contractor. In a site meeting, the contractor asked the structural engineer if it would be all right to use steel ‘H’ sections at the points where ‘UC’ columns were indicated on the drawings. The structural engineer was a little puzzled by this and pointed out that ‘UC’ stands for universal column, which are indeed steel ‘H’ sections. The contractor admitted, a little sheepishly, that he had thought that ‘UC’ stood for ‘U-shaped channel section’!

The structural engineer was so shaken by this conversation and its potential consequences that he strongly advised the client to sack the shopfitters and engage contractors who knew what they were doing.

3 How do structures (and parts of structures) behave?

Introduction

In this chapter we will discuss how parts of a structure behave when they are subjected to forces. We will consider the meanings of the terms ***compression***, ***tension***, ***bending*** and ***shear***, with examples of each. Later in the chapter we will look at the various elements that make up a structure, and at different types of structure.

Compression

Figure 3.1a shows an elevation – that is, a side-on view – of a concrete column in a building. The column is supporting beams, floor slabs and other columns above, and the load, or force, from all of these is acting downwards at the top of the column. This load is represented by the downward arrow at the top of the column. Intuitively, we know that the column is being squashed by this applied load – it is experiencing *compression*.

As we have seen briefly in Chapter 2 and will discuss more fully in Chapter 6, a downward force must be opposed by an equal upward force if the building is stationary – as it should be. This reaction is represented by the upward arrow at the bottom of the column in Fig. 3.1a. Now, not only must the rules of equilibrium (total force up = total force down) apply for the column as a whole; these rules must apply *at any and every point* within a stationary structure.

Let's consider what happens at the top of the column – specifically, point C in Fig. 3.1b. The downward force shown in Fig. 3.1a at point C must be opposed by an upward force – also at point C. Thus there will be an upward force within the column at this point, as represented by the upward broken arrow in Fig. 3.1b. Now let's consider what happens at the very bottom of the column – point D in Fig. 3.1b. The upward force shown in Fig. 3.1a at point D must be opposed by a downward force at the same point. This is represented by the downward broken arrow in Fig. 3.1b.

Look at the direction of the broken arrows in Fig. 3.1b. These arrows represent the internal forces in the column. You will notice that they are pointing away from each other. This is always the case when a structural element is in compression: the arrows used to denote compression *point away* from each other.

Tension

Figure 3.2 shows a heavy metal block suspended from the ceiling of a room by a piece of string. The metal block, under the effects of gravity, is pulling the string downwards, as represented by the downward arrow. The string is thus being stretched and is therefore in tension.

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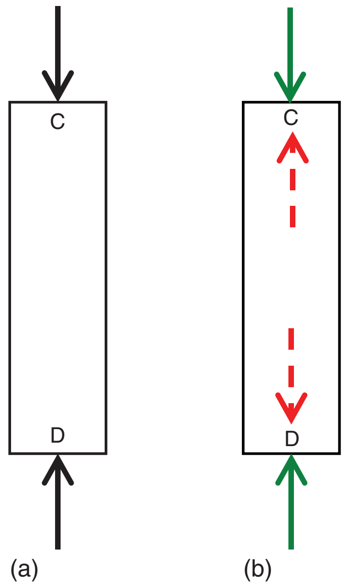

Fig. 3.1 **A column in compression.**

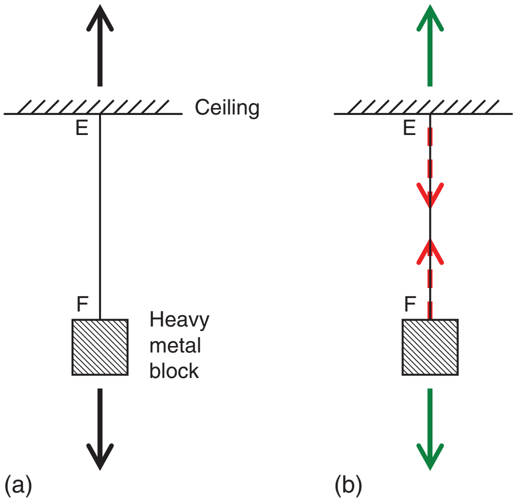

Fig. 3.2 **A piece of string in tension.**

For equilibrium, this downward force must be opposed by an equal upward force at the point where the string is fixed to the ceiling. This opposing force is represented by an upward arrow in Fig. 3.2a. Note that if the ceiling wasn't strong enough to carry the weight of the metal block, or the string was improperly tied to it, the weight would come crashing to the ground and there would be no upward force at this point. As with the column considered earlier, the rules of equilibrium (total force up = total force down) must apply at any and every point within this system if it is stationary.

Let's consider what happens at the top of the string. The upward force shown in Fig. 3.2a at point E must be opposed by a downward force – also at this point. Thus there

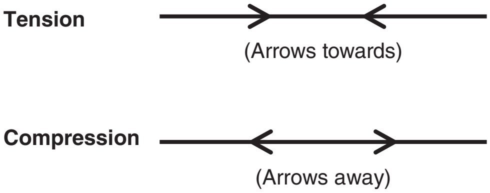

Fig. 3.3 **Arrow notations for the internal forces of tension and compression.**

will be a downward force within the string at this point, as represented by the downward broken arrow in Fig. 3.2b. Now let's consider what happens at the very bottom of the string – at the point where the metal block is attached (point F). The downward force shown in Fig. 3.2a at point F must be opposed by an upward force at this point. This upward force within the string at this point is represented by the upward broken arrow in Fig. 3.2b.

Look at the direction of the broken arrows in Fig. 3.2b. These arrows represent the internal forces in the string. You will notice that they are pointing towards each other. This is always the case when a structural element is in tension: the arrows used to denote tension *point towards* each other. (An easy way to remember this principle is the letter T, which stands for both Towards and Tension.)

The standard arrow notations for the internal forces of members in tension and compression are shown in Fig. 3.3. You should familiarise yourself with them as we shall meet them again in later chapters.

Note: Tension and compression are both examples of ***axial*** forces – they act along the *axis* (or centre line) of the structural member concerned.

Bending

Consider a simply supported beam (that is, a beam that simply rests on supports at its two ends) subjected to a central point load. The beam will tend to bend, as shown in Fig. 3.4. The extent to which the beam bends will depend on four things:

1) The ***material*** from which the beam is made. You would expect a beam made of rubber to bend more than a concrete beam of the same dimensions under a given load.
2) The ***cross-sectional characteristics*** of the beam. A large diameter wooden tree trunk is more difficult to bend than a thin twig spanning the same distance.
3) The ***span*** of the beam. Anyone who has ever tried to put up bookshelves at home will know that the shelves will sag to an unacceptable degree if not supported at regular intervals. The same applies to the hanger rail inside a wardrobe. The rail will sag noticeably under the weight of all those clothes if it is not supported centrally as well as at its ends, thereby reducing the span.
4) The ***load*** to which the beam is subjected. The greater the load, the greater the bending. Your bookshelves will sag to a greater extent under the weight of heavy encyclopedias than they would under the weight of a few light paperback books.

If you carry on increasing the loading, the beam will eventually break. Clearly, the stronger the material, the more difficult it is to break. A wooden ruler is quite easy to break by bending; a steel ruler of similar dimensions might bend quite readily, but it's unlikely that you would manage to break it with your bare hands!

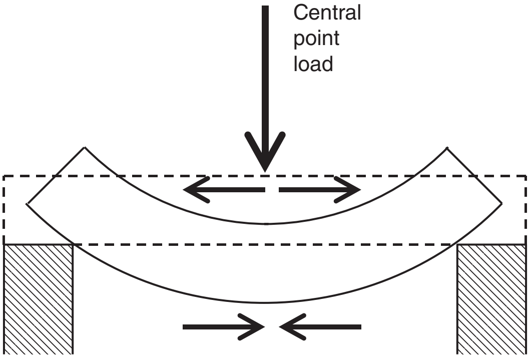

Fig. 3.4 **Bending in a beam.**

This is evidently one way in which a beam can fail – through excessive bending. Beams must be designed so that they do not fail in this way.

Incidentally, one way of determining the amount of bending that has taken place is to calculate the ***deflection***, which is the vertical distance through which a given point on the beam has moved from its original position. We'll discuss deflection later in the book.

Shear

Consider two steel plates that overlap each other slightly, with a bolt connecting the two plates through the overlapping part, as shown in Fig. 3.5a. Imagine now that a force is applied to the top plate, trying to pull it to the left. An equal force is applied to the bottom plate, trying to pull it to the right. Let's now suppose that the leftward force is slowly increased, as is the rightward force. (Remember that the two forces must be equal if the whole system is to remain stationary.) If the bolt is not as strong as the plates, eventually we will reach a point when the bolt will break. After the bolt has broken, the top part of it will move off to the left with the top plate and the bottom part will move off to the right with the bottom plate.

Let's examine in detail what happens to the failure surfaces (that is, the bottom face of the top part of the bolt and the top face of the bottom part of the bolt) immediately after failure. As you can see from the 'exploded' part of Fig. 3.5a, the two failure surfaces are sliding past each other. This is characteristic of a shear failure.

We'll now turn our attention to a timber joist supporting the first floor of a building, as shown in Fig. 3.5b. Let's imagine that timber joists are supported on masonry walls and that the joists themselves support floorboards, as would be the case in a typical domestic dwelling – such as, perhaps, the house you live in. Suppose that the joists are inappropriately undersized – in other words, they are not strong enough for the loads they are likely to have to support.

Now let's examine what would happen if a heavy object – for example, some large piece of machinery – was placed on the floor near its supports, as shown in Fig. 3.5b. If the heavy object is near the supporting walls, the joists may not bend unduly. However, if the object is heavy enough and the joists are weak enough, the joist may simply break. This type of failure is analogous to the bolt failure discussed earlier. With reference to Fig. 3.5b, the right-hand part of the beam will move downwards (as it crashes to the ground), while the left-hand part of the beam will stay put – in other words, it moves