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Research Paper

Engineering

# Study of Structural Systems for Composite Construction in High Rise Building

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**ABSTRACT**

The evolution of structural systems and the technological developments are driving force behind the growth of tall buildings around the world. Frame tube system is one of structural system used in tall buildings which forms a tube by closely spaced wide columns and deep spandrels connecting them. This system can be adopted for RCC and steel construction but due to shear lag phenomenon, capacity of structural members is not fully utilized. Also due to closely spaced columns, exterior view gets blocked and size of windows reduces. In order to eliminate these drawbacks and to improve economy, a relatively new structural system i.e. Megaframe with supercolumn with composite construction is developed. Composite construction has brought a new era for high rise buildings with advantages of better economy, high structural efficiency, light weight, better performance under gravity and lateral loading

**KEYWORDS** Structual Systems ,highrise building.

**1.1 Introduction**
As there is no finite definition for tall building or high rise structure, there are some elements through which tallness can be expressed. Those elements are Height, Proportion and Technologies as result of height. When it comes to height, even 20 story building also said to be a tall structures in city like Ahmedabad, but cities like Chicago, Hongkong etc. it will not be considered as tall structures. Proportion of any structure can be expressed as height to lateral dimension of building ratio. It means buildings with same height cannot be said to be tall if lateral dimension of one building is quite large and anothers is small. Generally, skyscrapper as defined as building with aspect ratio greater than or equal to 6. If the building contains technologies like specific vertical transport, structural wind bracing etc. also can be classified as tall. Today enumerable examples of high rise structures which are constructed of concrete, steel or composite

**High Rise Buildings and Structural System**
**1.2.1 Concrete structural systems**
Concrete offers a wide range of structural systems which are suitable for tall buildings. The selections of structural system depends on the geometry of building, degree of exposure to wind, seismicity of location and limits imposed on the size of the structural elements. Sometimes systems with combining characteristic of two or more can be employed to fulfill the specifics of the project. Basically all structural systems are classified under two categories as gravity load resisting systems and lateral load resisting systems. Gravity load resisting systems in concrete are

- Flat plates
- Flat slabs
- Waffle slabs
- Ribbed slabs
- Skip joist system
- Band beam system
- Haunch girder and joist system
- Beam and slab system
- Prestressing systems

**The lateral load resisting systems are:**
a. Frame action with columns and two way slabs

b. Flat slabs and shear walls

- Flat slabs, shear walls and columns
- Coupled shear walls
- Rigid frames
- Widely spaced perimeter tube
- Rigid frame with haunch girders
- Core supported structures
- Shear wall frame structures
- Frame tube systems
- Exterior diagonal tube
- Modular or Bundled tube

**1.2.2 Steel structural systems**
After second world war, the use structural steel has been rapidly increased. Steel members used in early structures were restricted to carrying gravity loads only, but it has been upgraded to include wind and seismic resistance in systems. Steel gravity load systems are enlisted below:

- Open web joist system
- Wide range beams
- Columns

**The systems which are employed to resist lateral loads in steel are given below:**

a. Frames with semi rigid connections
b. Rigid frame
c. Braced frame
d, Staggered truss system
e. Eccentric bracing system
f. Interacting system of braced and rigid frame
g. Outrigger and belt truss systems
h.Frame tube systems
i. Trussed tube systems
j. Bundled tube system

**1.2.3 Composite structural systems**
The term Composite construction refers to a structural system with members composed of more than one material and they are rigidly connected to each other such that no relative movement can occur. Now-a-days steel concrete composite systems have become quite popular because of their advantages against conventional construction practices like concrete and steel construction. Some of the advantages of composite

systems are mentioned below:

- High bearing capacity
- Effective utilization of materials
- Absorbs energy released due to seismic forces
- Fast rate of construction
- Less cost of formwork
- Possible to construct large span structure which gives large column free area
- Low weight of structure and low cost of foundation
- Good quality control
- Higher stiffness gives less deflection

**The disadvantages of composite construction are as follows:**

- Required of skilled labour
- Extensive care required during design and construction

The earlier composite construction consisted of steel beams and reinforced concrete slabs connected with shear connectors in between. Composite system called composite floor system, first developed for bridge construction. Its success inspired engineers to develop composite systems by combining steel and concrete. Now all high rise buildings cannot be built by using steel or concrete. Some of the composite column sections are as shown as shown in Fig. 1.1.

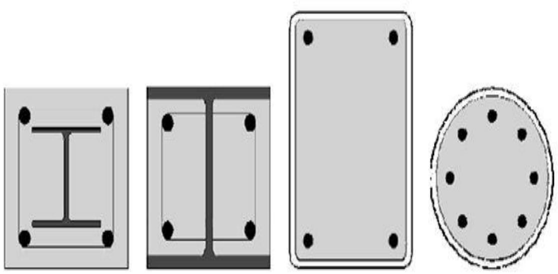


**Figure 1.1: Cross sections of composite columns**

Basically structural systems for any construction material i.e. concrete, steel and composite are classified as follows:

- Gravity load resisting systems
- Lateral load resisting systems

Gravity load resisting systems in composite construction are:

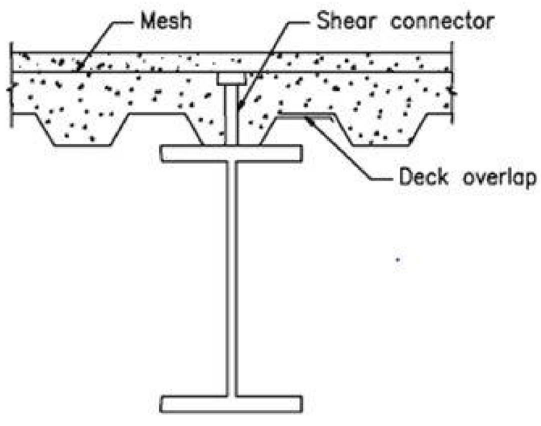



**Figure 1.2: Composite beam with slab**
Composite slab

- Composite beam/girder (See Fig. 1.2)
- Composite column (See Fig. 1.1)
- Composite shear wall (See Fig. 1.3)
- Composite truss

**Lateral load resisting systems for composite construction are:**

- Shear wall systems
- Shear wall- frame interacting systems
- Tube systems
- Vertically mixed systems
- Mega frame with super columns

In shear wall systems used in tall buildings, elevators, mechanical and electrical rooms and stairs are enclosed by core walls. Simple forms such as C and I shapes around elevators are interconnected by the links and connecting beams. Earlier application of this system in building were limited to 30 to 40 story range, but with advancement

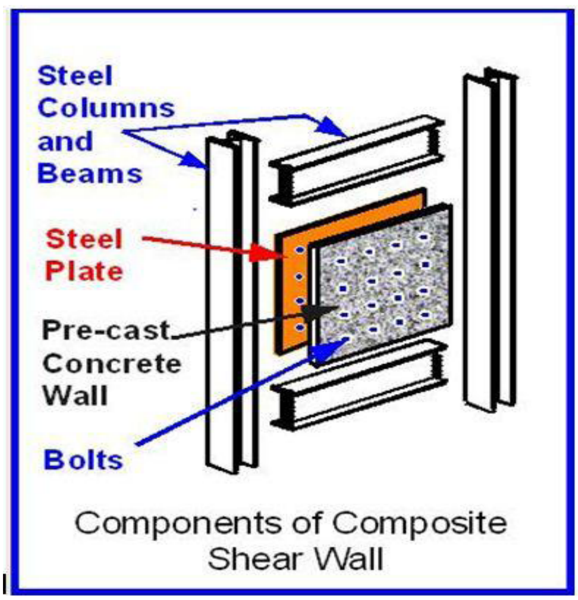



**Figure 1.3: Composite wall**

in super plasticizers and high strength concrete, now it is possible to use this system in buildings in the 50 to 60 story range. Lateral loads are resisted by the core in building and it does not present undue complications in its analysis. Basically the lateral load is resisted by the shear walls, hence remaining system can be built in structural steel system. There are two construction practices in which the system can be built. In first system, the concrete of core wall is done first using slip or jump formwork and then erection of steel system is done. The speed of erection of composite steel is less than conventional structural steel system but the combined construction time will be reduced because elevators can be installed rapidly in the core while construction outside the core proceeds.

Shear wall interacting system is applicable in buildings when building is not having sufficient core to resist the lateral loads. Combined system of moment frame and shear walls improve the overall stiffness and reduces the lateral drifts. Generally interior columns having beams spanning in four directions imposes difficulty in placing mild steel reinforcement and formwork around them. Otherwise it is easy in case of exterior columns.

Tube system comprises of wide columns placed closed to each other at perimeter forming tube connected by deep spandrels. There are two versions popular currently, one has composite columns and concrete spandrels and other has structural steel spandrels in place of concrete spandrels. In either version, speed of construction is maintained by erecting a steel skeleton first with interior steel columns, metal floor and light exterior columns. Generally frame is erected some 8 to 10 stories ahead of the exterior concrete tube.

Vertically mixed systems provide for more than one type occupancies in a building by stacking different amenities. For example, a building with lower levels housing the parking, middle one housing office floors and top floor housing residential apartments. Such different housing system economically favors the different types of construction. As mentioned earlier system, residential occupancies requires beamless at ceiling because of minimum finish required underneath the slab, also large span requires for more lease space for office building. In some construction practices, lower levels consume concrete and upper levels consume structural steel in construction. As mentioned earlier, efficient structure in tall buildings can be achieved by providing super column at the perimeter preferably at the corners. This concept has lead to invent a new structural system of composite materials characterized by the use of super columns which is known as Mega frame with super columns. Two construction practices for super columns are generally adopted, one is bigger diameter tubes or rectangular tube are filled with concrete and other one is steel sections generally I, are embedded in concrete. This type of construction usually saves the time as it avoids complicated .

**2.1 Concrete Frame Tube Structure**

The frame tube was a concept for concrete and steel consists of closely spaced columns connected by relatively deep spandrels. The exterior tube itself was sufficient to resist the lateral forces. When a frame tube structure subjected to wind, windward and leeward columns were in tension and compression respectively. These columns were considered as flanges and column in faces along wind direction were considered as web. But there was large concentration of forces at corner columns and relatively less in the middle ones. This was due to flexibility of spandrels connecting them and this was called as shear lag which major drawback in frame tube structures. The Fig. 2.1 shows the typical plan of a tube structure and Fig. 2.2 shows axial forces in tube columns.

**Kobielak S., Tatko R. and Piekaez R. "Method for approximate analysis of cracking effect on lateral stiffness of reinforced concrete framed-tube structures". Archieves of civil and mechanical engineering (Volume 10),2010,pg 230-241.. discussed behavior and method of analysis of f**

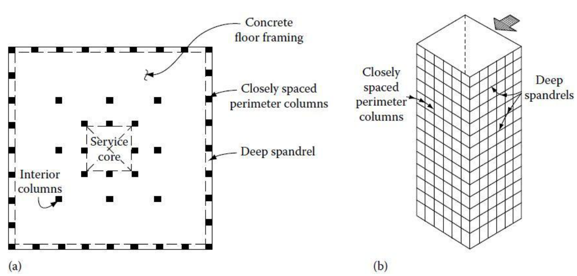



**Figure 2.1: Typical plan of frame tube building**

Framed-tube structures were one of the most significant structural systems of tall buildings as shown in Fig. 2.3. A frame-tube structure comprised of a single frame tube around the perimeter of building which was created from four orthogonal frame panels rigidly jointed in the corners. The frames consisted of closely spaced columns say 24 m between centers of joined deep spandrel girders. It was assumed that the stiffness ratio of columns to spandrel beam should be not greater than 2. Floors on the each story perform the function of rigid diaphragms and connect the external frame-tube with internal core in which were given for example stairs, elevators, systems of different installations. Framed-tube structures were used in concrete tall buildings from 40 to 60 stories. The paper presented analysis of framed-tube of tall reinforced concrete buildings subjected to horizontal loads. Authors took a cracking effect of frame spandrel girders of structure into account. Paper introduced simplified theoretical model of work of this kind of structures.

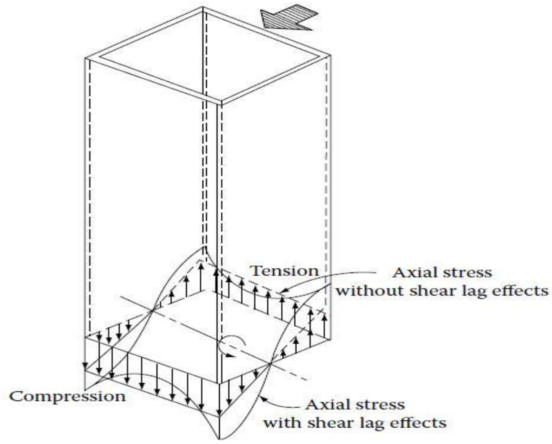



**Figure 2.2: Shear lag effect in frame tube building**

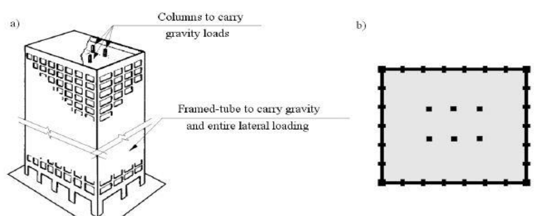



**Figure 2.3: Framed-tube structure a) general view of structure b) floor plan of** structure

Taranath B.S. "Steel, Conrete And Composite Design Of Tall Buildings". Mc-Graw Hill Publication,Second edition, pg 397-701. describes the structural system for National Bank Corporate Center, USA which was 62 story concrete frame tube structure which was 256m in height. The frame columns were 1370m in diameter, spaced at 6.1 m and spacing was reduced to half at perimeter. The system consists of a perimeter tube utilizes normal concrete with strength ranging 41.3 to 55MPa. Tube was provided not because it was able to resist lateral loads but also proved to be economical method dealing with the many setbacks and columns transfers imposed by the building architecture. The exterior beams were post tensioned with depth upto 457mm having spacing of 3.05m.

Lee David and Ng Martin. "Application of Tuned Liquid Dampers for the E_-cient Structural Design of Slender Tall Buildings". CTBUH Journal,2010 Issue IV, pg456-464. presented structural concept for Central Plaza, Hong Kong along with tuned liquid damper concept incorporated in it. It was an another example of rein-forced concrete frame tube which was 314m high, 78 story building. Wind was design crieterion, which was situated in an area influence by typhoons. The basic wind speed with 50 years return period was taken as 64m/sec. The structural system included RCC frame with inner concrete core made of walls with thickness of 1.3m at base. The size of columns at ground level was 2m in diameter with spacing of 8.6m. The concrete used for core was of 40 to 60MPa and for columns it was 60MPa

**2.2 Steel Frame Tube Structure**

Hamburger Ronald, Baker William, Jonathan Barnett, Marrion Christopher, Mike James and Nelson Harold." WTC 1 and WTC 2." Chapter 2, Published by Federal Emergency Management Agency,pg 422-504.. discussed the structural framing of 1 World Trade Center which was at North, at 417 metres (1,368 ft), and 2 World Trade Center which was at South,also combinely recognized as the "Twin Towers", were the tallest buildings in the world at the time of their completion. Fazlur Khan introduced the frame tube design which was a relatively new approach that allowed more open floor space than the conventional design that columns were provided throughout the interior to resist imposed loads. The World Trade Center towers used high strength, exterior steel columns that were spaced closely to form a strong, rigid tube, supporting all lateral loads such as wind load, and sharing the gravity load with the core columns or walls. The perimeter structure contained 59 columns per side was constructed with extensive use of prefabricated modular pieces connected by spandrel plates. The spandrel plates were welded to the columns. Adjacent modules were bolted together with the splices occurring at mid-span of the columns and spandrels. The spandrel were situated at each floor, transmitting shear stress between columns, allowing them to work together in resisting lateral loads. The core of the towers housed the elevator and mechanical shafts, restrooms, three staircases. The core of each tower was a rectangular in shape having area 87 by 135 feet (27 by 41 m) and contained 47 steel columns

Iyengar Hal. "Reections on The Hancock Concept". CTBUH Journal (Volume 1), May 2000,pg213-227. reviewed the structural design and concept of John Hancock Center which was 100 stories structure with a rectangular plan that tapers from ground level to the top level. It was constructed for multi use involving commercial, parking, office and apartments type space in one building . The structural system comprises of diagonally braced exterior frames which act together as a tube. The columns, ties and diagonals were I sections fabricated from three plates with maximum thickness of 150mm. The maximum dimension adopted for column sections was 920mm. Floor framing consists of lightweight concrete topping and metal deck resting on rolled beams with simple connections. The interior columns and beams were designed for gravity loads only. Connections were shop welded and field bolted except that field welding was used in spandrels, main ties and column splices.

**2.3 Megaframe With Supercolumn**

Xia Jun, Dennis Poon and Mass Douglas C. "Case Study:Shanghai Tower". CTBUH Journal,2010 Issue II,pg 355-366.. have discussed planning, structural system and sustainable technologies of Shanghai tower which was 632meter, 121 story mixed use tower. Shanghai tower will be highest tower in China faced with many challenges- a windy climate, active seismic zone and clay based soils of a river delta. The structural system shanghai tower comprised of concrete core, megaframe with supercolumn along with outrigger and belt trusses. Concrete core was 30meters square divided into 33 subsections. The core was connected to supercolumns by outriggers. There were total 8 columns, two columns on each face of the building. In addition, four diagonal mega columns were provided along each 45 degrees axis were required by the long distances between the main orthogonal supercolumns. The distance was approximately 50 meters which was again reduced to 25meters. The tower was divided into nine vertical zones and each zone comprises of 12-15 floors. At the interface of the each zone, a two story full area was constructed to house the mechanical, plumbing and electrical equipments and also serve as life safety refuge area. The resistance to lateral and gravity loading will be provided by the inner cylindrical tower. The primary resistance to lateral load was provided by the core, outrigger and supercolumn system. The supplementary system was mega frame consisting of all super columns including the diagonal megacolumns together with double belt truss at each interface between two zones, detailing as shown in Fig. 2.4. The core was of concrete, outrigger and belt trusses were of structural steel and the supercolumns were composite structure with concrete encased steel sections.

Sheih Shaw-Song, Ching-Chang Chang and Jong Jiun-Hong. "Structural Design Of Super-composite Column For The Taipei 101 Tower". Second Conference on Structural Steel Technology for Taiwan Strait Region. discussed the structural system for Taipei101, Taiwan which was 508m in height. It was more challenging to analysis, design and construct a tall structure in Taipei than any other location in the world, because it was considered as the one of highly seismic active and also the presence of typhoon winds and soft soil conditions. The system of Taipei 101 consisted of three sub-systems i.e. gravity system,

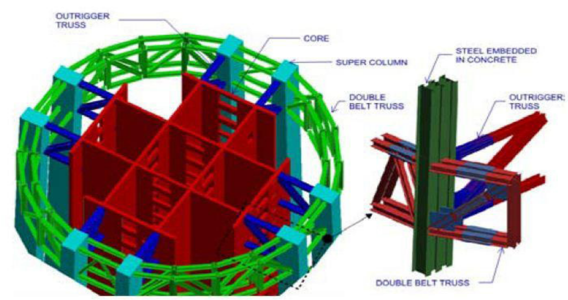



**Figure 2.4: Megaframe for Shanghai tower and outrigger detail**

lateral system and damping system. The damping system consisted of a tuned mass damper. The gravity system comprises of a steel frame with composite beams and composite slabs connected with shear studs. Also vertically the load was transferred by the variety of columns. The inner concrete has sixteen columns with diagonal bracing. The columns were steel encased box sections filled with high performance and high strength concrete. Up to the 26th floor, each face of the structure has two supercolumns along with two sub-super columns and two corner columns. After 26th floor sub-super columns were discontinued and only supercolumns were continued upward. The supercolumns were filled with concrete up to level of 62 and after that only hallow steel box section was used to reduce weight. At top levels the members sections were much smaller in plan. The lateral system comprised of combination of the core which was braced frame, outriggers from core to supercolumns and moment resisting frame at perimeter and other selected locations. The Fig. 2.5 shows the typical megaframe elevation.

Most of the lateral load was carried by the core and outriggers. There were outriggers at 11 locations in elevation out of which 6 were one story high, in mechanical floors and rest were two story high provided at per the architectural requirements. In other words, there were 16 outriggers occur on each such floor

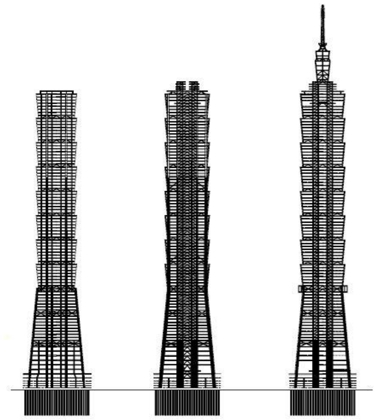
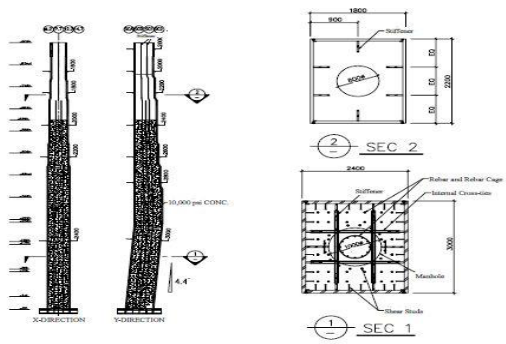


**Figure 2.5: Mega frame elevation of Taipei 101**

Supercolumn was the primary vertical members of the megastructure system. The general tube sections with maximum size of 2.4m x 3 m and vertical stiffener plates were provided to ease erection in steel section and concreting. The reasons behind providing vertical stiffeners were:

- Reduce width to thickness ratio of the plate.
- Increase strength.
- Prevent the column plates from deforming by welding rebars to the vertical stiffeners and enhance confinement to the concrete.

To facilitate welding, bolting, rebar splicing and concreting, a round manhole at the center was provided. Shear studs were provided to avoid separation of the steel plate and concrete due to shrinkage and creep. The Fig. 2.6 shows the details of the supercolumns.




**2.6: Details of Supercolumns (Taipei 101)**

525.8m to the roof,111 story and 6 basement levels was described by the Wijanto et al. in CTBUH conference 2009. Basically the system was a combination of core, outrigger and megaframe with supercolumns. The core was made of composite material which connected to supercolumns by outriggers which were of steel trusses. In addition to that steel belt trusses and steel oor trusses were provided to get the more column free space and to transfer to the gravity load to supercolumns. The core was 31m x 31m in plan, with embedded steel in concrete and resists most of the base shear. The thickness of the core walls at the ground level was 1.1m and decreases to 0.6m at the upper oors in order to maximum the usable areas. There were 3 out-riggers, two story deep, provided at level 33-35, 58-60 and 91-93 along with one head truss, one story deep at 109-110. Belt trusses were provided to link supercolumns to each other and form perimeter mega frame which were 3 two story high and 6 one story high. Functions of oor trusses were to reduce tension in supercolumn due to lateral loading and to avoid jumbo perimeter gravity column. Fig. 2.7 shows the con guration of core wall, supercolumn and outrigger truss and belt truss.

The Jin Mao tower which was 421 m tall, 88 story housing a ve star hotel, class A office, parking, retail uses. Sarkisian et al. described the structural system which consisted of the mixed use of structural steel and reinforced concrete with ma-jor structural members composed of both structural steel and reinforced concrete i.e. composite. The primary components of the lateral system for the tower include a central reinforced core linked to exterior composite mega columns by the structural steel truss outriggers. The central core was built to house elevators, mechanical room fans and washrooms. The shape of core was octagonal and was nominally 27m deep with flanges varying in thickness from 850mm at the top of the foundation and reduced to 450mm at the level 87 with concrete strength. The supercolumns were provided with varying size, 1500mm x 5000mm at the top of foundation and 1000mm x 3500 mm at the level 87. The outriggers interconnected the central core and the composite megacolumns at the three levels, 24-26, 51-53 and 85-87 which were 2 story deep. It engages the steel cap truss system which frames the top of the building between level 87 and the spire was used to span over the open core, support the gravity load of the heavy mechanical spaces, engage the structural steel spire and resist lateral load above the top of the central core and mega frame

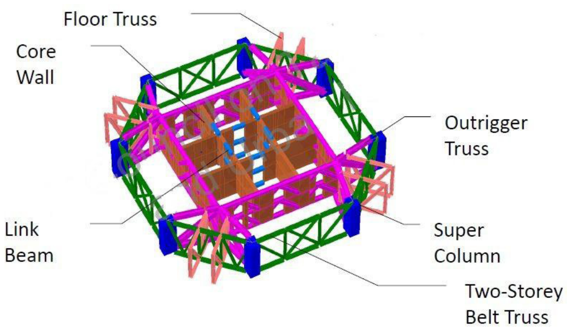



**Figure 2.7: Core wall+ Supercolumn+ Outrigger truss+ Belt module of Signature tower**

The structural system adopted for the World Finance Tower was also a combination of a core, outrigger and mega frame which was explained by Malott et al . The core was composite with primarily reinforced concrete wall and embedded steel plates/steel w-shapes and was 32m x 32m in plan. Flange wall 1.5m thick to 0.5m, web wall 0.8m thick to 0.4m thick. Some link beams have embedded steel shapes to satisfy code shear requirement. 4 two-story outriggers at MEP/ refuge levels were engaging supercolumns which were composite. The size of the supercolumns was 6.m x 3.2m at base and 2.9m x 1.4m at top with embedded steel ratio of 4-6% above ground and 8% in the basement. The exterior mega frame consists of 2-story/1-story high steel double belt trusses at MEP/refuge levels each zone linking supercolumns. The outriggers were constructed at level 25-27, 48-50, 79-81 and 95-96. Mega braces were provided between the belt trusses. The Fig. 2.8 shows the configuration of super columns, double belt trusses at seven zones.The belt trusses and supercolumn were designed to take 25% of the total base shear in strength. The mega frame was designed to attract 6% of the total base shear in the exterior mega frame based on relative sti ness. The Fig. 2.9 shows the configuration of the core, supercolumn, belt truss and outriggers at mechanical level.

**Peng et al**. described the Tianjin Golden Finance 117 tower as it hosts 370,000m$^2$ floor areas for o ce space and a luxury hotel. Its 597m height was the tallest structural roof level in china, while the height to width ratio reaches a challenging value of 9.5. To satisfy earthquake and wind resisting requirements, the structure consisted of a perimeter mega braced frame and a reinforced concrete core with composite shear wall. To effectively resist the vast wind load and seismic effect in this slender pro-le the columns were strategically located at four corners which were connected with mega braces and belt trusses to form the perimeter structure. This was supplemented by a central concrete core the walls of which were further strengthened by embedded steel plates at bottom levels. The plan shape of the mega columns was intended to satisfy the architectural pro le and structural connection requirements resembling a six sided polygonal concrete filled tube with around 4-6% steel ratio. The cross sectional area of the mega column was about 45m$^2$ at bottom of the tower which was reduced along the height of the tower with the external face of the columns held while steel ratio was kept basically the same. The Fig. gives overlook to the lateral load resisting system.

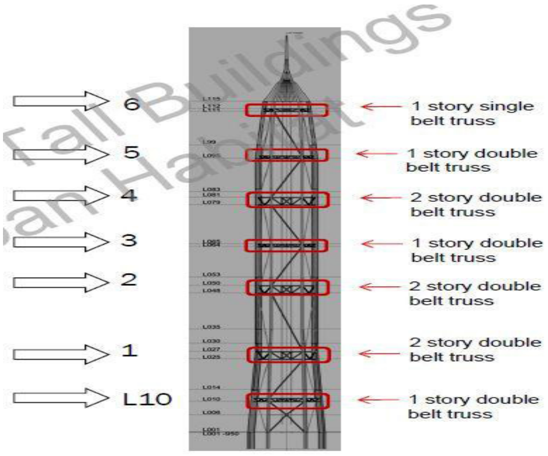
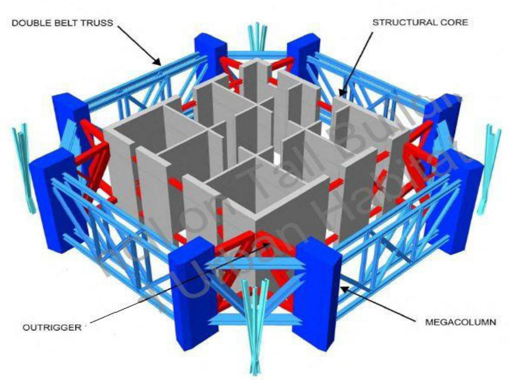



**Figure 2.8: Configuration of super columns, double belt trusses in World Finance tower**




**2.9: Configuration of the core, supercolumn, belt truss and outriggers at mechanical level**

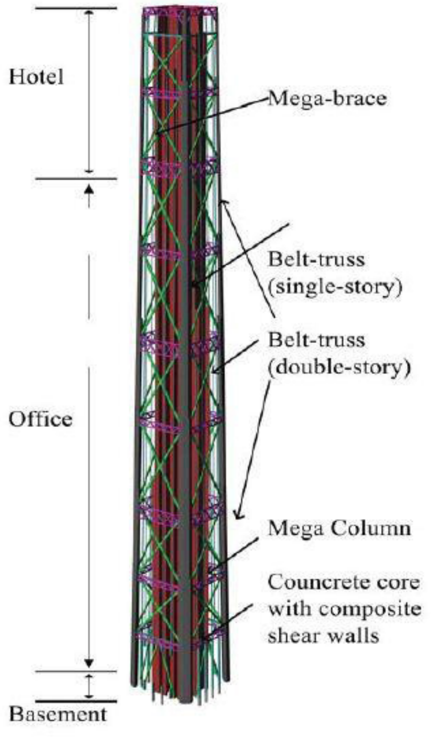



**Figure 2.10: Structural system for Tiajin Golden Finance tower**

## Conclusion

1) The composite megaf rame with super column is efficient compared to RCC frame tube and steel frame tube. Composite construction is proved to be economical based on cost analysis.

2) In composite megaframe with supercolumn, the capacity of members is utilized in efficient manner. In frame tube structures, capacity of columns is not fully utilized due presence of shear lag. The corner columns are subjected to 30-35% more axial compressive forces compared to forces in internal columns of the same face.

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