STRUCTURAL SYSTEMS USED IN VERTICAL CITIES A REVIEW

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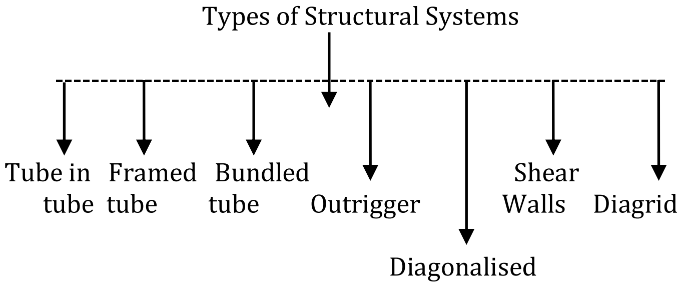
Abstract— Smart city mission in India promoted infrastructure development under various parameters like use of smart materials, smart villages, sanitation improvement, sustainable energy and many more. Introducing new vertical cities, iconic structures and use of multi-functional buildings in India is such a step ahead to achieve these parameters into reality. Vertical modern age buildings are already popular worldwide due to its advantages in terms of low consumption of area and multi-functional use. However, these buildings are subjected to intense loading due to wind, earthquake and therefore requires study to withstand safely against these complex forces and to achieve this, structural systems should be given top priority as it plays a vital role. This paper mainly focuses on the review of such structural systems which includes framed tube system, tube in tube system, bundled tube system, diagonalised-rigid system, outrigger system, shear walls, diagrid system which are usually used in high rise buildings, skyscrapers. Further study is done considering case studies of today's top 5 skyscrapers in the world which are Kingdom tower Jeddah, Burj Khalifa Dubai, Taipei Tower Seoul, Shanghai Tower Shanghai and International Commerce Centre Hong Kong. Concluding remarks are made discussing advantages, disadvantages, comparison and suitability of these structural systems under the Indian context.

Keywords—Smart Cities, types of loads, Structural systems, Case studies, Application.

I. INTRODUCTION

Smart Cities is a new concept introduced in India by Honourable Prime Minster Mr. Narendra Modi with a vision for overall infrastructure development of the country which includes growth over the several parameters including use of sustainable materials, smart technology, and green architecture at the same time functionally sound structures. One of the important characteristic in such development is the vertical development of a city on urban scale which has various advantages in terms of less usage of foot print and therefore getting popularity day by day. Structural systems play a vital role in such development and should be given prime focus considering the structural loads, structural materials, function of building, and many more. For studying this aspect of structure it becomes important to study the successful vertical cities in the world and therefore this paper aims to study such iconic vertical cities. Loading is critical in high rise, skyscraper due to their excessive height as wind pressure acting on them is tremendous. So care must be taken while selecting suitable structural system and the materials to carry such heavy loads. There are various structural systems like frame tube system, tube in tube system, bundled tube system, diagonalised-rigid system, outrigger structural system, shear walls and diagrid structural system. This paper is an attempt to understand these structural systems used across world so that in the coming years it could be effectively used in India as well.



II. LITERATURE REVIEW

A. Structural Systems for skyscrapers

Steel structural systems along with combination of concrete walls are used effectively to carry loads. There are various structural systems that are used successfully for high rise, skyscrapers in the world today out of which few important are discussed here in this paper includes-

- Tube in tube System: This consist of the framed tube of an outer frame tube known as Hull along with service core. Both core and frame tube act together to resist lateral and gravity loads. Height of columns is varied according to the height so that buckling of column will get reduced.[5]
- Framed tube system: These are the stiff moment resisting frames which form tube along the perimeter of structure.[5]
- Bundled Tube system: This system allows wider spacing of columns without compromising the interior space. This system has a advantage of providing dynamic shape due to the module parameter in it.[5]
- Diagonalised rigid system: In braced structures, diagonal members gives lateral resistance in braced frames while columns act as a chord.[5]
- Outrigger system: One or two storey deep truss connects core to the exterior columns. Outrigger system is used along the various levels throughout the height which helps in resisting the lateral effect of forces on height. This system helps to increase the bending rigidity.[5]
- Shear Walls: It is a type of rigid frame construction. It consists of laterally braced panels which are provided to carry lateral loads. Whenever in between columns need to be avoided, reinforced concrete thick shear walls can be used effectively.
- Diagrid System: This type of system helps in eliminating conventional columns as they are effective in carrying lateral and gravity loads.

Their appearance is aesthetically appealing and therefore seems to be popular in modern high rise and skyscrapers. They could also be used as a supporting system for kinetic facades hence reduces requirement of additional structural element.[5]

III. CASE STUDIES

To understand structural systems, skyscraper- case studies had been carried out for top five buildings in the world which includes Kingdom Tower- Jeddah, Burj Khalifa-Dubai, Taipei Tower-Seoul, Shainghai Tower-Shainghai, and International Commerce Centre- Hong Kong.

1. Kingdom Tower, Jeddah

Height: 1000+
No of Floors: 167
Structural System: Shear walls
Material Used: Reinforced concrete
Type/Purpose: Mixed Use
Foundation type: Bored pile foundation

The Y-shape plan of tower gives stability and helps in reducing the effect of wind on the structure. The tower has no columns or outriggers. It is designed with shear walls to carry the loads. These reinforced concrete shear walls are effective in acting as a sound absorbing mechanism between public and private corridors, provide minimum fire separation. Along with cast-in-situ reinforced concrete shear walls, coupling beams, flat plate concrete framing is used. The triangular core shape formed due to shear walls is effective in resisting torsional forces and hence proves to be effective. This structure is constructed on 270 bored piles with 1.5 m diameter. [2]

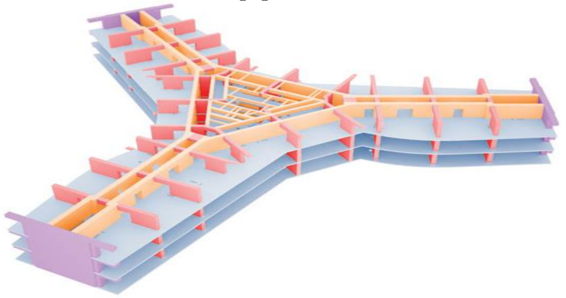


Fig.1 Structural Components of a kingdom tower
Source:http://www.ctbuh.org/TallBuildings/FeaturedTallBuildings/ArchiveJournal/KingdomTowerJeddah/tabid/4415/language/en-GB/Default.aspx

2. Burj Khalifa, Dubai

Height: 829.80m
No of Floors: 163
Structural System: tube in tube+ concrete walls
Material Used: Steel and concrete
Type/Purpose: Residential + Commercial
Foundation type: Pile Foundation

Structural system in Burj Khalifa can be described as a Buttressed core along with high performance concrete wall construction. The mechanical floor is connected through columns to interior column system using outrigger walls. Due to this the columns participate in resisting the heavy lateral loads. Central core of hexagonal shape provides torsional resistance to the structure. This existing World's tallest structure is constructed on pile foundation. [1]

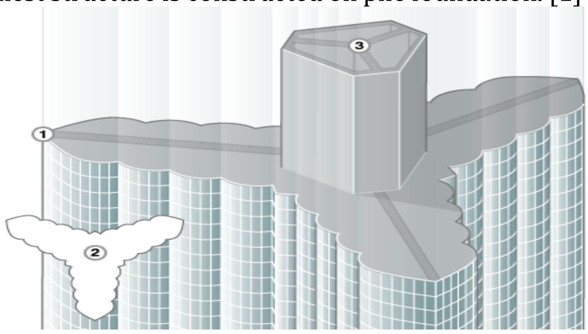


Fig. 2 Buttress core system in Burj Khalifa
Source: http://emmelynchua.blogspot.in/2014/04/

3.Taipei Tower, Seuol

Height: 509.20m
No of Floors: 101 above ground + 5 basement floors
Structural System: Outrigger + Belt trusses
Material Used:
Type/Purpose: Commercial offices
Foundation type: Pile Foundation

In this tower, central core is braced with outrigger trusses to top and bottom chords within framing of two adjacent floors and diagonals are used to connect mechanical, storage spaces. Outrigger columns along with outrigger trusses are helpful in stabilizing the narrow core. Belt trusses just above module setback are helpful in transfer of load to the super columns. Super columns are filled with concrete to increase the lateral stiffness. To reduce the intense effect of wind saw-tooth treatment is given to the exterior face. To reduce the effect of wind forces tuned mass damper is also provided having a total weight of 730tonnes which spans along four stories with steel plates. [6]

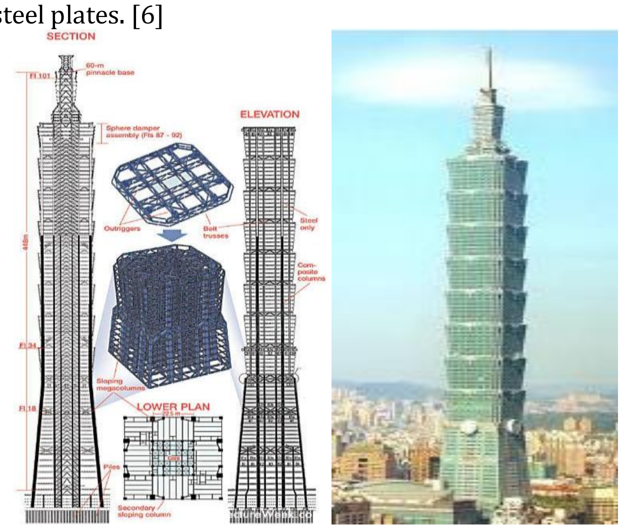


Fig.3. Structural System at Taipei Tower
Source: http://delhitasa.blogspot.in/2011/12/taipei-101-taiwan-building.html
https://en.wikiarquitectura.com/building/taipei-101/

4. Shainghai Tower, Shainghai

Height: 632m
No of Floors: 128
Structural System: Outrigger + Mega frame

Material Used: Structural Steel + Reinforced Concrete
Type/Purpose: Mixed Use
Foundation type: Pile Foundation

This tower faced various challenges during design process due to presence of soft soil. Structural engineers developed creative solutions like mega columns. This tower is divided into nine zones as zone 1 retail, zone 2 to zone 6 offices, zone 7 and 8 hotel while zone 9 is exclusively for observation deck. It has core-outrigger-mega frame which consists of three components in it - concrete composite core, exterior mega frame along with the outrigger trusses .Core is of 30m square shape in plan which is uniform from zone 1 to 4. The four corners are cut back at zone 5 and 6 while at reaching the zone of 7 and 8 it takes a shape of cruciform. Tower which is divided into nine zones where steel columns are provided embedded into the super columns. There are total eight super columns provided up to zone 8.Mega columns are provided along with the outrigger trusses at the eight levels throughout the entire height of tower. These trusses along with belt trusses helps to maintain the required stiffness of the structure .Provision of outrigger near the low zones helps in reducing oscillations while at top it helps to maintain overall ductility of structure. For façade a conventional approach of vertical trusses is adopted to transfer gravity loads. [2]

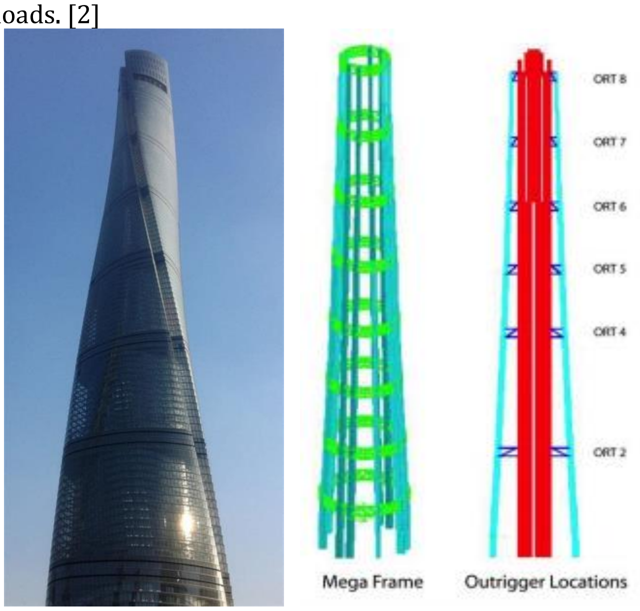


Fig. 2 Shainghai Tower and Structural systems Source:http://eeme.ntua.gr/proceedings/8th/Invited_Speakers/PAP_Velivasakis.pdf
https://www.earchitect.co.uk/wpcontent/uploads/2015/01/shanghai-tower-building-g100115-1.jpg

5. International Commerce Centre, Hong Kong

Height: 484m
No of Floors: 108 above ground + 4 basement
Structural System: Outrigger+ core
Material Used: Structural steel+ Reinforced concrete
Type/Purpose: Commercial offices + Hotels
Foundation type: Shaft grouted barrettes

This tower is divided into five zones which includes offices, an observatory desk and a five star hotel at top. This tower is constructed with outrigger system along with central core system. Four outriggers are provided at a separating interval of 25 stories out of which three are of steel while one is pre-stressed, connecting to mega columns at the exterior periphery. Connecting joint is provided between mega columns and outriggers to tackle the differential deflection of structure. To support this enormous structure a 62m thick cofferdam lined by diaphragm wall had been constructed before the foundation was constructed. Grade 90 high performance concrete is used for core while grade 60 concrete is used for mega columns. This massive structure is resting on 241 shaft grouted barrettes of 70 m depth. Each barrette is capable of carrying 40000kN of load. [9]

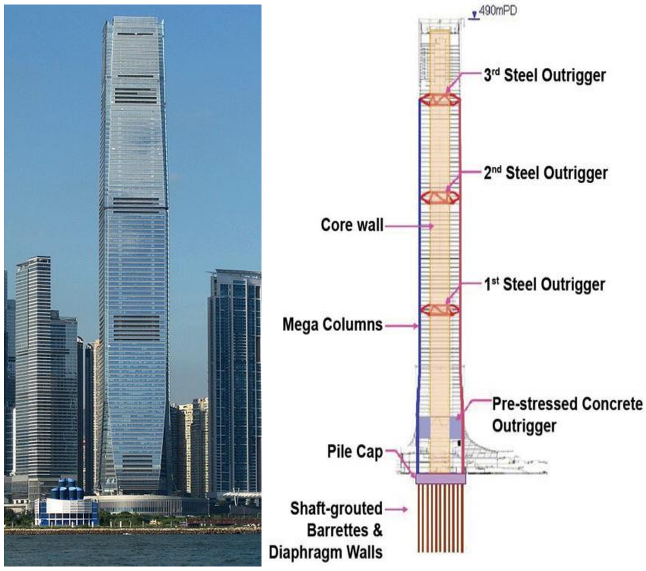


Fig. 4 International Commerce Centre and structural systemSource:http://www.hkengineer.org.hk/program/home/articlelist.php?cat=cover&volid=11
https://en.wikipedia.org/wiki/International_Commerce_Centre

IV. OBSERVATIONS

Table No.1 Comparison between case studies

Parameters for comparison	**Kingdom Tower**	**Burj Khalifa**	**Taipei Tower**	**Shanghai Tower**	**International Commerce Centre**
Height in meter	1000+	829.80	509.20	632	484
Structural System	Shear walls	Buttress core	Outrigger+ Belt trusses	Outrigger +Mega frame	Outrigger+ core
Material of structural system	Reinforced Concrete	Steel + high performance concrete	Steel+ Reinforced concrete	Steel+ Reinforced concrete	Steel+ Reinforced concrete
Soil and Foundation type	Pile on layered soil of varying capacity	Pile on silty sand	Pile on Clay	Pile	Shaft grouted barrettes
Shape of	Y-shape	Y-	Square	Taperi	Square

Parameters for comparison	**Kingdom Tower**	**Burj Khalifa**	**Taipei Tower**	**Shanghai Tower**	**International Commerce Centre**
plan		shape	with saw-tooth	ng Triangular	
Purpose of building	Mixed Use	Mixed Use	Commercial	Mixed Use	Commercial
Number of floors	167	163	101+5 basement	128	108+4 Basement

V. CONCLUSION

From the above study it is clear that, selecting structural system for tall structures like skyscrapers depends upon various parameters like type of soil, lateral loads, number of floors and type of material for facades. Here, it is observed in all case studies that there is not any single structural system used however it is always combined with other systems to have the advantages of both at the same time having capacity to carry the loads, maintain ductility of structure. Sometimes creative, innovative solution like mega columns proved to be economical and feasible solution. These buildings have full potential to be a functional building under Indian context due to the consumption of less footprint area which is must need in India and therefore should be treated as an opportunity to develop in a supplementary creative, sustainable and pioneering way. Further study is possible to understand the climatic zones of these sky scrapers and their relation under Indian context.

References

1) http://www.burjkhalifa.ae/en/thetower/structures.aspx
2) http://eeme.ntuagr/proceedings/8th/Invited_Speakers/PAP_Velivasakis
3) http://www.ctbuh.org/TallBuildings/FeaturedTallBuildings/ArchiveJournal/KingdomTowerJeddah/tabid/4415/language/en-GB/Default.aspx
4) Diagrid structural system: strategies to reduce lateral forces on high rise builindgs by Nishinth Panchal and Vinubhai R. Patel
5) Structural design of high-rise buildings by Erik Hellebrand and Wilhelm Jakobsson.
6) http://www.archinomy.com/case studies/671/ taipei -101 -a-case-study
7) www.loadtest.co.uk/projects/project_profiles/O-cells%20%
8) www.fugro-loadtest.com
9) A construction highlight for International commerce centre at West Kowloon Hong Kong by Raymond Wong
10) http://www.ctbuh.org/TallBuildings/FeaturedTallBuildings/ArchiveJournal/KingdomTowerJeddah/tabid/4415/language/en-GB/Default.aspx
11) Structural Design of Taipei 101 World's Tallest building by Denis C. K. Poon and Leonard. M. Joseph
12) http://www.building.com.hk/feature/2011_0517icc.pdf
13) http://www.hkengineer.org.hk/program/home/articlelist.php?cat=cover&volid=119