7 Multi-storey Buildings

7.1 Introduction

The buildings discussed in this chapter are structures of three or more storeys in height, consisting essentially of beams and columns making up an orthogonal three-dimensional framework. They would include multi-storey office buildings, apartment buildings, hospitals, schools, shopping centres, parking garages and warehouses. Features common to such buildings are uniform storey heights and the regular spacing of columns in each direction in plan.

Because of the relative simplicity of the structural layout the steelwork can be produced economically and erected quickly. In terms of the overall project, the steelwork usually represents a very small percentage of the total cost, in view of the expensive nature of the other work involved – building, finishes, fireproofing, services, etc. When construction time is taken into account, however, a steel-framed structure has the decided advantage of being able to be erected in a very short space of time, thus allowing the following trades to proceed without delay. It is this feature of quick erection that places structural steelwork ahead of any other construction medium when used in fast-track projects – and the relative advantage increases with the height of the structure.

At the architectural design stage of any project an early decision has to be made whether to use steel or reinforced concrete for the main load-bearing framework. When comparative cost estimates are made it is usually found that the two construction media are competitive on a price basis. If a case is to be made for the use of steel it is necessary to exploit the inherent advantages of this material fully. This chapter provides the basis of argument.

7.2 Structural layout

The primary structural elements of a multi-storey building, namely the columns and floor beams, should be laid out with a view to minimising both the cost of the steelwork and the time required for its erection. For any given structure a layout can be determined that optimises the combined beam and column content of the structure, but in most cases functional and architectural considerations have to be taken into account, which mitigates against the design of optimal bay sizes. Consultation between the architect and the engineer in the early stages of planning could help to prevent an uneconomical layout having to be adopted.

The third structural element, after the columns and beams, is the stabilising system necessary to provide lateral support to the building, i.e. to supply stability under gravity...
Loading and to resist the overturning effects of wind. Obviously, the taller the building the more important the bracing system becomes and in very tall structures the provision of adequate lateral support does in fact become the dominant consideration.

Lateral stability may be provided within the steel structure itself by means of bracing, or moment-resisting beam-column connections or steel shearwalls, or it may be imparted by other building elements, e.g. reinforced concrete service towers, or concrete or brick in-fill panels in the walls. In all cases the stabilising elements may be located within the plan dimensions of the building or in the perimeter walls, or they may even be external to the building.

If a building is to incorporate the stabilising system within the steel structure, the framework can be of the two-way braced, one-way braced and one-way-rigid, or two-way rigid type (as discussed in Section 4.4 of Chapter 4). Triangulated bracing is usually cheaper than a stiff moment-resisting frame and should be used wherever access problems do not arise, i.e. where door, window or service openings are not required.

In addition to vertical bracing systems it is necessary to provide stiffness within the plane of each floor, both to maintain the squareness of the floor in plan and to transmit the wind loading on the exterior of the building to the vertical bracing.

### 7.3 Stabilising systems – examples

Figs 7.1 to 7.5 give examples of various bracing systems that can be employed to provide stability to multi-storey buildings. The examples are of general application and illustrate the basic principles involved in such systems. The vertical steel bracing is shown as the X-type for simplicity, but could equally well be chevron bracing, knee bracing or some other type (the features of the various bracing types are discussed more fully in Chapter 11). The floors are shown as steel-braced, but in practice the bracing function could be furnished by the concrete floor slab, in which case only nominal squaring-up steel bracing would be required. The systems are applicable to buildings of almost any number of storeys.

**Two-way steel bracing**

The two-way steel braced system shown in Fig 7.1 is one of the most efficient in terms of stiffness, speed of erection and economy. All beam-to-column connections are of the simple (i.e. hinged) type, so labour input in both columns and beams is minimised and erection can proceed quickly. Being fully steel-framed, the structure is self-supporting and can be completely erected without having to be integrated with other trades. The only drawback is the presence of the braced panels in the exterior walls, which might interfere with the window pattern, but in the light of the current trend towards exposed steelwork the windows could be set back and the bracing system be expressed boldly as an architectural feature. In very long buildings it would be necessary to provide one or more interior sets of bracing, as shown dotted.
**One-way steel bracing**

The stiff frame shown in the alternative end elevation of Fig 7.1 is another method of providing transverse stiffness to the structure. All of the transverse frames not only the end ones, would be stiff, but the building would still rely for longitudinal stiffness on the two sets of one-way bracing in the sides. This would be a more costly arrangement than the two-way braced solution, but would remove the drawbacks of the triangulated bracing. It is more suited to long buildings and has the further advantage that the main (i.e. transverse) floor beams could be shallower, because of their continuity, with consequent reduction in storey height.

It must be emphasised, however, that on purely economic grounds triangulated bracing is very much more cost-effective than a moment frame, both in shop fabrication and in erection.

**Central service core**

Where a building is fairly compact in plan and does not have a great length-to-width ratio, a central service core is a very efficient means of providing stability, as shown in Fig 7.2.
All vertical steel bracing is eliminated and maximum structural economy is gained. The core would house the lifts, emergency stairs and other vertical services. Construction in concrete by the quick slip form method would permit steelwork erection to follow on rapidly.

The single-core system is especially applicable to buildings that are square or nearly square in plan. If the length-to-width ratio is significantly greater than 1,0, and especially if the core is not placed centrally within the plan area, allowance must be made in the design for the torsional effect of the wind loading about the vertical axis of the tower.

The beam end connections are all simple and are thus easy to fabricate and erect. Where the beams connect to the core it is necessary to build steel cleats into the core walls, to

Fig 7.2: Core-braced building

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The beam end connections are all simple and are thus easy to fabricate and erect. Where the beams connect to the core it is necessary to build steel cleats into the core walls, to
which the beam ends are then bolted. The cleats have anchors that are embedded into the concrete as the slip-forming proceeds, the outer faces of the cleats being flush so that the cleats can be contained within the shuttering. Projecting plates, with holes to receive the beam ends, are site-welded to the flush faces after the shuttering is removed.

As an alternative to concrete, a steel-framed core can be used, but this would probably be more costly because of the high steel content, which would entail columns, beams and vertical bracing. In addition, the steel tower would require brick infill panelling on all sides. An improvement in overall completion time of the structure would, however, be expected.

**Double external service towers**

The double service tower system shown in Fig 7.3 is applicable to buildings whose plan ratio of length to width is fairly high. This is an extremely efficient means of stabilising buildings of this nature. If the towers are located outside of the plan dimensions of the building itself, as shown, and are constructed in slip-formed concrete, they can be built in advance. Interference with the rectangular plan shape of the building would be minimal.
**Single external service tower**

A service tower placed externally at about mid-length of the building, as shown in Fig 7.4, can be used for buildings of moderate length, but must be supplemented by a panel of vertical steel or other bracing on the opposite side. This is an efficient method when applied to medium-height structures.

![Elevation](image)

**Fig 7.4: Single external service tower**

**End-wall bracing**

In buildings with narrow end walls, but with long side walls, the ends can be made to act as shear walls by means of masonry infill panels placed within the steel end frames. In low buildings the panels could be formed of brickwork, but for any appreciable height it would be necessary to use reinforced concrete. Stiffness in the longitudinal direction could be provided by steel bracing, or by shear panels. Wherever shear walls are used it would be necessary to provide light temporary steel bracing during erection of the frame to maintain squareness and plumbness of the structure, the bracing being located on the inner flanges of the columns so as not to interfere with the placing of the bricks or concrete.
Braced and framed tubes

A tall building with square or nearly square plan dimensions can be stabilised by providing bracing in the exterior faces of the building, as shown in details (a) and (b) of Fig 7.5. The bracing acts as a vertical cantilevered tube of square cross section and is very efficient because of its great width; it is thus especially applicable to taller buildings of, say, thirty storeys or more. The interior of the building is entirely free of bracing systems and space utilisation is thus unrestricted.

The bracing can be either of the triangulated type, as shown in detail (a), or of the stiff-frame type as in (b). The former is cheaper, but may cause obstruction to window openings, etc., unless it is placed on the outside of the facade and expressed architecturally.

The stiff frame shown in detail (b) obviously requires moment-resisting connections between the beams and the columns and is therefore more expensive to fabricate and
erect. The beams may have their ends shop-welded as stubs to the columns and have friction-grip bolted splices within their length at points of reduced moment, as shown in detail (c). In this way greater stiffness is obtained and the amount of site bolting considerably reduced.

### 7.4 Floor framing

In steel-framed buildings the floor framing system almost invariably consists of a series of main and secondary beams at right angles to each other in plan, with the secondary beams framing into or passing over the tops of the main beams. The floor slab or deck is then carried on top of the secondary beams.

Except where stiff-frame action is required, as discussed under Stabilising Systems above, the main beams are usually simply-supported spans between the columns. If the secondary beams have their top flanges flush with the tops of the main beams they would be framed into the webs of the main beams and would thus also be simply-supported; this would produce a floor grid of minimum depth and would result in a reduction in storey height. However, underfloor services running at right angles to the main beams would then have to pass through holes formed in the webs of these beams, or else be routed below the main beams, which would increase the floor depth.

If the secondary beams pass over the tops of the main beams, however, they would no longer be simply-supported but be continuous, significantly reducing the mass and especially deflection. The routing of services in both rectangular directions in plan would be facilitated by reason of the space available above the main beams.

The two beam framing systems referred to above represent conventional practice as used on the great majority of small to medium-sized buildings. The beams are of straightforward construction and employ standard end connections and are thus easy and cheap to fabricate. A number of non-standard options are available and are worth considering for larger buildings where a high level of repetition of components would justify their use. These are discussed below.

**Twin beams**

Main beams span between columns and can therefore not normally be made continuous. Continuity can, however, be achieved by replacing the beam by a pair of closely-spaced twin beams passing on each side of the column, as shown in Fig 7.6.

Because of their continuity the main beams can now be designed plastically, for a combined moment on the two beams of 70 per cent or less of that for the simply-supported single beam, and at a combined mass/m about equal to that of the single beam. As regards deflection, the twin-beam system would tend to be more stiff than a single simply-supported beam of the same load capacity because of the continuity. The labour input for the twin beams would be more, but this alternative is useful when it is desired to reduce the depth of the floor (and thus the storey height), or on long spans where the twin rolled I-sections replace a more expensive single welded plate girder.
Castellated beams

Castellated beams, as listed in the *South African Steel Construction Handbook* (Ref. 5), can be used instead of plain rolled sections requiring holes in the webs to accommodate services, or where increased depth is necessary to limit deflection. On a purely strength-for-strength basis the use of castellated beams can hardly be justified – the saving in mass is fairly small whereas the cost of forming and welding is quite high.

Where a moment resistance greater than that of the largest rolled I-section is required, castellated beams might be worth considering as an alternative to welded plate girders. For a given moment resistance the castellated beam would have a slightly lower mass and has the advantage of having web openings for services.

Stubgirders

A method of floor framing employed in the United States since about 1970 involves the use of short beam-section lengths or stubs welded on top of the main beams, as shown in Fig 7.7. The main beam acts as a composite Vierendeel flexural member together with the concrete, which provides the compressive resistance. The secondary beams pass over the top of the main beam and are thus continuous, while services running parallel to the secondary beams are placed in the spaces between these beams. The floor slab also acts compositely with the secondary beams in regions of positive moment. It is necessary for a stub to be placed at each end of the main beam to ensure adequate shear transfer between the slab and the beam. This system mobilises the strength of the full floor depth, while allowing for continuity of the secondary beams and providing space for services, and is thus extremely efficient in material usage. For a detailed description of stubgirders reference should be made to the book *Design and Construction of Composite Floor Systems* (Ref. 12).

**Fig 7.6: Twin main beams**
7.10

Fig 7.7: Stubgirders

7.5 Floors

The floors in multi-storey buildings are almost universally constructed in concrete. The slabs may be of conventional reinforced construction cast on temporary formwork, but the most popular type of floor consists of a slab acting compositely with steel decking that has a profile specially designed for this purpose and serves as permanent shuttering in addition. Such decking acts as tension reinforcement to the slab and eliminates the need for most, it not all, of the bottom reinforcement.

Steel decks available in South Africa are described in Table 9.1 of the Steel Construction Handbook (Ref. 5), while load tables for certain of the profiles acting compositely with various thicknesses of slab are contained in Section 14 of the Handbook.

Further composite action (at right angles to the composite floor action) can be obtained by designing the floor slab and the beam supporting it as an integral unit. The shear developed between the slab and the beam owing to the flexural action is resisted by shear studs welded to the top flange of the beam, which become embedded in the slab once it is cast. The slab does not only support the applied floor loading between the beams, but also contributes to their strength by virtue of the composite action between the two structural elements.

The fact that all the components contribute to the overall strength results in an extremely efficient structural system, while the action of the steel deck as permanent shuttering reduces shuttering costs significantly and saves the time that would be required to erect and remove temporary formwork. Furthermore, a minimum amount of temporary propping is required to support a profiled steel deck during construction.

The design requirements for composite beams are given in Clause 17 of SABS 0162-1 and the detailed design procedures are set out in Section 9 of the Steel Construction Handbook, both with reference to conventional slabs cast on flat removable shuttering and to slabs cast on profiled steel decks. In the latter application the decking does not participate in the composite action.
For reason of economy composite beams should be designed using partial shear connection, i.e. a reduced number of connectors able to transfer a shear force that is less than the full compressive resistance of the slab are used. This is considerably cheaper than using full shear transfer requiring high-cost stud connectors.

A cross section through a typical composite floor system employing steel decking is shown in Fig 7.8.

**Fig 7.8: Composite steel-concrete floor**

### 7.6 Columns

The columns in multi-storey buildings can usually be of simple rolled or welded I- or H-shapes. It is seldom necessary to resort to latticed, box or other built-up sections, although where very heavy loads are involved welded or bolted compound sections, as shown in detail (a) to (d) of Fig 7.9, can be used. Note that the box section shown in detail (d) may have either flush corners, requiring groove welds, or projecting flanges that require fillet welds only; the latter is obviously the cheaper detail. Where two-way moment resistance is required a section with strength about both axes will be needed; an example is shown in detail (e) of the figure. Where beam ends have to transmit moments it will usually be necessary to provide stiffeners, as shown dotted, to transmit the top and bottom flange forces.

**Fig 7.9: Compound column sections**
The open section shown in detail (e) has the advantage that the beam end plates can be bolted directly to the flanges, whereas with the closed shapes it would be necessary to weld outstanding plates to the column faces to pick up the beam end cleats.

Steel columns in tall commercial buildings are almost invariably encased in concrete for the sake of appearance and to provide fire protection and a rectangular outer shape against which the walls, partitions, windows, etc can be built. If structural quality concrete is used and is well compacted during pouring it can be considered as acting compositely with the steel. The resulting steel/concrete cross-section obviously represents and extremely efficient means of carrying compression. Serious difficulty will, however, be experienced in shuttering the beam to column connection zones.

If steel reinforcement is added, a smaller steel column section can be used and even greater economy be gained. In fact, the steel section can be reduced to the point where it is required to carry only the selfweight of the structure plus construction loading, with the balance of the design resistance being provided by the concrete encasement and the reinforcement.

An alternative form of composite column is the structural hollow section filled with concrete, as given in Clause 18 of SABS 0162-1. No shuttering is required in this instance and erection can proceed fairly quickly, although care must be taken to fill the rather small interior cross section of the column so that no voids occur in the concrete.

Composite column cross sections are shown in Fig 7.10. Further comments on economical column design and detailing are given in Chapter 10.

![Composite steel-concrete column sections](image)

**Fig 7.10: Composite steel-concrete column sections**

### 7.7 Floor bracing

All suspended floors need to be braced within their own plane in order to maintain squareness in plan and transfer externally applied horizontal loading to the vertical bracing systems.
Significant economies can be gained by designing the concrete floor slab to meet these requirements in addition to carrying the applied floor loading. The main means of load transfer is shear and it is not difficult to mobilise the inherent strength and stiffness of the slab. If necessary a small amount of extra reinforcement can be provided to cater for this load transfer.

Some steel bracing will usually be needed, however, to maintain squareness before the slab is cast. The function of the bracing is temporary and the simplest possible configuration and straightforward end connections should thus be adopted. Once the floor is cast bracing of this nature is usually left in place.

More detailed comment on various aspects of bracing systems, including connection details, is given in Chapter 11.

7.8 Summary

- Because of the relative simplicity of the framing in a multi-storey beam-and-column structure, steel construction offers an advantage over other forms of construction. Reduced erection time enables other trades to proceed without delay.

- Lateral stabilising systems forming part of the steel structure may take a number of forms, one of the cheapest being two-way triangulated bracing in the outer faces of the building. Where such a system is not feasible, one-way bracing plus stiff-joint framing in the other direction, or two-way stiff framing, could be employed.

- The use of concrete or brick in-fill panels in the sides or within the plan dimensions of a structure is an effective and cheap means of providing stability. When located in the end walls of long buildings such panels are especially efficient in giving transverse stiffness.

- Slip-formed reinforced concrete service towers are a cost-effective means of stabilising a building. These may be placed centrally in the case of buildings with compact plan shapes (core-braced), or at the ends or sides of wider buildings.

- Tall buildings with compact plan dimensions can be stabilised using the braced or framed tube system, which employs bracing or moment-resisting connections in the steel structure in the four outer faces of the tower.

- Floor framing systems invariably consist of simply-supported or continuous secondary beams framing into main beams that are usually simply-supported. The floor slab or deck is carried on top of the secondary beams and may be of conventional reinforced concrete or be designed compositely with the steel beams.

- Where the secondary beams are continuous and pass over the tops of the main beams adequate space is available in both directions for the routing of services.

- Main beams spanning from column to column can be made continuous by using twin beams passing on each side of the columns.

- Castellated beams are efficient on a strength-to-mass basis and enable services to be routed through the openings. Their economy on a strength-to-price ratio is less significant.
• The composite design of a reinforced concrete floor and the supporting steel beams combined with stub-girders is very cost-effective and gives adequate space between the slab and the beams for the location of services.

• Floor slabs may be constructed of reinforced concrete cast on shuttering or on permanent steel decking. In either case the slabs may be designed independently of or compositely with the supporting steel beams.

• For the sake of economy composite beams should be designed for partial shear connection. Temporary propping should be kept to a minimum.

• Columns can usually be of simple rolled I- or H-section. They should only be of welded section for very heavy loads.

• Where concrete encasement to columns is required for aesthetic or functional reasons the encasement can be combined structurally with the steel column section and be designed compositely. Special care is required to ensure good structural quality and thorough compaction. If steel reinforcement is added to the concrete for additional structural efficiency the steel column section may be reduced.

• In-plane bracing to floors is usually provided by the floor slab, but additional light steel bracing should be installed before the slab is cast to maintain squareness and stability during erection.