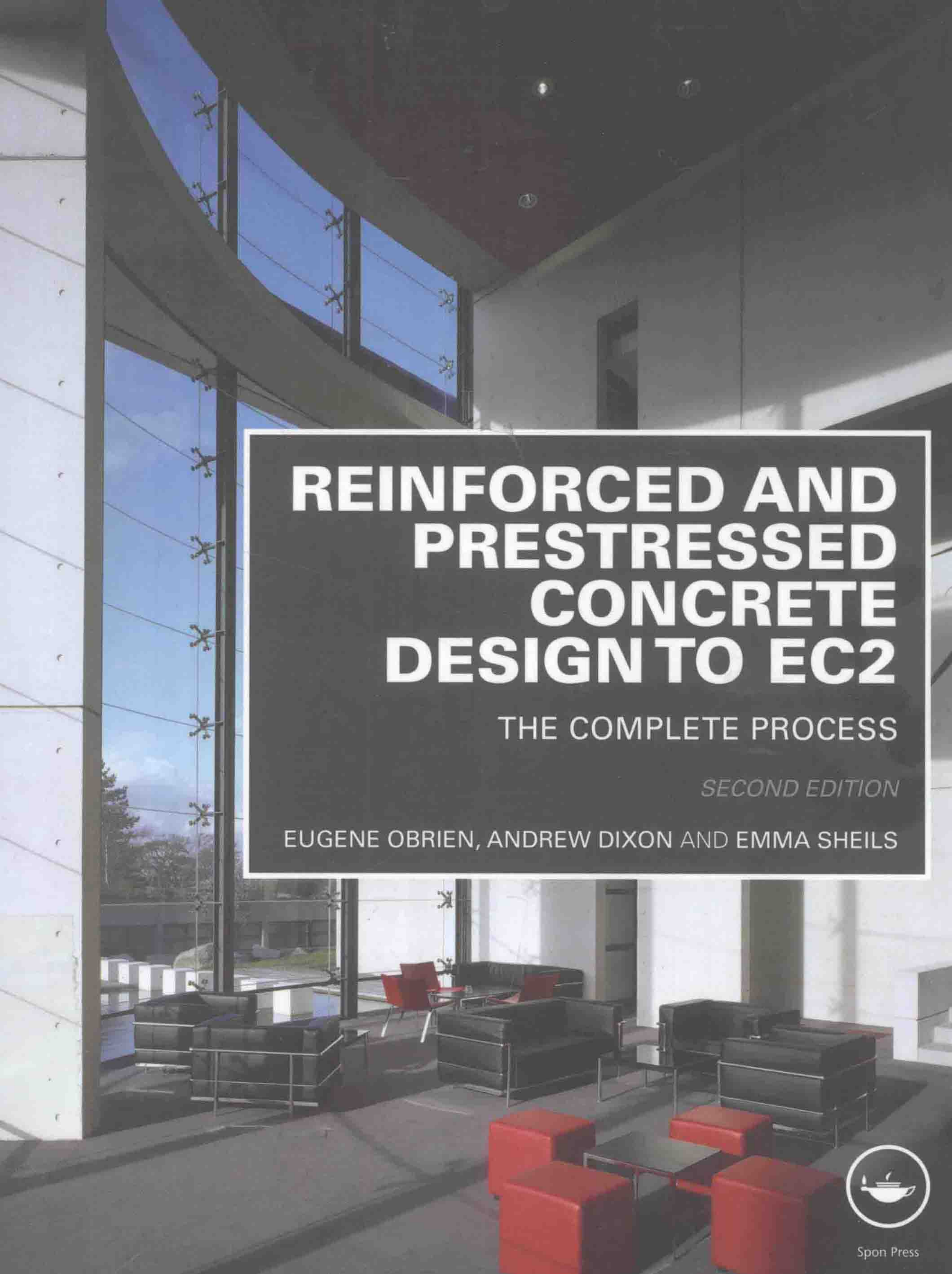

REINFORCED AND PRESTRESSED CONCRETE DESIGN TO EC2

THE COMPLETE PROCESS

SECOND EDITION

EUGENE OBRIEN, ANDREW DIXON AND EMMA SHEILS

Spon Press

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The complete process

Second edition

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Reinforced and Prestressed Concrete Design to EC2

Concrete is an integral part of twenty-first century structural engineering and an understanding of how to analyse and design concrete structures is a vital element in the subject. With Eurocodes having replaced European national standards it's important to get to know the new codes which, for most countries, are more complex than before. Newly revised to Eurocode 2, this second edition retains the original's emphasis on qualitative understanding of the overall behaviour of concrete structures.

A unique feature of the new edition is a whole chapter on case studies. This provides a unique insight into the way a structure is put together and the alternative structural schemes that are considered in the early stages of design. The concept has been used very successfully in a Problem Based Learning environment at University College Dublin. Groups of students are assigned case study problems, and after a few days they present their solutions to expert judges who give feedback on the practicalities of their chosen solutions. This highlight of the undergraduate experience teaches the students communication as well as design skills.

This book provides civil and structural engineering students and graduates with complete coverage of the analysis and design of reinforced and prestressed concrete structures. Great emphasis is placed on developing a qualitative understanding of the overall behaviour of structures and on bringing together all the strands in the design process – load paths, developing a structural scheme, preliminary sizing, analysis and detailed design.

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Preface

In his early years as a designer, the first author was asked to design a reinforced concrete floor slab for a plant room in the attic of a hotel. The plant room had no door, being accessed through a square opening in the slab from the room below, and the only location available for this opening was in an area where the slab moments were very high. He grappled with this problem for a great deal of time, looking for structural solutions, until he realized that he needed an overview of the problem – why was this opening needed anyway? A number of telephone calls later, the alternative emerged. Access to the plant room could be achieved through a doorway from elsewhere in the attic instead of through a hatch from below and the troublesome opening could in fact be omitted.

All of this taught him the philosophy behind this book, namely that every member of the design team must understand the complete design process – the thinking behind all the decisions that relate in any way to his/her contribution. Thus we have, in one volume, covered all aspects of the design process from initial conception of the structural alternatives through the process of analysis and on to the detailed design traditionally taught in concrete design courses. The second edition brings the text in line with the relevant Eurocodes and National Annex documents. What is most significant about this second edition, however, is that we have now included the final piece of the jigsaw – the case studies. The first edition included traditional material plus an explanation of how loads are carried by structures and how members are sized. This edition extends this to include, in Chapter 7, six detailed examples of how to go from the initial brief through to a full preliminary design. Alternative schemes are explored and the relative advantages compared, just as happens in the design office.

We have sought to strike a balance between the very practical knowledge of how to apply code clauses and a theoretical understanding of structural behaviour. The Eurocode can be tedious to apply, with seemingly endless notation and definition. We have tried to focus on the important principles, sparing those unfamiliar with the code from some of the more obscure detail. However, much of the detail was necessary as we wanted to ensure that readers have enough information to design most concrete structures.

We have compiled what might, at first sight, appear to be a rather strange collection of material – loading, some qualitative design (load paths, etc.), quite a lot of analysis, rules of thumb and methods of sizing up members, as well as some conventional reinforced and prestressed concrete design. We did this because we see the traditional separation of analysis and design as artificial and have found that many of our students graduating are confused about the distinction between an applied load and a capacity to resist it. We feel that they need to have all the material in one book in order to understand the interrelationships between conceptual design, analysis and detailed design of concrete structures.

There is much in this book that is unique or unusual in a concrete text – how to calculate the distribution of wind loads between cores and shear walls is not something found in most of our competitor books. In this we have been encouraged by feedback from young graduates who have found it most useful. We also feel that many textbooks are lacking on some very essential practical

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Special thanks go to Peter Flynn, Arup Consulting Engineers; John Considine, Barrett Mahony Consulting Engineers and Michael Quilligan, University of Limerick (formerly of PUNCH Consulting Engineers) for their guidance on the case studies in Chapter 7. Photographs and images are reproduced with the kind permission of Corus Panels and Profiles, Ancon, Keegan Quarries Ltd., CCL and Spiroll, the Board of Trinity College Dublin and Hy-Ten Ltd. The cover photograph is courtesy of the Irish Management Institute and Arthur Gibney & Partners, Architects. Many others have helped in various ways: Aidan Duffy of Dublin Institute of Technology with the carbon footprint of different materials, Ciaran McNally of University College Dublin with durability of concrete and FRC, and Tony Dempsey and Aonghus O'Keeffe of Roughan & O'Donovan with prestressed concrete.

Special thanks go to the authors of the STRAP analysis package which has been used extensively, particularly in Chapters 4 and 5.

This book is dedicated to Sheena, Milo, Bevin and Kevin.

points. For example, an explanation of the calculation of wind load is somewhat unsatisfactory, being largely based on empirical evidence. Nevertheless, it is a very necessary evil in the design office and we feel that all students should have some exposure to such basic essentials before graduating. This will give them some familiarity with the concepts before they are faced with real structures and will reduce the risk of a misinterpretation of the code.

Since 2010, EN 1992 (and its associated National Annexes) has been adopted in Europe as the legal standard for concrete design. They are not easy documents, especially for beginners! We hope that our book will help to ease your way as gently as possible into these new codes of practice.

Contents

Part I

Structural loading and qualitative design

Introduction

The first part of this book deals with what is arguably the most important aspect of structural design – qualitative design. Structural failures are rarely a result of a calculation error in which, say, a stress is thought to be 10 per cent less than its actual value. More commonly, failure results from the omission of reinforcement altogether from a critical connection or confusion over the role that each structural member plays in resisting the applied loads.

Chapter 1 presents an overview of the complete design process from conception to finished drawing. In addition, a description is given of the function of various types of structural member and structural system and the ways in which they resist load. The chapter also presents the factors that affect the choice of reinforced or prestressed concrete as an appropriate structural material. In Chapter 2, the ways of combining structural members to form complete structures are described. Also, a qualitative explanation is given of how loads are carried through the various structural members to the ground. Finally, in Chapter 3, the principal sources of loading are described. Poor decisions in the provision for load can result in a structure that is either unsafe at the one extreme or is uneconomical at the other. An explanation is given of the nature of loads and the means by which they are quantified.

It is hoped that, from Part I of the book, the reader will develop a qualitative understanding of how a structure resists loads.

Chapter 1

Fundamentals of qualitative design

1.1 The design process

Design in any field is a logical, creative process that requires a wide amalgamation of skills. As a complete process, structural engineering design can be divided into three main stages:

1. Conceptual design
2. Preliminary analysis and design
3. Detailed analysis and design.

The three stages are dealt with here in Parts I, II and III, respectively. The first stage, described in detail below, consists of the drawing up of one or a number of structural schemes that are safe, buildable, economical and robust. The second stage consists of performing preliminary calculations to determine if the proposed structural schemes are feasible. Rules of thumb are used to determine preliminary sizes for the various members and approximate methods are used to check these sizes and to estimate the quantities of reinforcement required. In the third stage of the design process, the adequacy of the preliminary member sizes is verified and the quantities of reinforcement calculated accurately. The whole process begins with **analysis** of the structure. That is to say, the distributions of bending moment, shear force, etc. due to all possible combinations of applied loading, are found. The various structural members are then **designed.** This is the process by which the capacity of each member to **resist** moment, shear, etc. is compared with the values due to applied loading. If the capacity is inadequate, the quantity of reinforcement and/or the member size is increased. Following completion of these three stages, drawings and specifications are prepared.

Conceptual design, which forms the first stage of the design process, involves the identification of design constraints and the putting together of structural schemes that comply with these constraints. The fundamental constraints are things like the allowable budget, site and size restrictions, provision for safe access, final appearance and utility. These are normally specified by the client's brief or by the body, such as the local planning council, that has given permission for the project. More detailed constraints emerge during the multidisciplinary design process. For example, the architect involved in the development of a large hotel may request a large open space in the central foyer to enable free movement of people in the area. If columns are allowed, as illustrated in Fig. 1.1(a), the span lengths and hence the beam depths will be modest (the required beam depth tends to be proportional to the span length). If, however, no columns are to be used, the span length and hence, the beam depth will be large, as shown in Fig. 1.1(b). This results in additional cost and increases the height of the overall structure. The spherical dome scheme illustrated in Fig. 1.1(c) would tend to be the most expensive of the three schemes as it would involve curved shuttering to form the shape of the concrete during construction. Nevertheless, it may be chosen over the alternatives for its superior aesthetic qualities.

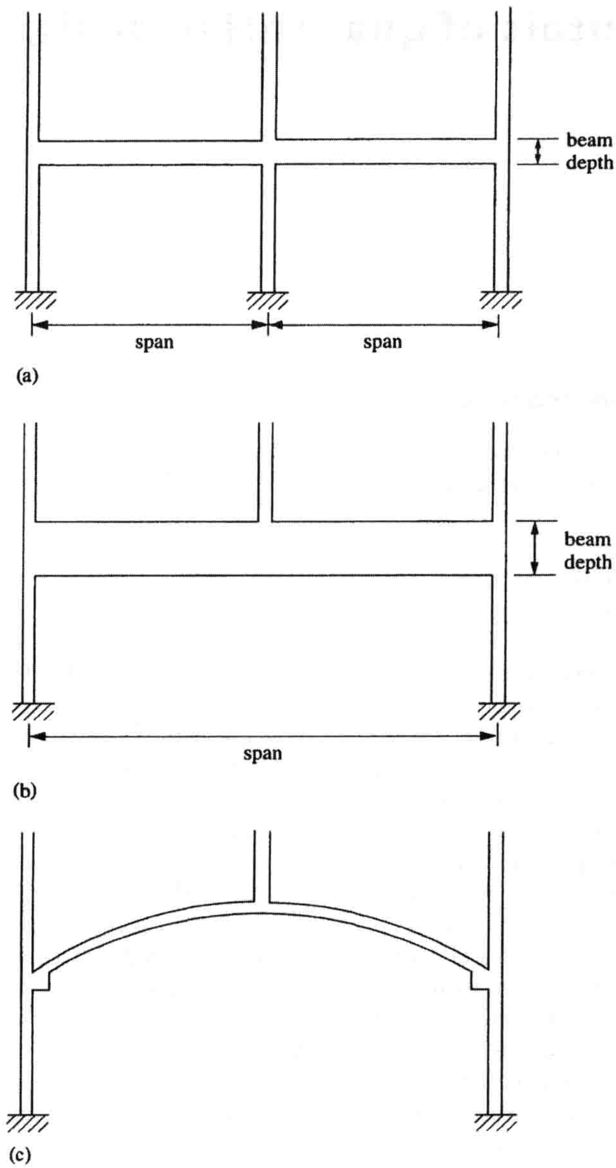

Figure 1.1 Alternative structural schemes: (a) two short spans; (b) one long span; (c) spherical dome

The form of a structure often emerges as a result of discussion between various parties, and good solutions are the result of clear lines of communication and the skill of the individuals involved in the project.

1.2 Structural materials

At an early stage in the design of a modern structure, the structural engineer chooses a suitable material or group of materials that will form the main structural elements. The selection of materials for construction depends on many factors. Due to improvements in technology, communication and transport worldwide, there are a wide variety of materials available for construction. However, the sustainability of a design is also important and factors such as the use of locally sourced materials or renewable resources and the recyclability of construction materials must also be considered. Due to these issues and the range of construction materials available, it is often necessary to carry out approximate preliminary designs for a number of material options to determine the most appropriate for the project. More often, however, the choice of material is founded on a knowledge of the properties of alternative materials and on experience gained from previous design projects.

The principal structural materials

The principal **raw materials** of structural design are steel, concrete (including concrete block units), timber and clay fired bricks. Of these, steel and concrete are the most widely used in practice. The main advantage of steel over other construction materials is its great strength, both in tension and compression. The strength of concrete is dependent on the type, quality and relative proportions of its constituents. To grade the strength of concrete, the compressive strength of simple cylinder (according to Eurocode) or cube samples at 28 days, is generally used. Values of the compressive strength of concrete at 28 days can vary from 5 N/mm^2 to 90 N/mm^2 but typically range between 30 N/mm^2 and 55 N/mm^2. An important characteristic of a hardened concrete is that its tensile strength is much less than its strength in compression, generally being between 1 N/mm^2 and 3 N/mm^2. For simplicity, designers will often assume the tensile strength to be equal to 0 N/mm^2.

The raw materials of construction are often combined to form what are loosely referred to as **structural materials**. In this way, the distinctive properties of the different raw materials can be used to the greatest advantage. The principal structural materials are described in the following sections.

Ordinary reinforced concrete

Concrete reinforced with steel is perhaps the most widespread structural material presently in use around the world. Concrete has many advantages such as its low cost, versatility and high compressive strength but it has the great disadvantage of being weak in tension. Steel has considerably higher tensile strength but tends to be more expensive per unit weight. In ordinary reinforced concrete (reinforced concrete for short), the advantages of both raw materials are utilized when the concrete resists compressive stresses while the steel resists tensile stresses. A typical reinforced concrete beam is illustrated in Fig. 1.2. Reinforced concrete members can be fabricated ***in situ***, that is, directly at the site of construction. Reinforced concrete members that are prepared and fabricated offsite and then assembled on site are known as **precast** concrete members. The choice between precast and *in situ* concrete depends on a number of factors that are discussed later in this section.

Fibre reinforced concrete

Fibre reinforcement in concrete has been used in the past to limit plastic shrinkage and settlement cracking on the surface of a concrete member. Fibres are now being used in flat slabs in place of longitudinal and transverse reinforcing steel, and can span up to about 6 m. They are also used in the concrete section as part of a composite design (see below). The fibres are scattered randomly into the concrete during mixing, as illustrated in Fig. 1.3. They are typically about 50 mm in length with a 1 mm diameter and can be made of steel or polymer. The polymer fibres have the added advantage of being non-corroding. However, steel fibres are generally used to reduce/avoid having a steel mesh, whereas polymer fibres are weaker and are usually only used for crack control.

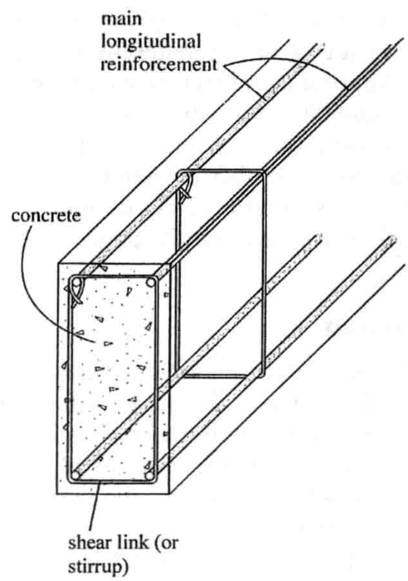

Figure 1.2 Reinforced concrete

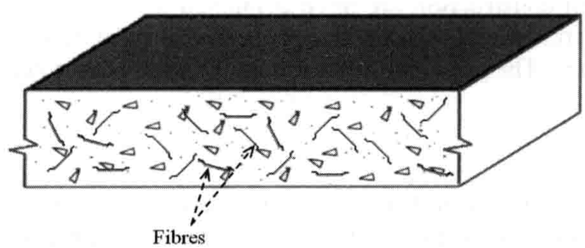

Figure 1.3 Fibre reinforced concrete

Prestressed concrete

Like ordinary reinforced concrete, prestressed concrete consists of concrete resisting compression and reinforcing steel resisting tension. However, unlike reinforced concrete, the concrete is compressed during construction and is held in this state throughout its design life by the reinforcing steel. Having the concrete in a compressed state avoids tensile cracking which prevents contaminants from getting into the steel, thereby increasing the resistance of the steel to corrosion. In addition, prestressing of the concrete increases the overall stiffness of the member and reduces deflections. A typical prestressed concrete member is illustrated in Fig. 1.4. In this member, the prestressed tendon is at the centroid of the cross-section. This causes compression throughout the concrete and results in a deflected shape as shown in Fig. 1.4. Like ordinary reinforced concrete, prestressed concrete members can be fabricated *in situ* or as precast units.

Structural steel

Unlike concrete, steel can be used by itself as a structural material for most types of member. Structural steel is available in many shapes, some illustrated in Fig. 1.5, which have evolved over

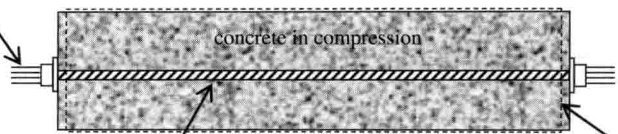

Figure 1.4 Prestressed concrete

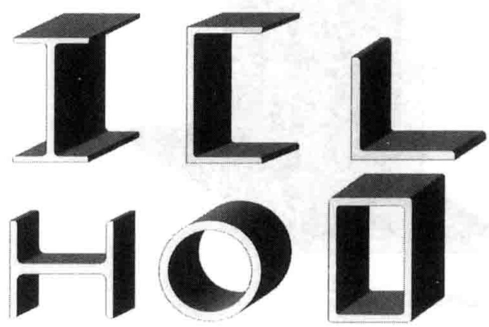

Figure 1.5 Structural steel sections

the years to produce sections that are efficient in resisting bending and buckling. Structural steel has approximately the same stress–strain relationship in tension and compression and so steel sections that carry their loads in bending will generally be symmetrical about the neutral axis. However, local buckling due to large shear forces often places further restrictions on the allowable compressive stresses in such members. The yield strength of structural steel depends on the steel grade but is typically in the range of 200 N/mm^2 to 400 N/mm^2.

Composite construction

The advantages of reinforced concrete and structural steel can be combined in what is known as composite construction. Fig. 1.6 illustrates a typical example of this increasingly popular structural 'material'. The cheaper reinforced concrete slab is used to span locally to create floor space while a combination of the structural steel beam and the concrete is used to support the slab and the loads applied to it.

Timber

Timber from mature trees is one of the earliest construction materials used by man. The strength of timber is directly related to the variety of tree. In addition, its strength will be affected by its density, moisture content, grain structure and a number of inherent defects such as cracks, knots and insect infestations. Typical permissible stresses for softwoods loaded parallel to the grain orientation are less than 6 N/mm^2 for members in compression, tension and bending. For members loaded normal to the grain, the permissible stress is even less. However, with the use of laminating techniques, in which