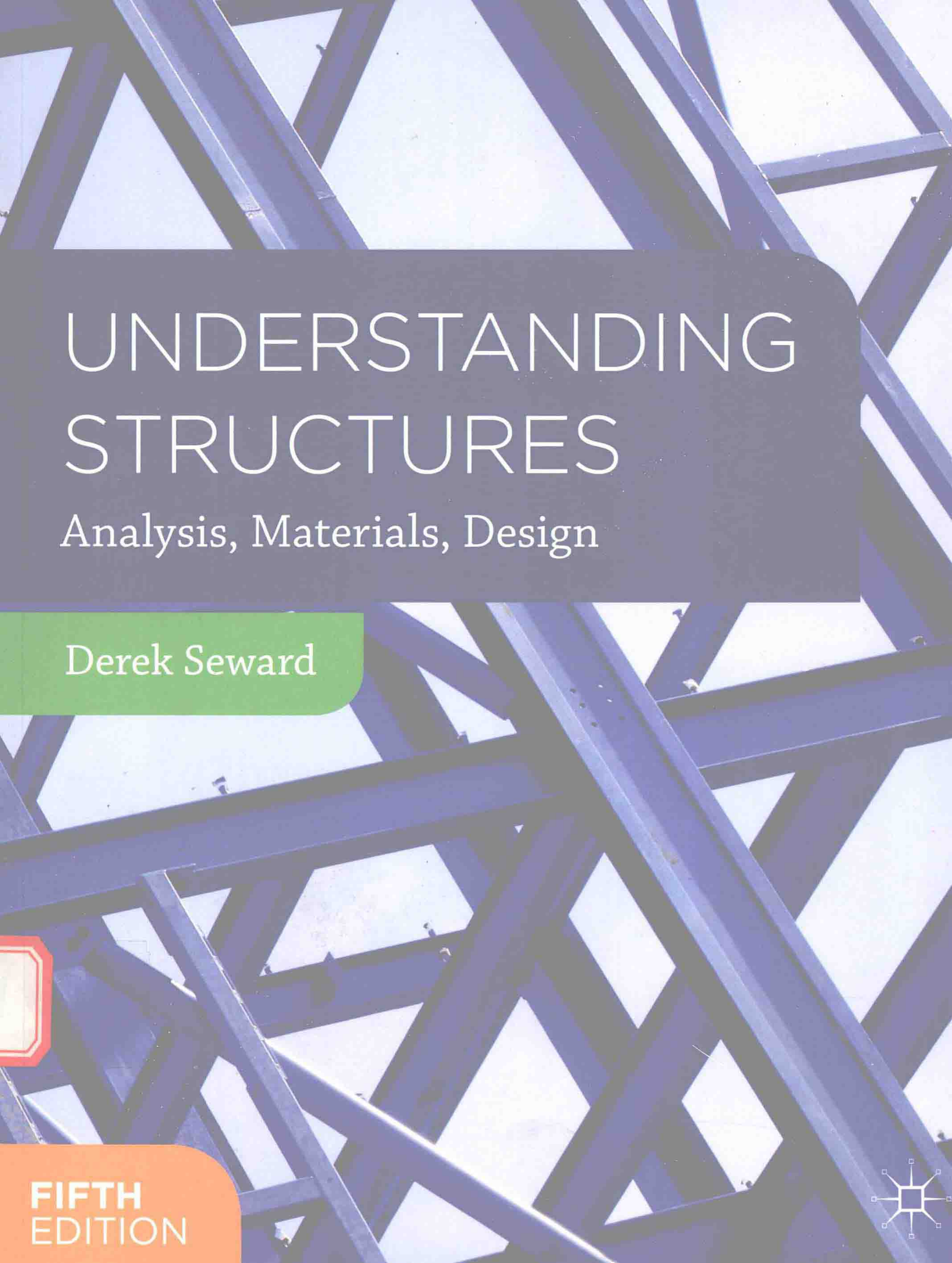

UNDERSTANDING STRUCTURES

Analysis, Materials, Design

Derek Seward

FIFTH EDITION

UNDERSTANDING STRUCTURES

Analysis, Materials, Design

FIFTH EDITION

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palgrave
macmillan

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Preface

This book explains the fundamentals of structural analysis, materials and design. These topics are often treated as separate subjects, but it is my belief that it is better to introduce all three topics in an integrated fashion. This enables the student to tackle realistic design problems in the shortest possible time, and, because he or she can see the relevance of the theory, it produces good motivation. It is also a way of providing early exposure to the actual **process** of design – from initial concept through to final details. Although much of the book deals with the design of individual structural elements in various materials, it also considers the way these elements are used in complete structures, which is the essence of structural form. To attempt to cover such a wide range of material in a modestly sized book has not been easy. In selecting material for inclusion I have given preference to those issues which occur most frequently in the real world of structural design.

Structural design must generally comply with official documents known as 'standards' and, at the time of writing, individual national standards are being phased out in favour of universal Eurocodes. This fifth edition is fully compatible with the new Eurocodes, although the emphasis is on the student gaining a deep understanding of the principles of structural design rather than dealing with each code on a clause-by-clause basis.

The book is intended for students of civil and structural engineering, building, architecture and surveying. It is of use at both first year degree and BTEC levels. Because it contains much real design data, it may also be useful as a work of reference for the non-specialist practitioner.

In order to produce safe and economic structures, a large part of the structural design process is inevitably numerical. However, where possible, the book avoids a mathematical approach. The aim is to develop a 'feel' and awareness for the physical behaviour of structures. As the title of the book suggests, the emphasis is placed on understanding. For this reason a large number of illustrations are used to portray structural behaviour. A minimum of mathematical knowledge is required – largely simple algebra and trigonometry. Where, as in certain proofs of formulae, slightly more advanced mathematics is unavoidable, it is presented in such a way that uninterested readers can avoid it without affecting their wider understanding of the book.

An unusual feature of the book is the inclusion of a chapter on structural loads. This vital stage in the design process is often difficult for the beginner, and yet is rarely covered in textbooks. A more controversial feature is the way that the book explains ultimate plastic bending strength before the elastic case. The basic design method adopted in Eurocodes for the principal structural materials now assumes that full plastic strength can be developed. Indeed, run-of-the-mill design of steel and reinforced concrete beams can now take place without any knowledge of elastic theory. Plastic strength is also easier to understand. It is only for historical reasons that elasticity is usually taught before plasticity.

Each stage of the design process is illustrated by a realistic numerical example which is based on genuine design data. It is hoped that after reading this book the student will have developed a real skill for structural design, as well as sharing in the satisfaction, pleasure and excitement of this highly creative process.

At the end of each chapter there are a number of exercises to test the understanding of the reader. Online solutions are available at www.palgrave.com/companion/seward-understanding-structures5

DEREK SEWARD

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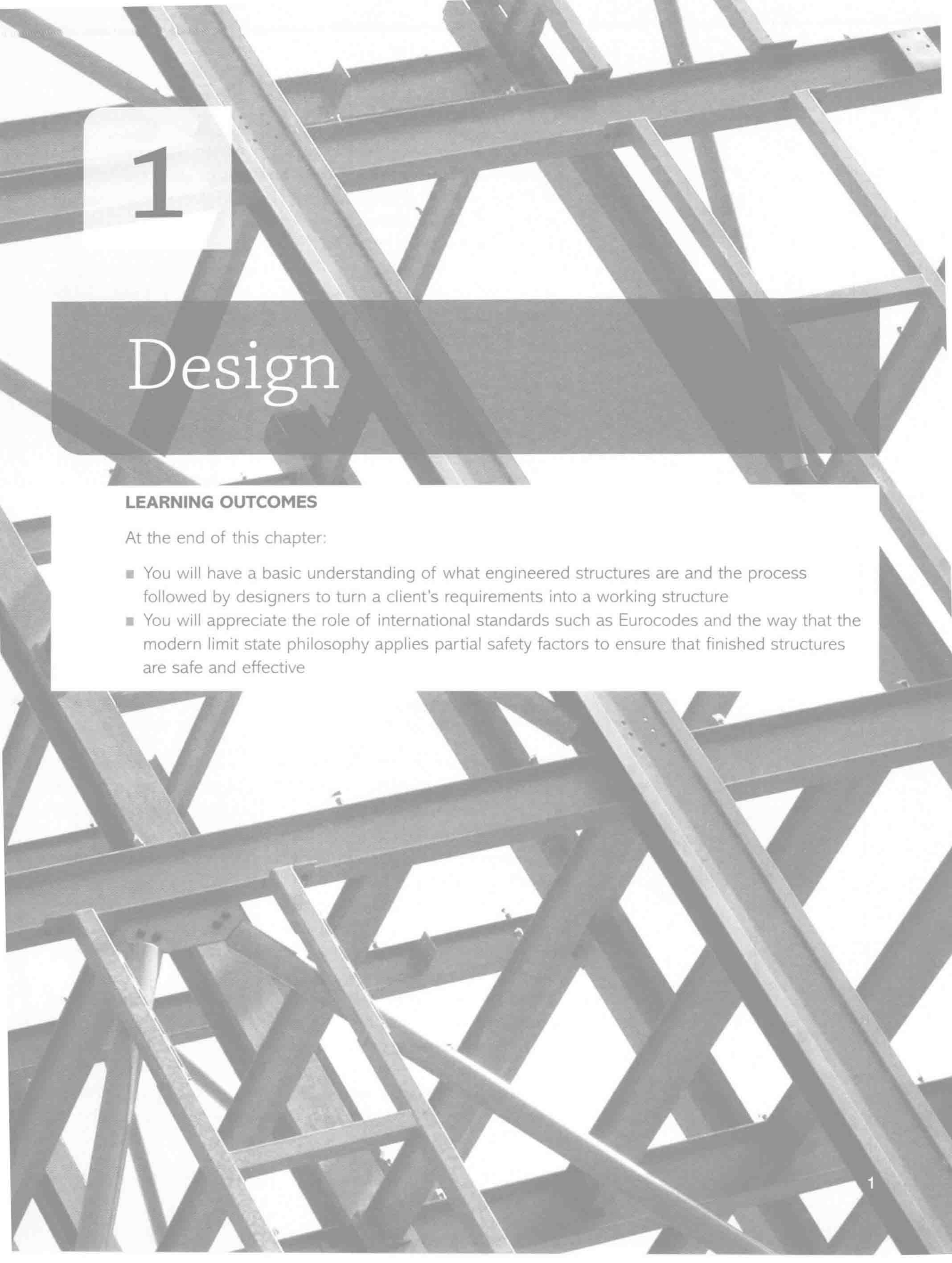
Symbols

A	cross-sectional area
A_c	area of concrete
A_{net}	net area
A_s	area of tensile reinforcement
A_{sc}	area of compressive reinforcement
A_{sv}	area of two legs of shear link
a	pitch angle of roof; length of plate in a cross-section
b	width of section; width of concrete
C	width of column
D	depth of arch
d	effective depth of reinforcement
d_s	depth of slab
E	modulus of elasticity
e	eccentricity of load
F	axial force
F_C	compressive force
F_{CC}	compressive force in concrete
F_{CS}	compressive force in steel
F_T	tensile force
f_{ck}	concrete cylinder characteristic strength
f_k	characteristic compressive strength of masonry
f_{kx}	characteristic tensile bending strength of masonry
f_u	steel ultimate strength
f_y	steel characteristic yield strength
f_{yk}	reinforcement characteristic strength
f_{yw}	characteristic strength in shear
G	shear modulus
G_k	characteristic permanent action
H	horizontal component of force
h	section depth
I	second moment of area
i	radius of gyration
j	number of joints
k_a	active earth pressure coefficient
k_p	passive earth pressure coefficient
L	length; length of span

L_e	effective length
M	bending moment
M_{Ed}	design bending moment
M_F	moment due to prestressing force
M_{Rd}	design resistance to bending moment
m	number of members
m_1	moment at node 1
N	number of stress cycles
N_{Ed}	design axial force
N_{ed}	design resistance to axial force
P	concentrated point load; column load
P_{crit}	critical buckling load
P_{1x}	force at node 1 in x direction
p	hydrostatic pressure
p_b	bending strength
p_c	compressive strength
Q	first moment of area about neutral axis
Q_k	characteristic imposed load
q	ground pressure under foundation; shear flow
R	radius of curvature; resultant force; radius of shaft
R_{AV}	vertical reaction force at A
S	magnitude of stress fluctuation
s	spacing of shear links
T	torque
t	wall thickness
t_f	flange thickness
t_w	web thickness
V	vertical component of force; shear force
v_{Ed}	design shear stress
$v_{Rd,c}$	concrete shear strength
W_{el}	elastic section modulus
W_{pl}	plastic section modulus
w	magnitude of uniformly distributed load
x	an arbitrary or unknown distance; neutral axis depth in concrete; torsional index
Y	distance from beam surface to neutral axis
y	distance from neutral axis
z	depth of liquid or soil; lever-arm in concrete beam
β_w	weld factor
γ	unit weight; shear strain
γ_f	partial safety factor for loads
γ_G	partial safety factor for permanent actions
γ_M	partial safety factor for material strength

γ_Q	partial safety factor for variable actions
Δ	deflection of structure
δ	extension of member
δ_{1x}	displacement of node 1 in x direction
ε	strain
θ	angle
θ_1	rotation at node 1
$\bar{\lambda}$	non-dimensional slenderness
μ	slip factor
σ	stress
σ_y	yield stress
σ_u	ultimate stress
τ	shear stress
ϕ	angle of twist
χ	reduction factor

Contents



1

Design

LEARNING OUTCOMES

At the end of this chapter:

- You will have a basic understanding of what engineered structures are and the process followed by designers to turn a client's requirements into a working structure
- You will appreciate the role of international standards such as Eurocodes and the way that the modern limit state philosophy applies partial safety factors to ensure that finished structures are safe and effective

1.1 Introduction

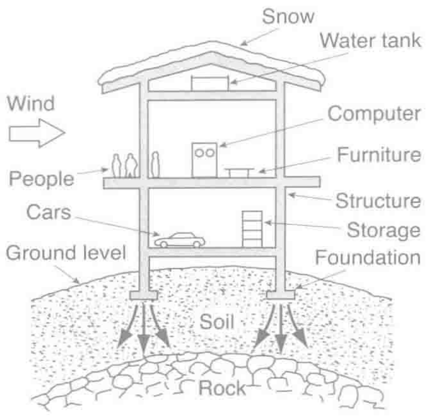


Figure 1.1
A building structure safely transmits loads down to earth

This book is about the **design** and **analysis of structures** in the commonly used structural materials. This chapter starts by looking at what we mean by these words, and then goes on to explain the process that designers perform in order to successfully evolve solutions to structural problems. Finally two distinct approaches or 'design philosophies' are explained – the traditional **permissible stress** method, and the more modem **limit state** method.

An important point to make at the outset is that structural design is a highly creative activity, and not just a case of plugging numbers into formulae. It is also an activity which must be done responsibly, in order to produce **safe** structures. In mechanical engineering most manufactured products with a structural component, like cars for example, can be repeatedly tested to destruction to prove the design at the prototype stage. Modifications can then be made before the product is put on the market. With most civil engineering and building structures there is no prototype. **The design must be right first time**. These structures can also have a very long working life of a hundred years or more, and it is the responsibility of the designer to ensure that the structure remains safe throughout its projected life.

1.2 Structure

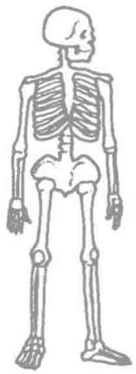


Figure 1.2a
The human skeleton is a structure which maintains the shape of the body, keeps the various organs and muscles in the right place and transmits loads down to the ground

The word **structure** can be used to describe any organised system, such as the 'management structure of a company' or the 'structure of the atom'. However, for the purposes of this book we will limit the definition to the following:

'A structure is a system for transferring loads from one place to another.'

In the case of **building structures** this often means transferring the load of people, furniture, the wind etc. (as well as the self-weight of the building itself) safely down to the foundations and hence into the ground (*figure 1.1*).

Also in this book we are limited to the consideration of **man-made** structures. Nature can show us many superbly efficient examples of structures which have evolved to support loads. Some of these are shown in *figures 1.2a–c*, and although natural structures can be analysed and investigated using the methods described in this book, we are really interested in the exciting task of creating new structures.

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1.3 Analysis

The word **analysis** is generally taken to mean the process whereby a **particular** structure with **known** loads is investigated to determine the distribution of forces throughout the various members that make up that structure. Also it includes determining the distribution of stresses within individual members, which result from the forces imposed on them. Finally, it covers the calculation of deflections (i.e. how far the structure will move) under a particular set of loads. The analysis of a structure is necessary to prove that it is strong enough to support a given set of loads and that it is stiff enough to limit deformations.

Analysis tends to be based on mathematics, and the aim is to get as close as possible to the uniquely correct solution. Analysis is a vital **part** of the design of safe and cost-effective structures, however it cannot take place until the basic form of the structure has been decided. We firstly need to settle such questions as 'should we use steel or concrete?', 'How many supports to the beam should we provide?' These early decisions are referred to as **design** and not analysis.

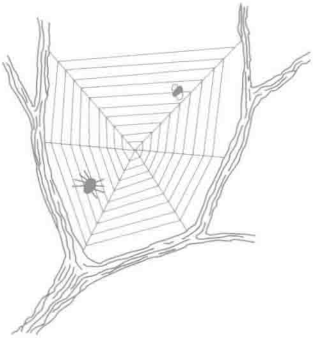

Figure 1.2b
The spider's web is a good example of a **tension** structure. The weight of the spider and its prey is supported by the tensile strength of the web

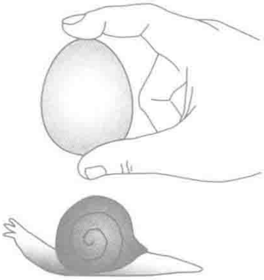

Figure 1.2c
Shells are particularly efficient structures – being rigid and lightweight. The curved surfaces can be very thin

1.4 Design

Design is a more difficult word to define than analysis because it means such different things to different people. The term **designer** is commonly used to describe people who design patterns on carpets, or determine the shape of motor car bodies. Whilst aesthetic design is very important it is **not** the subject of this book.

Engineering design or **structural design**, which **is** the subject of this book, is equally creative – just consider the brilliance of the Forth Railway Bridge or the Golden Gate Suspension Bridge (*figure 1.3*), two very different solutions to the similar problem of building a long-span bridge over water.

Even within our own field the word 'design' can be used in two very different ways. Firstly it is used to describe the whole creative process of finding a safe and efficient solution to an engineering problem. Consider, for example, the above case of designing a bridge across a river. There is of course no 'correct' answer, but out of the infinite number of possible solutions, some are clearly much better than others. It is the job of the designer to come up with the best solution within available resources. The design process is dealt with in more detail in the next section.

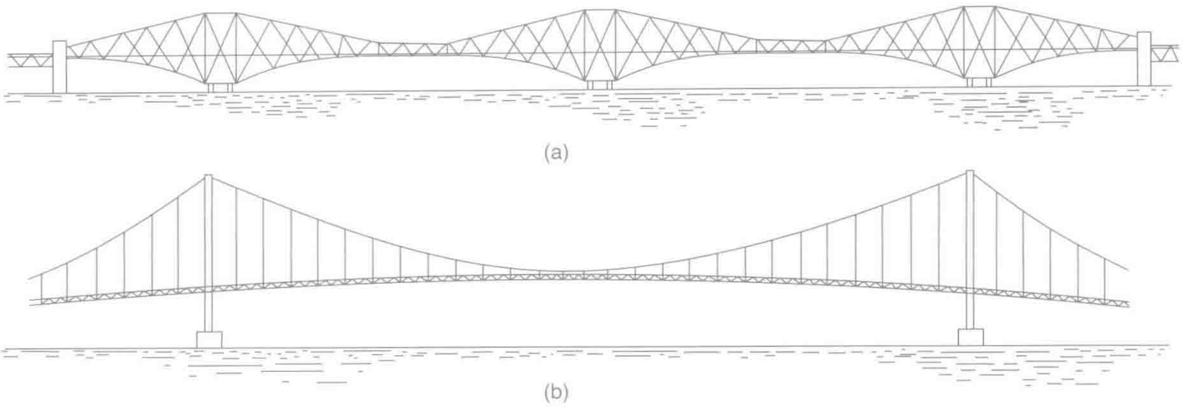

Figure 1.3
Two brilliant, but very different, solutions to a similar problem

(a) The Forth Railway Bridge, Edinburgh, Scotland, 1890

(b) The Golden Gate Bridge, San Francisco, USA, 1937

The second way that we use the word 'design' is in a more restricted sense. It refers to the activities, which often come after the analysis stage, when the forces in each structural member are known. It is the process of determining the actual size of a particular steel column or the number of reinforcing bars in a reinforced concrete beam. This is referred to as *element design*. Determining the number of bolts in a connection or the length of a weld is called *detail design*. There may be several choices open to the designer, but element design and detail design are not as creative as the broader design process. They are, however, very important, and bad detail design is a major cause of structural failures.

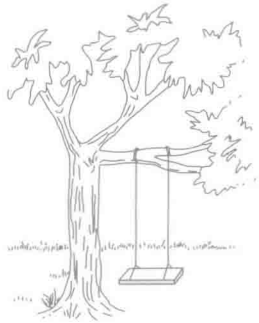

Figure 1.4a
Swing fixed to a tree

1.5 The design process

The best way to explain the general approach adopted by a designer in solving an engineering problem is to take a simple example – in this case the design of a child's garden swing. Clearly, with a small project like this, the formal procedure outlined here would not be consciously followed. The designer would simply use his or her judgement to determine the shape of the swing support structure and the size of the members. Nevertheless it illustrates the steps necessary for the successful completion of larger projects.

The usual starting point for a project is a **client** who has a **requirement**, and the client will approach the designer, who is often a consulting engineer or architect, and commission him or her to produce a design which satisfies the requirement. The first thing that the designer will request from the client is a clear description of exactly what is wanted. This is called the **design brief**.

Figure 1.4b
Tubular steel swing

In our case the client is a child who requires a garden swing, and the brief is:

> **'Provide, within a period of two weeks, a garden swing, which will be a play facility for many years.'**

To arrive at a satisfactory solution the designer will go through the following stages:

- **Stage 1** is the **site survey and investigation**. Suitable locations will be examined and checked to ensure that there are no obstructions within the arc of the swing. Problems of access must be considered and the ground conditions in wet weather taken into account. Finally a few trial-holes might be dug to check that any rock is not too close to the surface to prevent foundations being excavated.

- **Stage 2** involves investigating **alternative structural concepts**. There are an enormous range of structural shapes and materials which could be used and a few of these are shown in *figures 1.4a–f*. Each of these must now be evaluated against clear rational criteria in order to select just one or two schemes for further detailed consideration. The type of factors that would be considered in relation to each scheme are as follows:

  (a) Fixed to tree. This is the cheapest and best solution, but there is no convenient tree.

  (b) A tubular steel frame. They are available from the supermarket. Little labour is involved and the swing is mobile. There are some concerns about cost, durability and appearance, but it is worth bearing in mind.

  (c) Suspended from a helium balloon. An interesting solution, but totally impractical.

  (d) Welded and bolted steel beams. Very robust but it would have to be prefabricated by a local welder. The result is exceedingly ugly and would require painting to prevent rust.

  (e) Timber frame with concrete foundations. Good appearance and relatively cheap but high labour content and some maintenance required for good durability.

  (f) Timber and steel bracket fixed to wall. Unless it is possible to fix the swing away from the corner of the wall there will be safety problems.

The choice therefore comes down to either (b) from the super-

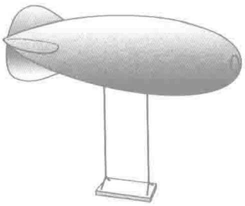

Figure 1.4c
Suspended from a helium balloon

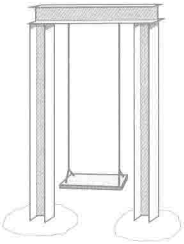

Figure 1.4d
Heavy steel sections

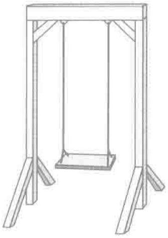

Figure 1.4e
A timber-framed structure

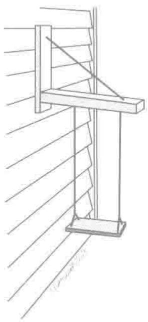

Figure 1.4f
Swing fixed to a wall

market or (e) the timber frame. We will assume that after due investigation of available products the decision is made to go for the timber frame.

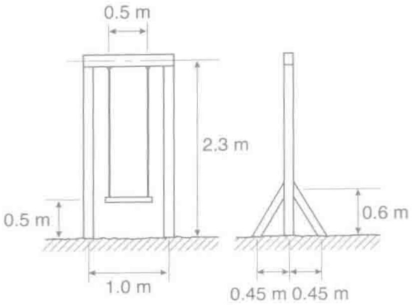

Figure 1.5
Basic dimensions

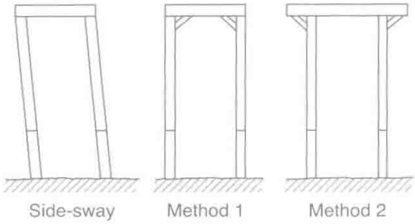

Figure 1.6
The problem of side-sway and two possible methods of preventing it

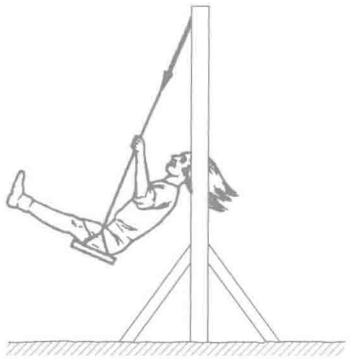

Figure 1.7
Inclined load acting at the top of the swing frame

- **Stage 3** involves more **detailed development** of the selected scheme. The basic overall dimensions must be decided (*figure 1.5*). A method of bracing the frame to prevent side-sway must be found (*figure 1.6*). The type of timber to be used will probably be decided at this stage and the range of available sizes investigated.

- **Stage 4** is the **assessment of loads** on the structure. This is not such a straightforward task as you might at first think. The following issues need to be settled.

  1. Should the swing be designed solely for the weight of a child, or should it be assumed that at some time during its life an adult may use it? I would suggest the latter.

  2. We need to increase the load by a percentage to allow for the fact that the load is **dynamic**, i.e. the load is moving, and we must take account of the effects of its inertia. Also the load may be suddenly applied if someone jumps onto the swing. Increasing the static load by, say, 100% ought to be enough to compensate for these effects.

  3. The load is not always applied vertically downwards. When the load is inclined, as shown in *figure 1.7*, it causes much more severe bending and overturning problems for the structure. Wind loads often cause severe lateral loads, although they are not much of a problem with thin skeletal structures such as this.

  4. Additional forces result from the actual self-weight of the structural members. With structures such as large bridges these forces are usually much bigger than those that result from the traffic passing over the bridge. These self-weight loads present a problem at this stage of the design process because we do not yet know the final size (and hence weight) of the structural members. The designer must therefore make intelligent estimates which should be checked later. Obviously, with increased experience the designer gets better at making these estimates. In our case the effect of self-weight will be very small and could be ignored.

- **Stage 5** is the **analysis** of the structure. Firstly we must transform the diagram of the proposed structure to obtain a simplified structural model which is amenable to analysis. This chiefly involves classifying the joints between the members as either pinned or continuous. This topic is dealt with in more detail later in the book. Our structural model is shown in *figure 1.8*.

The loads are now applied to the structural model and the frame analysed to determine the forces and the amount of bending in each member. It may be necessary to carry out more than one analysis for different load cases. For the swing structure we would probably do it twice – firstly with the load vertical and secondly with the load inclined to produce the worst overturning effect.

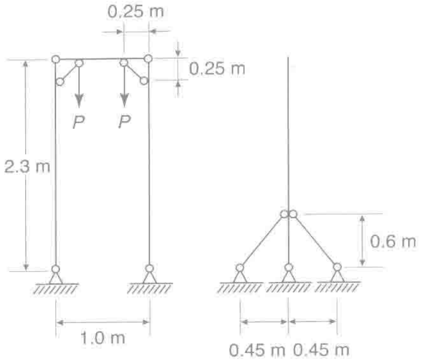

Figure 1.8
The structural model

- **Stage 6** is **element design** and **detail design**. Each member must be considered in turn. Taking into account the forces obtained from the analysis, the required size of the member is calculated so that acceptable stresses are not exceeded. Careful thought must be given to the connections so that forces are adequately transmitted from one member to another. The designer must check all the possible ways in which the structure could fail. Some of these are shown in *figure 1.9* and you may be able to think of some others.

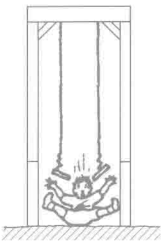

Figure 1.9a
Seat breaks

Figure 1.9b
Rope snaps

Figure 1.9c
Bracing connections fail

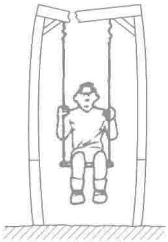

Figure 1.9d
Beam breaks

Finally, with real structures, the designer must clearly communicate his or her requirements to the builder by means of detailed drawings and specifications.

All stages of design are summarised in *figure 1.10*. It is not always possible to separate the process into such neat steps and often analysis and element design will proceed in parallel. Also the analysis to calculate the displacement of the structure can only take place after the member sizes are known.

1.6 National standards and Eurocodes

Because the safety of structures is so important, the major industrial countries developed guidance documents, or **codes of practice**, containing the wisdom and experience of eminent researchers and practising professionals. There tends to be separate documents for each structural material. In the UK these are British Standards or BSs, however all countries within Europe have now agreed a common set of **Eurocodes** that are replacing separate national standards.

The structural suite of Eurocodes consists of 58 individual documents that, in total, cost several thousand pounds. The docu-

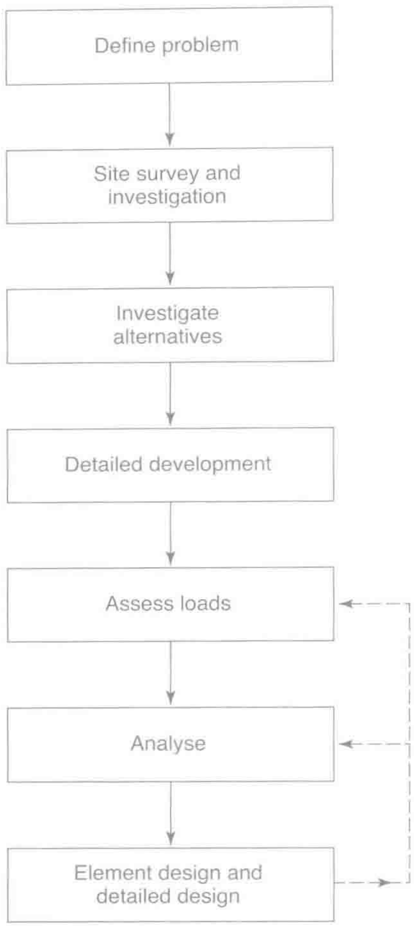

Figure 1.10
The stages of design

ments are published in ten sections. Some sections deal with general matters such as loading and some with specific materials as follows:

EN1990 Eurocode:	Basis of structural design
EN1991 Eurocode 1:	Actions on structures
EN1992 Eurocode 2:	Design of concrete structures
EN1993 Eurocode 3:	Design of steel structures
EN1994 Eurocode 4:	Design of composite steel and concrete structures
EN1995 Eurocode 5:	Design of timber structures
EN1996 Eurocode 6:	Design of masonry structures
EN1997 Eurocode 7:	Geotechnical design
EN1998 Eurocode 8:	Design of structures for earthquake resistance
EN1999 Eurocode 9:	Design of aluminium structures

Eurocode 3, which deals with steel structures, is the most complex and extensive and is published in twenty individual parts, each one dealing with a specific aspect of the material, such as fatigue strength, or type of structure, such as towers or bridges.

An added complication is that alongside each Eurocode lies a 'National Annex' that contains 'Nationally Determined Parameters'. These are factors, constants and procedures to ensure that the code is tuned to the practices and standards of each country. Thus, despite a common standards framework, structures may still be designed differently throughout Europe. In general this book will refer to the Nationally Determined Parameters relevant to the UK. Also, Eurocodes are supported by a series of NCCIs (Non-Contradictory Complementary Information). As the name suggests these are supplementary sources of guidance, explanation or information that are referred to in National Annexes.

These documents contain rules of a very general nature, and they should always be complied with where they are relevant. However, because they are so general, they do require interpretation by qualified designers who understand the underlying theory. They do not replace sound experience, understanding and judgement.

Very small structures, such as those involved in individual houses, are covered by national or local Building Regulations. These contain simple rules covering such issues as the minimum thickness of walls for certain heights. If designers stay within the stated limits then no calculations are required. However, designers are at liberty to go beyond the limits provided that they can justify it by calculation and reference to the relevant standards.

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