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MULTI-STOREY BUILDINGS - I

1.0 INTRODUCTION

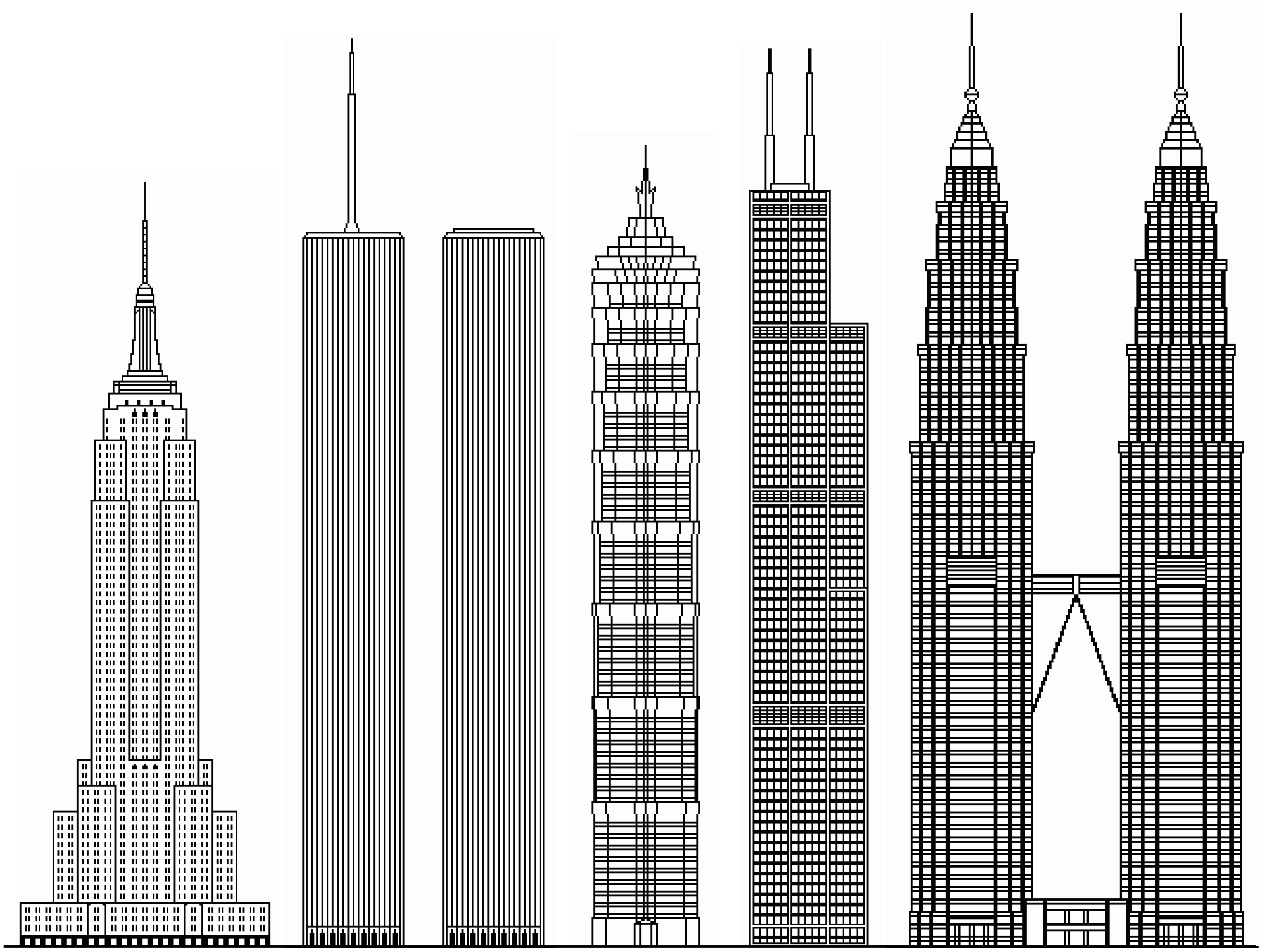
The tallness of a building is relative and can not be defined in absolute terms either in relation to height or the number of stories. But, from a structural engineer's point of view the tall building or multi-storeyed building can be defined as one that, by virtue of its height, is affected by lateral forces due to wind or earthquake or both to an extent that they play an important role in the structural design. Tall structures have fascinated mankind from the beginning of civilisation. The Egyptian Pyramids, one among the seven wonders of world, constructed in 2600 B.C. are among such ancient tall structures. Such structures were constructed for defence and to show pride of the population in their civilisation. The growth in modern multi-storeyed building construction, which began in late nineteenth century, is intended largely for commercial and residential purposes.

The development of the high-rise building has followed the growth of the city closely. The process of urbanisation, that started with the age of industrialisation, is still in progress in developing countries like India. Industrialisation causes migration of people to urban centres where job opportunities are significant. The land available for buildings to accommodate this migration is becoming scarce, resulting in rapid increase in the cost of land. Thus, developers have looked to the sky to make their profits. The result is multi-storeyed buildings, as they provide a large floor area in a relatively small area of land in urban centres.

The construction of multi-storeyed buildings is dependent on available materials, the level of construction technology and the availability of services such as elevators necessary for the use in the building. In ancient Rome, people used to build multi-storeyed structures with wood. For those buildings built after the Great Fire of Rome, Nero used brick and a form of concrete material for construction. Wood lacked strength for buildings of more than five stories and was more susceptible to fire hazard. But, the buildings constructed with brick and masonry occupied a large space for their walls. Technology responded to these drawbacks of construction materials with the development of high strength and structurally more efficient materials like wrought iron and then subsequently steel. These new materials resulted in construction of skyscrapers of the order of *120* storeys such as Petronas Towers, Sears Tower, World Trade Centre, Empire State Building etc. all over the world [Fig. 1]. In contrast, the tallest building in India is *35* storeys in reinforced concrete, Hotel Oberoi Sheraton (*116 m*). Even though in the last two decades a number of multi-storeyed buildings have been constructed in India, the tall building technology is at its infancy in India, particularly in structural steel.

In developed countries a very large percentage of multi-storeyed buildings are built with steel where as steel is hardly used in construction of multi-storeyed frames in India even though it has proved to be a better material than reinforced concrete. For example, over

90% of the new multi-storeyed buildings in London are built of steel or steel-composite framed construction. Buildings in the *100*-storey range are invariably erected with steel or steel-concrete composites in the West. A look at world-class high-rise steel-framed buildings constructed in various parts of world shown in Fig. 1 may inspire one to become a structural engineer of such a class of structures.



(a) Empire State Building (381 m) *(b) World Trade Centre (415 m) (417 m)* *(c) Jin Mao Building (421m)* *(d) Sears Tower (443 m)* *(e) Petronas Towers (452 m)*

Fig. 1 World's tallest buildings

The use of steel in multi-storey building construction results in many advantages for the builder and the user. The reasons for using steel frames in the construction of multi-storey buildings are listed below:

- Steel frames are faster to erect compared with reinforced concrete frames. The availability of the building in a shorter period of time results in economic advantages to the owner due to shorter period of deployment of capital, without return. For

example, at the time the steel-framed Empire State Building was completed, the tallest reinforced concrete building, the exchange building in Seattle, had attained a height of only *23* storeys.
- In comparison with concrete construction, steel frames are significantly lighter. This results in very much reduced loads on foundations.
- The elements of framework are usually prefabricated in the factory under effective quality control thus enabling a better product.
- This form of construction results in much reduced time on site activities, plant, materials and labour, causing little disruption to normal life of the community, unlike wet concrete construction process.
- The use of steel makes possible the creation of large, column-free internal spaces. This is of particular advantage for open-plan offices and large auditoria and concert halls.
- The use of steel frame when compared with R.C. frame results in sufficient extra space to accommodate all service conduits without significant loss in head room.
- Subsequent alterations or strengthening of floors are relatively easy in steel frames compared with concrete frames.
- The framework is not susceptible to delays due to slow strength gain, as in concrete construction.
- The material handling capacity required at site in steel construction is less than prefabricated concrete construction.
- Steel structure occupies lesser percentage of floor area in multi-storeyed buildings.
- The steel frame construction is more suitable to withstand lateral loads caused by wind or earthquake.

This chapter deals with the anatomy of multi-storey buildings; the different loads to be considered and various structural systems adopted in such steel-framed multi-storey buildings.

2.0 ANATOMY OF MULTI-STOREY BUILDINGS

The vertical or gravity load carrying system of a multi-storey steel-framed building comprises a system of vertical columns interconnected by horizontal beams, which supports the floors and roofing. The resistance to lateral loads is provided by diagonal bracing or shear walls or rigid frame action between the beams and columns. Thus, the components of a typical steel-framed structure are:

- Beams
- Columns
- Floors
- Bracing Systems
- Connections

2.1 Beam-and-Column Construction

This is often called as “skeleton construction”. The floor slabs, partitions, exterior walls etc. are all supported by a framework of steel beams and columns. This type of skeleton structure can be erected easily leading to very tall buildings.

In such a beam and column construction, the frame usually consists of columns spaced *6 -10 m* apart, with beams and girders framed into them from both directions at each floor level. An example of skeleton construction is shown in Fig. 2.

Generally columns used in the framework are hot-rolled I-sections or concrete encased steel columns. They give unobstructed access for beam connections through either the flange or the web. Where the loading requirements exceed the capacity of available section, additional plates are welded to the section.

The selection of beam sections depends upon the span, loading and limitations on overall depth from headroom considerations. Simple beams with precast floors or composite metal deck floors are likely to be the most economical for smaller spans. For larger spans, plate-girders or plated-beams are used.

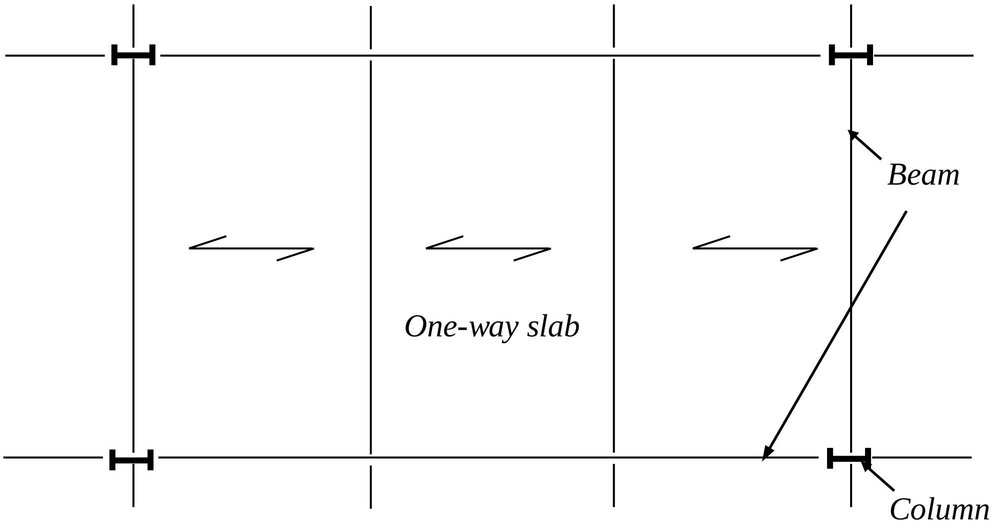


Fig. 2 Beam – and – column construction

2.2 Common types of floor system

The selection of an appropriate flooring in a steel-framed building depends on various factors like the loads to be supported, span length, fire resistance desired, sound and heat transmission, the likely dead weight of the floor, the facilities needed for locating the services, appearance, maintenance required, time required to construct, available depth for the floor etc. The different types of floors used in steel-framed buildings are as follows:

- Concrete slabs supported by open-web joists
- One-way and two-way reinforced concrete slabs supported on steel beams
- Concrete slab and steel beam composite floors
- Profiled decking floors
- Precast concrete slab floors.

2.2.1. Concrete slabs supported with open-web joists

This is one of the most common types of floor slabs used for steel frame buildings in U.S. Steel forms or decks are usually attached to the joists by welding and concrete slabs are poured on top. This is one of the lightest types of concrete floors. For structures with light loading, this type is economical. A sketch of an open-web joist floor is shown in Fig. 3

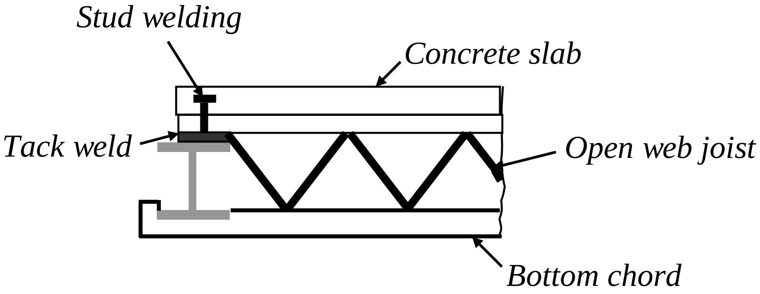


Fig. 3 Open- web joists

2.2.2. One-way and two-way reinforced concrete slabs.

These are much heavier than most of the newer light weight floor systems and they take more time to construct, thus negating the advantage of speed inherent in steel construction. This floor system is adopted for heavy loads. One way slabs are used when the longitudinal span is two or more times the short span. In one-way slabs, the short span direction is the direction in which loads get transferred from slab to the beams. Hence the main reinforcing bars are provided along this direction. However, temperature, shrinkage and distribution steel is provided along the longer direction.

The two-way concrete slab is used when aspect ratio of the slab supported along all four edges i.e. longitudinal span/transverse span is less than *2*. The main reinforcement runs in both the directions. A typical cross-section of a one-way slab floor with supporting steel beams is shown in Fig. 4

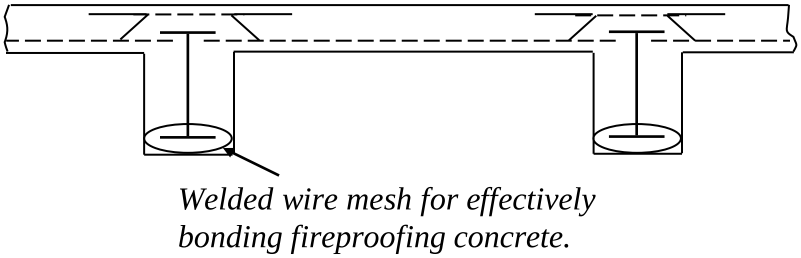
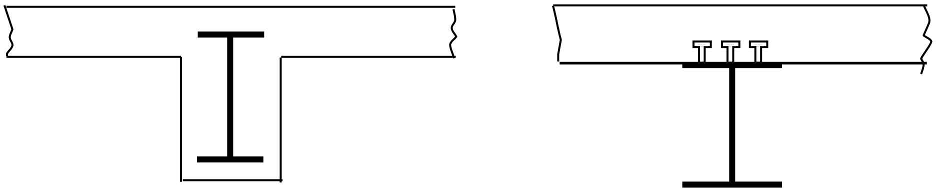


Fig. 4 Cross section of one-way slab floor

2.2.3. Composite floors with a reinforced concrete slab and steel beams

Composite floors have steel beams bonded with concrete slab in such a way that both of them act as a unit in resisting the total loads. The sizes of steel beams are significantly smaller in composite floors, because the slab acts as an integral part of the beam in compression. The composite floors require less steel tonnage in the structure and also result in reduction of total floor depth. These advantages are achieved by utilising the compressive strength of concrete by keeping all or nearly all of the concrete in compression and at the same time utilises a large percentage of the steel in tension.

The types of composite floor systems normally employed are shown in Fig. 5



(a) Steel beam encased in concrete (Rarely used nowadays)

(b) Steel beam acting composite with concrete slab using shear connectors

Fig. 5 Composite floors

2.2.4. Profiled - decking floors

In the last three decades, a new form of composite floor construction, consisting of profiled and formed steel decking with a concrete topping has become popular for office and apartment buildings. The structural behaviour is the same as that of reinforced concrete slab with steel sheeting acting as centring until concrete hardens and as the tension reinforcement after concrete hardens. It is popular where the loads are not very heavy. The advantages of steel-decking floors are given below:

(i) They do not need form work
(ii) The lightweight concrete is used resulting in reduced dead weight
(iii) The decking distributes shrinkage strains, thus prevents serious cracking
(iv) The decking stabilises the beam against lateral buckling, until the concrete hardens
(v) The cells in decking are convenient for locating services.

More details of composite construction using profiled decking floors are provided in chapters on Composite floors. Typical cross-section of steel decking floor is shown in Fig. 6

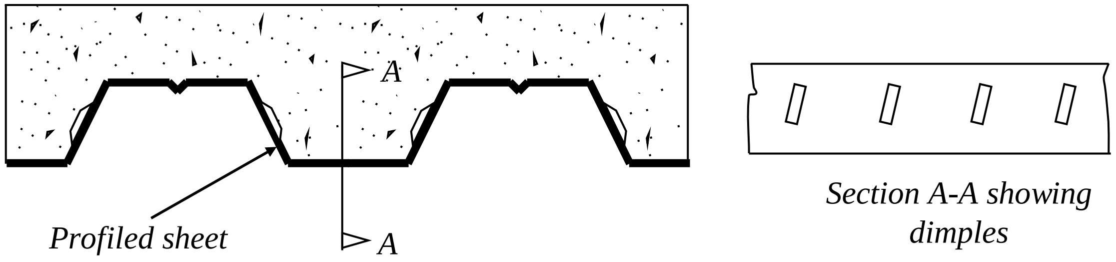


Fig. 6 Composite floor system using profiled sheets

2.2.5. Precast concrete floors

Precast concrete floors offer speedy erection and require only minimal formwork. Light-weight aggregates are generally used in the concrete, making the elements light and easy to handle. Typical precast concrete floor slab sections are shown in Fig.7. It is necessary to use cast in place mortar topping of *25 to 50 mm* before installing other floor coverings. Larger capacity handling machines are required for this type of construction when compared with those required for profiled decking. Usually prestressing of the precast element is required.

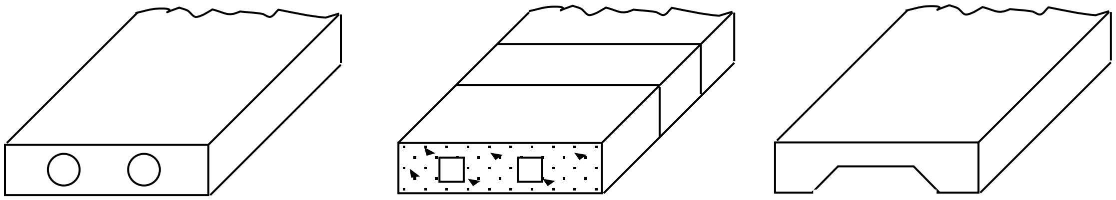


Fig. 7 Precast concrete floor slabs

2.3. Lateral load resisting systems

2.3.1. Lateral forces

Lateral forces due to wind or seismic loading must be considered for tall buildings along with gravity forces. Very often the design of tall buildings is governed by lateral load resistance requirement in conjunction with gravity load. High wind pressures on the sides of tall buildings produce base shear and overturning moments. These forces cause horizontal deflection in a multi-storey building. This horizontal deflection at the top of a building is called *drift*. The drift is measured by *drift index*, Δ/h, where, Δ is the horizontal deflection at top of the building and h is the height of the building. Lateral drift of a typical moment resisting frame is shown in Fig. 8.

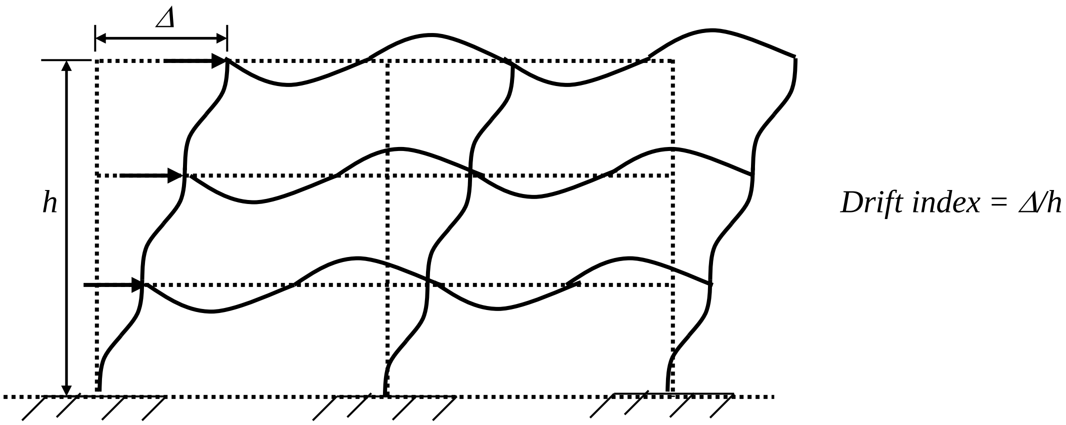
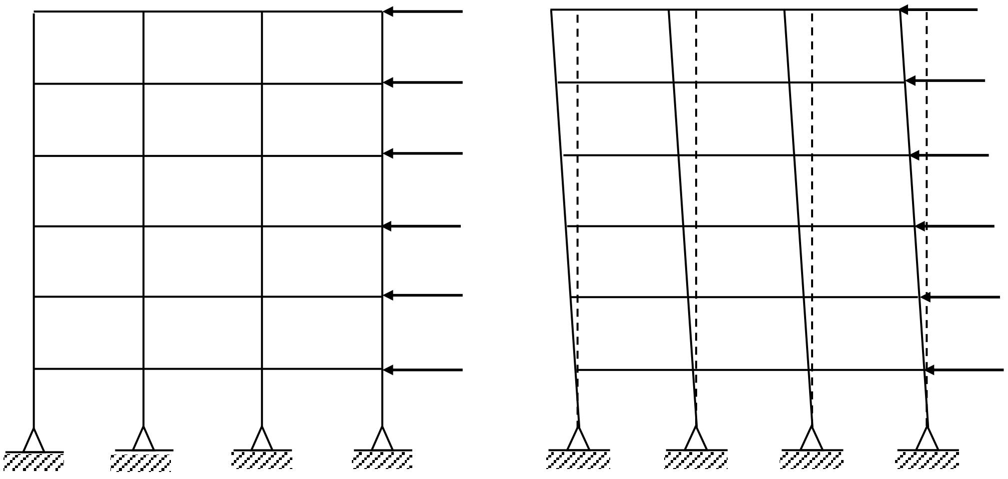


Fig. 8 Lateral drift

The usual practice in the design of multi-storey steel buildings is to provide a structure with sufficient lateral stiffness to keep the drift index between approximately *0.0015* and *0.0030* of the total height. Normally, the provision of lateral stiffness requires about *5* to *10%* of extra steel. The extra steel is used for bracing systems as described in the next section. The IS code require drift index to be not more than *0.002* of total height.

2.3.2 Lateral loading systems

A multi-storey building with no lateral bracing is shown in Fig. 9(*a*). When the beams and columns shown are connected with simple beam connections, the frame would have practically no resistance to the lateral forces and become geometrically unstable. The frame would laterally deflect as shown in Fig. 9(*b*) even under a small lateral load.



(a) *(b)*

Fig. 9 Multi-storey frame without lateral bracing

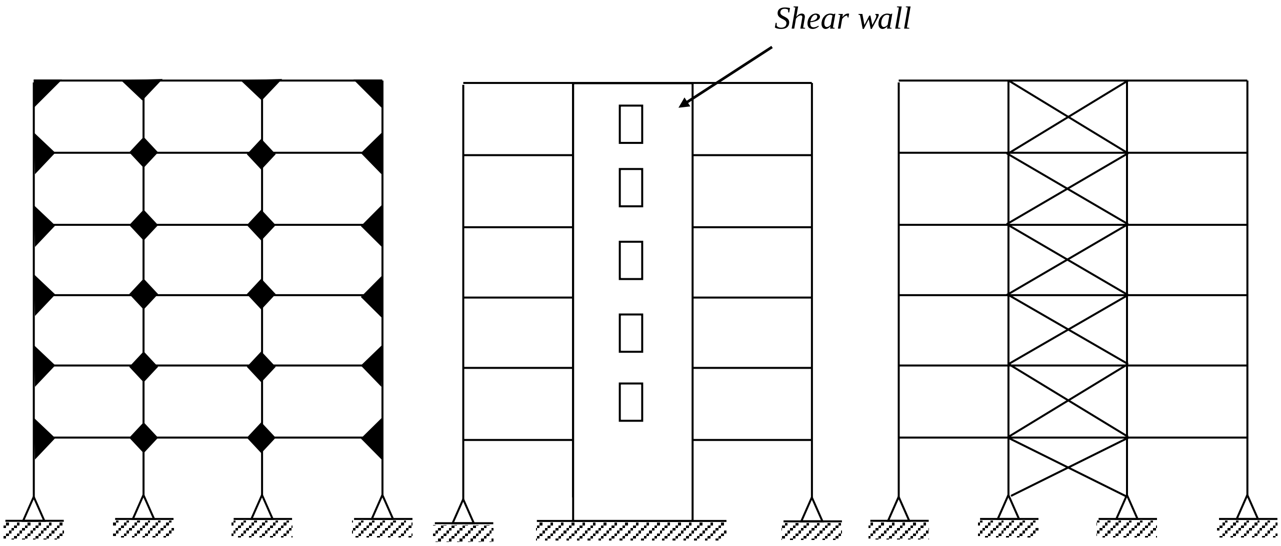
One of the following three types structural systems is used to resist the lateral loads and limit the drift within acceptable range mentioned above:

- Rigid Frames
- Shear walls.
- Braced frames

Combinations of these systems and certain other advanced forms are also used for very tall buildings. The advanced structural forms are discussed in section 3.0.

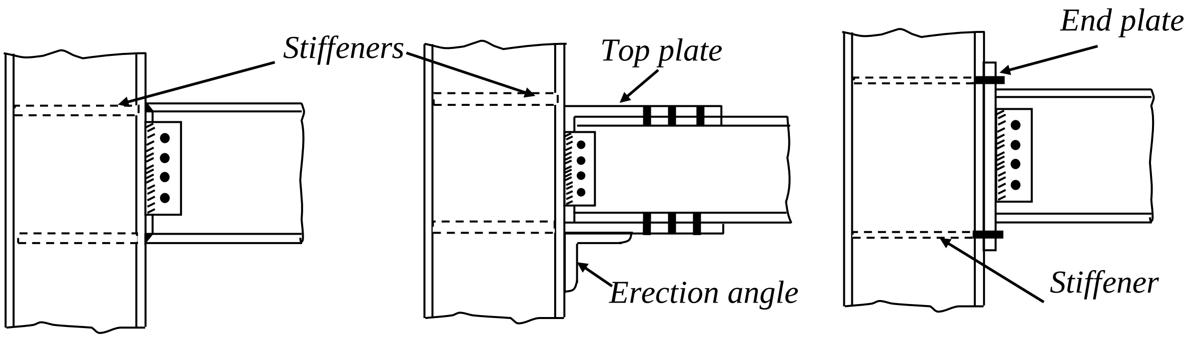
Rigid Frames

Rigidly jointed frames or sway-frames are those with moment resisting connections between beams and columns. A typical rigid frame is shown in Fig. 10(*a*). It may be used economically to provide lateral load resistance for low-rise buildings. Generally, it is less stiff than other systems. However, moment resisting connections may be necessary in locations where loads are applied eccentrically with respect to centre line of the columns. Three types of commonly employed moment resisting connections are shown in Fig. 11. The connection shown in Fig. 11(*a*) and 11(*c*) are more economical. However, the moment-rotation performance of the connection shown in Fig. 11(*b*) is likely to be superior to that of either Fig. 11(*a*) or Fig. 11(*c*).



(a) Moment resisting frames *(b) Shear wall frames* *(c) Braced frames*

Fig. 10 Lateral load resisting systems



(b) Shop welded and field bolted connection

(a) Field welded and field bolted connection

(c)End plated connection

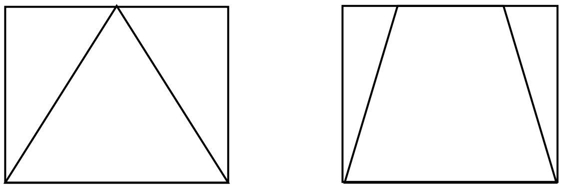
Fig. 11 Moment resistant connections

Shear Walls

The lateral loads are assumed to be concentrated at the floor levels. The rigid floors spread these forces to the columns or walls in the building. Lateral forces are particularly large in case of tall buildings or when seismic forces are considered. Specially designed reinforced concrete walls parallel to the directions of load are used to resist a large part of the lateral loads caused by wind or earthquakes by acting as deep cantilever beams fixed at foundation. These elements are called as *shear walls*. Frequently buildings have interior concrete core walls around the elevator, stair and service wells. Such walls may be considered as shear walls. The advantages of shear walls are (i) they are very rigid in their own plane and hence are effective in limiting deflections and (ii) they act as fire compartment walls. However, for low and medium rise buildings, the construction of shear walls takes more time and is less precise in dimensions than steelwork. Generally, reinforced concrete walls possess sufficient strength and stiffness to resist the lateral loading. Shear walls have lesser ductility and may not meet the energy required under severe earthquake. A typical framed structure braced with core wall is shown in Fig. 10(*b*).

Braced frames

To resist the lateral deflections, the simplest method from a theoretical standpoint is the intersection of full diagonal bracing or *X*-bracing as shown in Fig. 10(*c*). The *X*-bracing system works well for *20* to *60* storey height, but it does not give room for openings such as doors and windows. To provide more flexibility for the placing of windows and doors, the *K*-bracing system shown in Fig. 12(*a*) is preferred instead of *X*- bracing system. If, we need to provide larger openings, it is not possible with *K*-bracing system; we can use the full-storey knee bracing system shown in Fig. 12(*b*). Knee bracing is an eccentric bracing that is found to be efficient in energy dissipation during earthquake loads by forming plastic hinge in beam at the point of their intersection of the bracings with the beam.



(a) K- brace (b) Knee brace

Fig. 12 Alternative bracing systems

2.4 Connections

The most important aspect of structural steel work for buildings is the design of connections between individual frame components. Depending upon the structural behaviour, the connections can be classified as following:

Simple connections - The connection is detailed to allow the beam end to rotate freely and the beam behaves as a simply supported beam. Such a connection transfers shear and axial forces between the connecting members but does not transfer bending moment.

Rigid connections - The connection is detailed to ensure a monolithic joint such that the angle between beam and column before deformation remains the same even after deformation. Such a connection transfers shear, axial force and bending moment from the beam to the column.

Semi-rigid connections - Due to flexibility of the joint some relative rotation between the beam and column occurs. When this is substantial, the joints are designed as semi-rigid. These connections are designed to transmit the full shear force and a fraction of the rigid joint bending moment across the joint. The analysis of frames with such joints is complex and their application is dependent on development of joint characteristics based on experimental evidence. The procedures for analysis and design should be simple so that they can be easily adopted for manual computation in design offices. With the advent of computers, it is possible to account for flexibility of joints in the frame analysis by adopting suitable computer packages. Recent advances in research on the topic have led to results that can be used in practical analysis and design of semi-rigid connections.

3.0 ADVANCED STRUCTURAL FORMS

The bracing systems discussed so far are not efficient for buildings taller than *60* stories. This section introduces more advanced types of structural forms that are adopted in steel-framed multi-storeyed buildings larger than *60* storey high. Common types of advanced structural forms are:

3.1 Framed -Tube Structures

The framed tube is one of the most significant modern developments in high-rise structural form. The frames consist of closely spaced columns, *2 - 4 m* between centres, joined by deep girders. The idea is to create a tube that will act like a continuous perforated chimney or stack. The lateral resistance of framed tube structures is provided by very stiff moment resisting frames that form a tube around the perimeter of the building. The gravity loading is shared between the tube and interior columns. This structural form offers an efficient, easily constructed structure appropriate for buildings having *40* to*100* storeys.

When lateral loads act, the perimeter frames aligned in the direction of loads act as the webs of the massive tube cantilever and those normal to the direction of the loading act as the flanges. Even though framed tube is a structurally efficient form, flange frames tend to suffer from shear lag. This results in the mid face flange columns being less stressed than the corner columns and therefore not contributing to their full potential lateral strength. Aesthetically, the tube looks like the grid-like façade as small windowed and is repetitious and hence use of prefabrication in steel makes the construction faster. A typical framed tube is shown in Fig. 13(*a*).

3.2 Braced tube structures

Further improvements of the tubular system can be made by cross bracing the frame with *X*-bracing over many stories, as illustrated in Fig. 13(*b*). This arrangement was first used in a steel structure, in Chicago's John Hancock Building, in 1969.

As the diagonals of a braced tube are connected to the columns at each intersection, they virtually eliminate the effects of shear lag in both the flange and web frames. As a result the structure behaves under lateral loads more like a braced frame reducing bending in the members of the frames. Hence, the spacing of the columns can be increased and the depth of the girders will be less, thereby allowing large size windows than in the conventional framed tube structures.

In the braced tube structure, the braces transfer axial load from the more highly stressed columns to the less highly stressed columns and eliminates differences between load stresses in the columns.

3.3 Tube-in-Tube Structures

This is a type of framed tube consisting of an outer-framed tube together with an internal elevator and service core. The inner tube may consist of braced frames. The outer and inner tubes act jointly in resisting both gravity and lateral loading in steel-framed buildings. However, the outer tube usually plays a dominant role because of its much greater structural depth. This type of structures is also called as Hull (Outer tube) and Core (Inner tube) structures. A typical Tube-in-Tube structure is shown in Fig. 14.

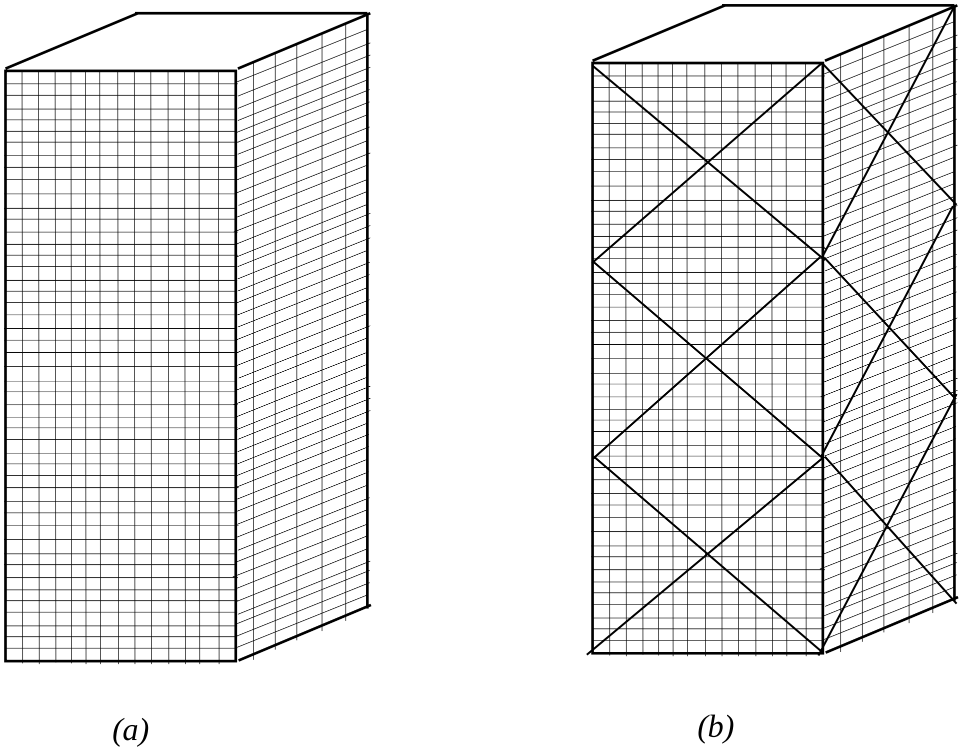


Fig. 13 (a) Framed tube (b) Braced framed tube

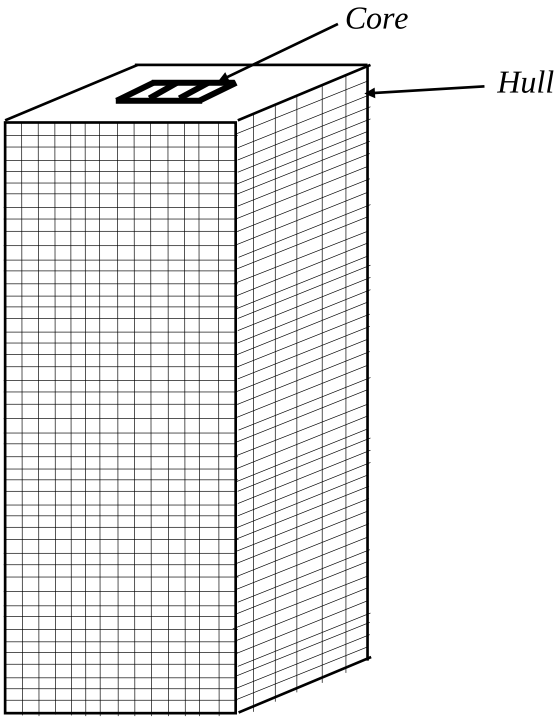


Fig. 14 Tube-in-Tube frame

3.4 Bundled Tube

The bundled tube system can be visualised as an assemblage of individual tubes resulting in multiple cell tube. The increase in stiffness is apparent. The system allows for the greatest height and the most floor area. This structural form was used in the Sears Tower in Chicago. Fig. 1(*d*) shows bundled tubes in the Sears Tower. In this system, introduction of the internal webs greatly reduces the shear lag in the flanges. Hence, their columns are more evenly stressed than in the single tube structure and their contribution to the lateral stiffness is greater.

4.0 LOADING

Loading on tall buildings is different from low-rise buildings in many ways such as large accumulation of gravity loads on the floors from top to bottom, increased significance of wind loading and greater importance of dynamic effects. Thus, multi-storeyed structures need correct assessment of loads for safe and economical design. Excepting dead loads, the assessment of loads can not be done accurately. Live loads can be anticipated approximately from a combination of experience and the previous field observations. But, wind and earthquake loads are random in nature. It is difficult to predict them exactly. These are estimated based on probabilistic approach. The following discussion describes the influence of the most common kinds of loads on multi-storeyed structures.

4.1 Gravity loads

Dead loads due the weight of every element within the structure and live loads that are acting on the structure when in service constitute gravity loads. The dead loads are calculated from the member sizes and estimated material densities. Live loads prescribed by codes are empirical and conservative based on experience and accepted practice. The equivalent minimum loads for office and residential buildings are specified in Table - 1.

Table – 1 Live load magnitudes [IS: 875 - 1987 Part -II]

Occupancy classification	Uniformly distributed load (kN/m^2)	Concentrated load (kN)
Office buildings		
• Offices and Staff rooms	2.5	2.7
• Class rooms	3.0	2.7
• Corridors, Store rooms and Reading rooms	4.0	4.5
Residential buildings		
• Apartments	2.0	1.8
• Restaurants	4.0	2.7
• Corridors	3.0	4.5

A floor should be designed for the most adverse effect of uniformly distributed load and concentrated load over *0.3 m* by *0.3 m* as specified in Table-1, but they should not be considered to act simultaneously. All other structural elements such as beams and columns are designed for the corresponding uniformly distributed loads on floors.

Reduction in imposed load may be made in designing columns, load bearing walls etc., if there is no specific load like plant or machinery on the floor. This is allowed to account for improbability of total loading being applied over larger areas. The supporting members of the roof of the multi-storeyed building is designed for *100%* of uniformly distributed load; further reductions of *10%* for each successive floor down to a minimum of *50%* of uniformly distributed load is done. The live load at floor level can be reduced in the design of beams, girders or trusses by *5%* for each $50m^2$ area supported, subject to a maximum reduction of *25%*. In case the reduced load of a lower floor is less than the reduced load of an upper floor, then the reduced load of the upper floor should be adopted in the lower floor also.

4.2 Wind load

The wind loading is the most important factor that determines the design of tall buildings over *10* storeys, where storey height approximately lies between *2.7 – 3.0 m*. Buildings of up to *10* storeys, designed for gravity loading can accommodate wind loading without any additional steel for lateral system. Usually, buildings taller than *10* storeys would generally require additional steel for lateral system. This is due to the fact that wind loading on a tall building acts over a very large building surface, with greater intensity at the greater heights and with a larger moment arm about the base. So, the additional steel required for wind resistance increases non-linearly with height as shown in Fig. 15.

As shown in Fig. 15 the lateral stiffness of the building is a more important consideration than its strength for multi-storeyed structures. Wind has become a major load for the designer of multi-storeyed buildings. Prediction of wind loading in precise scientific terms may not be possible, as it is influenced by many factors such as the form of terrain, the shape, slenderness, the solidarity ratio of building and the arrangement of adjacent buildings. The appropriate design wind loads are estimated based on two approaches. Static approach is one, which assumes the building to be a fixed rigid body in the wind. This method is suitable for buildings of normal height, slenderness, or susceptible to vibration in the wind. The other approach is the dynamic approach. This is adopted for exceptionally tall, slender, or vibration prone buildings. Sometimes wind sensitive tall buildings will have to be designed for interference effects caused by the environment in which the building stands. The loading due to these interference effects is best ascertained using wind tunnel modelled structures in the laboratory.

However, in the Indian context, where the tallest multi-storeyed building is only *35* storey high, multi-storeyed buildings do not suffer wind-induced oscillation and generally do not require to be examined for the dynamic effects. For detailed information on evaluating wind load, the reader is referred to IS: 875 - 1987 (Part - III).

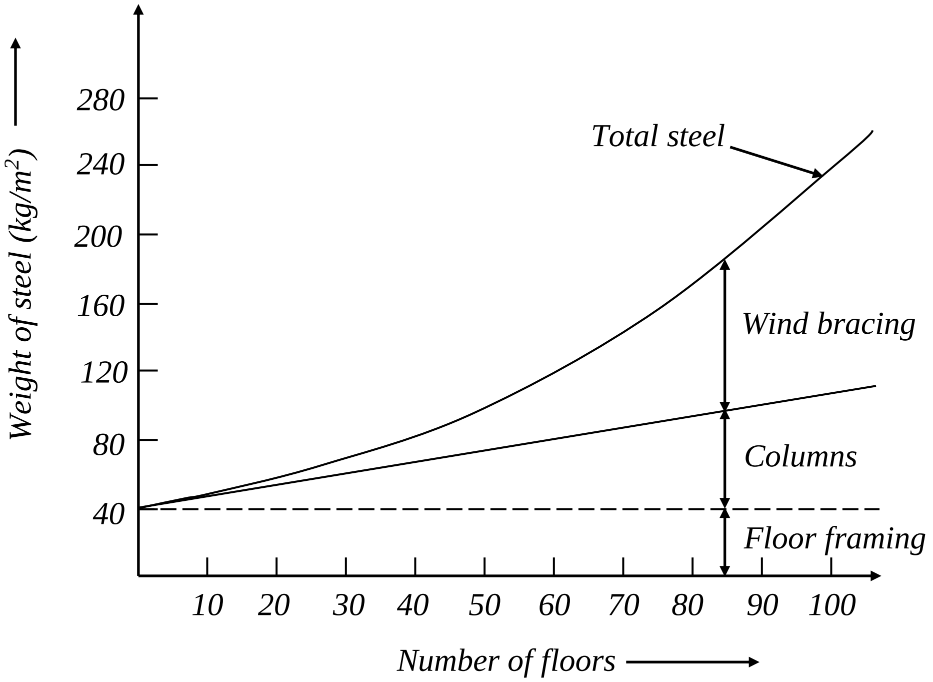
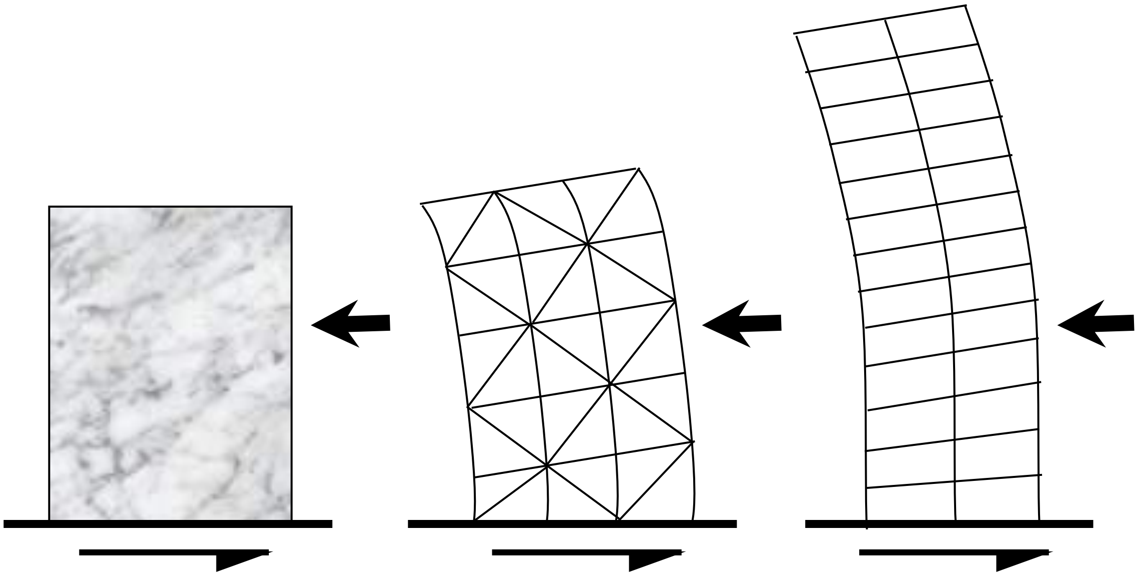


Fig. 15 Weight of steel in multi-storeyed buildings

4.3 Earthquake load

Seismic motion consists of horizontal and vertical ground motions, with the vertical motion usually having a much smaller magnitude. Further, factor of safety provided against gravity loads usually can accommodate additional forces due to vertical acceleration due to earthquakes. So, the horizontal motion of the ground causes the most significant effect on the structure by shaking the foundation back and forth. The mass of building resists this motion by setting up inertia forces throughout the structure.

The magnitude of the horizontal shear force F shown in Fig. 16 depends on the mass of the building M, the acceleration of the ground a, and the nature of the structure. If a building and the foundation were rigid, it would have the same acceleration as the ground as given by Newton's second law of motion, i.e. $F = Ma$. However, in practice all buildings are flexible to some degree. For a structure that deforms slightly, thereby absorbing some energy, the force will be less than the product of mass and acceleration [Fig. 16(*b*)]. But, a very flexible structure will be subject to a much larger force under repetitive ground motion [Fig. 16(*c*)]. This shows the magnitude of the lateral force on a building is not only dependent on acceleration of the ground but it will also depend on the type of the structure. As an inertia problem, the dynamic response of the building plays a large part in influencing and in estimating the effective loading on the structure. The earthquake load is estimated by Seismic co-efficient method or Response spectrum method. The later takes account of dynamic characteristics of structure along with ground motion. For detailed information on evaluating earthquake load, reader is referred to IS: 1893 - 1984 and the chapter on Earth quake resistant design.



(a) F = Ma (b) F < Ma (c) F > Ma

Fig. 16 Force developed by earthquake

5.0 SUMMARY

Pride seems to be the prime motivation for the construction of ancient tall structures such as the pyramids of Egypt, the Mayan temples of Mexico and the Kutub Minar of India. Industrialisation and urbanisation have led to the evolution of modern tall buildings for residential and commercial purposes. Significant advances in the design and construction of high-rise buildings have occurred in recent years. This has been possible on account of developments in the use of new materials, construction techniques or forms of service. This chapter mainly concentrated with the evolution, anatomy and different types of tall structural systems and loadings. Meeting the design challenges are described in conceptual way.

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