Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 09, September-2021

Structural Development of Skyscrapers

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***Abstract*: This paper presents a review on the evolution of the structural system of skyscrapers from earlier to the modern and the effects of this on the society and environment**

Index terms: Skyscrapper/Tall Buildings, Height Premium, Internal, external and hybrid structural system, Building Loads, Shear Walls, lateral rigidity, Lateral Sway, Floor Vibration

I. INTRODUCTION

Tall buildings emerged in the late nineteenth century in the United States of America. They constituted a so-called "American Building Type," meaning that most important tall buildings were built in the U.S.A. Today, however, they are a worldwide architectural phenomenon. Many tall buildings are built worldwide, especially in Asian countries, such as China, Korea, Japan, and Malaysia.

The distribution of tall buildings has changed radically with Asia now having the largest share with 38%, and North America's at 22%(Fig. 1). This data demonstrates the rapid growth of tall building construction in Asian while North American construction has slowed.

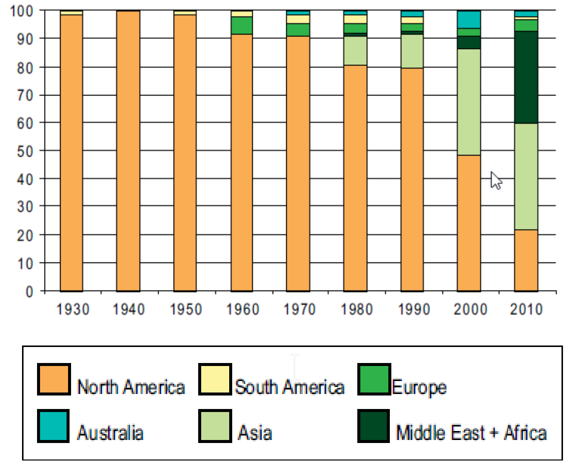


Figure 1: 100 Tallest buildings of the world by region

II. BRIEF HISTORY

Till mid 1800's the maximum height for the buildings was 4-6 stories due to several factors:

1. Too many steps to climb up & down daily
2. Masonry wall thickness is too high at base, eating up floor space
3. Framing could go up so high before become unstable in wind

The Bessemer Process was the first industrial process for the mass-production of Steel from molten pig iron. The inventor Henry Bessemer took out a patent on the process in 1855.

In 1857, Elisha Otis and the Otis Elevator Company began manufacturing passenger elevators. Invention of Elevator allowed vertical transportation of people and goods without stair

Chicago is the birthplace of the skyscraper The Home Insurance building (1885) in Chicago, (ten storied with 42 meter in height) is generally referred as the first high rise building (Architect :William Jenney) The Home Insurance Building was built followed by the Great Chicago Fire, 1871

- The physical envelope of construction was traditional load-bearing system.
- Thick masonry external walls creates comfortable indoor thermal environment
- Large window and high ceiling was provided to allow the daylight to the interiors.
- Maximizing the financial return over a fixed plot size, initiates the development of modern high rise building in North America during mid-nineteenth century

III. PREMIUM FOR HEIGHT

The primary structural skeleton of a tall building can be visualized as a vertical cantilever beam with its base fixed in the ground. The structure has to carry the vertical gravity loads and the lateral wind and earthquake loads. Gravity loads are caused by dead and live loads. Lateral loads tend to snap the building or topple it. The building must therefore have adequate shear and bending resistance and must not lose its vertical load-carrying capability.

Fazlur Khan realized for the first time that as buildings became taller, there is a "premium for height" due to lateral loads and the demand on the structural system dramatically increased, and as a result, the total structural material consumption increases drastically (Ali, 2001). Further to this, the columns need to be even heavier towards the base to resist lateral loads. The net result is that as the building becomes taller and the building's sway due to lateral forces becomes critical, there is a greater demand on the girders and columns that make up the rigid-frame system to carry lateral forces. The concept of premium for height is illustrated in Figure 2.

If we assume the same bay sizes, the material quantities required for floor framing is almost the same regardless of the number of stories. The material needed for floor framing depends upon the span of the framing elements, that is, column-to-column distance and not on the building height. The quantity of materials required for resisting lateral loads, on the other hand, is even more increased and would begin to exceed other structural costs if a rigid-frame system is used for very tall structures. This calls for a structural system that goes well beyond the simple rigid frame concept. Based on his investigations Khan argued that as the height increases beyond 10 stories, the lateral drift starts controlling the design, the stiffness rather than strength becomes the dominant factor, and the premium for height increases rapidly with the number of stories. Following this line of reasoning, Khan recognized that a hierarchy of structural systems could be categorized with respect to relative effectiveness in resisting lateral loads for buildings beyond the 20- to 30-story range (Khan, 1969).

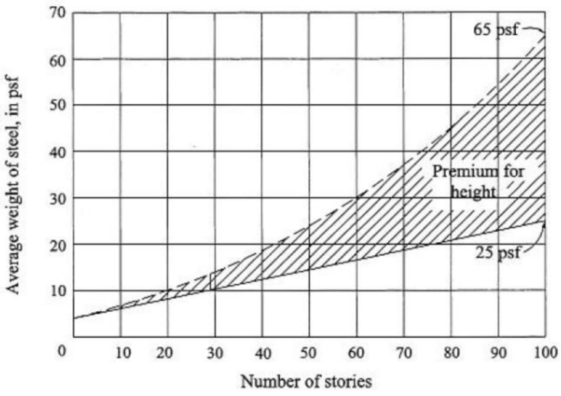


Figure 2: Premium for height.

IV. CLASSIFICATION OF SKYSCRAPERS STRUCTURAL SYSTEMS

The Structural system of the skyscrapers can be classified in three types:

1. Internal
2. External
3. Hybrid

1. **Internal:** A system is categorized as an interior structure when the major part of the lateral load resisting system is located within the interior of the building. It includes mainly Rigid Frame System, Vertical Shear Truss System, Frame - Shear Truss System

   Rigid Frame System:

   Rigid Frame or moment-resisting frame (MRF) consists of Girder and Column rigidly connected together in a planar grid Such frames resist load primarily through the flexural stiffness of the members. The size of the columns is mainly controlled by the gravity loads, progressively larger column sizes towards the base The size of the girders, is controlled by stiffness of the frame to ensure acceptable lateral sway of the building.

   Some of rigid frame tall buildings is - 860 & 880 Lake Shore Drive Apartments (1949) Chicago, 82 m, 26 stories

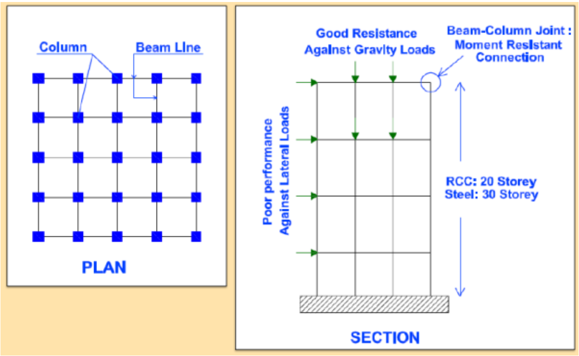


Figure 3: Rigid Frame Buidings

Vertical Shear Truss:

Vertical Shear Truss System (RC coupled shear wall) can effectively resist lateral forces caused by wind and earthquakes. They are treated as vertical cantilevers fixed at the base.

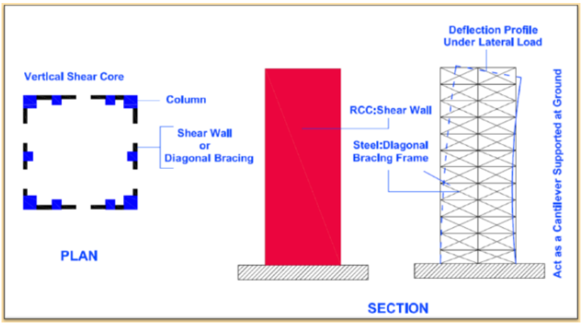


Figure 4: Vertical Shear Truss

Frame - Shear Truss System:

Rigid Frame is not efficient for buildings over 30 stories because the sway caused by the bending of columns is excessive. Vertical Shear Trusses alone provide resistance up to 35 stories.

When vertical Shear Trusses are combined with Rigid Frame , the interactive system, results in a common deflected shape of the structure.

The upper part of the truss is restrained by the frame, The lower part, frame is restrained by the truss. This effect produces increased lateral rigidity of the building. Some of the frame truss buildings are The Empire State Building (1931) New York, 381m, 102 Storied, 311 South Wacker Drive (1949) Chicago, 293 m, 65 stories

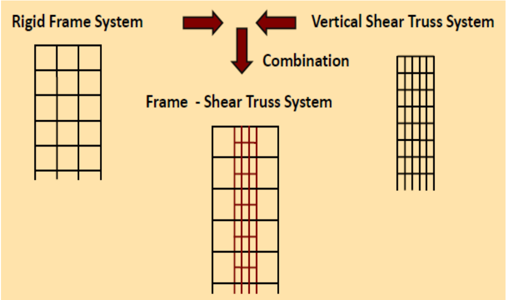


Figure 5: Frame - Shear Truss System

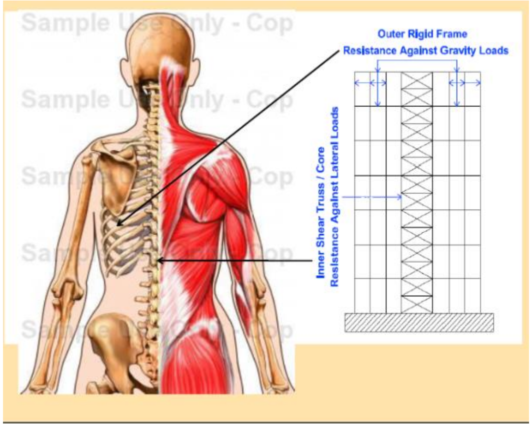


Figure 6: Frame - Shear Truss System nature example

2. **External:** If the major part of the lateral load-resisting system is located at the building perimeter, a system is categorized as an exterior structure.

   It is desirable to provide lateral load-resisting system components as far as possible on the perimeter of tall buildings to increase their structural depth. Tubes are known as basic exterior structures. It can be defined as a three-dimensional structural system utilizing the entire building perimeter to resist lateral loads. It includes mainly Frame Tube System, Braced Tube System, Tube in Tube System, Bundled Tube System

Frame Tube System:

It has closely spaced columns and deep spandrel beams rigidly connected together throughout the exterior frames. Depending upon the structural geometry and proportions, exterior column spacing should be from 5 to 15ft (1.5 to 4.5m) Practical spandrel beam depths should vary from 24 to 48in (600 to 1200mm). Resulting structural organization the lateral load resisted by the whole tube. Some of the frame tube buildings are Water Tower Place (1975) Chicago, 262 m, 74 stories; Aon Center (1973) Chicago, 346 m, 83 stories; WTC(1971) New York, 417m, 110 storied

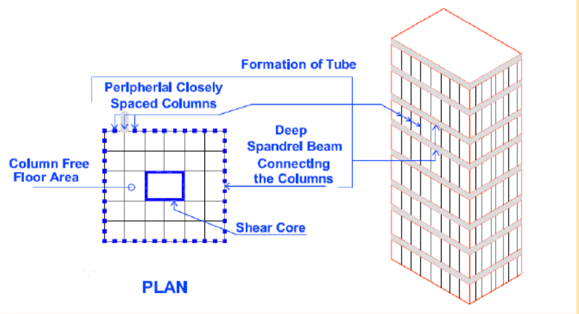


Figure 7: Frame Tube System

Braced Tube System:

It is possible to stiffen the building Structure by introducing diagonal braces. Introduction of Diagonals also increase the spacing of columns in frame tube.

The diagonals participate in dual role action as it collect gravity loads from floors as inclined columns also act as a stiffener in case of lateral loads. Some of Braced tube structures are John Hancock Center (1970) Chicago, 344 m ,100 stories; Onterie Center (1986) Chicago, 174 m ,58 stories.

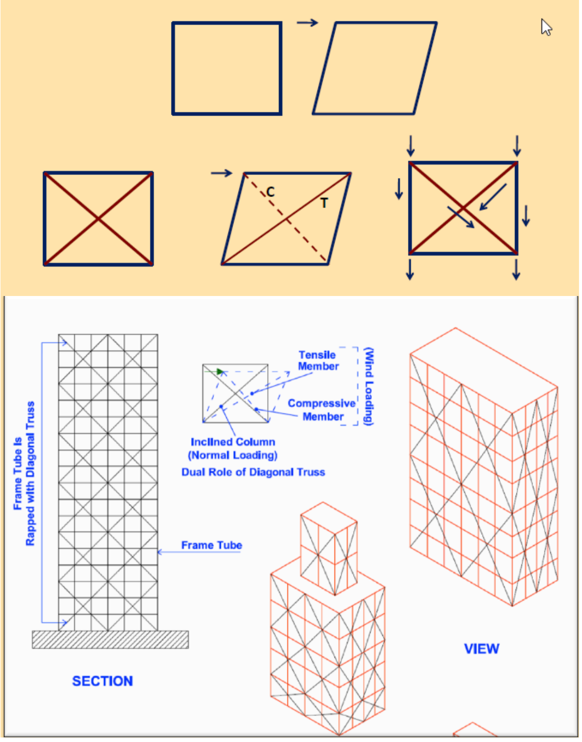


Figure 8: Braced Tube System

Tube in Tube System:

The stiffness of a Framed Tube can be further enhanced by using a core tube to resist part of the lateral load resulting in a tube-in-tube system. The floor diaphragm connecting the core and the outer tube transfer the lateral loads to both systems. It is also possible to introduce more than one tube inside the perimeter tube.

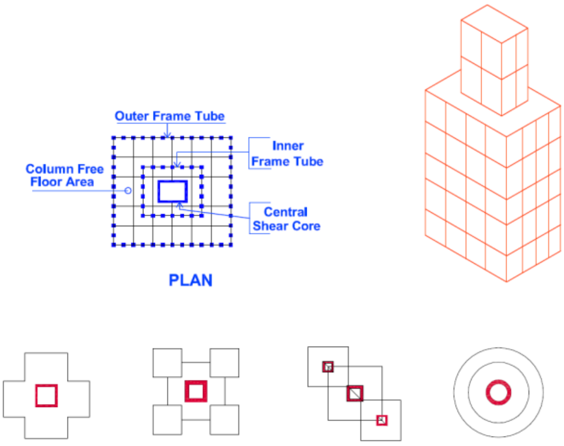


Figure 9: Tube in Tube System

Bundled Tube System:

In tall buildings with larger floor areas, simple frame tube system become very uneconomical structural solution. To overcome this, many frame tubes are symmetrically grouped together to create larger floor space. Further these grouping

of frame tubes (called bundled tubes) are actively participate to transmit the super-structure load to the ground as well as provide the lateral stability against the transverse loading.
Some of the Bundled tube structure are Sears Tower (1973) Chicago, 442 m,108 Stories; Burj Khalifa (2010) Dubai, 828m, 163 habitable floors plus 46 maintenance levels

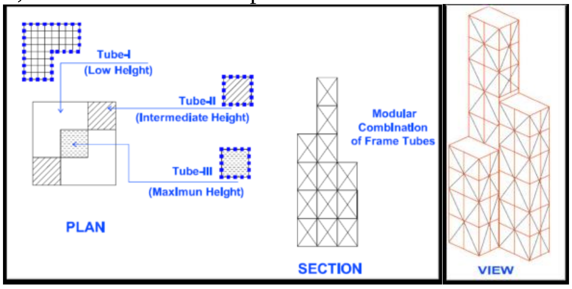


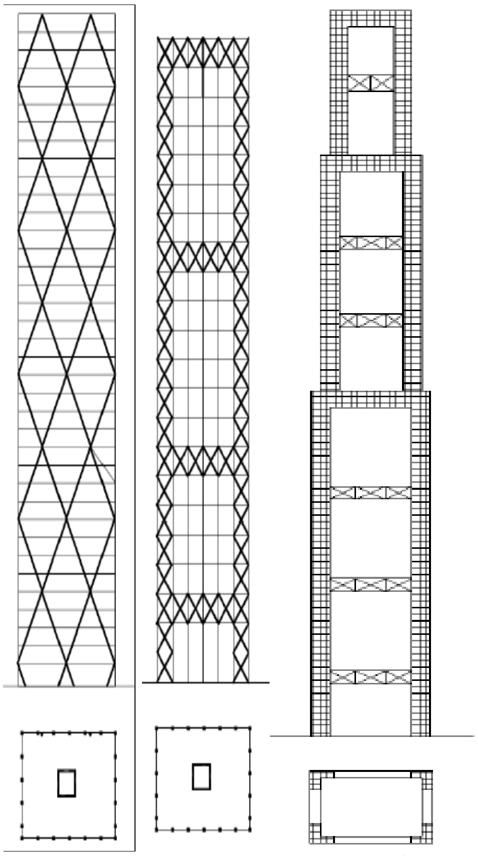
Figure 10: Bundled Tube System

3. **Hybrid:** These are the advance structural systems. It includes Diagrid, Exoskelton, Super frames, Outrigger

Diagrid:
Almost all the conventional vertical columns are eliminated. This is possible because the diagonal members in diagrid can carry gravity loads as well as lateral forces due to their triangulated configuration in a distributive and uniform manner. Some of diagrid buildings are Hearst Building (2006) New York, 182m, 46 Stories, Swiss Re Building (2004) London, 181m, 41 Stories

***Exoskelton**:*
In exoskeleton structures, lateral load-resisting systems are placed outside the building lines away from their facades. The system is associated with other conventional types Due to the system's compositional characteristics, it acts as a primary building identifier. Some of Exoskelton buildings are
Burj Al Arab, Dubai.

Superframe:
A super-frame is composed of mega columns comprising braced frames of large dimensions at building corners Like Exo-skeleton, the system is also associated with other conventional types The mega columns usually linked by multistory trusses at about every 15 to 20 stories. Some of Superframe buildings are Parque Central Tower (1979) Caracas, Venezuela, 221 m ,56 stories.



Diagrid Exoskelton Superframe

Figure 11

Outrigger:
The Frame-Shear Truss system is further modified with introduction of outriggers band in differential vertical levels The outriggers are generally in the form of trusses in steel structures, or walls in concrete structures.

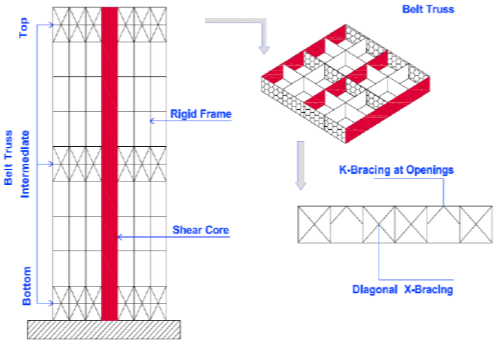


Figure 12. Outrigger Truss System

Outriggers reduce the overturning moment in the core Outriggers can also be supported on mega-columns in the perimeter of the building. thus resisting the lateral push on the building by 'feet – spread' technique as shown in figure 13.

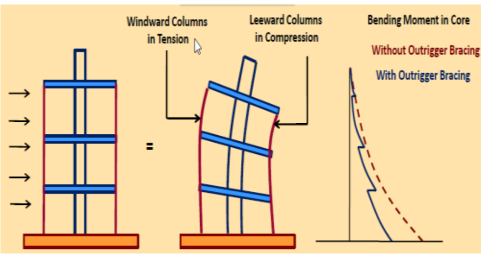


Figure 13.

Outrigger systems have been historically used by sailing ships to help resist the wind forces in their sails as shown in figure 14.

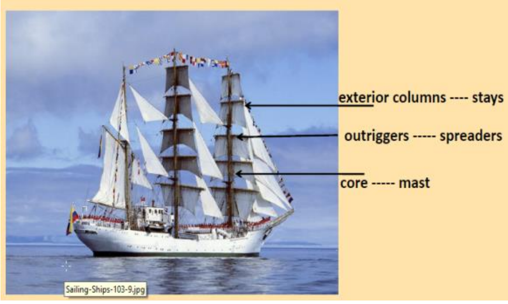


Figure 14.

Some of the outrigger buildings are
Taipei 101(2004) Taiwan, 509 m, 101 Storied, Jin Mao Building (1999) Shanghai, China, 421 m ,88 Stories

V. CONCLUSION

This paper has presented a general review of structural systems for tall buildings. Various structural systems within each category of the new classification have been described with emphasis on innovations. This paper demonstrates that structural systems have come a long way since the late nineteenth century when they were conceived as framed systems. With the development of increasingly taller buildings using lighter members, serviceability issues like lateral sway, floor vibration, and occupant comfort need to be given more attention by researchers. More research is needed for exterior structural systems which are technically more efficient.

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