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Optimization of Tall Structures under Constraints of Wind Loads and Fire Safety Strategy using STAAD Pro

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Abstract-*The paper deals with two major problems faced in building high rise buildings; lateral displacement due to wind loads and structural vulnerability to fire.*

Fires represent a two pronged problem to structures; these are one of the major causes behind building collapses. General public is vary of tall structures and their inaccessibility in case of severe fires. Consequently, a qualitative analysis is done compare and come up with innovations which are most suitable to solve the problem.

To identify best geometries to resist wind loads, quantitative comparison of multiple geometries has been done using analysis software (STAAD. Pro V8i). Four geometries have been chosen, and have been compared based on axial forces, lateral deformations, steel volume and used, component shear forces and bending moments. The study concludes that outrigger and belt truss systems are the most efficient for tall buildings and super tall buildings (150m+), and shear wall bracing systems are more suitable for moderately tall high rise(100m-150m) buildings.

Key Words: Fire Resistant Structures, Fire Emergency Escape Strategies, Fly Ash, Wind, Lateral Deflection, Bracings, Shear Walls, Outrigger And Belt Truss Systems.

1. INTRODUCTION

1.1. Background and problem description

With the burgeoning growth of population and the following scarcity of land, high rise buildings are becoming an increasingly pragmatic solution for the contemporary world. According to the US National Fire Protection Association, a building higher than 75 feet (23 metre tall) or about seven stories or more is considered to be a tall building. Although high rise buildings had surfaced in the ancient Roman and Egypt itself but with the advent of superior materials, high compressive strength of concrete, and cutting-edge construction technology in the 20th and 21st century more and more high rise buildings are being constructed all over the world. Burj Khalifa in Dubai, Shanghai Tower in China, Taipei 101 in Taiwan, Petronas Twin Towers in Malaysia etc are a few of the tallest buildings of the world from 2004-2010. These modern marvels provide some great insight into the technologies used for constructing tall structures in the modern times.
Tall buildings, as for bridges and other large structures, require huge amount of material, energy, planning and economy to get built. In every tall building project it is important for structural engineering companies to be able to present attractive offers, when competing with other companies, to acquire a certain design project. It is of interest to present an efficient structure in order to give a proposal that is attractive to the contractors as well as the owners.

An efficient structure does not only provide minimum material usage and economic solution, but also it minimizes the carbon footprint which is a major factor for a structural engineer to consider when designing large structures. This is of major concern in the world today in general, namely that too large emissions are taking place that damages the nature of our planet. This is why the problem description of this project concerns minimizing volume of material so that the carbon footprint is minimized. The taller a building is the more inefficient it becomes. Simultaneously as the height of building increases, the construction costs increases.

1.2. Objective

(i) To compare structural geometries on the basis of lateral deflection considering lateral wind loads.
(ii) To identify the best technique to be adapted for high rise buildings in New Delhi to prevent structural collapse due to fires.

2. LITERATURE REVIEW

High rise structures pose various structural, material and financial challenges in their construction. The use of Wind Tunnel Testing was recommended (Kwon and Kareem, 2013) recently. But it had its own limitations like time and cost constraints as well as reduced scale. CFD(Computational Fluid Dynamics) was a rather better technique over Wind Tunnel Testing as it conquered the limitations of Wind Tunnel Testing. Nowadays Staad.Pro is widely used for analysing the high-rise structures for seismic and wind load combinations.

The catastrophic loss of life and property in the collapse of World Trade Centre in 2001 brought attention to fire safety in high rise buildings. The fire protection strategy of any structure is majorly divided into fire resistant design and evacuation strategy. Material properties of concrete decide its behaviour during elevated temperatures. Hence additives are added to concrete to improve its strength hence its resistance to fire. Cardington Fire Tests from 1995 to 1997 provide analytical and computational data on behaviour of structures in conditions of fire. Fly ash is the most economical and conventionally used material to improve the fire resistance properties of concrete. The use of fly ash can be traced back to World War II. Fly ash was also used in the construction of one of the tallest buildings of the world Petronas Twin Towers. Silica fume is also used for the same but it leads to the formation of dense structure by filling the voids with cementitious material. This could lead to explosive spalling in case of fire (Metin Husem, March 2006).

The beginning of the use of Tuned Mass Dampers (TMD) in 1970s was a major breakthrough in high rise buildings. Citigroup Centre in New York City completed in 1977 was one of the first skyscrapers to use a tuned mass damper to reduce sway. It is also known as harmonic absorber or seismic damper and is used to reduce the mechanical vibrations. Further Taipei 101 that applied the concept of TMD emerged as the newest tallest building of the world in 2004.

3. METHODOLOGY

The study has been divided into two sections, the first section discusses fire as a major hazard faced by buildings, including structural collapse and safety concerns, and thus does a qualitative analysis of different new strategies that have been used, decides on parameters and provides the most innovative solutions.

The second section provides a quantitative analysis of multiple geometrical structures that have been used globally. Various parameters have been considered; hence the most effective building structure has been finalized after discussing multiple parameters. Details of methodology adopted have been given further down the section.

3.1. Fire Resistant Structures and Strategies

Fire is one of the major threats that leads to the failure of high-rise buildings. Fire safety in high rise buildings consists of fire-resistant design and evacuation in case of fire. As the height of the building increases, the evacuation of people at higher floors becomes more time taking which means evacuation time becomes larger (of the order of minutes). Thus, the evacuation time becomes comparable to the heating time of structural elements. The fire safety strategy of a high-rise building is divided into two components, namely egress strategy and building performance.

1. Egress Strategy – It is the time required to evacuate. In high rise buildings staircase is made the safe zone. So a tall building basically acts like a collection of single storey buildings.

2. Building Performance – It is further divided into structural performance and fire spread mitigation. The structural design of tall buildings depends on efficient load transfer. During a condition of a fire the deformations that occur locally and the resultant loading is redistributed throughout the structure. Structural performance depends on the size and nature of fire too (standard fire / travelling fire). In high rise buildings the evacuation and structural failure is at the risk of overlapping.

The following section shows the detailed results that have been obtained in the qualitative study.

3.2. Wind Lateral Deflection and Analysis

The design wind velocity (Vz) is given by:

$$V_z = V_b . K_1 . K_2 . K_3 \quad (3.1)$$

The design wind pressure (Pa) is given by

$$P_z = 0.6 V_z^2 \quad (3.2)$$

Where Vb = basic wind speed as per IS 875: PART -3, Vz is design wind pressure at height z in m/s, k1 is the probability factor given in IS 875 part 3 table 1 , k2 is the terrain roughness and height factor given in table 2, k3 is topographical factor and k4 is cyclonic factor.

Wind loads have been calculated using IS 875: Part - 3.

Further on, parameters including dynamic response factor, topography, importance factor for cyclonic region, and design wind pressure have been specifically calculated into wind loads, detailed tabular information in available IS 875: Part-3. Any confusion regarding values to be considered for IS Codes in the Indian context versus international standards has been resolved with the help of Further, wind load calculations have been done with the help of Bhandari N.M. and Krishna K.

Analysis methodology has been taken from Smith B.S. and Coull A. (1991). Further, inspiration for geometries selected for this project has been from Merza N. and Zangana A. (2014).

Final design analysis includes creating geometries on given analysis software STAAD.PRO v8i, applying wind loads as per IS Codes and comparing the four geometries on five parameters:

1. Lateral Deflection: The most important criterion for comparing suitability of different geometries in tall buildings is the lateral deflection. Geometries with least lateral deflection will be the most effective, this being our main case of analysis.

2. Percentage increase in Lateral Deflection halfway: An important parameter while comparing use of multiple geometries of structures in designing tall buildings is the % increase in lateral deflection as height increases, and possibility whether increase in lateral deflection declines on increase of height. It means that, as super tall buildings (500m+) will face an exponential increase in lateral deflection, most appropriate structure should show a significant damping of lateral deflection. The larger the lateral deflection at building height increases, the more inappropriate the structure.

3. Ratio of Maximum Axial Force on Section to Shear Force: Axial Strength of Steel Section = 1.73*Shear Strength of Steel. Thus, lateral bracings are used in a geometry to make sure that the axial reaction force component is the highest in a steel section. Therefore, the ideal building structure will be the one which tolerates the maximum amount of axial force in ratio compared to shear force.

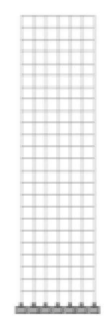
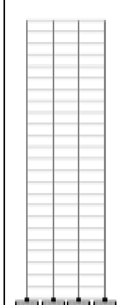
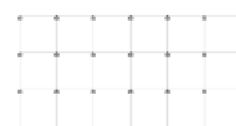
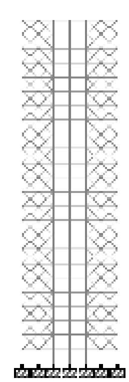
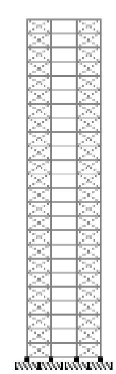
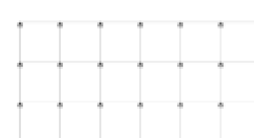
4. Comparison of maximum bending moment and maximum shear force on structures: As the height of a building increases, we find that wind load due to moment increases manifold times compared to shear force. It has been found that below a height of 150 m, shear force component is more dominant, but for buildings taller than 150+ m bending moment component starts dominating, till heights are reached where shear force component becomes negligible.

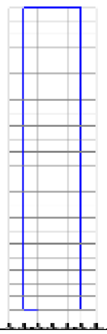
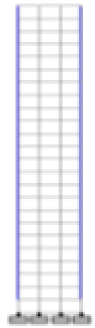
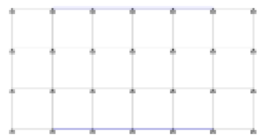
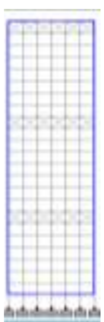
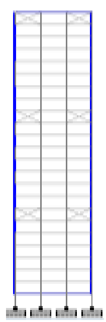
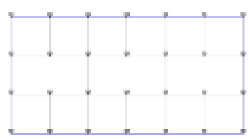
5. Volume Analysis: A fair comparison between geometries can be done by making sure similar amount of materials is used in all geometries. This means that between two geometries having same amounts of steel used, the better geometry will be the one that excels in other parameters, while comparing two geometries with same parameters, a better optimized system will be the one which uses lesser volume of material.

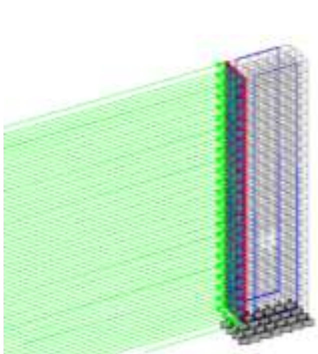
Table 3.1: Building Specifications Used in Analysis

Lateral Beams	0.45mx0.45m
Columns	0.6mx0.6m
Bracings	0.25mx0.25m
Shear Wall	0.25m
Grade Of Concrete	M25
Grade Of Steel	Fe415
No. Of Storey	G+23
Total Height	120m
Height of Ground Storey	5m
Height Of Floor to Floor	5m

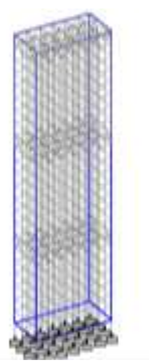
Table 3.2: Building Geometries Sections

Building Structure	x-y plan	y-z plan	x-z plan
Non-Braced Frame			
Centric Braced Frame			

Shear Wall Frame			
Outrigger And Belt Truss Frame			

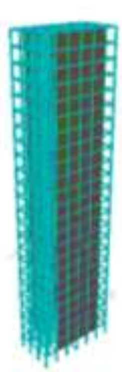


(a)



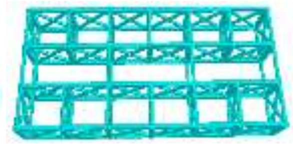
(b)

(c)



(d)

(e)



(f)

Figure 3.1: Simulation of Buildings Produced in Analysis

(a) Lateral Wind Loads Simulation for Geometries
(b)Simulations for Shear Wall Bracing Systems
(c) Real Simulation for Outrigger and Belt Truss System
(d) Real Simulation for Shear Wall Bracing System
(e) & (f) Outrigger and Belt Systems designed for analysis

4. RESULTS AND DISCUSSIONS

4.1. Fire Resistant Design and Calculations

Fire resistant design mostly includes using high performance concrete. Since the behaviour of structure in case of fire will depend on the performance of material during high temperatures. In some buildings Transfer plates are used as well. But with thicknesses such as 1.5 to 2.0 metre the thermal cracking associated to heat of hydration could be a major issue. High grades of concrete are used for the same. Still use of additives mostly pozzolonic materials or supplementary cementitious materials to control the heat of hydration is a common practice. These additives lead to pozzolonic reactions that continue to gain strength over long periods of time. Durability can be another major concern since sometimes the building rests over poor soil. Hence supplementing the concrete to have higher sulphate and chloride resistance is usually preferred. Fly ash is the most common and economical additive that is used in concrete. There is a major drawback with high performance concrete. Experiments show that here is a 75% loss of compressive strength as opposed to 50% in normal concrete after exposing to high temperatures. The rate of heating is higher in high performance concrete. This is owed to the dense structure created by silica fumes getting into the voids of cementitious materials. Spalling can occur due to build up of strain energy. Or due to expansion of aggregate at high temperatures followed by contraction of cement paste due to loss of moisture leading to shrinkage stress. Or because of high pore water pressure of the capillary pore water. Failure can occur in either of the two ways. With the advent of modern glass construction use of glass walling can be used in high-rise buildings.

Hence, high performance concrete shall be used for higher durability in piles as it won't be exposed to fire. Concrete of low heat of hydration is needed in a transfer plate of 1.5 to 2.0 meter. But they are exposed to fire, so it can be cast in two stages. First 400-500mm slab will act as formwork for pouring subsequently. This will need the provision of shear links as well to support the mat reinforcement at the top. Because of staging we can use normal concrete of grade 30 without resorting to high performance concrete. One must detail the transfer plate with multiple layers of reinforcement if the use of high performance concrete is necessary. In columns use of high performance concrete must be avoided. In beams and slabs normal concrete is highly recommended.

4.2. Lateral Wind Analysis

4.2.1. Absolute Displacement

Out of the four geometries considered , we find that centric truss and shear wall bracings do reduce lateral deflection, with shear wall bracings being better than the former. However, outrigger bracing truss outperforms both building structures.

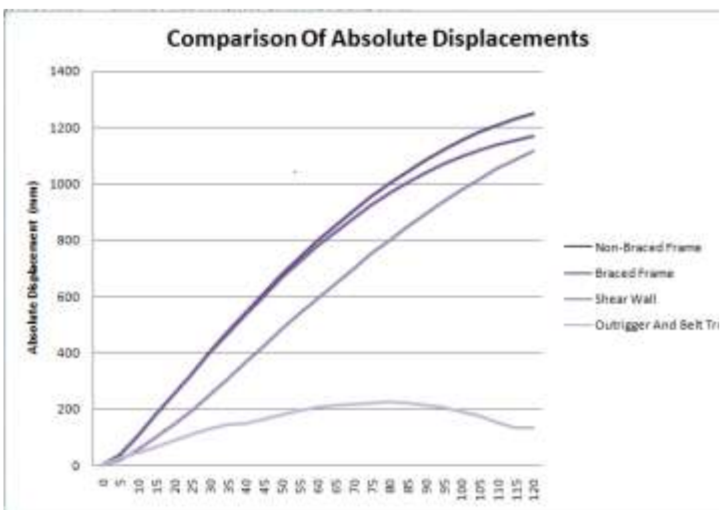


Figure 4.1: The Absolute Displacement of Four Geometries with respect to increasing height

Table 4.1 explains the difference in between the two given readings. Outrigger truss deflection at highest point gives an 89.35% decreased lateral deflection over non-braced frame, compared to a minor 6.36% and 12.92% decrease compared to Centric Truss Braced frame and Shear Wall Braced Frame respectively.

Table 4.1: Maximum Lateral Deflection with Respect to Building Structure

Building Structure	Maximum Lateral Deflection (mm)
Non Braced-Frame	1249.474
Braced Frame	1170.704
Shear Wall Braced Frame	1117.336
Outrigger And Belt Truss	132.981

4.2.2. Percentage Increase In Lateral Deflection

Table 4.2: Percentage change of Deflection between heights 60m and 120m

Building Structure	Percentage Change (%)
Non Braced-Frame	69.09%
Braced Frame	61.68%
Shear Wall Braced Frame	107.57%
Outrigger And Belt Truss	-32.03%

a. Table 4.2 shows that the only sustainable structure in super tall buildings (500m+) is outrigger and belt truss systems. Since the placements of outrigger and belt truss systems in the structure is extremely flexible, it means that with sufficient addition to outriggers, lateral deflection in a building can be minimized to a very small amount. Also, since the outrigger system is the only one which shows real decrease in lateral deflection over an increase in height, it is the only practical system feasible.

b. Also, another insight gathered from the report is that shear walls, although being more efficient in minimizing lateral deflections in a building, are not practically feasible to use in case of extremely tall buildings, simply because the show a large increase in lateral deflection percentage (107.57%), compared to Non-Braced Frame and Braced Frame, showing a comparatively smaller changes (69.09% & 61.8%).

4.2.3. Axial Force on Members Compared to Shear Loads

Table 4.3: Maximum Absolute Axial Force, Maximum Shear Force and Maximum Bending Moment in members of given Structures

Building Structure	Maximum Axial Force (C1)	Maximum Shear Force (C2)	Maximum Bending Moment (C3)
Non-Braced Frame	3100.84	613.84	274.445
Braced Frame	1683.465	152.553	390.186
Shear Wall	2714.46	179.34	614.893
Outrigger And Belt Truss	6131.31	438.96	1195.65

Ratio 1 has been taken as Axial Force/ Shear Force. Considering ratio 1, we find that the ideal structure in this case is the shear wall bracing frame, as it resists the shear lateral forces effectively in a tall structure, and the maximum portion of forces has been effectively transferred axially. Outrigger and Belt Truss is effective too, however Braced Frames are comparatively not effective enough in this case. Non-braced frames are very ineffective in handling lateral forces, as shown by figure.

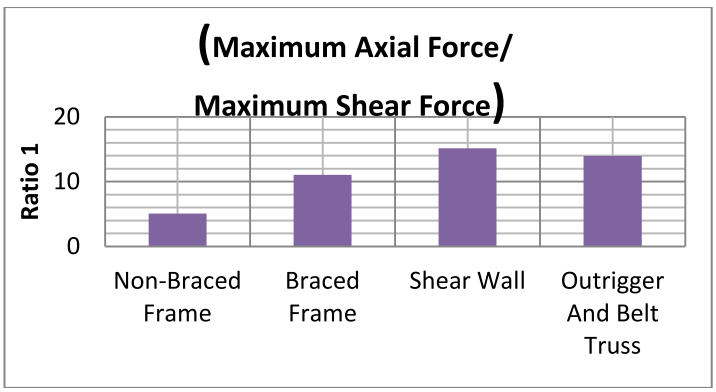


Figure 4.2: Ratio for Maximum Axial Force to Maximum Shear Force for all geometries (Ratio 1)

4.2.4. Bending Moment and Shear Force Comparison

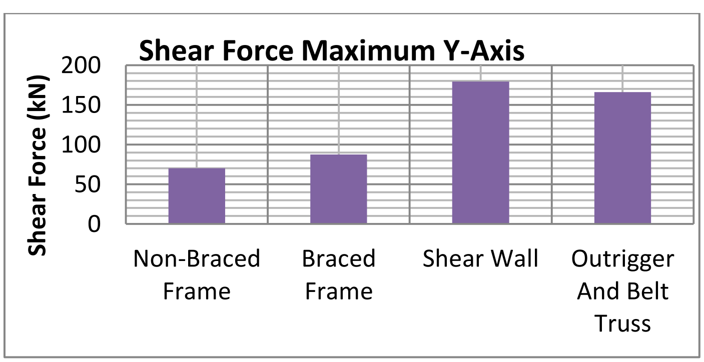


Figure 4.3: Maximum Shear Force given Geometries

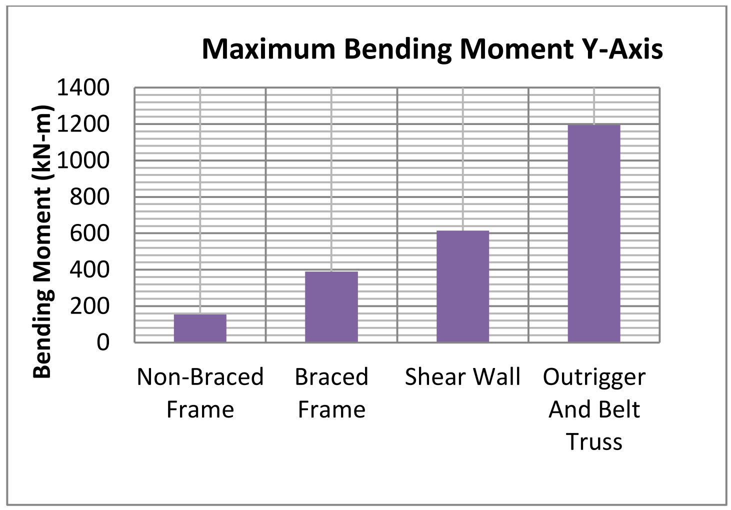


Figure 4.4: Bending Moment Maximum for given Geometries

Figure 4.3 shows that shear walls are comparatively more effective than all other structures, showing higher maximum shear resistance than other structures, this shows that for high rise buildings of moderate heights (100m-150m), shear walls are more effective. However, Figure 4.4 shows that Outrigger and Belt Truss clearly outperforms all structures in the second case. This means that outrigger trusses are more efficient for buildings of taller heights (150m+).

4.2.5. Volume Analysis

Table 4.4: Volume of Steel Used By All Building Geometries in STAAD.Pro (v8i)

Building Type	Steel Total Volume Used (m^3)
Non-Braced Frame	2257.5
Centric Braced Frame	2885.53
Shear Braced Frame	2257.5
Outrigger and Belt Truss	2245.795

We find that the given geometries use almost similar amounts of materials, with an increase centric braced frames, due to placement of lateral steel bracings increasing volumes used to the given value. The outrigger and belt truss system uses the least amount of steel; 0.49% less than the non-braced frame, courtesy the removal of a portion column from the geometry while remaining the most stable structure, highlighting an efficient placement of lateral bracings.

Whereas, centric braced frame uses 27.2% more steel than non-braced frames while also not being the best structure in this case, signaling a lack of efficiency.

5. CONCLUSION

After the study and analysis of given geometries we come upon the following conclusions:

1. Outrigger and Belt Truss Systems are the only practical solution among the given geometries for super-tall buildings (300m+), due to the unique decline in lateral deflection with increase in height as observed.
2. Braced frame structures are comparatively inefficient compared to the other geometries used, producing higher lateral deflections with more steel volume used. This shows that a more efficient placement of bracings is required to decrease lateral deflection and volume of steel used simultaneously.
3. Shear wall bracing systems are comparatively the most efficient systems in load transfer from shear to axial loadings. These are also ideal for resisting large lateral shear loads thus making them ideal for moderately tall high rise buildings (75m-150m).
4. Outrigger and Belt Truss Systems are the best structures for buildings taller than 150m, due to their better handling of displacement due to bending moments, and also their flexibility and cost optimisation.

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