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Innovative Application of Dispersed Shear Wall to a Kilometer-High Concrete Skyscraper

Feroz Alam

Department of Civil Engineering, The Institute of Engineers, Dhaka, Bangladesh

Email address:
ferozalamabc@yahoo.com

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Abstract: There are numerous structural lateral systems used in high-rise building design such as shear frames, frames with shear core, framed tubes, tube and tube, super frames etc. Generally, the structural systems of tall buildings are considered to be two types. One is interior and the other one is exterior type. A system is categorized as an interior structure when the major parts of the lateral load resisting system are located within the interior of the building. Likewise, if the major parts of the lateral load resisting system are located at the building perimeter, the system is categorized as an exterior structure. In this study it is intended to model an advanced structural system which can be applied to buildings taller than the existing tallest building in the world. In this innovative concept, several parallel shear walls have been arranged in both directions and connected with beams and R.C. floor slabs. The shear walls are continuous down to the base to which they are rigidly attached to form vertical cantilevers. Their high in plane stiffness and strength make them well suited for bracing buildings up to about 278 stories. Fewer widely spaced gravity columns are arranged in the core area of the building to carry floor loads. Because of the absence of core bracing and of a large number of heavy interior columns, the net leasable area for such a building increases. Static and Dynamic analysis (Time History Analysis) has been carried out. The drift by static analysis is 1884 mm which is below the allowable limit of 2001.6mm (If considered H/500, where H is the height of the structure [9]). Also it is found by research that, when this structural arrangement is applied to around 830 meter tall structure with aspect ratio 9.8:1, no additional structural supporting system (like Outriggers, Perimeter Belts, Cross Bracing, Tuned Mass Dampers etc.) is required. This shear walls arrangement is applicable for the tall buildings of any height to avoid additional supports to resist the lateral forces while taking advantage of the creative approach of this unique concept.

Keywords: Innovative, High-Rise, Dynamic, Drift, Outriggers, Skyscraper

1. Introduction

In the last few decades there has been an enormous increase in the number of high-rise buildings worldwide. A tall building is not defined by its height or number of stories. The important criterion is whether or not the design is influenced by some aspect ''tallness''. It is a building in which tallness strongly influences planning, design, construction and use. It is a building whose height creates conditions different from those that exist in common buildings of a certain region and period [7]. There are physical, code prescribed and practical reasons why tall buildings tend to be safer than low-rise buildings [8]. Undoubtedly, the factor that governs the design of a tall and slender structure most of the times is not the fully stressed state, but the drift/acceleration of the building for wind loading. It is easy to understand that higher the building, the more important is the lateral behavior. Thus, to understand the performance of high-rise buildings, the lateral resisting system of tall buildings becomes a key factor that needs to be investigated and understood.

In 1969, Fazlur Rahman Khan classified structural systems for tall buildings relating to their height with considerations for efficiency in the form of 'Height for Structural Systems' diagram (Fig. 1). This marked the beginning of a new era of skyscraper revolution in terms of multiple structural systems. Feasible structural systems, according to him, are rigid frames, frame shear trusses, belt trusses, framed tubes, Truss-Tube with Interior Columns, Bundle Tubes and Truss-Tube without Interior columns [1]. These structural system can reach up to about 140 stories.

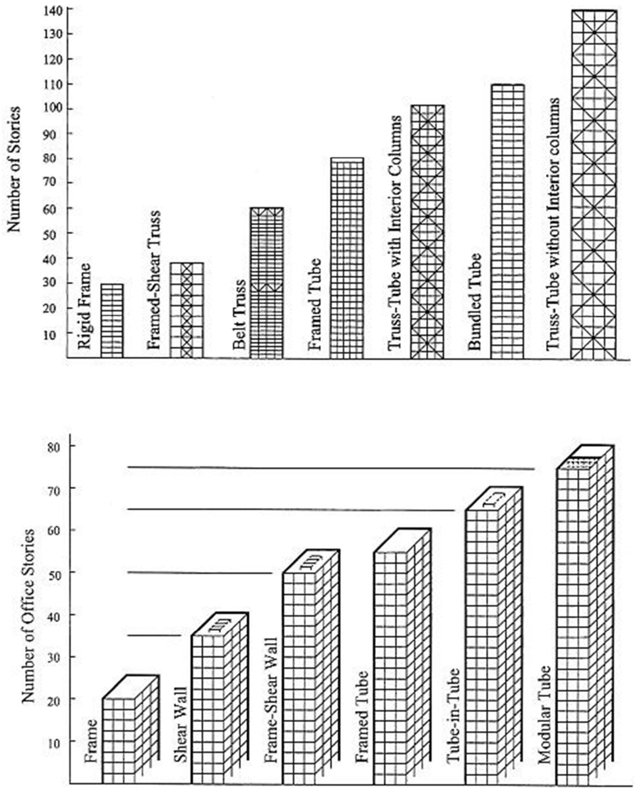

Figure 1. *Diagram of Structural Systems by F.R. Khan [1].*

The objective of this paper is to apply a new ‘Parallel Shear Walls Concept’ to a 1000.8 meters tall structural model which consists of five vertical portions (Fig. 2 & 3), which covers 278 stories taller than the existing tallest building in the world. To gain an adequate footprint for stability, this tower extends to nearly 102m x 102m at base, resulting in the 9.8:1 aspect ratio (The ratio of the height of the building to its smaller width at the base) a ratio greater than the one hold by existing tallest building in the world, Burl Khalifa which is close to 9:1 [11].

In this ‘Parallel Shear Walls Concept’, as each grid contain a number of shear walls, these shear walls near the perimeter undergo maximum stresses due to wind force and the stresses linearly decrease towards the core and it is minimum at the center of the building, i.e. all the shear walls in a grid taking part to resist the wind force. All the grids in each side of the building are resisting the wind forces. So the axial deformation of all the walls in a raw is nearly same. Therefore no “shear lag effect” will occur. On the other hand, the walls are connected by rigid beams to form vertical cantilever, when the walls deflect under the action of the lateral forces, the connecting beam’s ends are forced to rotate and displace vertically, so those beams bend in double curvature and thus resist the free bending of the walls [5, p-214]. But for the exterior or interior tube systems (tubular frames), the wind loads are resisted and concentrated on peripheral columns or to the inner core respectively. When the corner columns of the periphery suffer a compressive deformation, it will tend to compress the adjacent column, since the two are connected by the spandrel beams. The compressive deformations will not be identical (Fig. 4) since the flexible connecting spandrel beam will bend, and the axial deformation of the adjacent column will be less, by an amount depending on the stiffness of the connecting beam. Each successive interior column will suffer a smaller deformation and hence a lower stress than the outer one [5]. This phenomenon is called the shear lag effect. Shear lag may lead to wrapping of floor slabs, local bulking on compression side & cracking on tension side.

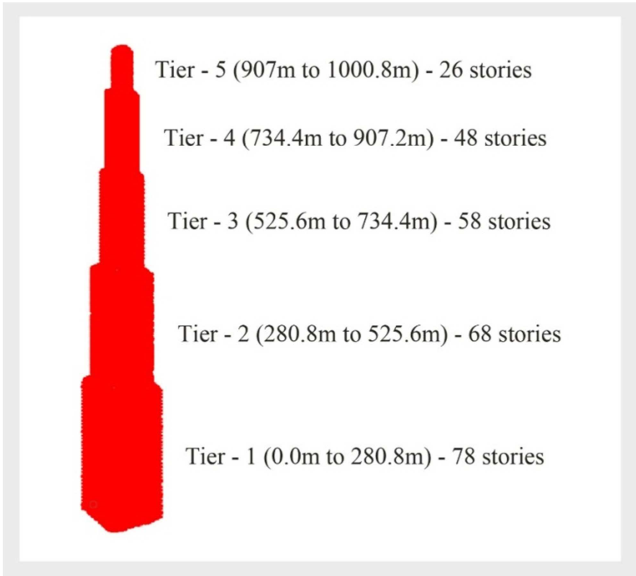

Figure 2. *Levels and number of stories.*

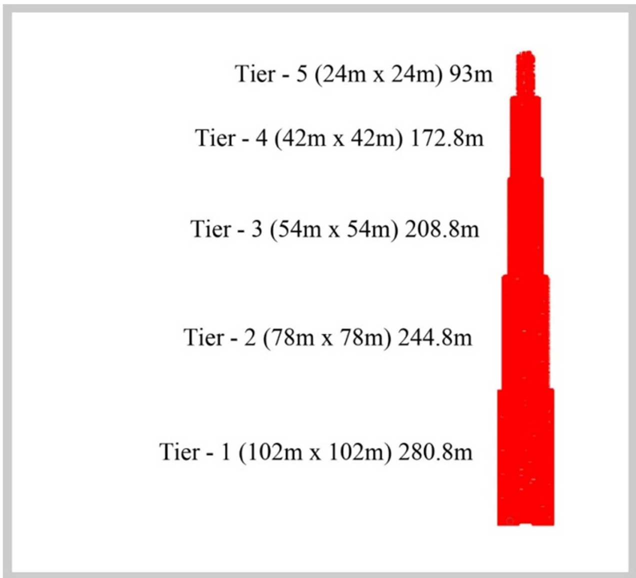

Figure 3. *Floor dimensions and Tier heights.*

This is a theoretical study so the author’s intension is to use the top of the structure as a habitable floor maximizing the total floor area to increase high value lease spaces. Usually the gross floor area can be reduced by making three voids from top to bottom on each side of the building perimeter. These voids will reduce up to 30% from Tier-1, 28% from Tier-2 & 8% from Tier-3. Besides, the central core area is so far from any natural light at the perimeter, can be a central void further to reduce the floor area. Because these voids will not affect the structural behavior as there is no structural element. The connecting beams have to be in their own positions.

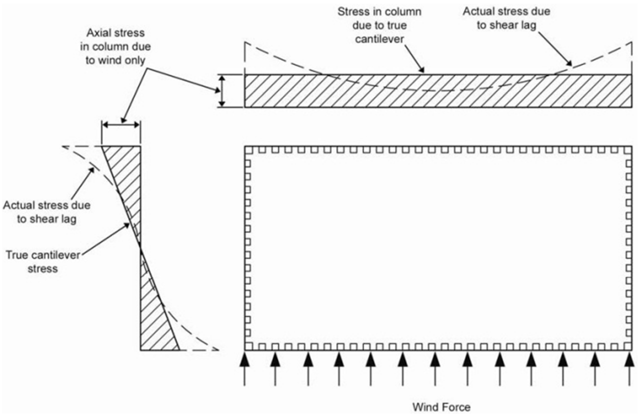

Figure 4. *Axial stress distribution in columns of laterally loaded framed tube [1].*

Table 1. *Building's Data.*

Height from ground floor to roof	3282 feet (1000.8 m)
Number of stories	278
Building uses (assumed)	Hotel, Office and Residential.
Frame Material	Concrete Structure
Typical floor live load	3kn/m^2 (60 psf).
Basic wind velocity (100 years returned period for Qatar, wind load considered for Qatar, because now a days middle east has the tendency to build tall buildings)	41.67 m/sec, (150km/hour).
Allowable Sway (Drift) [9]-(Commentary Appendix C-Sec: CC.1.2 ASCE 7-10)	H/500 (H = Height of the Structure)
Allowable Sway at top	1000.8m/500 = 2001.6 mm (6'-6")
Sway of the Structure at top for dynamic analysis	1930 mm (6' - 4")
Earthquake loading (Not considered in analysis) -Qatar	Z = 0.15, (zone 2A)
Type of structure	Arrangements of Concrete Shear Walls and Beams for Tier-1, Tier-2, Tier-3 and Tier-4. Tier-5 is the frame structure
Foundation Type	Future Assignment
Typical Floor height	3.6 m
Floor type	R.C.C. Slab
Shear Wall spacing	12m, 9m & 6m c/c
Core area	Column-beam framing
Shear Wall thickness at ground floor	1.6m, 1.5m, 1.4m & 1.3m , gradually decreasing the thicknesses toward top
Typical Beam sizes	Depth 0.8 m, Width 1.1m & 1.2 m
Column spacing at base	6m (20 feet) c/c
Column sizes at base	1.5m x 1.5m
Covered area at base by Shear Walls & Columns	14.53%
Concrete Strength	Shear Walls & Columns 80MPa, Beams & Slab 40MPa

2. Primary Structural Arrangement

The tower is characterized by its symmetry. There are no transfers of vertical elements through the main body of the tower. It allows a uniform distribution of gravity forces through the structure. These characteristics allow for a more efficient structure.

There is no separation between the gravity system and the lateral system. The vertical structure is organized in such a way that the elements are all sized on sufficient lateral stiffness while at the same time providing strength consideration. This creates an extremely efficient structure where the materials perform double-duty (gravity and lateral support). This structure creates a uniform distribution of load reducing the differential shortening.

The building has 5 Tiers of different heights (Fig. 2 & 3).

The structural system consists of several parallel shear walls in each direction of the face of building (Fig. 3 to 9) which are essentially analogous with the buildings' central core columns, coupling beams and conventionally reinforced concrete floor framing. This produces a completely interconnected structural system (Fig. 5). The shear wall arrangements of this tower are in such a way that they provide large amount of inertia forces and stiffness to the structure. So the amount of moments carried by the beams due to wind is less. Therefore the author has selected the depth of 0.8 m and width 1.1m of all the beams for theoretical purposes. However, maximum sizes of few beams will be 1.3m (depth) x 1.4m (width) near the Tier-1 during practical application as the author checked the maximum moments.

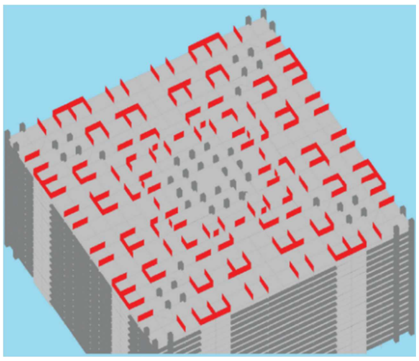

Figure 5. *Floor layout in relation to structure.*

Table 2. *Drifts at top of the structure.*

Height:	**1000.8 meters**
Drift for Static analysis	1884 mm
Drift for Dynamic analysis	1930 mm

Each side of the building will resist the wind force by several parallel shear walls. The wind forces will be distributed to the structure almost uniformly to all grids due to the shear wall placements (Fig. 6). Each Tier has its own core which starts from base. Several experiments show that Tiers with different heights (height of Tier-1 will be longest and gradually decrease towards top) give better results than the Tiers of uniform height.

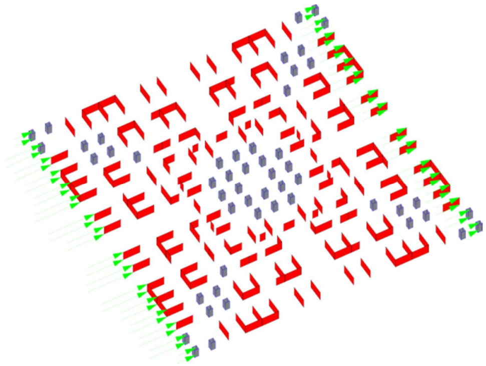

Figure 6. *Wind forces are distributed in all grids.*

In this structural system the corner portions of the Tier-1, Tier-2 & Tier-3 are kept free for views & lightings which makes the highest value lease spaces (Fig. 7 to 9).

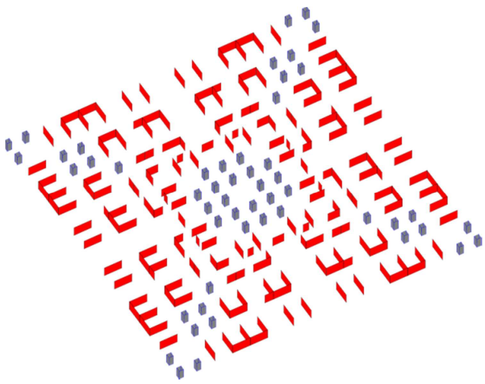

Figure 7. *Typical shear walls arrangement of Tier-1.*

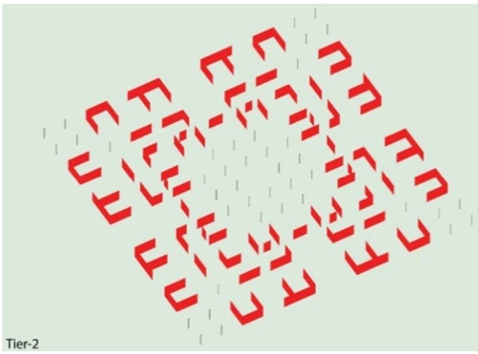

Figure 8. *Typical shear walls arrangement of Tier-2.*

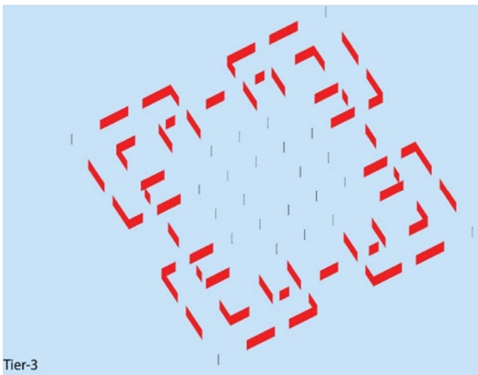

Figure 9. *Typical shear walls arrangement of Tier-3.*

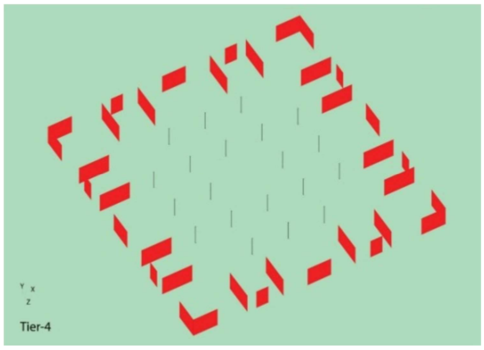

Figure 10. *Typical shear walls arrangement of Tier-4.*

The Tier-5 is a frame structure of full height and is composed of reinforced concrete beams, Columns and slabs (Fig. 11).

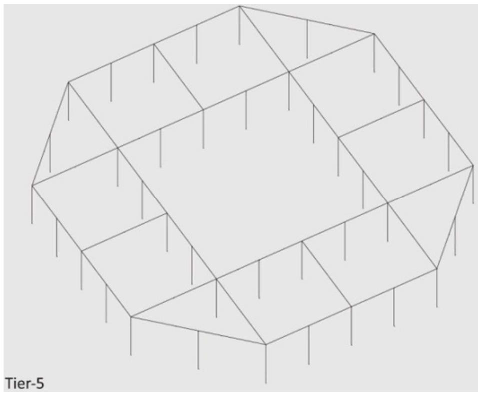

Figure 11. *Frame structure of Tier-5.*

Various options have been studied through this parametric modeling method. The main goals were to maximize the lever arm of the shear walls, maintain the shear wall line in one single vertical plan, so as to minimize secondary forces. This shear wall arrangement can be said as an optimal balance and the most effective lateral load-resisting structure to stabilize this mega tall structure.

Cracked sections have been considered in the analysis and therefore moment of inertia has been taken half of the amount of no crack section.

Base area of Tier-1 is maximum while base areas of other Tiers gradually decreasing towards the top. The author has chosen and tuned the height increments towards bottom and gradually decreasing towards top because the moments and the shears are high at the bottom. Tower design of any height with this "Parallel Shear Wall Concept", the structural engineers will have to tune and choose the different heights of the Tiers accordingly.

3. Results Analysis

Drift Limits in common usage for building design are in the order of 1/600 to 1/400 of the building height (ASCE). Generally, for tall buildings allowable drift is considered as H/500, which becomes 2001.6 mm for this 'One Kilometer Structure'.

The dynamic analysis (Time History Analysis) for wind has been carried out by STAAD/PRO. Below are the results for dynamic & static analysis at the top.

SRSS value for six Modes (Square Root of the Sum of Squares) of dynamic wind analysis is 1995 mm.

Dynamic analysis of this 1 KM tower shows that the habitable/usable floor is at height 723m (Record breaking habitable height at 201 story) where acceleration is 30 milli-g which is acceptable according to NBCC 1990 [3].

Whereas the habitable floor level for the existing tallest building of the world at the height of 584.5m (154th Story).

Damping is an important issue as the human comfort due to excessive acceleration beyond 25 milli-g, in the range of 35 to 50 milli-g, may have to be designed for. Tuned mass dampers and viscoelastic dampers are often used [10].

Acceleration due to dynamic analysis at top is 47.7 milli-g. Tuned Mass Dampers (TMDs) transmit inertial force to the building's frame to reduce its motion around up to 50%. Therefore 47.7 milli-g acceleration of this 1 KM high tower can be reduced by introducing Tuned Mass Damper accordingly to make this height habitable floor level.

In table-3, there are some examples of tall buildings which reduced their accelerations by introducing TDMs.

Table 3. *Configurations of some TMDs corrently in use.*

Host Structure	Description	Results
Hancock Tower (244m) in Boston, USA	Two TMDs were installed at opposite ends of 58th floor, each weighing 300 tons.	Can reduce building's response 50% [4].
Citicorp Building (278m) in New York, USA	A 40 ton concrete block with two spring damping mechanisms installed in 63rd floor	Reduces wind induced response 40% [4].
Sydney Tower (305m), Australia	Doughnut-shaped water tanks & energy dissipating shock absorbers.	Response reduced 40-50% [4].
Sendai AERU (145.5m) IN Sendai	TMD w/laminated rubber bearing + coil spring.	Response reduced ½ [4].
Petronas Twin Tower (452m) in Kuala Lumpur	12 Fluid Dampers	Prevent vortex shedding & reduce wind-induced excitation. [4].
Taipei 101 Skyscraper (509.2m) in Taiwan	Installed world's largest & heaviest TDMs weighing 728 short-ton.	To offset movements in the building caused by strong gusts. [6].
Burj Al Arab (321m) in Dubai	Installed 11 TMDs	Reduced wind induced response. [14]

Vanity/Spire height: In theory, we're in the midst of a "golden age" of skyscraper construction. But why, of the ten tallest building on Earth, nearly 30 percent of each structure totally unusable spire? In truth, this information is readily available to anyone with eyeballs. All supertalls (e.g, any building over 1,000 feet tall) have substantial spires and unoccupied upper floors, which serve to house hardware, observation decks, and often, mass damper that counter the sway of the building in the wind. But even taking into account the necessary infrastructure, the majority of spires are totally unnecessary.

In fact, without the vanity height, 60 percent of the world's supertalls wouldn't actually be supertalls at all. The burj Khalifa would lose more than 700 feet. If an angry giant broke off the Burj's spire and planted it on the ground, it'd still be the 11th tallest building in Europe. The worst offender of all is the Burj Al Arab, of which 39 percent is vanity spire [12].

In table 4, there are some examples of vanity height of tall buildings.

Table 4. *Vanity Height of the Towers [13].*

Towers	Total Height(Meter)	Vanity Height (Meter)	Percentage of vanity height
Zifeng Tower – China	450	133	30
Bank of America Tower-New York	366	131	36
Burj Al-Arab-Dubai	321	124	39
Emirates Tower One-Dubai	355	133	32
New York Times-New York	319	99	31
Nakheel Tower-Dubai	1000	N/A	10

If the author add the vanity height (194m) of Burj Khalifa then author's 1000.8 meters tower would be 1194.8m.

4. Author's 831 Meters High Tower by Applying Same Structural Arrangements (Comparison with the World's Existing Tallest Building)

Author's 1K.m. tower has been reduced to 831.6m tall (nearly same height of the World's existing Tallest Building). The 831.6m tower height is achieved by removing 169.2m from the top of the 1000.8m tower.

Results of the analysis show that drift and acceleration at 831.6m (top) are 1041 mm and 26.9 milli-g (acceptable) respectively. So the habitable/usable floor is at height 831.6m (231 stories).Whereas the world tallest building (Burj Khalifa) will have a drift of 2000 mm [2] at top (828m) and habitable floor at height 584.5m (154 stories).

5. Covered Vertical Area at Base and Structural Materials

Area covered by shear walls at ground floor = 1440.24 m^2

Area covered by columns at ground floor = 72 m^2

Gross area at ground floor = 102m x 102m = 10404 m^2

Area covered by vertical elements (shear walls and columns) at ground floor in percentage

$$[(1440.2+72)/10404]\text{x}100 \Rightarrow 14.53\%$$

Note: Percentage of gross floor area with respect to vertical elements (shear walls and columns) is one of the main efficiencies of structural arrangements.

This one kilometer high tower requires Young's Modulus of 42038 MPa and compressive strength of 80 MPa for columns, shear walls and Young's Modulus of 29725 MPa and compressive strength of 40 MPa for beams and slabs.

6. Impact on Sway for Different Tier Heights

During the research work, the structure is analyzed in two different shapes (Type-1 & Type-2). The total height, thickness & sizes of the structural members are kept the same. Only the Tier heights have been changed.

a) Type-1 (Equal Tier height): This building consisted of five Tiers. Height of first 4 Tiers from bottom is 226.8m & height of top Tier is 93.6m. The result of the analysis show that sway at top is 220.18mm.

b) Type-2 (Different Tier heights) There are 4 different Tier heights keeping the top Tier height same as Type-1. Tier-1 (280.8m), Tier-2 (244.8m), Tier-3 (208.8m) & Tier-4 (172.8m). The result of the analysis shows that the sway at top is 1930mm. So it is observed that the height of Tiers is greatly influence the drift (sway) of the structure.

7. Philosophy Behind This One Kilometer Tower's Structural Arrangements

Consider a beam cantilevered from the earth. When lateral forces are applied to the beam, the beam will bend. The maximum compression and tension stresses will be on the two opposite sides along the force direction. Tension and compression will decrease linearly towards middle & will be zero at the mid. Now consider a mega tall building of height 1000.8 meters and base 102m x 102m with the shear walls being placed perpendicular to the face of building (can be called 'Shear Walls toward periphery') around the periphery and continuing towards center of the building for a certain distance (Fig. 6 to 9) along the direction of force. Let the summation of moment of inertia be 'Im' with respect to the line passing through the center & the maximum stress will be at compression face say 'e1'.

On the other hand if the same number of shear walls are placed around the center to make an inner core to resist the lateral force, the summation of moment of inertia will be less than 'Im'& the maximum stress at compression face will be greater than 'e1'. As the deflection is inversely proportional to the inertia forces, the deflection will be more for inner core system.

So when the structure is becoming taller, it is wiser to consider the outer core arrangement concept (Shear walls toward periphery) for resisting lateral forces.

This concept with some additional structure arrangements is applied to the 'One Kilometer Tower' research work.

To understand this phenomenon, consider the building as a cantilever beam. The horizontal cross sectional area at any height of the shear walls are considered the beam's sectional area which absorbs the bending and axial stresses and at the same time resists the deflection of the structure.

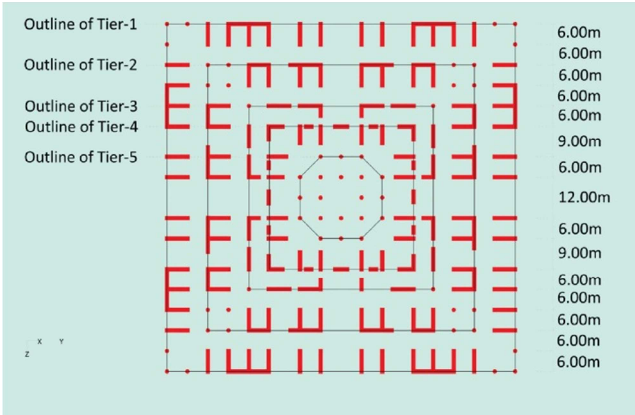

Figure 12. *Typical shear walls spacing.*

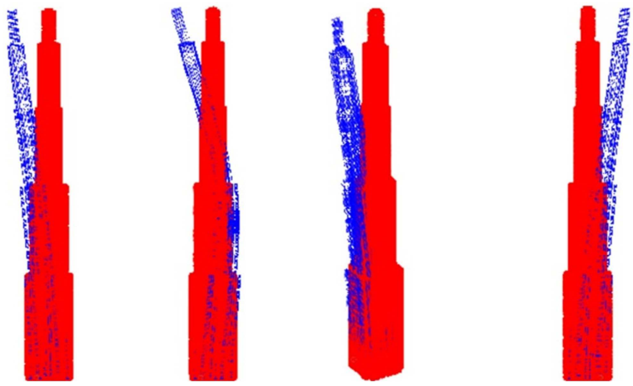

Figure 13. *Four different mode shapes due to dynamic responses. Horizontal displacements are shown in large scale.*

8. Basic Concept for Tower of Different Heights

The proper arrangement of the shear walls is the main task of this concept. The shear walls arrangement as shown in the figures is sufficient to withstand One Kilometer High Tower with aspect ratio around 9.8:1. For the tower of lower heights, the structural engineer can minimizes length & thickness of the shear walls in every grid, and can minimizes the spacing of the shear walls in a grid as well as the grid spacing (Fig. 12). But the shear walls in a grid should be connected with the beams to get composite action of the shear walls. The grids and the shear walls in a grid can be moved, if required for the architectural issue. But it should be kept in mind that the centroid of all the shear wall's cross sections should be as near as possible to the mid of building's face to minimize the twisting effects of the building due to lateral loads.

9. Advantages of This New Structural Concept

1) The main concept of this system is to place the shear walls parallel to each other. When wind force is applied to the structure, each grid (consisting of several shear walls) will function individually to resist the wind force of their average span length (See figure-12). Due to this phenomenon, when this structural system is subjected to lateral loads such as wind load, the axial stresses in the shear walls is nearly linear. Therefore Shear Lag effect is minimized.
2) Shear walls can be moved on both sides from mid (if required for architectural demands) by keeping the area of centroid of the vertical sections at the same position. This has a negligible effect on the sway.
3) The shear walls are placed almost uniformly over the base, so the gravity loads are distributed almost uniformly to all the vertical elements (shear walls). Therefore reduce the differential settlement.
4) Plenty of natural sunlight will pass through the building perimeter due to parallel shear wall arrangements.
5) Simple framing system.
6) No additional lateral load resisting system is required, like outriggers, belts or cross bracings, except tuned mass dampers (TMD).
7) Parallel shear walls from both the direction forming a perpendicular arrangement. "The effect of the perpendicular walls will be to stiffen the structure in torsion, to reduce the twist, and, in doing so, to influence the contributions to the parallel wall shear and moment that result from the structure's twisting [5, page-189].

10. Conclusions

Engineering field professionals are trying to build buildings taller than the existing tallest ones. Generally these high-rise buildings require additional lateral systems to control the drift. But the use of the 'Parallel Shear Walls' concept in Skyscraper design is a relatively new idea which does not take any help of additional lateral systems except TMD (If the building's height is above 850 meters). This structural arrangement can be applied to any tall building of any height to get a perfect and optimized structure.

The research work carried out on three models of heights 1000.8 meters, 830 meters & 734 meters with this Structuctural Arrangement. It is observed that the structures of heights 830 meters & 734 meters have less value for drift and acceleration than the allowable limits as per International codes/standards. No bracings, outriggers or damper is required for such mega tall structures. Only damping system is required for 1000.8 meters high structure.

That is, this "Innovative Structural Arrangement" is a simple method to go for tall and mega tall structures.

The details and further analysis of the structural models are kept (STAAD/PRO software) for further reference, can be discussed as needed.

Acknowledgement

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