A proposal for the classification of structural systems of tall buildings

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Abstract

In the early structures at the beginning of the 20th century, structural members were assumed to carry primarily the gravity loads. Today, however, by the advances in structural design/systems and high-strength materials, building weight is reduced, and slenderness is increased, which necessitates taking into consideration mainly the lateral loads such as wind and earthquake. Understandably, especially for the tall buildings, as the slenderness, and so the flexibility increases, buildings suffer from the lateral loads resulting from wind and earthquake more and more. As a general rule, when other things being equal, the taller the building, the more necessary it is to identify the proper structural system for resisting the lateral loads. Currently, there are many structural systems that can be used for the lateral resistance of tall buildings. In this context, authors classify these systems based on the basic reaction mechanism/structural behavior for resisting the lateral loads.

Keywords: Tall building; Structural system; Lateral loads

1. Introduction

The resistance of tall buildings to wind as well as to earthquakes is the main determinant in the formulation of new structural systems that evolve by the continuous efforts of structural engineers to increase building height while keeping the deflection within acceptable limits and minimizing the amount of materials. Thanks to the sophisticated computer technology, modern materials and innovative structural concepts, structural systems have gone beyond the traditional frame construction of the home insurance building and have allowed skyscrapers to grow to heights of Taipei 101 never dreamed of in Jenney’s day.

Basically, there are three main types of buildings: steel buildings, reinforced concrete buildings, and composite buildings.

Most of the tallest buildings in the world have steel structural system, due to its high strength-to-weight ratio, ease of assembly and field installation, economy in transport to the site, availability of various strength levels, and wider selection of sections. Innovative framing systems and modern design methods, improved fire protection, corrosion resistance, fabrication, and erection techniques combined with the advanced analytical techniques made possible by computers, have also permitted the use of steel in just any rational structural system for tall buildings.

Although concrete as a structural material has been known since early times, the practical use of reinforced concrete was only introduced in 1867 [1]. The invention of reinforced concrete increased the significance and use of concrete in the construction industry to a great extent. Particularly, because of its moldability characteristics, and natural fireproof property, architects and engineers utilize the reinforced concrete to shape the building, and its elements in different and elegant forms. Besides this, when compared to steel, reinforced concrete tall buildings have better damping ratios contributing to minimize motion perception and heavier concrete structures offer improved stability against wind loads. New innovations in construction technology, methods of design and means of construction, have all contributed to the ease of working with concrete in the construction of tall buildings. Moreover, high-strength concrete as in the case of the Petronas Towers (Malaysia, 1998) and the Jin Mao Building (China,
1999), and lightweight structural concrete as in the case of the One Shell Plaza (Texas, 1971) allow using smaller member sizes and less steel reinforcement [2]. Similar to steel or composite construction, reinforced concrete offers a broad range of structural systems for tall buildings.

Concrete and steel systems evolved independently of each other until 1969, the year in which the composite construction, basically described as a steel frame stabilized by reinforced concrete, of a 20-storey building was done by Dr. Fazlur Khan [3].

All tall buildings can be considered as composite buildings since it is impossible to construct a functional building by using only steel or concrete. That is, in a critical sense, using mild steel reinforcement can make a concrete building a composite structure, and in the same way, reinforced concrete slabs can make a steel building a composite building. In this paper, buildings having reinforced concrete beams, columns, and shear walls are accepted as reinforced concrete (or concrete) buildings, and in the same way, buildings having steel beams, columns, and bracings are accepted as steel buildings. Namely, the frame and bracing or shear walls—but not the floor slabs—are the determining parameters for the building type. On the other hand, here, the term composite system means any and all combinations of steel and reinforced concrete elements.

2. Structural systems for tall buildings

In this research, taking into consideration the studies in the literature [3–8] the following classification is proposed for the structural systems of tall buildings for all the types, namely, steel buildings, reinforced concrete buildings, and composite buildings:

1. rigid frame systems
2. braced frame and shear-walled frame systems
3. outrigger systems
4. framed-tube systems
5. braced-tube systems
6. bundled-tube systems

2.1. Rigid frame systems

Rigid frame systems are utilized in both steel and reinforced concrete construction. Rigid frame systems for resisting lateral and vertical loads have long been accepted for the design of the buildings. Rigid framing, namely moment framing, is based on the fact that beam-to-column connections have enough rigidity to hold the nearly unchanged original angles between intersecting components. Owing to the natural monolithical behavior, hence the inherent stiffness of the joist, rigid framing is ideally suitable for reinforced concrete buildings. On the other hand, for steel buildings, rigid framing is done by modifying the joints by increasing the stiffness in order to maintain enough rigidity in the joints.

For a rigid frame, the strength and stiffness are proportional to the dimension of the beam and the column dimension, and inversely proportional to the column spacing. Columns are placed where they are least disturbing to the architecture, but at spacing close enough to allow a minimum depth of floor. Thus, in order to obtain an efficient frame action, closely spaced columns and deep beams at the building exterior must be used. Especially for the buildings constructed in seismic zones, a special attention should be given to the design and detailing of

Fig. 1. Lever House, New York, USA, 1952.

Fig. 2. Types of braces: (a) X – the least available space; (b) diagonal – less available space; (c) K – openings possible; (d) Knee – larger openings.
joints, since rigid frames are more ductile and less vulnerable to severe earthquakes when compared to steel-braced or shear-walled structures.

In buildings up to 30 stories, frame action usually takes care of lateral resistance except for very slender buildings. For buildings with over 30 stories, the rigidity of the frame system remains mostly insufficient for lateral sway resulting from wind and earthquake actions [3]. The 21-storey-high Lever House (1952) (Fig. 1) in New York, built with steel is a good example of the frame system.

2.2. Braced frame and shear-walled frame systems

Rigid frame systems are not efficient for buildings taller than 30 stories, because lateral deflection due to the bending of columns causes the drift to be too large [3]. On the other hand, steel bracing or shear walls with or without rigid frame (brace systems and shear wall systems), increases the total rigidity of the building and the resulting system is named as braced frame or shear-walled frame system. Namely, systems composed of steel bracing or shear walls alone, or interacting with the rigid frames can be accepted as an improvement of the rigid frame system. These systems are stiffer when compared to the rigid frame system, and can be used for buildings over 30 stories, but mostly applicable for buildings about 50 stories in height. However, there are examples for these systems reaching over 100-storey height. While braced frame system is utilized in steel construction, shear-walled frame system is utilized in both reinforced concrete and composite construction.

2.2.1. Braced frame systems

Braced frame systems are utilized in steel construction. This system is a highly efficient and economical system for resisting horizontal loading, and attempts to improve the effectiveness of a rigid frame by almost eliminating the bending of columns and girders, by the help of additional bracings. It behaves structurally like a vertical truss, and comprises of the usual columns and girders, essentially carrying the gravity loads, and diagonal bracing components so that the total set of members forms a vertical cantilever truss to resist the horizontal loading.

Depending on architectural and structural characteristics, braces can be classified as four main groups as shown in Fig. 2. These are, X, diagonal, K, and Knee bracings.

The areas around elevator, stairs, and service shafts, where frame diagonals may be enclosed within permanent walls, are the most preferable places for the braces; and the arrangement of the bracing is generally dictated by the requirements for openings.

Historically, bracing has been utilized to stabilize the building laterally in many of the world’s tallest structures, including 77-storey-high Chrysler Building (1930) (Fig. 3) and 102-storey-high Empire State Building (1931) (Fig. 4) in New York.

2.2.2. Shear-walled frame systems

Shear-walled frame systems are utilized in both reinforced concrete and composite construction. Shear walls may be described as vertical cantilevered beams, which
resist lateral wind and seismic loads acting on a building and transmitted to them by the floor diaphragms. Shear walls are generally parts of the elevator and service cores, and frames to create a stiffer and stronger structure. These elements can have various shapes such as, circular, curvilinear, oval, box-like, triangular, or rectilinear. This system structurally behaves like a concrete building with shear walls resisting all the lateral loads. The 68-storey-high Metropolitan Tower (1987) (Fig. 5) in New York is a good example of this system. The 88-storey-high Petronas Towers (1998) (Fig. 6), which was the tallest building in the world until the construction of Taipei 101 in 2004, also utilized this system in composite construction.

2.3. Outrigger systems

Outrigger systems are modified form of braced frame and shear-walled frame systems, and utilized in steel and composite constructions. As an innovative and efficient structural system, the outrigger system comprises a central core, including either braced frames or shear walls, with horizontal “outrigger” trusses or girders connecting the core to the external columns. Furthermore, in most cases, the external columns are interconnected by exterior belt girder. If the building is subjected to the horizontal loading, the rotation of the core is prevented by the column-restrained outriggers. The outriggers and belt girder (Fig. 7) should be at least one and often two stories deep to realize adequate stiffness. Thus, they are generally positioned at plant levels to reduce the obstruction they create.
Depending upon the number of levels of outriggers and their stiffness, the perimeter columns of an outrigger structure perform a composite behavior with the core. When compared to single-storey outrigger structures, multi-storey outriggers have better lateral resistance, and thus efficiency in the structural behavior. However, each extra outrigger storey enhances the lateral stiffness, but by a smaller amount than the previous one.

Outrigger structures can be used for buildings with over 100 stories. The 42-storey-high First Wisconsin Center with its steel structure (1974) (Fig. 8) in Milwaukee, the 88-storey-high Jin Mao Building (1999) (Fig. 9) with its composite structure in Shanghai, and the tallest building of the world, the 101-storey-high Taipei 101 [9] (2004) (Fig. 10) with its composite structure in Taipei are excellent examples of this system.
2.4. Framed-tube systems

Framed-tube systems, are proper for steel, reinforced concrete and composite construction, and represent a logical evolution of the conventional frame structure. Since braced frame and shear-walled frame systems become inefficient in very tall buildings, framed tube becomes an alternative of these systems. The primary characteristic of a tube is the employment of closely spaced perimeter columns interconnected by deep spandrels, so that the whole building works as a huge vertical cantilever to resist overturning moments.

It is an efficient system to provide lateral resistance with or without interior columns. The efficiency of this system is derived from the great number of rigid joints acting along the periphery, creating a large tube. Exterior tube carries all the lateral loading. The gravity loading is shared between the tube and the interior columns or walls, if they exist. Besides its structural efficiency, framed-tube buildings leave the interior floor plan relatively free of core bracing and heavy columns, enhancing the net usable floor area thanks to the perimeter framing system resisting the whole lateral load. Because of the closely spaced perimeter columns, on the other hand, views from the interior of the building may be hindered.

The method of achieving the tubular behavior by using columns on close centers connected by a deep spandrel is the most common system because of the rectangular windows arrangement. There are two popular versions used currently for this system for composite construction: one system utilizes composite columns and concrete spandrels while the other utilizes structural steel spandrels instead of concrete ones.

The difficult access to the public lobby area resulting from the closely spaced column configuration at the base could be overcome by using a large transfer girder or an inclined column arrangement as was the case in the World Trade Center Twin Buildings.

Height-to-width ratio, plan dimensions, spacing, and size of columns and spandrels of the buildings, directly affect the efficiency of the system. Even though the tube form was developed originally for rectangular or square buildings, and probably its most efficient use in those shapes, circular, triangular, and trapezoidal forms could be employed as well.

Framed-tube systems can be categorized into three groups:

1. systems without interior columns, shear walls, or steel bracings;
2. systems with interior columns, shear walls, or steel bracings;
3. tube-in-tube systems.

When lateral sway is critical and starts controlling the design, the “framed tube” can be supplemented by a tube in the core to create “tube-in-tube” system, which can be constructed over 100 stories height. The 110-storey-high World Trade Center Twin Towers (1972) (Fig. 11) with its “tube-in-tube” steel structure and the DeWitt-Chestnut Apartment Building (1965) (Fig. 12) with its reinforced concrete structure are good examples of the framed-tube system.

2.5. Braced-tube systems

Braced-tube systems can be utilized in steel, reinforced concrete, and composite construction. By adding multistory diagonal bracings to the face of the tube, the rigidity and efficiency of the framed tube can be improved, thus the obtained braced-tube system, also known as trussed tube or exterior diagonal-tube system, could be utilized for greater heights, and allows larger spacing between the columns. It offers an excellent solution by utilizing a minimum number of diagonals on each face of the tube intersecting at the same point as the corner columns. In steel buildings, steel diagonals/trusses, are used, while in reinforced concrete buildings, diagonals are created by filling the window openings by reinforced concrete shear walls to achieve the same effect as a diagonal bracing.

New York’s 50-storey-high 780 Third Avenue Building (1985) (Fig. 13) was the first reinforced concrete building to
use this concept. The 58-storey-high One European Center (1986) in Chicago is another example of such a system in concrete.

On the other hand, the bracing guarantees that the perimeter columns act together in carrying both gravity and horizontal wind loads. Therefore, a very rigid cantilever tube is generated whose behavior under lateral load is very close to that of a pure rigid tube. This configuration is well suited for tall, slender buildings with small floor areas and was firstly used in a steel building, the 100-storey-high John Hancock Center (1969) (Fig. 14) by the great structural engineer Fazlur Khan, developer of trussed tube concept. The 72-storey-high Bank of China Tower (1990) (Fig. 15) in Hong Kong is another excellent example of this concept in composite construction.

A braced tube eliminates the risk of the excessive axial load taken by the corner columns. In this context, one of
the main problems in the framed tube can be overcome by stiffening the exterior frames. Although replacing vertical columns with closely spaced diagonals in both directions is the most effective braced-tube action, braced-tube system is not widely used due to its problems in curtain wall details. This system can be used for buildings with over 100 stories.

2.6. Bundled-tube systems

Bundled-tube systems are proper for steel, reinforced concrete, and composite construction. A single framed tube does not have an adequate structural efficiency, if the building dimensions increase in both height and width. Namely, the wider the structure is in plan, the less effective is the tube. In such cases, the bundled tube, also known as modular tube, with larger spaced columns is preferred. This concept, being created by the need for vertical modulation in a logical fashion, can be defined as a cluster of tubes interconnected with common interior panels to generate a perforated multicell tube.

Since this system is originated from the arrangement of individual tubes, a variety of floor configurations could be achieved by simply terminating a tube at any desired height without sacrificing structural stiffness. This feature makes the setbacks with different shapes and sizes possible. It has advantages in structuring unsymmetrical shapes. Since the “bundled-tube” design is derived from the layout of individual tubes, the cells can be in different shapes such as triangular, hexagonal, or semicircular units. The disadvantage, however, is that the floors are divided into tight cells by a series of columns that run across the building width. Thanks to its larger spaced columns, and thinner spandrels, this system allows bigger window openings when compared to the single-tube structure. Moreover, this system also makes the architectural planning of the building more flexible since any tube module can be dropped out whenever required by the planning of the interior spaces.

Two versions are possible using either framed or diagonally braced tubes, as well as a mixture of the two. The 57-storey-high One Magnificent Mile Building (1983) (Fig. 16) in Chicago is a good example of a concrete bundled-tube design. The best example of a steel bundled-tube concept is the 108-storey-high Sears Tower (1974) (Fig. 17) in Chicago. In this building, the advantage of the...
bundled form was taken into consideration and some of the tubes are made disconnected, and the plan of the building was reduced at stages along the height.

Bundled-tube concept has a broad application because of its modular quality. The tubes or cells can be organized in a variety of ways to create different massing; it can be utilized for a 30-storey-high building as well as for ultra-tall structures with over 100 stories.

3. Discussion and conclusions

In this study, structural systems that can be used for the lateral resistance of tall buildings are classified based on the basic reaction mechanism/structural behavior for resisting the lateral loads.

For all the types of buildings, namely, steel buildings, reinforced concrete buildings, and composite buildings, these structural systems are:

1. rigid frame systems
2. braced frame and shear-walled frame systems
3. outrigger systems
4. framed-tube systems
5. braced-tube systems
6. bundled-tube systems

The above classification is the expansion of the following basic structural systems: frame systems, braced or shear-walled systems, and tube systems.

‘Brace systems and shear wall systems’ which are the systems composed of only braces or shear walls, are the subsets of ‘braced frame and shear-walled frame systems’.

Nowadays, reinforced concrete and composite structures are in serious competition with the steel structures, and by the advancements in concrete technology, such as manufacturing ultra-high-strength concrete, except ‘outrigger systems’, all the structural systems classified above can be applied in reinforced concrete.

In the near future, it is thought that, the preference of composite and concrete tall building structures will increase. Furthermore, tall buildings with new structural classification which can be called as ‘mixed systems’ and ‘bundled systems’ will be introduced. ‘Mixed systems’ use the combination of two or more of the above six different systems. On the other hand, ‘bundled systems’ utilize the bundled form of structural systems as in the case of Burj Dubai where the structure utilizes bundled shear wall system, which is also named as ‘buttressed core system’.

References