Structural Steelwork

Design to Limit State Theory

Fourth Edition

Dennis Lam
Thien-Cheong Ang
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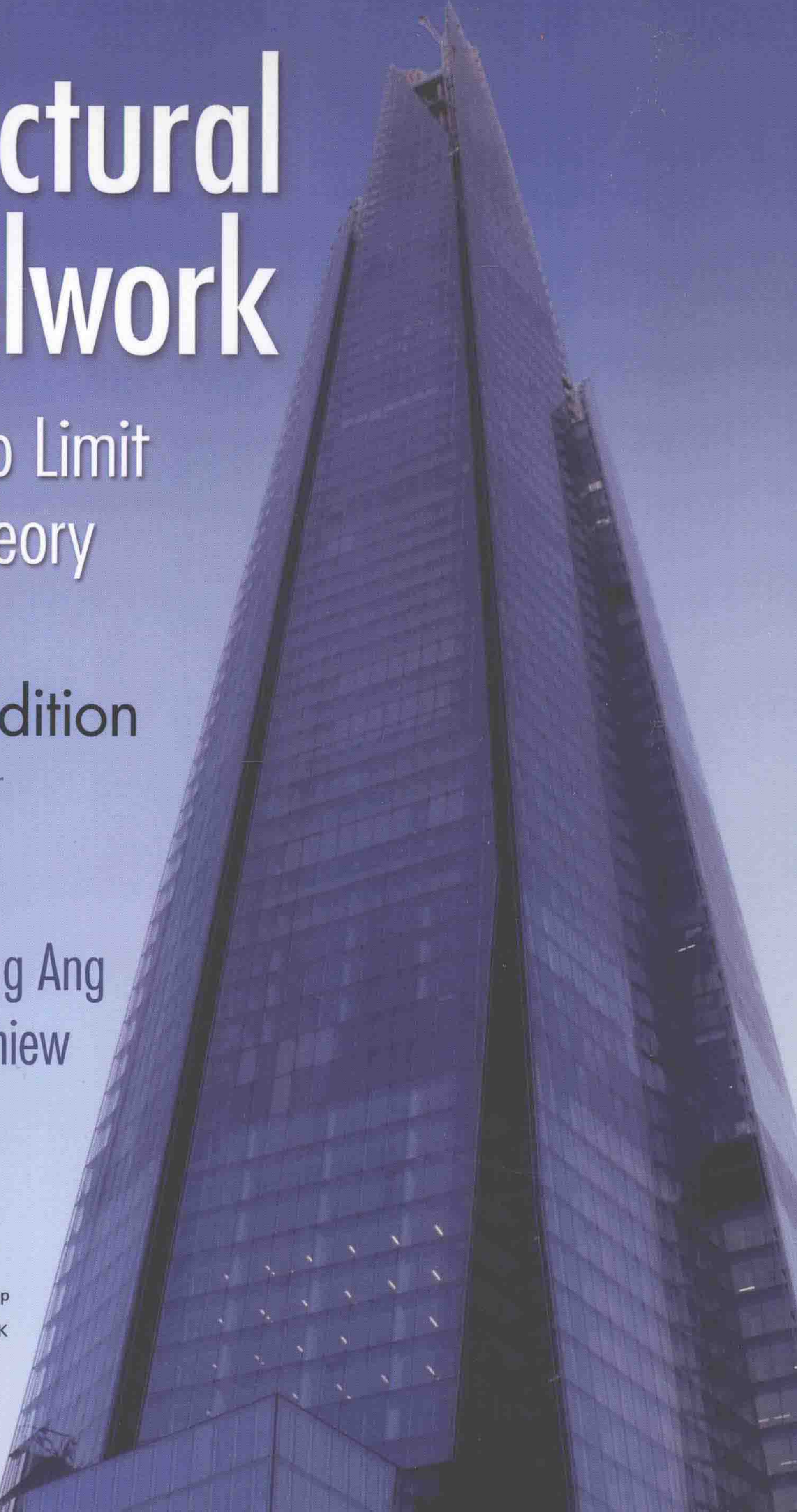

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Preface

This is the fourth edition of the *Structural Steelwork: Design to Limit State Theory*, which proved to be very popular with both students and practising engineers. All the chapters have been updated and rearranged to comply with the Eurocode 3, Design of Steel Structures. In addition, it is also compliant with the other Eurocodes such as Eurocode 0, Basis of Structural Design, and Eurocode 1, Action of Structures. The book contains a detailed explanation of the principles underlying steel design and is intended for students reading for civil and/or structural engineering degrees in universities. It will also be useful for final year students involved in design projects and for practising engineers and architects who require an introduction to the Eurocodes. The topics are illustrated with fully worked examples, and problems are also provided for practice.

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Contents

Chapter 1

Introduction

1.1 STEEL STRUCTURES

Steel-frame buildings consist of a skeletal framework that carries all the loads to which the building is subjected. The sections through three common types of buildings are shown in Figure 1.1. These are

1. Single-storey lattice roof building
2. Single-storey portal frame building
3. Medium-rise braced multistorey building

These three types cover many of the uses of steel-frame buildings such as factories, warehouses, offices, flats and schools. A design for the lattice roof building (Figure 1.1a) is given, and the design of the elements for the braced multistorey building (Figure 1.1c) is also included. The design of portal frame is described separately in Chapter 9.

The building frame is made up of separate elements – the beams, columns, trusses and bracing – listed beside each section in Figure 1.1. These must be joined together, and the building attached to the foundations. The elements are discussed more fully in Section 1.2.

Buildings are 3D and only the sectional frame has been shown in Figure 1.1. These frames must be propped and braced laterally so that they remain in position and carry the loads without buckling out of the plane of the section. Structural framing plans are shown in Figures 1.2 and 1.3 for the building types illustrated in Figure 1.1a and c.

Various methods for analysis and design have been developed over the years. In Figure 1.1, the single-storey structure in (a) and the multistorey building in (c) are designed by the simple design method, whilst the portal frame in (b) is designed by the continuous design method. All design is based on Eurocode 3 (EN1993). Design theories are discussed briefly in Section 1.4, and design methods are set out in detail in Chapter 2.

1.2 STRUCTURAL ELEMENTS

As mentioned earlier, steel buildings are composed of distinct elements:

1. *Beams and girders*: members carrying lateral loads in bending and shear.
2. *Ties*: members carrying axial loads in tension.
3. *Struts, columns or stanchions*: members carrying axial loads in compression. These members are often subjected to bending as well as compression.
4. *Trusses and lattice girders*: framed members carrying lateral loads. These are composed of struts and ties.

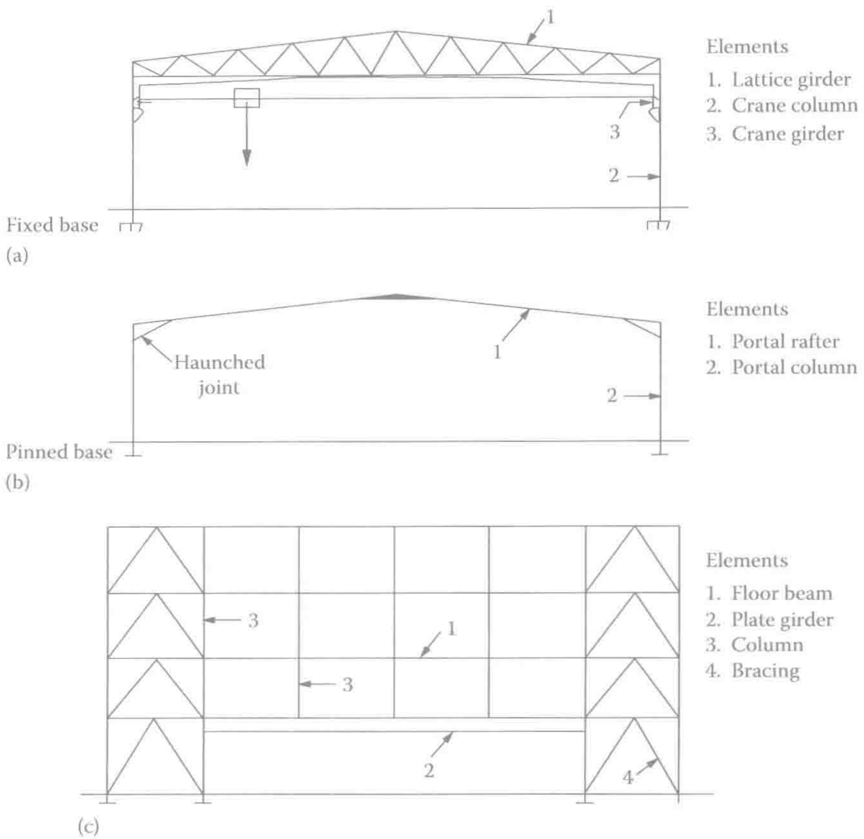

Figure 1.1 Three common types of steel buildings: (a) single-storey lattice roof building with crane; (b) single-storey rigid pinned base portal; (c) multistorey building.

5. *Purlins*: beam members carrying roof sheeting.
6. *Sheeting rails*: beam members supporting wall cladding.
7. *Bracing*: diagonal struts and ties that, with columns and roof trusses, form vertical and horizontal trusses to resist wind loads and hence provided the stability of the building.

Joints connect members together such as the joints in trusses, joints between floor beams and columns or other floor beams. Bases transmit the loads from the columns to the foundations.

The structural elements are listed in Figures 1.1 through 1.3, and the types of members making up the various elements are discussed in Chapter 3. Some details for a factory and a multistorey building are shown in Figure 1.4.

1.3 STRUCTURAL DESIGN

Nowadays, building design is usually carried out by a multidiscipline design team. An architect draws up plans for a building to meet the client's requirements. The structural engineer examines various alternative framing arrangements and may carry out

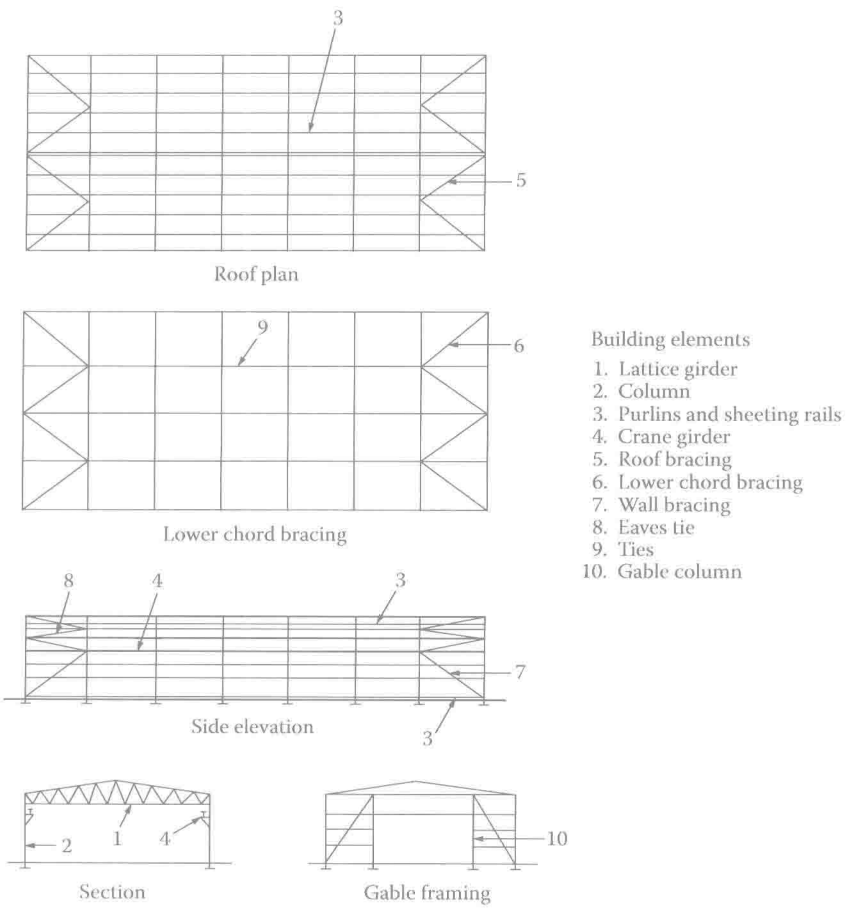

Figure 1.2 Factory building.

preliminary designs to determine which is the most economical. This is termed the 'conceptual design stage'. For a given framing arrangement, the problem in structural design consists of

1. Estimation of loading
2. Analysis of main frames, trusses or lattice girders, floor systems, bracing and connections to determine axial loads, shears and moments at critical points in all members
3. Design of the elements and connections using design data from step 2
4. Production of arrangement and detail drawings from the designer's sketches

This book covers the design of elements first. Then, to show various elements in their true context in a building, the design for the basic single-storey structure with lattice roof shown in Figure 1.2 is given.

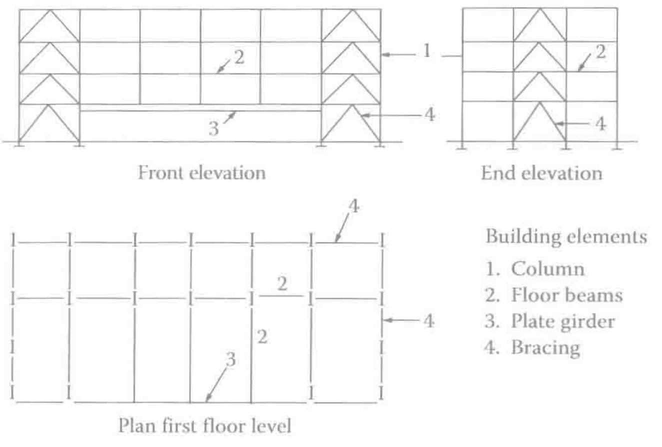

Figure 1.3 Multistorey office building.

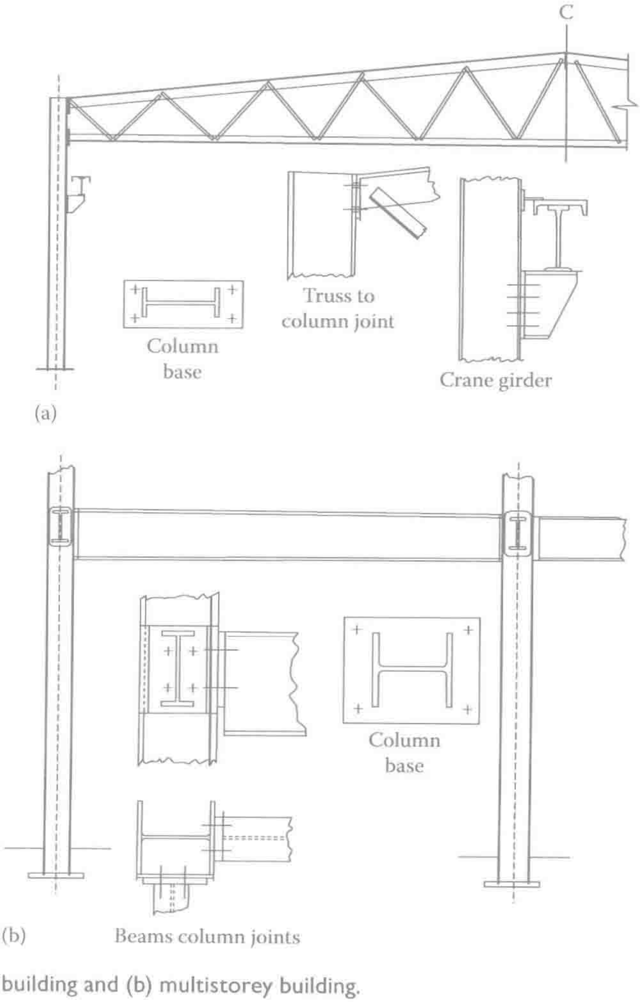

Figure 1.4 (a) Factory building and (b) multistorey building.

1.4 DESIGN METHODS

Steel design may be based on three design theories:

1. Elastic design
2. Plastic design
3. Limit-state design

Elastic design is the traditional method and is still commonly used in the United States. Steel is almost perfectly elastic up to the yield point, and elastic theory is a very good method on which the method is based. Structures are analysed by elastic theory, and sections are sized so that the permissible stresses are not exceeded. This method was used in the United Kingdom in accordance with BS 449-2: 1967: *The Use of Structural Steel in Building*.

Plastic theory developed to take account of behaviour past the yield point is based on finding the load that causes the structure to collapse. Then the working load is the collapse load divided by a load factor. This too was permitted under BS 449.

Finally, limit-state design has been developed to take account of all conditions that can make the structure become unfit for use. The design is based on the actual behaviour of materials and structures in use and is in accordance with EC 3 (EN1993).

The code requirements relevant to the worked problems are noted and discussed. The complete code should be obtained and read in conjunction with this book.

The aim of structural design is to produce a safe and economical structure that fulfils its required purpose. Theoretical knowledge of structural analysis must be combined with knowledge of design principles and theory and the constraints given in the standard to give a safe design. A thorough knowledge of properties of materials, methods of fabrication and erection is essential for the experienced designer. The learner must start with the basics and gradually build up experience through doing coursework exercises in conjunction with a study of design principles and theory.

The ECs are drawn up by panels of experts from the professional institutions and include engineers from educational and research institutions, consulting engineers, government authorities and fabrication and construction industries. The standards give the design methods, factors of safety, design loads, design strengths, deflection limits and safe construction practices.

As well as the main design standard for structural steelwork, EN1993, reference must be made to other relevant standards, including

1. BS EN 10020: 2000: This gives definition and classification of grades of steel.
2. BS EN 10029: 1991 (plates); BS EN 10025: 1993 (sections); BS EN 10210-1: 1994 (hot-finished hollow sections); and BS EN 10219-1: 1997 (cold-formed hollow sections). This gives the mechanical properties for the various types of steel sections.
3. EN1991-1-1: Actions on structures (general actions), densities, self-weight, and imposed loads for buildings.
4. EN1991-1-4: Actions on structures (general actions), wind actions.
5. EN1991-1-3: Actions on structures (general actions), snow loads.

Representative loading may be taken for element design. Wind loading depends on the complete building and must be estimated using the wind code.

1.5 DESIGN CALCULATIONS AND COMPUTING

Calculations are needed in the design process to determine the loading on the structure, carry out the analysis and design the elements and joints and must be set out clearly in a standard form. Design sketches to illustrate and amplify the calculations are an integral part of the procedure and are used to produce the detail drawings.

Computing now forms an increasingly larger part of design work, and all routine calculations can be readily carried out on a PC. The use of the computer speeds up calculation and enables alternative sections to be checked, giving the designer a wider choice than would be possible with manual working. However, it is most important that students understand the design principles involved before using computer programs.

It is through doing exercises that the student consolidates the design theory given in lectures. Problems are given at the end of most chapters.

1.6 DETAILING

Chapter 12 deals with the detailing of structural steelwork. In the earlier chapters, sketches are made in design problems to show building arrangements, loading on frames, trusses, members, connections and other features pertinent to the design. It is often necessary to make a sketch showing the arrangement of a joint before the design can be carried out. At the end of the problem, sketches are made to show basic design information such as section size, span, plate sizes, drilling and welding. These sketches are used to produce the working drawings.

The general arrangement drawing and marking plans give the information for erection. The detailed drawings show all the particulars for fabrication of the elements. The designer must know the conventions for making steelwork drawings, such as the scales to be used, the methods for specifying members, plates, bolts and welding. He or she must be able to draw standard joint details and must also have the knowledge of methods of fabrication and erection. AutoCAD is becoming generally available, and the student should be given an appreciation of their use.

Chapter 2

Limit-state design

2.1 LIMIT-STATE DESIGN PRINCIPLES

The central concepts of limit-state design are as follows:

1. All separate conditions that make the structure unfit for use are taken into account. These are the separate limit states.
2. The design is based on the actual behaviour of materials and performance of structures and members in service.
3. Ideally, design should be based on statistical methods with a small probability of the structure reaching a limit state.

The three concepts are examined in more detail as follows.

Requirement (1) means that the structure should not overturn under applied loads and its members and joints should be strong enough to carry the forces to which they are subjected. In addition, other conditions such as excessive deflection of beams or unacceptable vibration, though not in fact causing collapse, should not make the structure unfit for use.

In concept (2), the strengths are calculated using plastic theory, and post-buckling behaviour is taken into account. The effect of imperfections on design strength is also included. It is recognized that calculations cannot be made in all cases to ensure that limit states are not reached. In cases such as brittle fracture, good practice must be followed to ensure that damage or failure does not occur.

Concept (3) implies recognition of the fact that loads and material strengths vary, approximations are used in design and imperfections in fabrication and erection affect the strength in service. All these factors can only be realistically assessed in statistical terms. However, it is not yet possible to adopt a complete probability basis for design, and the method adopted is to ensure safety by using suitable factors. Partial factors of safety are introduced to take account of all the uncertainties in loads, materials strengths, etc. mentioned earlier. These are discussed more fully later.

2.2 LIMIT STATES FOR STEEL DESIGN

The limit states for which steelwork is to be designed are covered in Section 2 of EN1993-1-1 and Section 2 of EN1990. These are as follows.

2.2.1 Ultimate limit states

The ultimate limit states include the following:

1. Strength (including general yielding, rupture, buckling and transformation into a mechanism)
2. Stability against overturning and sway
3. Fracture due to fatigue
4. Brittle fracture

When the ultimate limit states are exceeded, the whole structure or part of it collapses.

2.2.2 Serviceability limit states

The serviceability limit states consist of the following:

5. Deflection
6. Vibration (e.g. wind-induced oscillation)
7. Repairable damage due to fatigue
8. Corrosion and durability

The serviceability limit states, when exceeded, make the structure or part of it unfit for normal use but do not indicate that collapse has occurred.

All relevant limit states should be considered, but usually it will be appropriate to design on the basis of strength and stability at ultimate loading and then check that deflection is not excessive under serviceability loading. Some recommendations regarding the other limit states will be noted when appropriate, but detailed treatment of these topics is outside the scope of this book.

2.3 WORKING AND FACTORED LOADS

2.3.1 Working loads

The working loads (also known as the specified, characteristic or nominal loads) are the actual loads the structure is designed to carry. These are normally thought of as the maximum loads that will not be exceeded during the life of the structure. In statistical terms, characteristic loads have a 95% probability of not being exceeded. The main loads on buildings may be classified as

1. *Dead loads*: These are due to the weights of floor slabs, roofs, walls, ceilings, partitions, finishes, services and self-weight of steel. When sizes are known, dead loads can be calculated from weights of materials or from the manufacturer's literature. However, at the start of a design, sizes are not known accurately, and dead loads must often be estimated from experience. The values used should be checked when the final design is complete. For examples on element design, representative loading has been chosen, but for the building design examples, actual loads from EN1991-1-1 are used.
2. *Imposed loads*: These take account of the loads caused by people, furniture, equipment, stock, etc. on the floors of buildings and snow on roofs. The values of the floor loads used depend on the use of the building. Imposed loads are given in EN1993-1-1, and snow load is given in EN1993-1-3.

3. *Wind loads*: These loads depend on the location and building size. Wind loads are given in EN1991-1-4.
4. *Dynamic loads*: These are caused mainly by cranes. An allowance is made for impact by increasing the static vertical loads, and the inertia effects are taken into account by applying a proportion of the vertical loads as horizontal loads. Dynamic loads from cranes are given in EN1991-3.

Other loads on the structures are caused by waves, ice, seismic effects, etc. and these are outside the scope of this book.

2.3.2 Factored loads for the ultimate limit states

In accordance with EN1990, factored loads are used in design calculations for strength and equilibrium.

Factored load = working or nominal load × relevant partial load factor, γ_f

The partial load factor takes account of

1. The unfavourable deviation of loads from their nominal values
2. The reduced probability that various loads will all be at their nominal value simultaneously

It also allows for the uncertainties in the behaviour of materials by using material partial factors, γ_M, and of the structure as opposed to those assumed in design.

The partial load factors, γ_f, are given in Annex A1 of EN1990. The factored loads should be applied in the most unfavourable manner, and members and connections should not fail under these load conditions. Brief comments are given on some of the load combinations:

1. The main load for design of most members and structures is dead plus imposed load.
2. In light roof structures, uplift and load reversal occurs, and tall structures must be checked for overturning. The load combination of dead plus wind load is used in these cases with a load factor of 1.0 for dead and 1.5 for wind load.
3. It is improbable that wind and imposed loads will simultaneously reach their maximum values and load factors are reduced accordingly.
4. It is also unlikely that the impact and surge load from cranes will reach maximum values together, and so the load factors are reduced. Again, when wind is considered with crane loads, the factors are further reduced.

2.4 STABILITY LIMIT STATES

To ensure stability, EN1990 states that structures must be checked using factored loads for the following two conditions:

1. *Overturning*: The structure must not overturn or lift off its seat.
2. *Sway*: To ensure adequate resistance, design checks are required:
   a. Design to resist the applied horizontal loads in addition with.
   b. The design for notional horizontal loads: These are to be taken as 0.5% of the factored dead plus imposed load and are to be applied at the roof and each floor level. They are to act with 1.35 times the dead and 1.5 times the imposed load.

Sway resistance may be provided by bracing rigid-construction shear walls, stair wells or lift shafts. The designer should clearly indicate the system he or she is using. In examples in this book, stability against sway will be ensured by bracing and rigid portal action.

2.5 STRUCTURAL INTEGRITY

The provisions of Annex A of EN1991-1-7 ensure that the structure complies with the building regulations and has the ability to resist progressive collapse following accidental damage. The main parts of the clause are summarized as follows:

1. All structures must be effectively tied at all floors and roofs. Columns must be anchored in two directions approximately at right angles. The ties may be steel beams or reinforcement in slabs. End connections must be able to resist a factored tensile load of 75 kN for floors and for roofs.
2. Additional requirements are set out for certain multistorey buildings where the extent of accidental damage must be limited. In general, tied buildings will be satisfactory if the following five conditions are met:
   a. Sway resistance is distributed throughout the building.
   b. Extra tying is to be provided as specified.
   c. Column splices are designed to resist a specified tensile force.
   d. Any beam carrying a column is checked as set out in (3) later.
   e. Precast floor units are tied and anchored.
3. Where required in (2), the aforementioned damage must be localized by checking to see if at any storey, any single column or beam carrying a column may be removed without causing more than a limited amount of damage. If the removal of a member causes more than the permissible limit, it must be designed as a key element. These critical members are designed for accidental loads set out in the building regulations. The recommended value for building structures is 34 kN/m^2.

The complete section in the code and the building regulations should be consulted.

2.6 SERVICEABILITY LIMIT-STATE DEFLECTION

Deflection is the main serviceability limit state that must be considered in design. The limit state of vibration is outside the scope of this book, and fatigue was briefly discussed in Section 2.2.1 and, again, is not covered in detail. The protection for steel to prevent the limit state of corrosion being reached was mentioned in Section 2.2.4.

NA to BS EN1993-1-1 states in NA2.23 that deflection under serviceability loads of a building or part should not impair the strength or efficiency of the structure or its components or cause damage to the finishings. The serviceability loads used are the unfactored imposed loads except in the following cases: Table 2.1 gives suggested limits for calculated vertical deflections of certain members under the characteristic load combination due to variable loads and should not include permanent loads.

The structure is considered to be elastic and the most adverse combination of loads is assumed. Deflection limitations are given in NA 2.23 and NA 2.24. These are given here in Table 2.1. These limitations cover beams and structures other than pitched-roof portal frames.

Table 2.1 Deflection limits

Deflection of beams due to unfactored imposed loads	
Cantilevers	Length/180
Beams carrying plaster or other brittle finish	Span/360
All other beams (except purlins and sheeting rails)	Span/200
Purlins and sheeting rails	To suit the characteristics of particular cladding
Horizontal deflection of columns due to unfactored imposed and wind loads	
Tops of columns in single-storey buildings except portal frames	Height/300
In each storey of a building with more than one storey	Storey height/300

It should be noted that calculated deflections are seldom realized in the finished structure. The deflection is based on the beam or frame steel section only, and composite action with slabs or sheeting is ignored. Again, the full value of the imposed load used in the calculations is rarely achieved in practice.

2.7 DESIGN STRENGTH OF MATERIALS

The design strengths for steel are given in Section 3.2 of EN1993-1-1. Note that the material partial factor, γ_{M0}, part of the overall safety factor in limit-state design, is taken as 1.0 in the code. The design strength may be taken as

- The ratio f_u/f_y of the specified minimum ultimate tensile strength f_u to the specified minimum yield strength, f_y
- The elongation at failure on a gauge length of $5.65\sqrt{A_0}$ (where A_0 is the original cross-sectional area)
- The ultimate strain ε_u, where ε_u corresponds to the ultimate strength f_u

Note: The limiting values of the ratio f_u/f_y, the elongation at failure and the ultimate strain ε_u may be defined in the National Annex (NA). The following values are recommended:

- $f_u/f_y \geq 1,10$
- Elongation at failure not less than 15%
- $\varepsilon_u \geq 15\varepsilon_y$, where ε_y is the yield strain ($\varepsilon_y = f_y/E$)

The values of f_y and f_u are given in Table 3.1 of the EN1993-1-1.

The code states that the following values for the elastic properties are to be used:

Modulus of elasticity, $E = 210{,}000\ \text{N/mm}^2$

Shear modulus, $G = \dfrac{E}{2(1+\nu)} \approx 81{,}000\ \text{N/mm}^2$

Poisson's ratio, $\nu = 0.30$

Coefficient of linear thermal expansion $\alpha = 12 \times 10^{-6}/\text{K}$ (for $T \leq 100°\text{C}$)