CHAPTER 1

CONTENTS

Overview of Structural Concepts

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1.1 WHAT ARE STRUCTURAL CONCEPTS?

Structural concepts are one of the foundations for study, analysis and design in civil and structural engineering. However, there are several different views on the meaning of structural concepts, as there is no agreed definition. Therefore, there is a need to define structural concepts in the context of this book before they and their uses are examined.

One dictionary definition [1] of a concept is *a truth or belief that is accepted as a base for reasoning or action*. This general definition can be applied to structural concepts if the truth or belief relate to structural engineering. However, a more specific definition of a structural concept is given as:

> *A structural concept is a qualitative and concise representation of a* ***mathematical*** *relationship between* ***physical*** *quantities which captures the essence of the relationship and provides a basis for* ***practical*** *applications in structural engineering.*

This definition illustrates the significance and usefulness of understanding structural concepts, as it states the physical essence of mathematical equations for practical application and brings mathematics, physical understanding and practical application together.

This definition of structural concepts can be demonstrated using examples from theory and practice.

1.1.1 A Structural Concept Derived from Theory

The maximum deflection Δ of a simply supported uniform beam subjected to a uniformly distributed load q is:

$$\Delta = \frac{5}{384}\frac{qL^4}{EI} \tag{1.1}$$

Equation 1.1 has a theoretical basis and is derived from the differential equation of equilibrium for the bending of a uniform beam. It shows a relationship between five physical quantities: maximum deflection Δ, uniformly distributed load q, span L, modulus of elasticity E and second moment of area I. A structural concept abstracted from Equation 1.1 can be presented as:

> *Deflection is proportional to the span to the power of four and to the inverse of the second moment of area of the cross section.*

This statement captures the physical essence of the equation and its application can be extended beyond simply supported uniform beams. Applications using this concept include the use of props and cable stays (reducing spans) and I-section beams (increasing the second moment of area). It can even be extended to tall buildings (when treated as cantilever beams) and to floors and roofs that are beyond the model of a beam. This concept has contributed to designing some innovative structures and to solving some challenging practical problems. Several practical examples can be seen in Chapters 4, 8, 10 and 24.

Equation 1.1 also shows that the deflection is proportional to the load q and to the inverse of the modulus of elasticity E, but they are less significant than the span and the second moment of area in practical applications. Thus, they are not included in this presentation of the concept.

1.1.2 A Concept Observed in Practice

Dance-type activities, such as keep-fit exercises and aerobics, are usually held on dance floors and in sports centres, and grandstands that are used for pop concerts may encounter similar activities. Thus, the use and design of these structures should consider the effect of human-induced rhythmic loads. Research has been undertaken to determine the frequencies of human loads on the venues where pop concerts might be held. Site measurements were taken at different venues during pop concerts. It was observed, from dynamic measurements, that the structure under human action responded at the beat frequency of the music and at integer multiples of the beat frequency. This observation can be expressed as

$$f_p = f_m \tag{1.2}$$

where:

f_p is the first frequency of human loading
f_m is the beat frequency of the music played

This relationship (Equation 1.2) is straightforward and the concept can be easily interpreted as:

The first frequency of human loads at pop concerts is equal to the beat frequency of the music played.

The application of this concept allows the frequency of dance-type loads to be determined from the beat frequency of songs played on these occasions instead of taking vibration measurements on-site. Two undergraduate students, who were music fans, determined the beat frequencies of 210 modern songs that were played at pop concerts from the 1960s to the 1990s [2]. Using the concept, based on Equation 1.2, a significant amount of time and money was saved in gaining a better understanding of how to deal with dance-type loads on structures.

The two examples explain the definitions of structural concepts and also illustrate the effectiveness of understanding and using structural concepts. The first one is general and has a wide range of applications, whilst the second is specific and leads to the solution of a particular problem in a simple and effective manner.

One question related to the present definition of a structural concept is the exclusion of the concepts that are effective and widely used in practice but which have not been linked to a theoretical equation. It is believed that any structural concept, that will be effective in practice, will have a theoretical basis, although it may have not yet been identified. For example, the concept of direct load paths has been used in structural design for many years, without an appropriate theoretical support. However, the theoretical basis for the concept of direct internal force paths has now been established and is presented in Chapter 9.

Structural concepts are different from the conceptual design of structures. The conceptual design of structures is the first design stage, where options and the feasibility of possible structural designs are assessed, covering loading, structure, foundation, material and construction methods and so on. To produce a design that is safe, economical and elegant requires that the designers demonstrate a high level of intuitive understanding of structural behaviour, structural action and structural adequacy. The study and understanding of structural concepts can help the conceptual design of structures.

Understanding structural behaviour is related to, but different from, understanding structural concepts. Structural behaviour describes, mathematically or descriptively, how structures behave under loading. Qualitative analysis, or approximate analysis, is often conducted to help understand the behaviour of a structure, for example the likely deformed shapes and distribution of internal forces, and is a useful stage of the conceptual design process. Structural behaviour and structural concepts emphasise different aspects of structural engineering, but they are interrelated. Structural behaviour and structural concepts are discussed further in Chapter 13.

1.2 WHY STUDY STRUCTURAL CONCEPTS?

Structural concepts provide a basis for study, analysis and design in civil and structural engineering, and therefore their use is ideal for educating civil and structural engineering students. There are many reasons to emphasise the importance of the understanding and use of structural concepts in education and in practice.

1. In the past, our understanding of structural concepts was developed through working with hand calculations, many of which have now been replaced by computer-based calculations. Indeed, understanding structural concepts is fundamental to the sound and innovative design of structures and is of increasing importance due to the wide use of computers and the, often unquestioning, reliance placed on the results of computer analyses. Computed results will be flawed if they are based on incorrect assumptions and modelling, and engineers must understand this fact.
2. Analysis of the structural response to loads is much less demanding today than it was 20 or more years ago. Structural behaviour can be easily and quickly analysed using a personal computer (PC) and finite element (FE) software. It is the input loads and the model of a structure that are critical, as the output from a computer cannot be any better than the input. A good understanding of structural concepts will help to avoid errors when creating computer input.
3. Engineers aim to produce designs that are safe, economical and elegant but these three objectives are often not compatible, though they can, however, sometimes be achieved simultaneously when appropriate structural concepts are used.
4. Buildings become taller, bridges span longer and roofs cover larger areas than before. The effective use of structural concepts can help to deal with these ever-increasing challenges for design.
5. A relatively large civil engineering project is normally completed by different groups of people consisting of a small number of senior engineers who provide ideas and conceptual designs, a greater number of engineers/designers who produce the detailed analysis and designs and many more workers who construct the project on-site. University education should aim to prepare students to be the future senior engineers, for whom the understanding of structural concepts and behaviour will play an essential role.

This, admittedly incomplete list of reasons, shows the significance of structural concepts in learning and in practice. However, there are only a few research papers and books on structural concepts. This is perhaps due to three reasons.

First, it is sometimes thought that *structural concepts are too simple to study as they are taught at university*. People with this view simply miss the opportunity to appreciate the beauty and potential use of structural concepts. It is true that many structural concepts are well established and presented in textbooks. However, they could be presented in a different way, allowing students and engineers to gain a better understanding and appreciation of their application. In addition, new concepts will emerge from future engineering problems.

Second, in contrast to the first reason, it might be thought that *structural concepts are too hard to study as they are too abstract*. Unlike the study of particular structures, where the methodology and techniques have been established, there are no recognised ways to study structural concepts and few clear examples of their use. However, there are opportunities for studying and using structural concepts which can only be beneficial. Some approaches are discussed in Chapter 24.

Third, new structural concepts may have not yet been abstracted from current engineering practice. For example, engineers and architects devise intuitive, creative and ingenious solutions when solving challenging problems and realising innovative designs/solutions. Although some projects may be reported and published, little further work has been undertaken to identify the underlying structural concepts and how they have been used. Therefore, this important source of information may not have been fully explored.

As the understanding and using of structural concepts in education and engineering practice are important, new ways of studying structural concepts should be explored.

1.3 APPROACHES TO LEARNING STRUCTURAL CONCEPTS

The objectives for learning are to understand and recognise the use of structural concepts. Thus, appropriate approaches have been developed to achieve this target [3].

1. Theoretical content should be presented in such a way that structural concepts are highlighted.
2. Physical models should be used, where possible, for demonstrating structural concepts or the effect of the concepts, in order to gain an intuitive understanding.
3. Appropriate practical examples, either from engineering projects or from products in everyday life, should be provided to identify and illustrate the use of structural concepts.
4. Students should be engaged, through coursework of their own choice, on topics relating to structural concepts to stimulate further interest.

1.3.1 Theoretical Content

It would be helpful to students if structural concepts were highlighted in textbooks, such as that given for Equation 1.1 in Section 1.1.1. This would capture the essence of an equation for understanding rather than simply memorising it for an examination. Structural concepts are highlighted in this book in two ways.

First, the definitions and concepts are provided directly using bullet points and presented concisely in a memorable manner without using equations. Thus, readers can easily find related definitions and concepts in this book.

Second, concepts are abstracted and presented immediately after the equations on which they are based, and written in *italics*, as shown for Equation 1.1. Examples are often presented in pairs to demonstrate the effects of concepts in a quantitative manner.

1.3.2 Physical Models

Unlike in many current textbooks, many physical models are used in this book. But why is it so important to use physical models in learning?

When we talked to first-year students some 15 years ago, we asked what particular difficulties they experienced in their studies. Among their comments, the students said that they found it difficult to understand structural theory and structural concepts. They mentioned examples, such as, why does the normal stress due to bending vary linearly and become zero at the neutral axis for a given section, whilst shear stress varies quadrilaterally and becomes a maximum at the neutral axis? They also felt that a lot of the theory and many concepts were abstract since they could not be seen or touched. This triggered the thought that students might gain a better understanding of structural concepts if aspects of the theory could be 'seen' and 'touched'. It is true that stresses cannot be seen or touched easily, but the effects of stresses can be seen and touched. This led to the idea of developing physical demonstration models.

Two questions then had to be answered: How to develop physical models? and which models could be produced? Hence, Year 3 students were encouraged to study 'seeing and touching structural concepts' as Year 3 investigative projects. They reviewed several textbooks used at university level, mainly *Mechanics of Materials* and *Analysis of Structures*, and listed a number of definitions, concepts and methods from the textbooks. These were classified into three categories for possible model making:

1. Concepts that could be easily understood by reading definitions or by examining simple diagrams. For example, loads, displacements, internal forces, strain, redundancy, potential energy and elasticity.
2. Concepts that could not be understood easily from text or diagrams but could be demonstrated by using physical models. For example, force paths, resonance, stress distribution, stability, prestressing, centre of mass, equilibrium and vibration modes.

(a) (b)

FIGURE 1.1
From a practical case to demonstration models. (a) Cross section of a concrete-filled steel column. (b) Effect of constrained and unconstrained sponge blocks subjected to the same weights.

3. Concepts that could not be understood easily from text or diagrams and were not readily suited to physical models. For example, strain energy, moment area method and Castigliano's theorem.

Students and lecturers examined each concept/definition in the three categories concentrating on, and trying to extend, the contents in Category 2. The models to be developed initially were for demonstration purposes, with the intent of eventually creating finished products that would be portable, durable and capable of reuse. Short assembly times and ease of handling during demonstrations were two desirable factors; however, the key issue was that the models should be able to demonstrate the related concepts effectively.

Other sources for generating ideas for producing demonstration models come from engineering practice and research. Practising engineers have the opportunity to solve challenging practical problems which often reflect intuitive approaches to developing innovative measures for solutions in which structural concepts are embedded. When such examples are identified, physical models can then be developed to demonstrate the effect of such measures. One such example follows.

Concrete-filled steel tube (CFT) column systems have been widely used in practice. Their main advantages are that the buckling capacity of the steel tube is increased by the restraint of the concrete and the load capacity of the concrete is increased by the confining effect of the steel tube. Figure 1.1a shows the cross section of a CFT column. This suggested an idea for producing a model to demonstrate the confining effect. Two similar sponge blocks are placed in two open plastic boxes. One box has gaps between the box walls and the sponge block, allowing unconstrained deformation of the sponge when it is loaded vertically. The other box is a tight fit between the box walls and the sponge block, preventing the sponge from deforming in the horizontal directions. Figure 1.1b shows the significant difference in the deformations of the constrained and the unconstrained sponge blocks when subjected to the same vertical loads. This set of models is used to explain the confined behaviour of the concrete in a CFT column.

Many such physical models have been developed to demonstrate assumptions, principles and concepts and the effects of concepts. For demonstrating the effect of a concept, a pair of similar models is normally produced, such as those shown in Figure 1.1b. This shows the effect of a concept in a qualitative manner and leads to an intuitive understanding.

1.3.3 Practical Examples

The purpose of learning and understanding structural concepts is to use them in analysis and design wherever possible. However, textbooks do not normally provide practical examples to show the applications of structural concepts. Consequently, the use of theory for both teaching and learning is often limited to solving theoretical questions. In parallel to demonstrations using physical models, appropriate real examples should be used to enrich teaching and stimulate interest.

Engineers and architects are creative when dealing with practical projects. Studying their projects can show what particular measures are used in solving challenging problems and what structural concepts are embedded in these measures. Fortunately, many well-known and excellent structures worldwide are well documented in technical papers or in books for the general public. Some professional journals and websites also provide a good source for practical examples in which structural concepts are used creatively.

Valuable lessons can also be learnt from failures, and some failures have been due to misunderstanding or an ignorance of structural concepts. Such examples are provided in Chapters 9 and 11.

Relevant practical examples can also be sought on the basis of particular structural concepts. For example, load paths, or internal force paths, is an important concept used in structural design. Thus, good examples with more direct load paths and other examples with less direct load paths can be sought from well-known structures and from local structures.

Research in structural engineering also helps to identify new structural concepts for understanding and developing new applications based on existing concepts to improve structural efficiency and solve practical problems. This can also be used to further enrich teaching. For example, the contents in Chapters 9, 10, 13, 15, 20 and 21 are developed based on our own research on practical problems.

There are often gaps between theory and practice, but a good understanding of structural concepts and their applications can help to bridge these gaps. Therefore, the need to gain a good understanding of structural concepts is particularly emphasised in this book through the use of dedicated physical models and appropriate practical examples.

1.3.4 Engaging Students

Motivating and engaging students to learn is perhaps as effective as, or more effective than, improving lectures. In addition to providing students with good teaching and learning material, students should be given opportunities for practice.

The Royal Academy of Engineering's publication, *Educating Engineers in the 21st Century* [4], showed that industry's top priorities for engineering graduate skills are *practical application*, *theoretical understanding* and *creativity and innovation*. It summarised the requirements of industry for its graduate entrants as '*A sound understanding* of the relevant engineering fundamentals plus *the ability to apply them* in an *innovative* way to the solution of *practical engineering problems*'. An individual piece of student coursework, containing the three previously mentioned components, has been developed and practised at Manchester for over eight years. This coursework encourages students to use structural concepts and theory for dealing with real problems in a creative way.

Past coursework submissions have been interesting and varied and have included some really creative components. It is hoped that the coursework has encouraged students to consider and explain structural concepts in a simple manner, to develop physical models to demonstrate the effects of structural concepts and to look for examples in everyday life in which structural concepts are innovatively used. These motivate further study and the development of a greater understanding and awareness of structural concepts. This has proved to be the case.

The specification of coursework and the ways to help students to conduct coursework are discussed in Section 1.5.1.

1.4 ORGANISATION OF THE TEXT

This book consists of three parts: Statics, Dynamics and Synthesis, which integrates both statics and dynamics. The Statics part has 12 chapters, the Dynamics part has 7 chapters and the Synthesis part has 4 chapters. The headings of chapters are related to concepts rather than to structures, as the use of the concepts is not limited by the type of structure.

In the first two parts of the book, Statics and Dynamics, each chapter contains four sections.

1. Definitions and concepts: Definitions of the terms used in the chapter are provided. The concepts are presented concisely, in one or two sentences, and in a memorable manner. Key points are also given in some chapters.
2. Theoretical background: If the theory is readily available in textbooks, only a brief summary is presented, together with appropriate references. More details are given when the theory is not readily available elsewhere. Selected examples are provided which aim to show the use of the theory and link it with the demonstration models illustrated in the next section.
3. Model demonstrations: Demonstration models are illustrated with photographs. Normally, two related models are provided to show differences in behaviour, thus illustrating the concept. Small-scale experiments are also included in some chapters.
4. Practical examples: Appropriate engineering examples are given to show how the concepts have been applied in practice. Some examples come from everyday life and will be familiar to most people.

A small number of questions are provided at the end of each chapter for practice. Some of the questions come from our classroom teaching and from our examination questions testing the understanding of structural concepts.

The third part of the book discusses more general topics in structural engineering. These topics are selected as they are fundamental but have not been presented elsewhere. The four chapters consider the relationships between static and modal stiffnesses, static and dynamic problems, experimental and theoretical studies, and theory and practice. All of these relationships are linked to structural concepts. The presentation of the chapters in this part follows the nature of each topic, which is different from the first two parts.

To facilitate learning, bold typeface is used for words that provide definitions. Such definitions are normally presented in the first pages of the chapters in the Statics and Dynamics parts of the book. Italics and bullet points are used to highlight important statements and key sentences in all chapters.

Accompanying this book, we have created a website, Seeing and Touching Structural Concepts, which can be found at www.structuralconcepts.org. The website contains most of the contents presented in the first, third and fourth sections of each chapter in the first two parts of the book. Colour photos can be downloaded from the website and video clips can be played.

1.5 HOW TO USE THIS BOOK

1.5.1 For Students

This book provides useful and interesting information to enhance the understanding of structural concepts and to complement class studies. The level of contents spans from the first year to the fourth year of a typical undergraduate course.

The contents of the book can be used in different ways.

1. You can look at any particular chapter, after you have been introduced to a concept in the classroom, to help you to gain a better understanding. Try to answer the questions at the end of related chapters.
2. You can use the book to revise what you have learnt in the past about structural concepts. In particular, the sections on physical models and practical examples could be useful.
3. You may challenge yourself to produce another physical model to demonstrate one of the structural concepts listed (or indeed one that is not listed) or to identify an existing structure or product in which one structural concept plays an important role.

Many of the models in the book were developed by our students as they knew which concepts were difficult to understand and which concepts could be physically demonstrated. Samples of our student submissions may help you generate similar ideas; these can be found on our website, www.structuralconcepts.org. You may also read the contents in Section 1.5.2 for more detailed information.

1.5.2 For Lecturers

It is hoped that the book provides useful material to supplement the teaching of structural concepts. There are two ways that the contents of the book can assist teaching. The easier way is that you simply download the related photos from our website and insert them into your existing teaching materials. With the aid of related physical models and practical examples, your students may be more attentive in the class and more interested in the contents you deliver.

The other way is to add four one-hour lectures to accompany the study undertaken by students on *Understanding and Using Structural Concepts*. We have conducted this exercise at Manchester since 2006 and improvements have been made year by year. The contents of the lectures are as follows:

1. Lecture 1: *Concepts for designing stiffer structures*. This shows how new structural concepts have been identified from a textbook equation for calculating the displacements of simple trusses and how these concepts can be used effectively to deal with practical engineering problems. It also introduces the route from textbook contents to practical applications and from structural elements to complete structures through the use of examples. The contents of this lecture are covered in Chapters 9 and 10.
2. Lecture 2: *Theory*, *concepts and practice*. This gives students a global view of studying and understanding structural concepts. It shows, through a number of examples, paths from theory to structural concepts and then to practice, and inversely from practice to structural concepts and then to theory. This helps to bridge the gaps between theory and practice. The contents of this lecture are provided in Chapter 24.
3. Lecture 3 explains and assigns appropriate individual coursework to students and shows many of the good coursework samples produced by our previous students to encourage students to involve themselves in learning about structural concepts and to stimulate their ideas. The coursework specification and samples of student submissions can be found on our website. You may use the examples produced by your own students in subsequent years!
4. Lecture 4 is given at the end of the course unit to summarise the coursework submissions, provide feedback and give prizes to the best three submissions, voted for by the students. This time, you use the submissions produced by your own students.

Students are required to learn from the website, *www.structuralconcepts.org*, at their own pace in conjunction with the assignment of the individual piece of coursework which has the general title, Understanding and Using Structural Concepts. They are asked to design/make/use a physical model to demonstrate one structural concept or to identify an example from engineering practice or everyday life in which a structural concept has been used creatively. As a guide rather than a limitation, students are asked to make a two A4-page submission using a prescribed template which allows them to focus on the quality of the contents. It has been found that students have been stimulated by this coursework. One interesting observation is that the number of coursework submissions has often been larger than the number of students in the class, indicating that some students were sufficiently enthused to make more than one submission!

In Manchester, all the coursework submissions are made through ‘Blackboard’, an online teaching package. They are slightly edited for consistency of format and compiled into a booklet, effectively written by the students, which is ‘published’ internally. Thus, students can learn from each other and further improve their understanding of structural concepts. To encourage students to learn from each other, the ‘X factor’ style of voting is used to select the best three coursework submissions for which small prizes are awarded. Students are also encouraged to design the covers of their booklets for the internal publication.

Figure 1.2a shows the cover of a typical booklet designed by students together with three examples of student submissions. Figure 1.2b shows a string-reinforced ice beam that can carry several

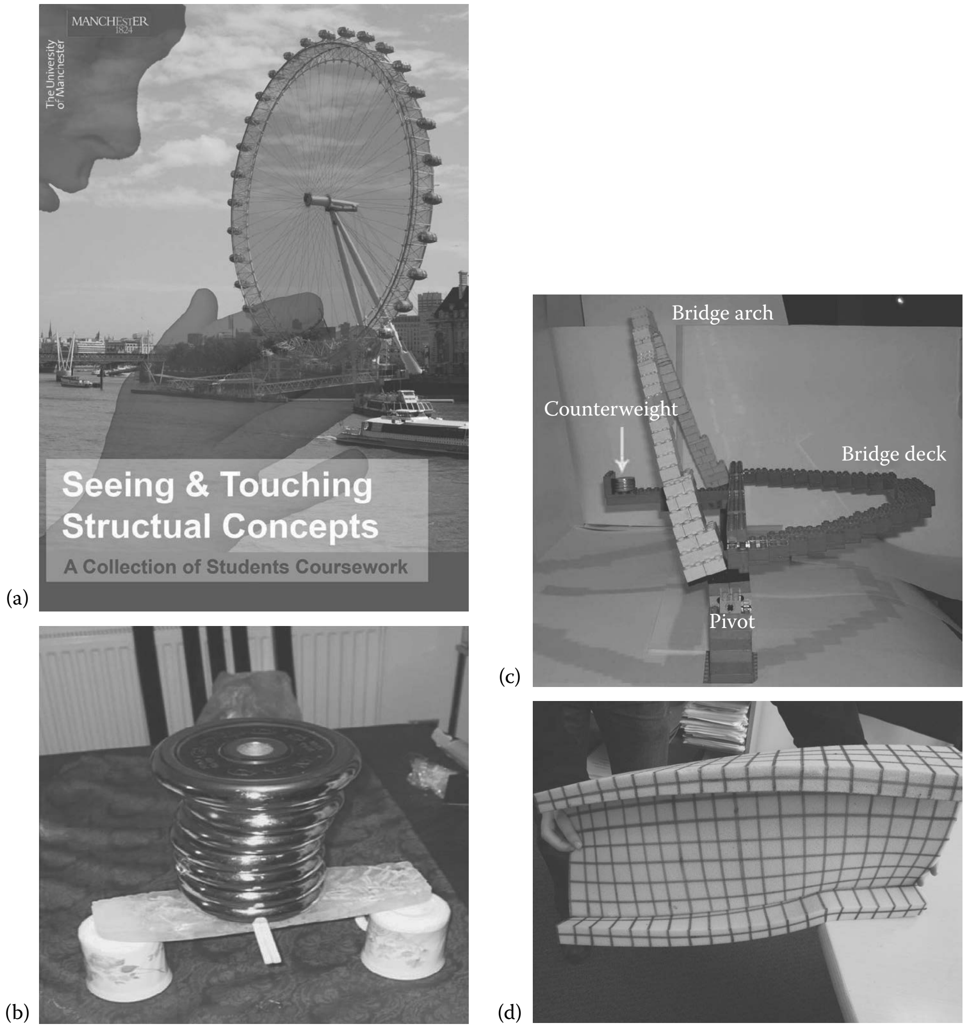

FIGURE 1.2
A cover of a student booklet and three coursework examples. (a) Book cover. (b) String-reinforced ice beam. (c) LEGO model of a footbridge. (d) Torsion of an I-section beam.

weights (an unreinforced ice beam cannot carry a single weight). Figure 1.2c shows a LEGO model of a footbridge and Figure 1.2d shows a sponge model that demonstrates torsion of an I-section beam.

The coursework specification, samples of our student submissions and further information have been provided at our website, www.structuralconcepts.org.

As the learning resource is provided at our website and coursework is specified, students should be able to spend sufficient time learning and conducting the coursework by themselves.

1.5.3 For Engineers

The contents of this book are useful to engineers, in particular recent graduate engineers. Unlike university students, you will have gained practical experience but may have forgotten some structural concepts studied at university. You may find the book useful in four ways.

1. You can quickly and effectively revise many structural concepts.
2. You can read the models and examples sections to develop your intuitive understanding of structures which could eventually be very helpful in your work.

3. You can examine the use of each of the concepts in practice through the examples provided. It is hoped that this may generate your own ideas for applying the concepts, or indeed any other structural concepts, in your work.
4. You may identify, using your own experience, how any of the structural concepts have been used in your work or in the work of your colleagues. Then consider how the application of the concepts helps in enhancing your understanding of structural behaviour and providing more efficient structures.

Engineers aim to achieve safe, economical and elegant structures. A sound understanding of structural concepts will help you to use them productively in your work.

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