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Drift and Cost Comparison of Different Structural Systems for Tall Buildings

Asif Hameed, Imran Azeem, Asad-ullah Qazi, Burhan Sharif and Noor Muhammad Khan

Civil Engineering Department, University of Engineering and Technology Lahore, Pakistan

Corresponding Autor :asifhameed@uet.edu.pk,

Abstract

The race towards new heights and architecture has not been without challenges. Tall structures have continued to climb higher and higher facing strange loading effects and very high loading values due to dominating lateral loads. The design criteria for tall buildings are strength, serviceability, stability and human comfort. But the factors govern the design of tall and slender buildings all the times are serviceability and human comfort against lateral loads. As a result, lateral stiffness is a major consideration in the design of tall buildings. The first parameter that is used to estimate the lateral stiffness of a tall building is drift index. Different lateral load resisting structural subsystems can be used to impart stiffness and reduce drift in the building. Lateral load resisting subsystems can take many forms depending upon the orientation, integration and addition of the various structural components. In this research, sixteen different lateral load resisting structural subsystems are used to design a tall building and finally the most economical structural system is selected amongst these. For this purpose a hundred and five storey square shaped prismatic steel building uniform through the height is selected, analyzed and designed for gravity and wind loads. Analysis and design of selected lateral load resisting structural subsystems reveals that, for the building configuration selected, the structural system containing composite super columns with portals subsystem is most efficient.

Key Words: Tall Buildings, Lateral load resisting subsystems, Drift index, Cost effectiveness

1. Introduction

Humans have always admired tall structures since ancient times for visibility, their individual social status, highest respect of their societies and subjects of legends. Now a days high cost of land in developed cities of the world, need to cluster population at or near commercial hubs and need to maintain agricultural production have forced the structures to expand in vertical direction. Moreover new achievements in material science, computer-aided design and construction technology have also attracted architects towards more sophisticated, elegant, state of the art non traditional architectural and structural systems for tall structures.

Tallness is a relative term. A quantitative definition of tall buildings cannot be applied universally. From structural engineering viewpoint, a tall building may be defined as the one whose structural design is dominated by the lateral forces [1]. The race towards the new heights has not been without challenges. Usually increase in height is combined with unintended increase in flexibility. Possible lack of stiffness or damping adds vulnerability to the structures against lateral loads [2].

The design criteria for tall buildings are strength, serviceability, stability and human comfort. But the factors govern the design of tall and slender buildings all the times are the human comfort and maximum column free space. When a tall building is subjected to lateral loads, the resulting oscillatory movement induces a wide range of responses in the building and its occupants. As far as the ultimate limit state is concerned, lateral deflections must be limited to prevent second-order P-Δ effects due to gravity loading being of such a magnitude as to precipitate collapse. In terms of serviceability limit states, deflections must be maintained at a sufficient low level to allow proper functioning of nonstructural components and to avoid distress in the structure to prevent excessive cracking and consequent loss of stiffness and to avoid any redistribution of the loads to non structural components. Considering human comfort level, the structure must be sufficiently stiff to prevent dynamic motions becoming large enough to cause discomfort to occupants. As a result, lateral deflection and lateral stiffness are major considerations in the design of tall buildings. Design of structural systems for steel buildings is one of the most complex design problems in development of tall buildings [3].

Selection of structural system for tall buildings depends upon shape, horizontal and vertical aspect ratios, nature and magnitude of lateral loads, internal planning of the building, availability of material of construction, facade treatment and location and routing of the HVAC (heating, ventilation, and air conditioning) system [1]. The selected structural system should be strong enough to withstand anticipated loads without failure, stiff enough to keep lateral deflections and lateral load induced motions within limits with minimum cost [4]. Every structural system has a wide range of height applications depending upon design concept and criteria. For each set of design concept and criteria, there is always an optimum structural system [5].

The first parameter that is used to estimate the lateral stiffness of tall building is drift index. Drift Index is the ratio of the maximum lateral deflections at the top of the building to the total height of super structure.

The efficiency of the structural system is roughly compared in terms of cost of structural system per unit area of the building. So major parameter of interest in final selection of structural system is the structural mass per unit area of building. An ideal situation is the one when steel required to carry the gravity loads alone could carry the lateral loads. But in tall buildings it is not possible and compensation for lateral loads is always required [6].

The objective of this research is to find out the most efficient, economical and viable structural scheme that satisfies design criteria and remain integrated with the architectural design. In this research, various structural systems for tall buildings have been studied and analyzed. Topic of research is broad and wide. Each structural system is a complete subject in itself and normally in actual design; a combination of different structural systems is adopted for most economical and optimal solution. Considering each system individually and then in combination and for variety of heights is beyond scope of this research. So work is limited to a cost comparison (in terms of mass of steel) of individual structural systems for a square shaped prismatic steel building, uniform throughout the height and subjected to gravity and wind loads only.

To compare different structural systems for drift, a square shaped prismatic steel building uniform throughout the height is selected. The building adopted for the research has following configuration.

Length of building (L) =54.86 m (180 ft)
Width of building (B) =54.86 m (180 ft)
Roof level = 386 m (1266 ft)
Height of spire= Spire not considered
Total height of building (H) = 386 m (1266 ft)
Floor height = 3.65 m (12 ft) Typ.
No. of stories = 105
Horizontal aspect ratio (L/B) = 1
Vertical aspect ratio (H/L, H/B) = 7
Floor area (A) = 3010.7 m^2 (32400 $sqft^2$)
Service core area (A') = 655.8 m^2 (7056 ft^2)

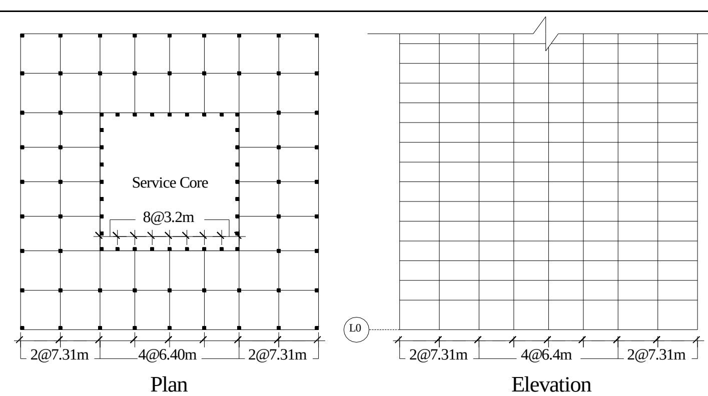
2. Structural System Configurations

A total of 16 structural systems are considered for comparison purpose which have been developed and employed with success all around the world [1]. They are described in Table 1.

Table 1: Structural Systems Configurations

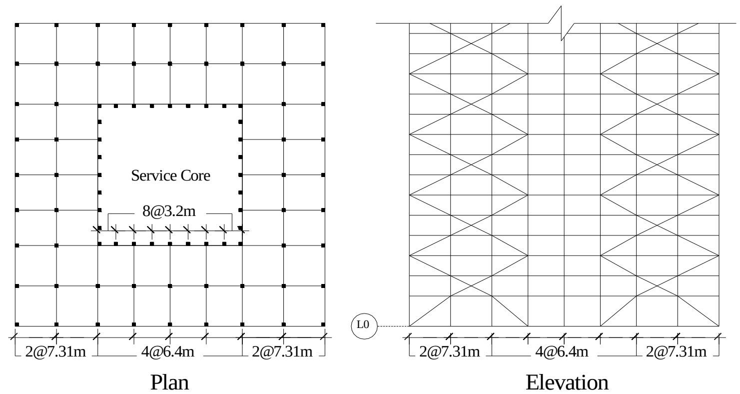
2.1 Ordinary Moment Frame

This configuration consists of an assembly of vertical columns and horizontal beams distributed throughout the plan and joined by moment connections. Panel dimensions are 7.31m x 7.31m and 6.4m x 7.31m. Service core substructure consists of a framed tube with column spacing of 3.2m. Floor beams are rigidly connected with core structural subsystem and contribute in lateral load resistance. Depth of internal beams is restricted up to 685mm for clearance requirements.



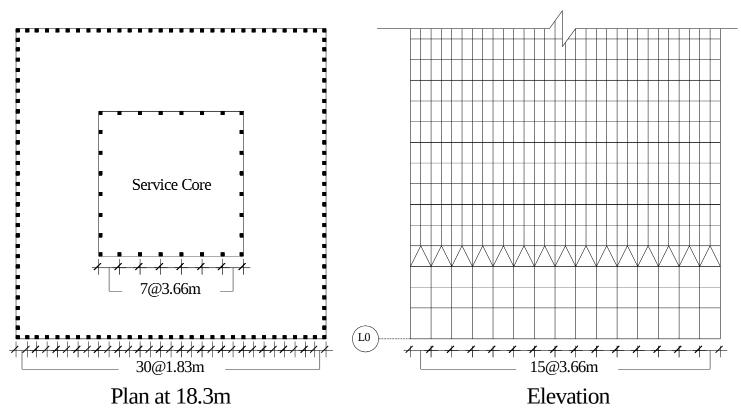
2.2 Braced Moment Frame Configuration

This configuration consists of an assembly of vertical columns and horizontal beams distributed throughout the plan and joined by moment connections. Diagonal bracing members affective only in tension are provided in the exterior panels. Panel dimensions are 7.31m x 7.31m and 6.4m x 7.31m. Service core substructure consists of a framed tube with column spacing of 3.2m. Floor beams are rigidly connected with core structural subsystem and contribute in lateral load resistance. Depth of internal beams is restricted up to 685mm for clearance requirements.



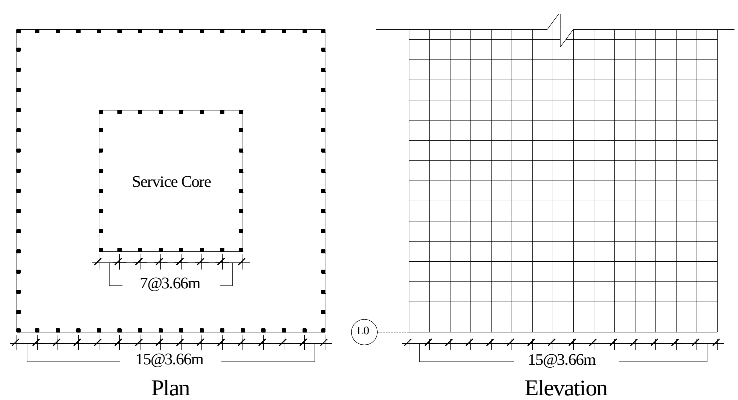
2.3 Framed Tube (Closely Spaced) Configuration

This configuration consists of an assembly of closely spaced vertical columns and deep spandrels joined by moment connections. These columns and spandrels are aligned at perimeter of the building. Column spacing at perimeter is 3.66m from first to fourth floor and 1.83m above. Service core substructure consists of a framed tube with column spacing of 3.66m.



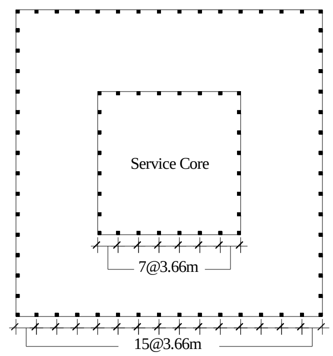
2.4 Framed Tube (Widely Spaced) Configuration

This configuration consists of an assembly of vertical columns and deep spandrels joined by moment connections. These columns and spandrels are aligned at perimeter of the building. Column spacing at perimeter is 3.66 m and is uniform through the height. Service core substructure consists of a framed tube with column spacing of 3.66 m.

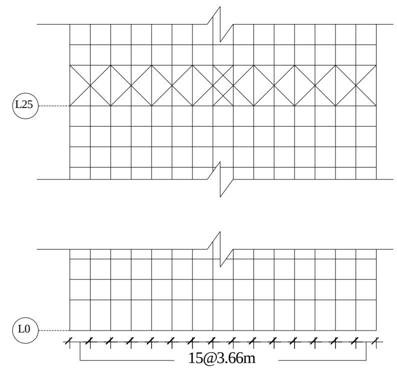


2.5 Framed Tube With Belt Trusses Configuration

This configuration consists of an assembly of closely spaced vertical columns and deep spandrels joined by moment connections. These columns and spandrels are aligned at perimeter of the building. Column spacing at perimeter is 3.66m and is uniform through the height. Two level deep belt trusses are added in the perimeter structure at floor # 27, 53, 79 and 105. Service core substructure consists of a framed tube with column spacing of 3.66m.



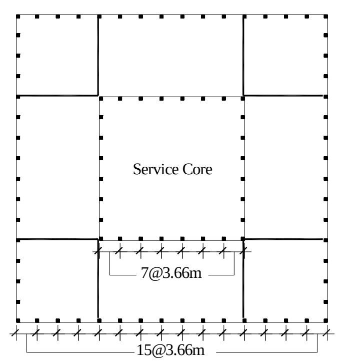
Plan



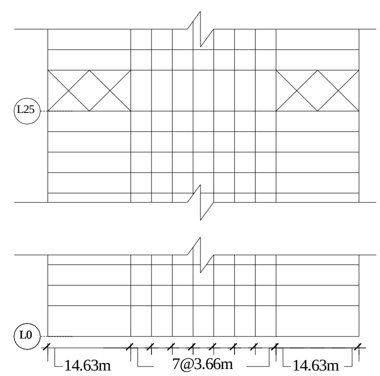
Elevation

2.6 Framed Tube With Belt Trusses and Outriggers Configuration

This configuration consists of an assembly of closely spaced vertical columns and deep spandrels joined by moment connections. These columns and spandrels are aligned at perimeter of the building. Column spacing at perimeter is 3.66m and is uniform through the height. Two level deep belt trusses are added in the perimeter structure at floor # 27, 53, 79 and 105 whereas two level deep outrigger trusses are added between service core substructure and perimeter columns at floor # 27, 53, 79 and 105. Service core substructure consists of a framed tube with column spacing of 3.66m.



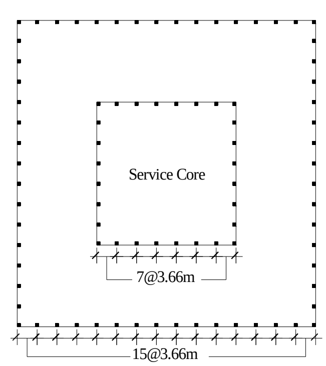
Plan at outrigger level



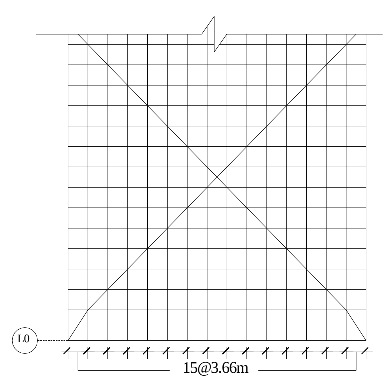
Elevation at 14.63m,43.89m

2.7 Braced Tube (Closely Spaced) Configuration

This configuration consists of an assembly of closely spaced vertical columns and deep spandrels joined by moment connections. These columns and spandrels are aligned at perimeter of the building. Full face pin ended diagonal members are added in the perimeter structure. Column spacing at perimeter is 3.66m and is uniform through the height. Service core substructure consists of a framed tube with column spacing of 3.66m.



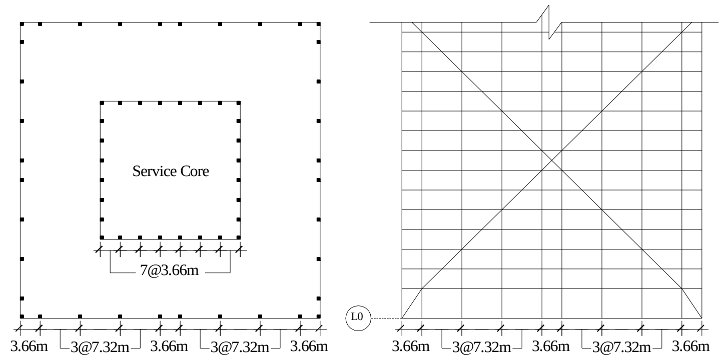
Plan



Elevation

2.8 Braced Tube (Widely Spaced) Configuration

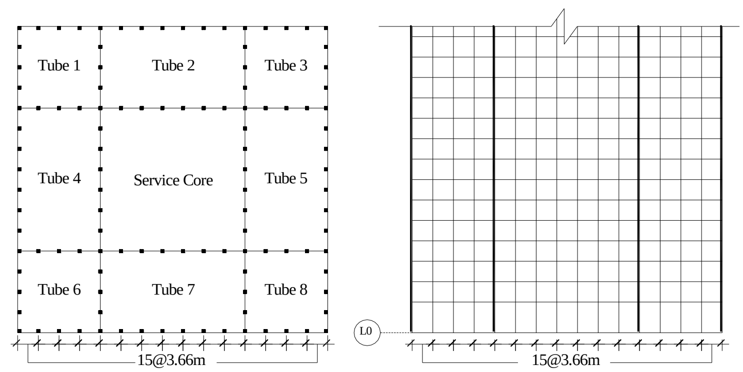
This configuration consists of an assembly of vertical columns and deep spandrels joined by moment connections. These columns and spandrels are aligned at perimeter of the building. Full face pin ended diagonal members are added in the perimeter structure. Column spacing at perimeter is 3.66m and 7.32m. Service core substructure consists of a framed tube with column spacing of 3.66m.



Plan Elevation

2.9 Bundled Tube Configuration

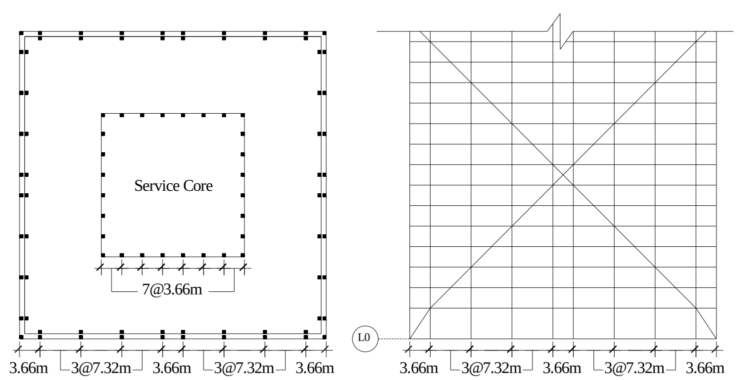
It is a modified form of framed tube subsystem in which additional lines of rigid frames, similar in configuration with outer tube, are introduced orthogonally inside the tube. This addition results in formation of a bundle of individual tubes connected and acting together. It consists of an assembly of multiple framed tubes joined together to form a bundle. Column spacing of framed tubes is 3.66m. Service core substructure is formed by the sides of adjoining framed tubes.



Plan Elevation

2.10 Exoskeleton Configuration

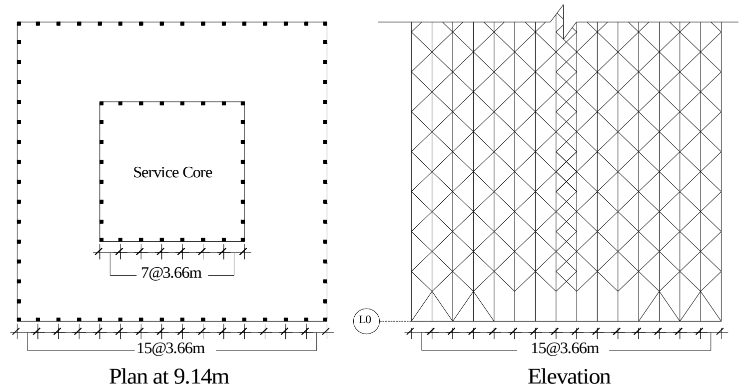
It consists of independent vertical load resisting subsystems and lateral load resisting subsystems. Lateral load resisting subsystem is located out side the building lines away from facade. Any basic form of lateral load resisting subsystem can be selected as exoskeleton This configuration consists of independent vertical and lateral load resisting subsystems. Lateral load resisting subsystems is oriented outside the perimeter of the building as a braced tube with column spacing of 3.66m and 7.32m.



Plan Elevation

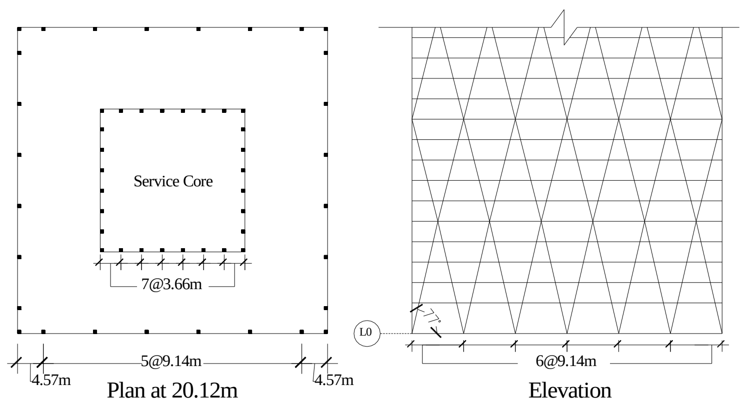
2.11 Lattice Tube Configuration

This configuration consists of an assembly of vertical columns and pin ended diagonal members aligned at perimeter of the building. Spandrel beams are eliminated from the perimeter structure. Column spacing at perimeter is 3.66m and is uniform through the height. For clearance requirements, diagonal members are eliminated from central seven bays of ground floor. Service core substructure consists of a framed tube with column spacing of 3.66m.



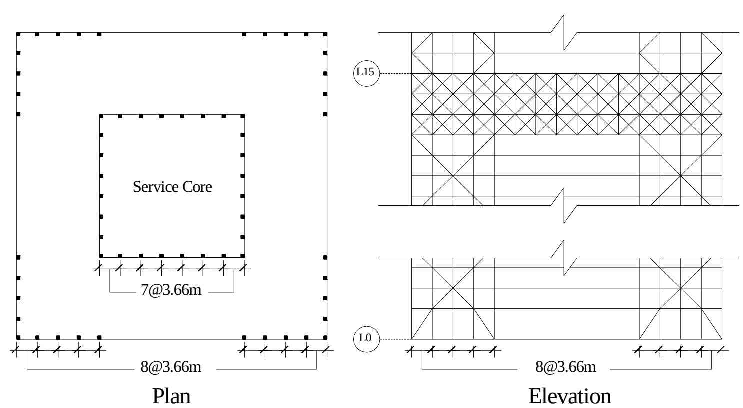
2.12 Diagrid Configuration

It is another modified form of tube subsystem concept. It consists of an assembly of inclined/diagonal members and horizontal spandrels without conventional vertical columns. Inclined/diagonal members are designed to carry all the loads. In this research this system consists of an assembly of inclined columns and spandrel beams aligned at perimeter of the building. Vertical columns other than corner columns are eliminated from perimeter structure. Column spacing at perimeter is 9.14m at an inclination of 77°. Service core substructure consists of a framed tube with column spacing of 3.66m.



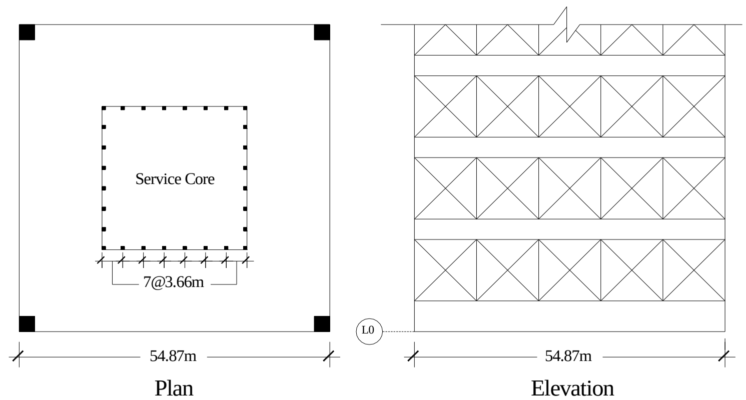
2.13 Mega Frame Configuration

It consists of stiff planer assemblies concentrated near corners of the building and connected through horizontal elements/ multistory trusses at intervals. These interconnected assemblies take the form of a portal frame. This portal frame resists lateral loads as an exterior structure. Here this configuration consists of an assembly of groups of vertical columns, spandrel beams and diagonal members aligned at perimeter, near corners of the building. These groups are joined together with three level deep portals/belt trusses at every 15th floor. Column spacing at perimeter is 3.66m. Service core substructure consists of a framed tube with column spacing of 3.66m.



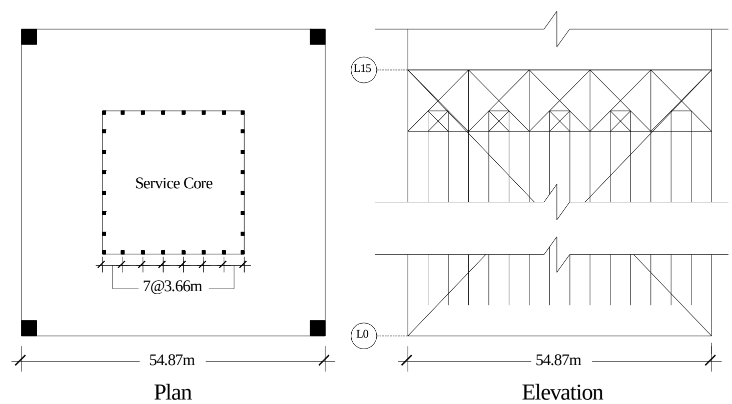
2.14 Steel Super Columns With Portals Configuration

Columns with portal configuration consist of three or more massive columns located at appropriate locations and joined together through portals or braces. Philosophy behind locating super/mega columns at extremities is concentration of resistance at maximum available distance to get maximum resistive couple and inertia with economy. Steel super columns with portals configuration consists of an assembly of four vertical steel super columns located at corners of the building. These columns are joined together with three level deep trusses/portals at every 4th floor. Service core substructure consists of a framed tube with column spacing of 3.66m.



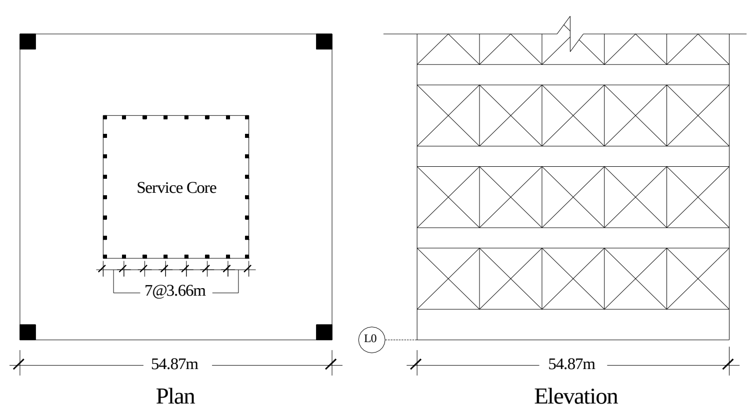
2.15 Composite Steel Super Columns With Bracing Configuration

Composite steel super columns with bracing configuration consist of an assembly of four vertical composite steel filled super columns located at corners of the building. These columns are joined together with three level deep trusses/portals at every 15th floor and diagonal bracing members effective only in tension. Hangers at a distance of 3.66m are provided from trusses/portals to support floor system. Service core substructure consists of a framed tube with column spacing of 3.66m.



2.16 Composite Steel Super Columns With Portals Configuration

Composite steel super columns with portals configuration consists of an assembly of four vertical composite steel filled super columns located at corners of the building. These columns are joined together with three level deep trusses/portals at every 4th floor. Service core substructure consists of a framed tube with column spacing of 3.66m.



3. Constant Research Parameters

Following parameters are taken either constant or similar.

i) Structural system of service/core area is same for all cases.

ii) Floor subsystem and scheme for all cases other than ordinary moment frame and braced moment frame is same.

iii) Material specification for structural steel for all cases is same.

iv) Limiting drift value for all cases is same.

v) Initial stiffness and inertia assignment to members of subsystems falling in same category is same.

vi) Member cross sections and inertia for all cases are similar.

vii) Orientation and spacing between members of subsystems falling in a category is similar.

4. Research Assumptions

Following assumptions are made in the study.

i) Horizontal floors are considered as rigid diaphragms.

ii) Hull and core are considered connected through rigid diaphragms.

iii) Bracing elements for "braced moment frame" and "composite super column with bracing" subsystems are considered effective only in tension.

iv) Steel mass for secondary floor components like steel floor deck, stud bolts etc. are not considered in comparison.

v) Floor area excluding service area is considered for various comparisons.

The structural systems discussed above are modeled, analyzed and designed. SAP2000 is used for modeling, analysis and design of the vertical and lateral load resisting subsystems whereas floor subsystem is modeled, analyzed and designed in ETABS-9. For brevity the only final results are discussed here. The complete analysis and design results can be found in reference [7].

In table 2 mass of the structural steel and drift associated with each structural system analyzed and designed along with structural steel mass per unit area of building is summarized.

Fig.1 shows the comparison of normalized steel mass of each structural system analyzed and designed in the research with respect to least mass system. Ordinate shows normalized mass whereas abscissa shows subsystem codes defined in Table 1. Values on the bars are ratios of normalized steel mass. e.g., there is a difference of 21% between two least mass systems (S16 and S14).

Fig.2 present in the form of a bar charts, comparison of structural steel mass per unit building area associated with each structural system. Values on the bars are quantities of steel mass in Kg/sqm. S1 structural system has the maximum required structural steel per unit area while S16 have minimum structural steel per unit area.

Fig.3 shows the comparison of drift in each structural system. Ordinate shows drift in millimeters whereas abscissa shows subsystem codes of the structural systems. Values on the bars are drifts in the structures at top level in millimeters. The drift in all the structural systems is either less or nearly equal to the permissible drift.

Fig.4 presents the comparison of structural steel mass per unit building area and drift associated with each structural system. Ordinate shows steel mass per unit building area in Kg/sqm and drifts in millimeters whereas abscissa shows subsystem codes. Values on the bars are quantities of steel mass in Kg/sqm and drifts at top level in millimeters.

5. Discussions on Results

- Structural system with subsystem S16 i.e. "Composite super column with portals" yields minimum steel with drift at top level well below the permissible limit.
- Drift in some of the systems is less than the prescribed limit of H/500. This difference is due to the inherent stiffness of the members of the structural systems.
- Drift at top level in structural systems with super/mega column subsystems is quite less than permissible drift.

Table 2 Subsystems, total structural steel mass in each system, structural steel mass per unit area of building and corresponding drift.

Subsystem Code	Subsystem	Total Structural Steel	Structural Steel per Unit Area	Drift
		x10^3 Kg	(Kg/sqm)	(mm)
S1	Ordinary moment frame	54,208	219.15	772
S2	Braced moment frame	48,537	196.23	748
S3	Framed tube (Closely spaced)	43,079	174.16	772
S4	Framed tube (Widely spaced)	46,211	186.82	783
S5	Framed tube (Widely spaced) with belt trusses	46128	186.49	770
S6	Framed tube (Widely spaced) with outriggers and belt trusses	45429	183.66	759
S7	Braced tube (Closely spaced)	36681	148.30	766
S8	Braced tube (Widely spaced)	36037	145.69	771
S9	Bundled tube	46598	188.39	753
S10	Exoskeleton	48148	194.65	770
S11	Lattice tube	37873	153.12	700
S12	Diagrid	36442	147.33	756
S13	Mega frame	43348	175.25	747
S14	Steel super column with portals	34897	141.08	722
S15	Composite super column with bracing	36758	148.61	635
S16	Composite super column with portals	28926	116.94	703

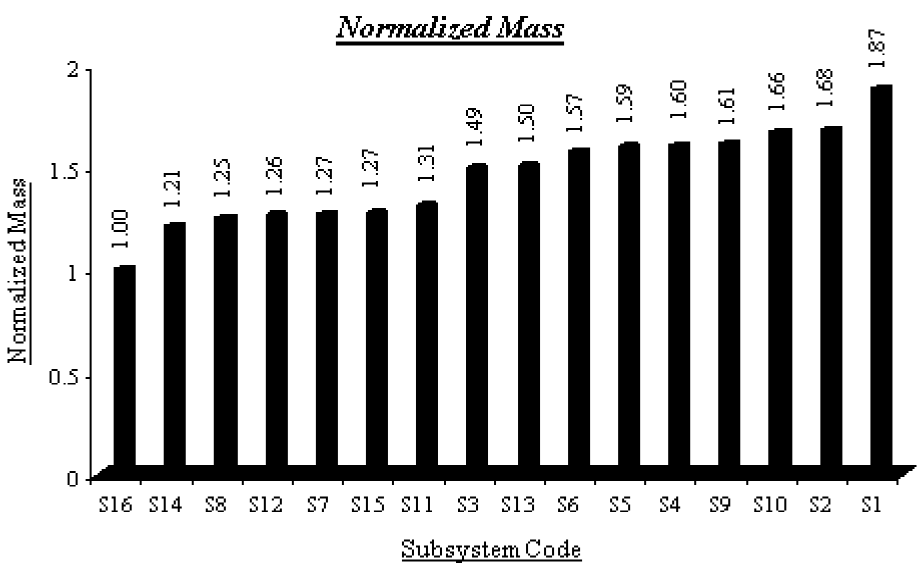


Fig.1: Normalized mass w.r.t least mass structure

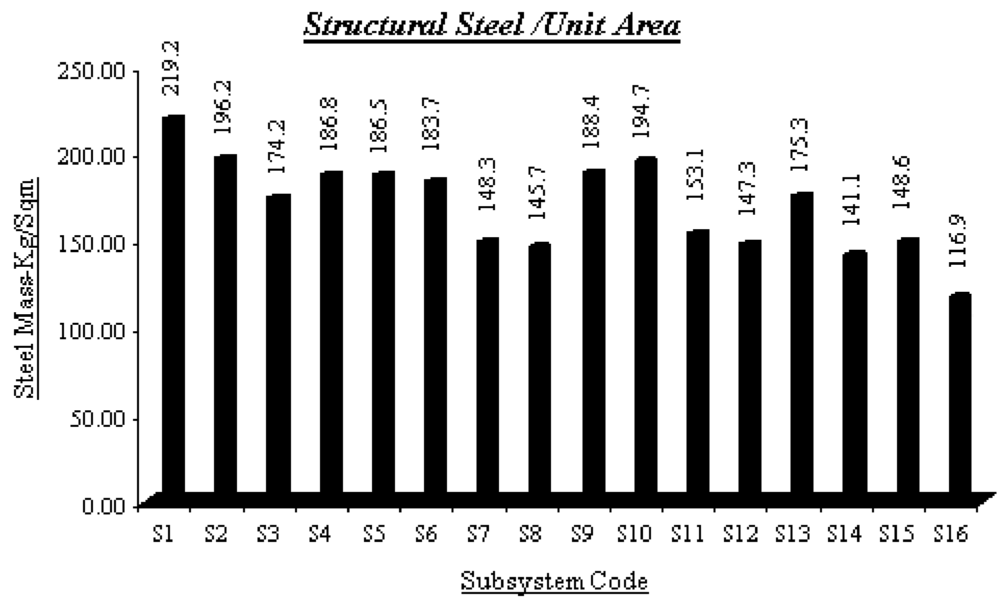


Fig.2: Comparison of structural steel mass per unit floor area

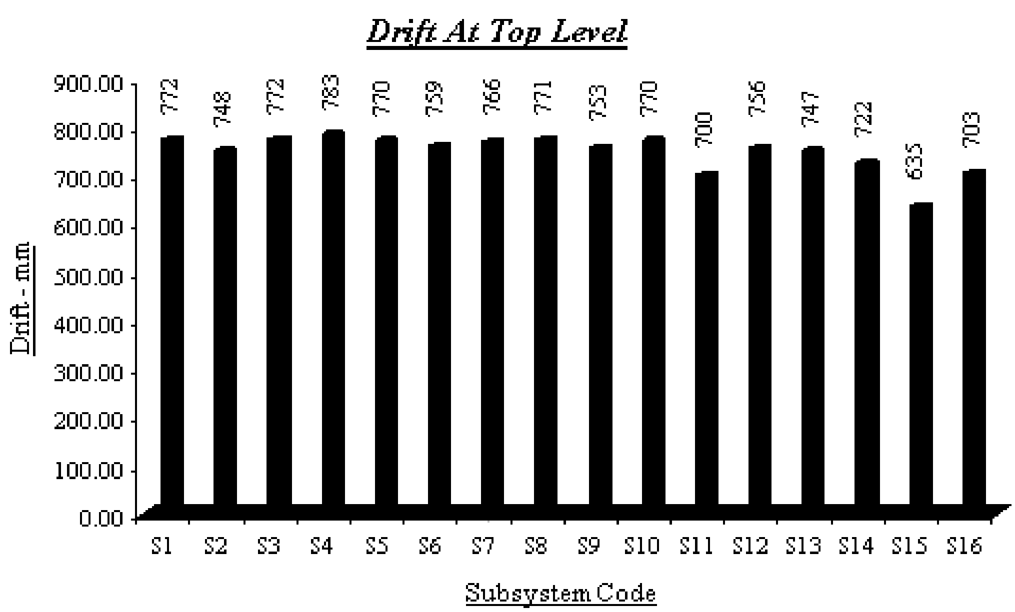


Fig. 3: Comparison of drift at top level associated with each structural system

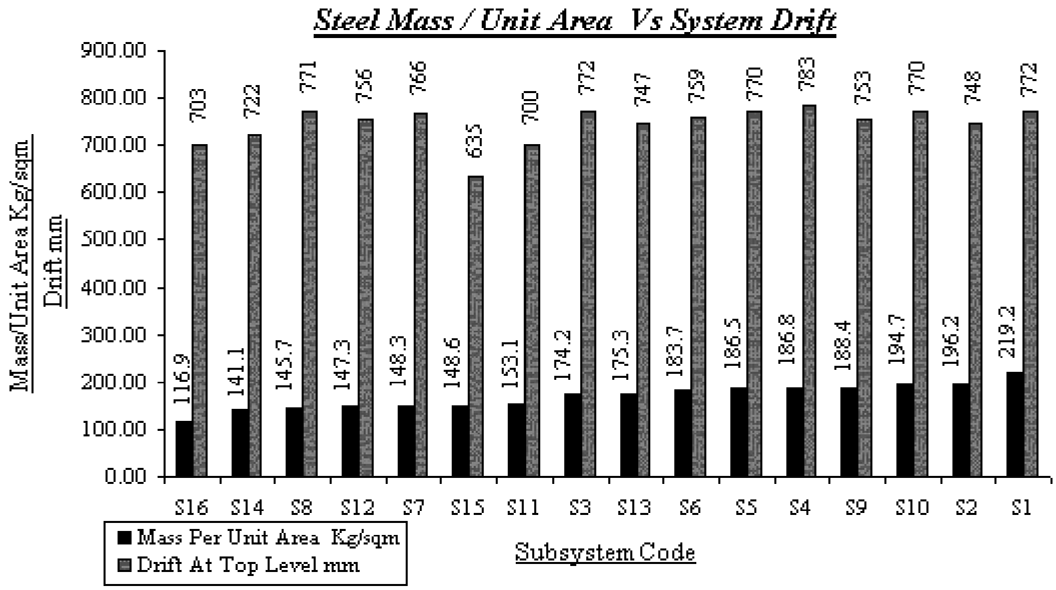


Fig. 4: Structural steel mass per unit area in ascending order and corresponding drift at top level

- Both least mass structural systems (S16 and S14) are quite efficient in terms of drift. Least mass structural system is also efficient than the second least mass system, in terms of drift.
- There is a difference of 21% between steel masses of first and second least mass systems (S16 and S14). On the other hand difference in maximum drift of both the systems is 2.7% in same sense which if equalized will result in an increase in difference of steel masses.
- There is a difference of 3.2% between steel masses of second and third least mass systems. On the other hand difference in maximum drift of both the systems is 6.8% in same sense which if equalized will result in an increase in difference of steel masses.
- There is a difference of 27% between steel masses of structural systems with subsystem S15 and S16. On the other hand difference in maximum drift of both the systems is 10.6% in opposite sense which if equalized will result in reduction in difference of steel masses.
- The drift in all the structural systems is either less or nearly equal to the permissible drift.

6. Conclusions

On the basis of results of the analysis and design the following conclusions are drawn:

1. For the building configuration selected, structural system “Composite Super Columns with Portals” subsystem is most efficient.
2. Structural system with “Ordinary Moment Frame” is least economical in terms of structural steel mass.
3. Structural system with subsystem “ Closely Spaced Frame Tube” is more economical than “Widely Spaced Framed Tube”
4. Structural systems containing super columns at appropriate locations are most economical and efficient for extremely tall and slender buildings.
5. Composite super columns with portals, super columns with portals and braced tube widely spaced are recommended as they can result in most efficient and economical structures.

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