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A COMPREHENSIVE REVIEW OF THE STRUCTURAL BEHAVIOUR AND LATERAL LOAD RESISTANCE OF TUBULAR STRUCTURAL SYSTEMS IN HIGH-RISE BUILDINGS

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Abstract

Tubular systems rank among the most effective ways of resisting lateral loads in tall buildings, because the main load-bearing material is concentrated at the outer edge of the building, which then behaves like a hollow cantilever tube under wind and earthquake action. This review examines the fundamental characteristics of the principal tubular configurations, namely the framed, bundled, braced and diagrid forms. It covers several key features of the different types of tubular structures which include lateral stiffness, storey drift, shear lag, axial force distribution, overturning moment, structural behavior under wind and seismic loads, material efficiency, and architectural considerations. As framed tube systems suffer from a phenomenon called shear lag, reducing their efficiency in tall structures, while bundling tubes eliminate shear lag with internal webs and braced tubes and diagrid systems provide shear resistance through the axial load of the diagonal members.

Keywords: Tubular structures, High-rise buildings, Framed tube, Bundled tube, Braced tube, Diagrid, Shear lag, Lateral load resistance.

1. Introduction

Urbanization and limited space have created the need for constructing skyscrapers. As buildings grow taller, wind and earthquake loads increasingly govern the design over gravity loads, so overall structural efficiency depends strongly on how effectively the lateral system limits drift and overturning. There are a number of structural forms that have been developed for tall buildings; however, the tube structures have proven to be the most efficient structures as the structural elements are placed around the perimeter of the structure where they offer maximum resistance against bending and twisting [1].

1.1. Evolution of Tall Buildings and the Demand for Efficient Systems to Resist Lateral Loads

Structural schemes for tall buildings range from rigid frames and shear walls to newer, more efficient interior and exterior (perimeter) systems [2]. Rigid frame systems were extensively employed during the first half of the twentieth century; however, they have turned out to be structurally inefficient once the building exceeds certain heights and the development of the tube structure has enabled the construction of buildings at higher heights while consuming relatively low material [3]. Tall building systems can also be grouped according to how they resist lateral forces [4]. Due to the high rate of increase in lateral drift, floor acceleration, and overturning force in slender structures, the system dependent on bending of individual columns and beams soon turns out to be economically inefficient. The tubular systems take care of this issue through a perimeter structure acting like a three-dimensional hollow cantilever providing higher stiffness against bending and torsion with relatively lower consumption of material.

1.2. Framed, Bundled, Braced and Diagrid Tubular Systems

The framed tube is the initial tubular structure in which the perimeter columns are placed in close proximity and interconnected through deep spandrel beams. This form becomes less efficient because of shear lag, whereby the axial stresses across the columns are unevenly distributed, with the corner columns taking the higher load than the central columns [5]. Hence, the framed tube loses its efficiency beyond 60 storeys. Bundled, braced and diagrid configurations were developed to overcome this limitation of the framed tube, and the braced tube exhibits less shear lag than the framed tube [6].

A bundled tube joins several tubes into a single multicell tube, whose internal webs relieve shear lag in the flange frames. In a braced tube, large diagonal members stiffen the perimeter frame within its own plane so that it behaves like a wall, and the diagrid is an enhanced braced tube where the closely-spaced diagonals act as both the vertical columns and load-carrying members [7].

More recently, advanced versions of these tubular forms have been adopted for supertall buildings. Several research studies on the diagrid systems are discussed in Table 2. Therefore, a comparison of these systems is very crucial.

1.3. Aims of the Study

The aims of this review are:

- To critically examine the working principles, structural behaviour, merits and limitations of framed, bundled, braced and diagrid tube systems in tall buildings.
- To comparatively evaluate their lateral load resistance in terms of lateral stiffness, storey drift, shear lag, axial force distribution, and overturning moment.
- To assess their wind and seismic performance, material efficiency, and architectural and construction implications.
- To identify research gaps and future opportunities for the development and application of advanced tubular structural systems.

2. Tubular Systems for Tall Buildings

In a tube structure, the elements that resist lateral load are placed at or near the building perimeter, allowing the whole plan to behave as a hollow tube cantilevering from its base.

The wind and seismic forces are taken up mostly by the web frames (aligned with the force direction) through shearing action and the flange frames (those perpendicular to the loading direction) through axial compression and tension. The performance of the tube is determined by how close it comes to the ideal cantilever effect, which is what the various tubes strive for.

2.1. Framed Tube

Framed tube is made up of exterior columns that are close to each other and deep spandrel beams that are rigidly jointed to make a perforated tube. Close columns form the face of the structure as well as its openings and it is capable of resisting the lateral load through a combination of frame bending and cantilevering of tube.

For a solid-walled tube, the axial stress varies linearly along the web and remains uniform across the flange. Since walls of the framed tube have openings for windows, the axial stress distribution becomes non-linear due to shear lag phenomenon.

2.2. Bundled Tube

A bundled tube is formed by combining several framed tubes into one multicell tube. Essentially, the interior frames serve as additional webs that handle the shear and shear lag on the flanged frame tubes; hence, the system is more effective compared to a singular tube when dealing with tall structures with large floor plans. The best-known example is the Willis Tower in Chicago (formerly the Sears Tower), which comprises nine framed tubes bundled together at its base.

2.3. Braced Tubes and Diagrids

A braced tube is created by adding diagonal bracing to the exterior frame of the structure. This stiffens the outer frame within its own plane and makes it function as a wall thus making the structure taller; the technique was first applied in the 100-storey John Hancock Center in Chicago. The diagrid is a refinement of the braced tube in which many small diagonals intersect each other on the surface and there are no vertical members present, thus carrying both gravity and lateral forces in axial direction [8]. Diagrids and braced tubes perform similarly structurally and the diagonal inclination is a major factor affecting their stiffness, material consumption and appearance [9]. There are other versions such as hexagrid which use hexagonal periphery for this purpose, as given in table 2.

2.4. Comparative Characteristics of Framed, Bundled and Braced Tube/Diagrid Systems

The differentiating factor between the four tube shapes lies in their method of transferring the shearing and overturning forces to the base. Frame tube shapes depend largely on bending of frames, bundled tubes have additional webs introduced to reduce shear lag, and braced tubes and diagrids use the axial force of the diagonals for the same purpose.

Table 1. Comparative characteristics of framed, bundled and braced tube/diagrid systems

Parameter	Framed Tube	Bundled Tube	Braced Tube / Diagrid
Basic configuration	Perimeter columns at close spacing, connected by deep spandrel beams	Several framed tubes combined into a multicell tube	Perimeter frame stiffened by large diagonals (braced tube) or closely spaced diagonals replacing most vertical columns (diagrid)
Primary lateral load path	Bending of columns and spandrels (frame action) with tube cantilever action	Frame action of flange and web frames, with internal webs carrying additional shear	Axial action of diagonals in tension and compression
Lateral stiffness	Moderate	High	Very high
Shear lag	Pronounced	Reduced by internal webs	Largely reduced
Efficient height range	Up to about 60–80 storeys	Taller than a single framed tube	Tall and supertall buildings
Perimeter columns	Closely spaced	Closely spaced in each cell	Retained in braced tubes; largely eliminated in diagrids
Interior planning	Column-free interior possible	Restricted by internal frames	Column-free interior possible
Façade and openings	Small, regularly spaced windows	Small, regularly spaced windows	Openings defined by the diagonal geometry
Material efficiency	Moderate	Good	Generally high
Seismic behaviour	Good ductility with proper detailing	Good redundancy through multiple tubes	High stiffness; ductile detailing of nodes is important
Wind behaviour	Adequate at moderate heights	Good	Very good
Connection complexity	Moderate	Moderate	High (diagonal nodes)
Construction	Repetitive and relatively simple	More complex due to multiple cells	Complex nodes; prefabrication is advantageous
Major limitation	Shear lag and limited efficient height	Restricted floor planning	Complex joints and façade geometry
Typical examples	DeWitt-Chestnut Apartments, Chicago	Willis Tower, Chicago	John Hancock Center, Chicago; Hearst Tower, New York

3. Structural Behaviour and Lateral Load Resistance

The lateral load-resisting capacity of a tubular system is based on the capacity of the system to utilise its entire perimeter as a cantilevered tube, which is dependent on the stiffness of the perimeter elements, the connections of these elements, and the geometry of the building. The systems can be evaluated on the basis of parameters such as lateral stiffness, shear lag and axial force distribution, among others, as described in Table 2 below.

- **Lateral stiffness and drift:** In the case of a framed tube, the lateral deflection includes the deflection due to bending (or cantilevering) and a deflection due to shear arising from frame action. The contribution of shear deformations becomes significant with increasing building height. Braced tubes and the diagrids lower the shear deformation since the diagonals take the shear forces axially and result in improved lateral stiffness and reduced story drift for a similar height.
- **Shear lag:** Shear lag causes the axial stress in the flange columns of a framed tube to be unevenly distributed, unlike the uniform distribution predicted by beam theory, with the corner columns being over-stressed and the middle columns underutilised. Investigations of framed, diagrid and hexagrid buildings of differing heights show that system configuration governs the relative share of shear and flexural deformation as well as the magnitude of shear lag (Table 2). The bundled and braced tubes control the shear lag with the help of internal webs and diagonals, respectively.
- **Axial force distribution and load path:** In a diagrid, the axial forces in the diagonals act against the lateral as well as gravity loads, such that the interior part of the structure acts against gravity loads only. Thus, the

distribution of axial force in the diagonals is influenced primarily by the angle of the diagonals and height of the building.

- **Overturning moment and base shear:** In the case of tubular structures, the overturning moments are counteracted by the axial forces in the flange frame columns or diagonals acting on large levers, which is one of the reasons for the efficiency of the structures. The stiff systems such as braced tubes and diagrids usually have lower periods of vibration, which can affect the seismic base shear and the wind load response.
- **Effect of geometric parameters:** Geometric parameters such as aspect ratio, shape of the plan, column or diagonal spacing and sizes of the members influence the tube action of the system. In the case of diagrid, the most significant geometric parameter is the angle of diagonals, which influence their behaviour in relation to bending or shear resistance and optimal angles of about 60°-70° have been recommended for tall diagrids.
- **Variable angle diagrid and other innovative configurations:** Diagrids with variable angles of diagonals that decrease gradually with height have been recommended in order to balance the changing shear and overturning demands. Novel systems such as hexagrids have also been considered (Table 2).

In general, the framed tubes are efficient up to certain height due to shear lag, bundled tubes improve efficiency using webs but reduce planning flexibility, while braced tubes and diagrids have maximum lateral stiffness due to shear deformation being taken axially.

Table 2. Summary of Previous Research on Tubular Structural Systems in High-Rise Buildings

Author, Year	Topic Covered	Title of the Study
Mashhadiali et al. (2021) [10]	This work analysed shear lag in 50-, 80- and 110-storey framed tube, diagrid and hexagrid buildings under wind loading, and assessed the role of the lateral deformation components in it.	*Investigation of shear lag effect in tall tube-type buildings*
Kim and Lee (2012) [11]	Using nonlinear analysis, the study assessed how diagrid buildings perform seismically and characterised their response to earthquake loading.	*Seismic performance evaluation of diagrid system buildings*
Zhang et al. (2012) [12]	A diagrid tube layout was proposed in which straight diagonals change angle gradually over the building height, and its influence on structural performance was investigated.	*Diagrid tube structures composed of straight diagonals with gradually varying angles*
Liu et al. (2018) [13]	A review of diagrid systems in tall buildings was presented, addressing their evolution, structural performance and design issues.	*A review of the diagrid structural system for tall buildings*
Mashhadiali and Kheyroddin (2013) [14]	The hexagrid was introduced as a new perimeter system for tall buildings, and its structural performance was benchmarked against conventional tubular systems.	*Proposing the hexagrid system as a new structural system for tall buildings*

4. Wind and Seismic Performance, Efficiency and Design Considerations

Tubular structures must meet the criteria of strength, serviceability and economy in terms of both wind and seismic loads. Design of tubular systems is mainly based on lateral drift, floor accelerations and economy in material utilization and all these should be considered in each individual case.

4.1. Wind-Induced Response

For tall slenderness structures, wind load and wind excitation usually dominate the structure's design. Since the structure is very stiff due to braced tube and diagrid configuration, and considering that the building's shape plays an important role in wind load, aerodynamic treatments like corner treatment can improve wind characteristics and may result in decreased load requirements on the structure [15]. The design of Burj Khalifa [16] and full-scale dynamic monitoring of the building's behavior [17] serve as good references for prediction of super-tall buildings.

4.2. Seismic Performance

The tubular structure should be strong enough when subjected to earthquake loads. The nonlinear analysis of the diagrid structure has been done to assess the seismic behavior and response characteristics (see Table 2) of such structures, while the seismic fragility analysis has been conducted for the steel diagrid structure to find out the probability of the occurrence of damage under earthquakes [18]. Recent research has been carried out for the diagrid

and hybrid diagrid structures of tall tilted buildings with respect to time period, storey drift, lateral displacement and load distribution [19].

4.3. Material Efficiency and Structural Weight

Tubular structures have high concentration of the structural materials at the periphery of the structure making it possible to create tall buildings using low number of materials. Diagrids depend on the degree of inclination of the diagonals for the amount of steel to be used; low angle leads to heavier and dense diagrid while steep angle produces light diagrid.

4.4. Architectural and Functional Considerations

The close column spacing in the tubular frame system and the bracing used in the braced tube system make design of the façade difficult, and in the bundled tube system the interior frames make the layout of the floor plan more complicated. The Diagrid system combines efficiency with aesthetic design, and the triangular shape of the structure suits tall building designs [20].

4.5. Construction and Economic Considerations

Tubular system cost is affected by the volume of structural materials, connection complexity, and erection time. Frames consist of repetitive members which can be erected easily compared to diagrids and braced frames which have complicated joints but low material volume. It is thus necessary for there to be a balance between efficiency, erection and costs when choosing a tubular system.

4.6. Landmark Applications

Tubular systems underpin several landmark buildings, including Chicago's John Hancock Building and Willis Tower and, more recently, diagrid structures such as New York City's Hearst Tower. This underlines the relevance of the various tubular systems in current times.

5. Conclusion

This paper has reviewed the structural behaviour and lateral load resistance of framed, bundled, braced and diagrid tube structures. The framed tube performs well in buildings of moderate height but it becomes inefficient in taller structures due to the phenomenon of shear lag. The bundled tube structure reduces the problem of shear lag by the webs inside and it is appropriate for tall buildings and large building plans but limits the interior planning. The braced tube structure and diagrid structure offer high lateral resistance and use materials efficiently by resisting the shear force through the axial resistance of diagonal members. However, the angles of the diagonals and nodes must be properly designed. Future researches will focus on the optimization of hybrid and variable-angle structures, shear lag problem under wind and seismic loading, performance based seismic design and collapse resistance and also the combination of tubular structures with outrigger and damping system.

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