Part One

Advanced Analysis of Steel Frames

1 Introduction

1.1 TYPE OF STEEL FRAMES

Steel frames have been widely used in single-storey, low-rise industrial buildings (Figure 1.1(a)), power plants (Figure 1.1(b)), ore mines (Figure 1.1(c)), oil and gas offshore platforms (Figure 1.1(d)) and multi-storey, high-rise buildings (Figure 1.1(e)). The discussions contained in this book will be mainly on, but not limited to, the steel frames used in buildings. According to the elevation view, steel frames used in low-rise and high-rise buildings can be categorized into (1) pure frame (Figure 1.2), (2) concentrically braced frame (Figure 1.3), (3) eccentrically braced frame (Figure 1.4) and (4) frame tube (Figure 1.5).

A pure frame has good ductility with not so good sway stiffness for multi-storey buildings. Strengthened with braces to pure frame, the sway stiffness of a concentrically braced frame is much improved. However, its capacity against lateral loading will be easily reduced if braces in compression are buckled, which is unfavourable under conditions such as earthquakes. An eccentrically braced frame is a compromise in sway stiffness and capacity between the pure frame and the concentrically braced frame. Buckling of braces in compression can be prevented by introducing shear yielding of an eccentric shear beam, which provides good energy-consuming performance to the eccentrically braced frame (Li, 2004). A frame tube is actually a frame group with very close columns, where because of small span and relatively large stiffness of steel beams, columns in the peripheral bend as a thin-walled tube to resist sway loads. Because it has good sway stiffness and load capacity, the frame tube is generally used in high-rise buildings (Council on Tall Buildings, 1979).

1.2 TYPE OF COMPONENTS FOR STEEL FRAMES

For convenience of fabrication, the prismatic components with uniform section (Figure 1.6(a)) are usually used for steel frames. However, to reduce steel consumption, tapered beams and columns (Figure 1.6(b)) are normally employed for steel portal frames (Figure 1.7) to keep relatively uniform strength to resist the dominant vertical loads (Li, 2001). In multi-storey steel buildings, the cast in-site concrete is widely used for floor slabs (Figure 1.8). To utilize the capacity of concrete slabs, a composite beam can be designed, and with headed shear studs, the composite action between concrete slabs and steel beams can be obtained (Nethercot, 2003), as shown in Figure 1.9.

Advanced Analysis and Design of Steel Frames Guo-Qiang Li and Jin-Jun Li

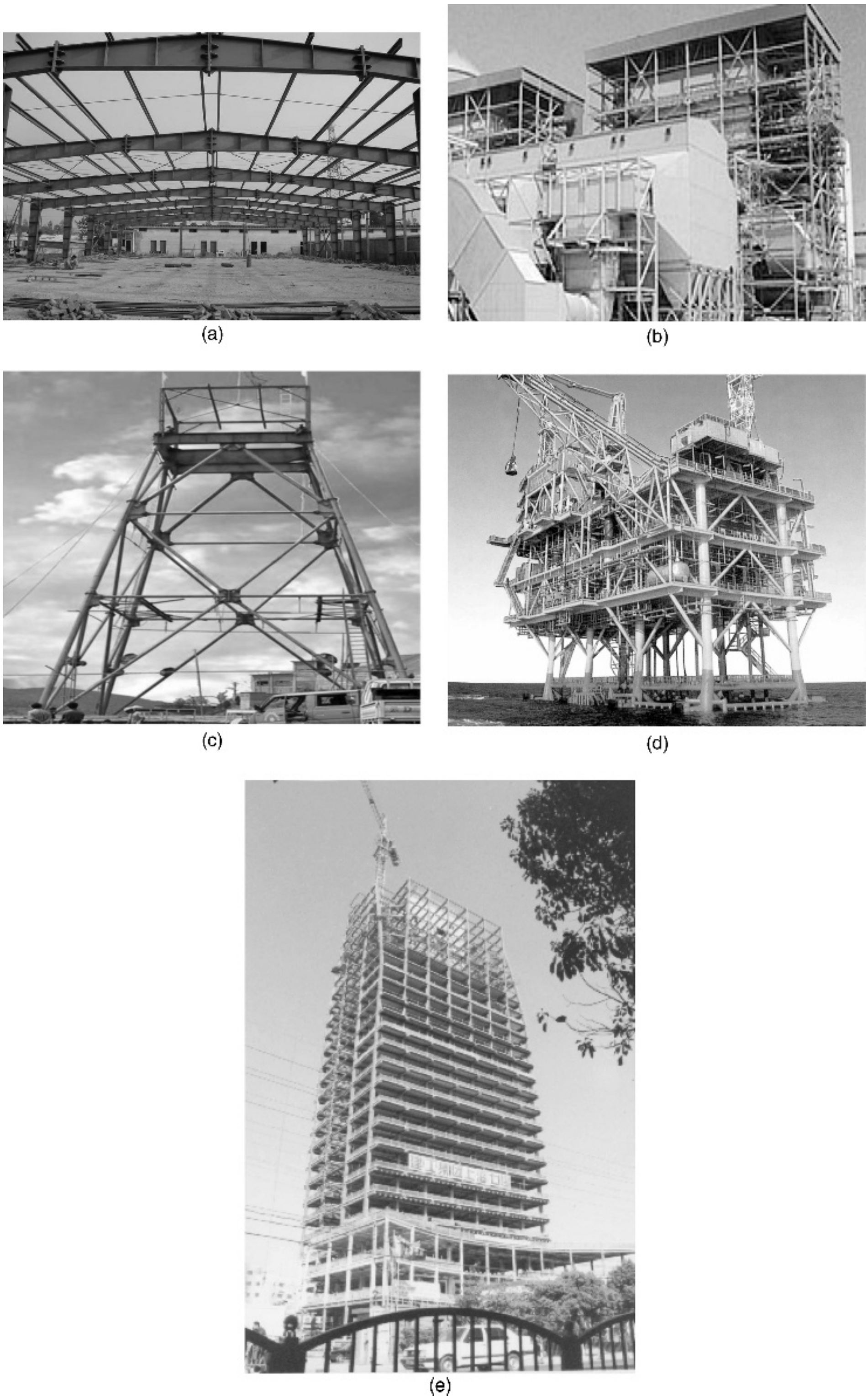

Figure 1.1 Application of steel frames: (a) single-storey industrial building; (b) power plant; (c) ore miners tower; (d) oil and gas offshore platform; (e) high-rise building

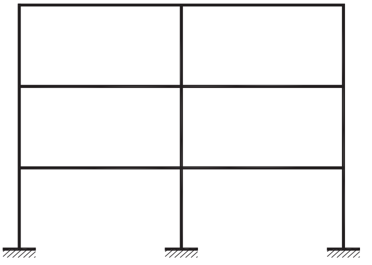

Figure 1.2 Pure frame

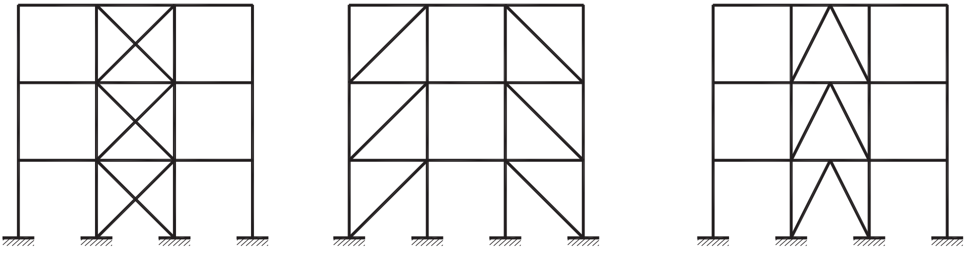

Figure 1.3 Concentrically braced frames

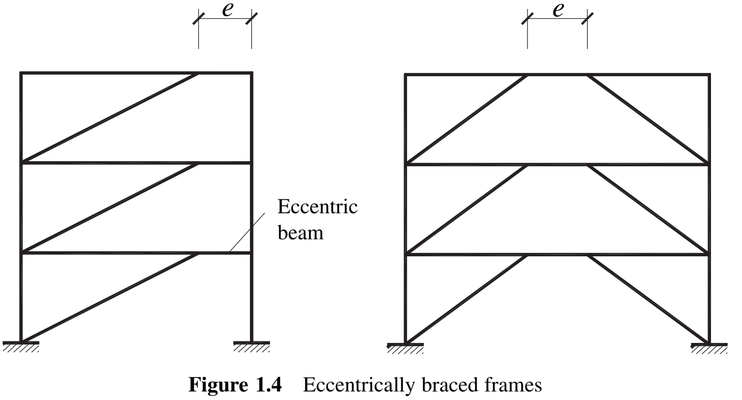

Figure 1.4 Eccentrically braced frames

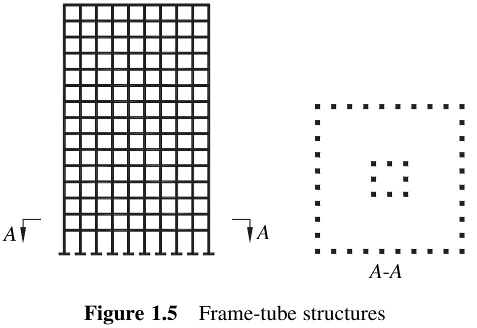

Figure 1.5 Frame-tube structures

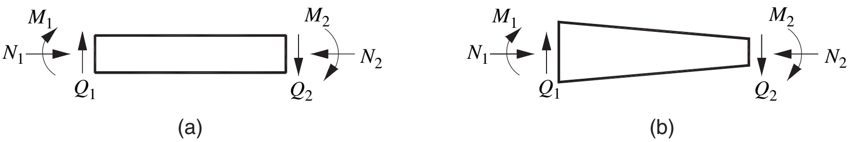

Figure 1.6 (a) Prismatic and (b) tapered members in steel frames

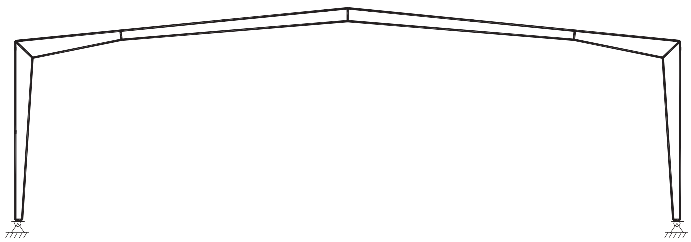

Figure 1.7 Steel portal frame with tapered members

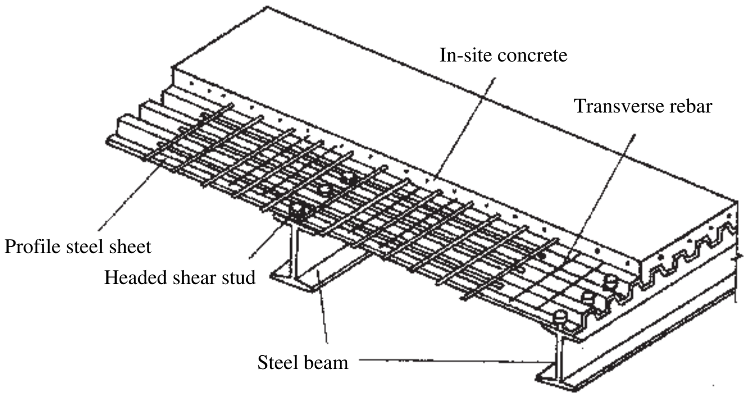

Figure 1.8 Floor system in multi-storey, high-rise steel buildings

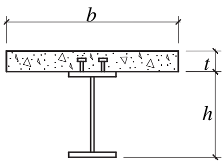

Figure 1.9 Section of a steel–concrete composite beam

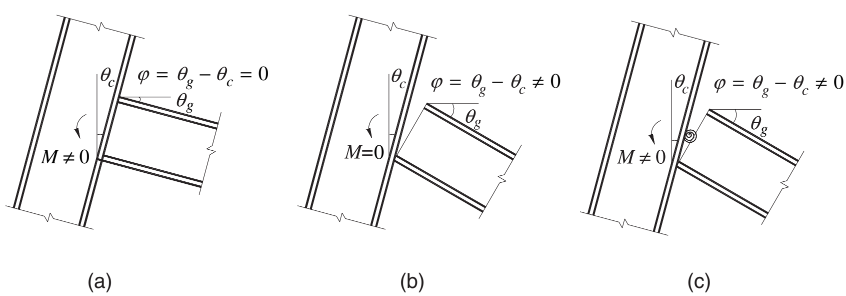

Figure 1.10 Forces and deformations of beam–column connections

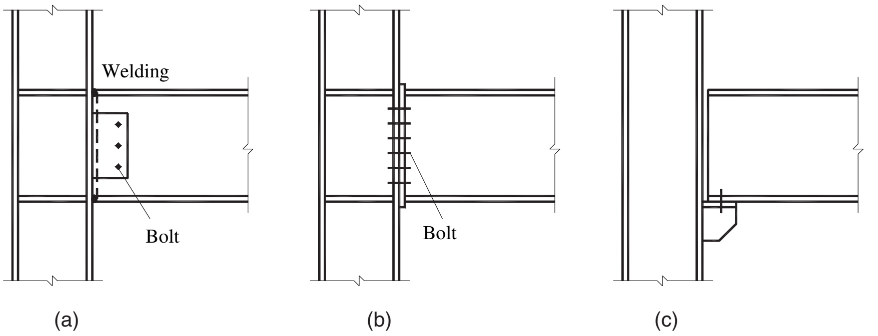

Figure 1.11 Typical configurations of beam–column connections in steel frames

1.3 TYPE OF BEAM–COLUMN CONNECTIONS

According to the moment–curvature characteristic, connections of beam to column in steel frames can be categorized into (Chen, Goto and Liew, 1996)

(1) rigid connection, where no relative rotation occurs between adjacent beams and columns and bending moment can be transferred fully from a beam to the neighbouring column (Figure 1.10(a));

(2) pinned connection, where relative rotation occurs and bending moment cannot be transferred at all (Figure 1.10(b));

(3) semi-rigid connection, where relative rotation occurs and bending moment can be transferred partially (Figure 1.10(c)).

Some typical beam-to-column connection configurations are illustrated in Figure 1.11(a)–(c) for rigid, pinned and semi-rigid connections, respectively. Semi-rigid connections are often engineering options in the application of steel frames.

1.4 DEFORMATION OF JOINT PANEL

Joint panel is the connection zone of beam and column members in steel frames, as shown in Figure 1.12. Subjected to reaction forces of the beam and column ends adjacent to a joint panel, three possible deformations can occur in the joint panel (Figure 1.13): (1) stretch/contract, (2) bending and (3) shear deformations.

Due to restraint of adjacent beams, stretch/contract and bending deformations of the joint panel are very small and can be ignored. Shear deformation is therefore dominant for the joint panel and an experimental deformation of the joint panel is shown in Figure 1.14 (Li and Shen, 1998).

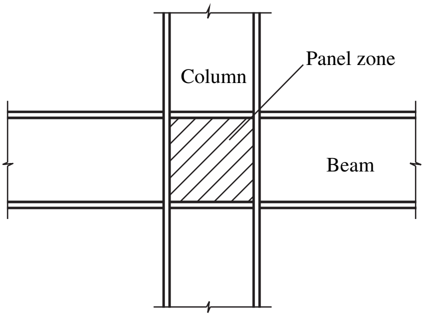

Figure 1.12 Joint panel in steel frames

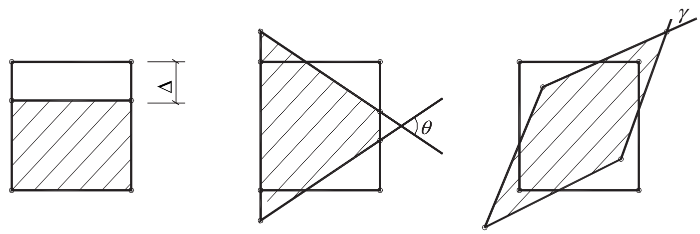

Figure 1.13 Deformations of the joint panel

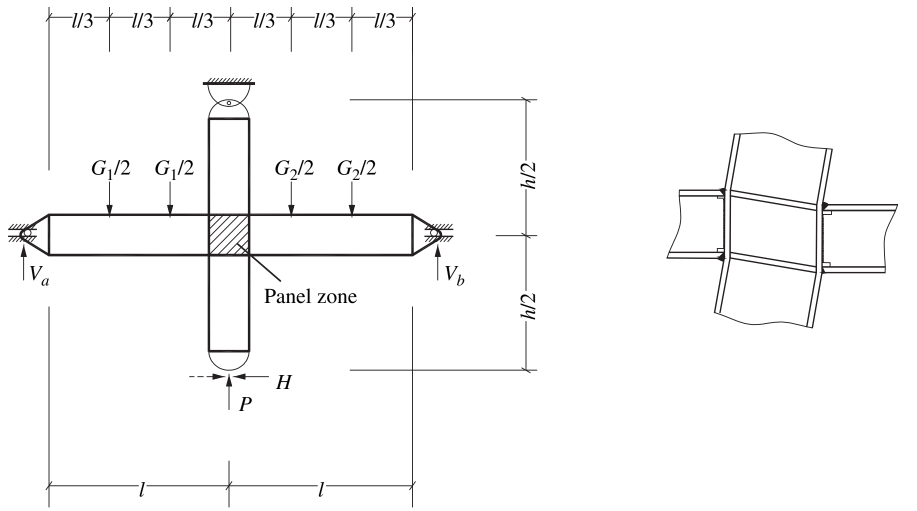

Figure 1.14 Joint panel in the experiment

1.5 ANALYSIS TASKS AND METHOD FOR STEEL FRAME DESIGN

The analysis tasks for the steel frame design include (1) linearly elastic frame analysis to determine resultant forces and deformation of frame members, (2) elastic stability analysis of the frame under vertical loads, (3) nonlinear frame analysis to determine the load-bearing capacity, and (4) elastic and elasto-plastic seismic frame analysis (Liu and Ge, 2005). The first analysis task is the most common practice in structural design, and the latter three analyses will be discussed in this book.

Traditional structure analysis methods such as the force method, displacement method and moment distribution method can be used in linearly elastic analysis of steel frames. However, for the frames with many storeys and bays when nonlinear analysis is performed, traditional analysis methods are not applicable. With the development of computer hardware and software, the matrix analysis method based on finite elements has been widely employed in structural engineering. For the analysis of steel frames, the procedures of the matrix analysis method based on finite component elements are (Bath, 1996)

(1) *Discretizing frame*. Generally, the whole beam, column or brace component can be represented with one element. In elasto-plastic analysis, subdivision is necessary if the plastic deformation occurs within two ends of beams. If effects of the joint panel are necessarily considered in the analysis, the joint panel should be represented with an independent element.

(2) *Establishing elemental stiffness equations*. Elemental stiffness equation is the relationship between nodal forces and deformations of the element, which can be expressed with the matrix and vector

equation as $[k]\{\delta\} = \{f\}$, where $[k]$ is the elemental stiffness matrix, and $\{\delta\}$ and $\{f\}$ are nodal deformation and force vectors. In linearly elastic analysis, $[k]$ is a constant matrix, whereas in nonlinear analysis it relates to the history of elemental force and deformation.

(3) *Assembling the global stiffness equation*. Elemental stiffness equations can be assembled into a global stiffness equation through incidence between the local node number of the elements and the global node number of the frame for the analysis, and with nodal force equilibrium.

(4) *Calculating nodal deformation*. With consideration of boundary conditions, nodal deformation in global coordinates can be solved from the global stiffness equation.

(5) *Determining elemental resultant*. Nodal deformation in global coordinates can be transformed to that in local coordinates, namely elemental deformation. Then the elemental resultant can be calculated using the elemental stiffness equation with the given elemental deformation.

It can be found from the above procedures that the key step in finite element analysis of steel frames is the development of the elemental stiffness equation because other steps are standard and commonplace in the finite element method.

1.6 DEFINITION OF ELEMENTS IN STEEL FRAMES

The following elements are defined in this book for the analysis of steel frames (Li and Shen, 1998):

(1) *Beam element*. A beam element is often subjected to uniaxial bending moment and minor axial force with negligible axial deformation. Generally, beam members in steel frames can be represented with the beam element due to restraints of floor slabs or floor braces. In addition, column members in steel frames can also be represented with the beam element if the axial deformation can be ignored. It should be noted that, although axial deformation is excluded, effects of axial force on bending stiffness can be involved in the beam element.

(2) *Column element*. A column element is usually subjected to uniaxial or biaxial bending moment and significant axial force. Column members in steel frames can be represented with the column element, and the beam in steel frames can also be represented with the column element if effects of axial deformation are considered. In addition, braces, for example eccentric braces, can be treated as column elements if buckling is precluded.

(3) *Brace element*. A brace element is subjected to no more than axial force. Brace members in steel frames are dominated by axial forces and can be represented with the brace element.

(4) *Shear beam element*. It is a special beam element where shear deformation and shear yielding failure are dominant. An eccentric beam in eccentrically braced frames should be represented with the shear beam element.

(5) *Joint-panel element*. It is a special element to represent the shear deformation of the joint panel in the beam–column connection zone.