Comparative Study of Structural Systems for High Rise Steel Buildings

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Abstract— **The structural design of high-rise buildings is governed by the lateral loads caused by wind or earthquake. In tall structure, stiffness is generally more important than its strength. As tall structures are considered as vertical cantilever, lateral load increases rapidly with increase in structure's height. Under wind loading the overturning moment at the base of a building is proportional to the square of the height of building and deflection is proportional to the fourth power of the building height. So, the structural system selected should have the adequate stiffness against the lateral loading caused by the wind or earthquake. Different structural systems are suitable for high-rise building to satisfy the design requirements. But it is important that the selected structural system should be such that the structural members can be utilized to its full design capacity. In the present study Moment Resisting Frame, Shear-Wall Frame and Outrigger structural systems are considered for design of 50 storey steel building. In case of Moment resisting frame hollow steel columns are provided at internal and at periphery of the structure. Unstiffened steel plate shear wall at central core is considered in Shear-Wall frame system while in Outrigger system, single outrigger provided at mid-level of building height is considered for the study. The comparison of analysis results of structural systems in terms of time period, top storey displacement and maximum drift is presented. Comparison of amount of steel required for satisfying the strength and serviceability requirement in all three structural systems is also presented.**

Index Terms — **Moment Resisting Frame, Outrigger Structure, Shear-Wall Frame structure, Tall structure, Wind loading**

I. INTRODUCTION

Development in the structural systems of tall buildings has been a continuously evolving process since 1880s. The tall buildings are generally affected by the lateral forces. Building can be classified as 'super tall' if its height is more than 300m. The factors responsible for the increasing high-rise buildings are lack of availability of urban land, advances in construction technology and high strength materials, efficient structural systems and computational techniques etc. Most of the tall buildings in the world have steel structural systems because of its high strength to weight ratio, easy to assemble and field installation, availability of various strength and wider selection of section.

In case of tall structure, stiffness is more important than its strength. It is necessary to ensure that the top storey displacement, lateral drift and human comfort level in tall structure are within the permissible limit. To satisfy the design requirements different structural systems are developed for high-rise building [1,3]. The amount of structural materials, like concrete and steel, required is very important factor in case of high-rise building. It is very important that the structural system is economical along with the safety. Moment resisting frame is an assembly of columns and girders, connected by the moment resistant connection. The main advantage of this system is that the internal planning is not obstructed because of its rectangular arrangement. This system can be economically used up to 25 stories. As the number of storey increases drift of the structure become difficult and costly to control [1].

In tall structure as the height of building increases lateral load govern the design. To resist the lateral load either steel bracings or RCC shear walls are used as a primary lateral load resisting system. However, the Steel Plate Shear Wall (SPSW) can also be used to resist the lateral load. SPSW consist of steel infill plate connected with beam and column. Steel plate shear wall resist the lateral load through diagonal tension in the web plate and overturning forces in the vertical boundary elements (columns) [2].

Outriggers have been historically used in the sailing ships to resist the wind loading and the same concept has been used in the high-rise structure as a lateral load resisting system. Outrigger structural system consists of a central core either of braced frames or shear walls and horizontal cantilever outrigger trusses or deep girders connecting the core to the periphery columns. In case of lateral loading, the rotation of the central core will be restrained by the deep outrigger by producing tension in the windward columns and compression in the leeward columns [3].

Gunel and Ilgin [4] discussed the structural systems that can be used for the tall buildings to resist lateral loading. Classifications were proposed for the structural systems of tall buildings for steel, concrete and composite buildings. Discussion had been carried out on rigid frame, braced frame, shear-wall frame, outrigger, framed-tube, braced-tube and bundled tube system. Kyoung Sun Moon [5] presented the amount of steel used in The Empire State building, John Hancock Center, World Trade Center NY and Sears Tower. He also presented the material-saving strategies, which can be used for the design of tall structure.

In this study a comparisons of the Moment Resisting Frame, Shear-Wall Frame and Outrigger Structure are carried out in terms of time period, top storey displacement, maximum drift and total quantity of Steel. 50 storey building is considered for the study. The building is modeled, analysed and designed using ETABS software [6]. The comparison of the amount of steel required for different structural system is also presented.

II. MODELING AND ANALYSIS OF BUILDING

A. General

In the present study 50 storey steel building is considered. Modelling and analysis of the building is carried out using ETABS software. The plan dimensions of Building are 24 m × 24m. Typical storey height is 3.5 m and total height of structure is 175 m.

B. Load and load combinations

Following loading data are considered for analysis and design

1) Dead Load:

Dead load includes the self-weight of the structural members and load of floor finish.

Floor Finish on roof : 1.5 kN/m^2
Floor Finish on floor : 1 kN/m^2

2) Live Load:

Live load on roof : 1.5 kN/m^2
Live load on floor : 3 kN/m^2

3) Earthquake Load:

Location : Ahmedabad
Seismic Zone : III
Importance factor : 1
Response reduction factor : 5

The static earthquake loading data are specified in ETABS.

4) Wind Load:

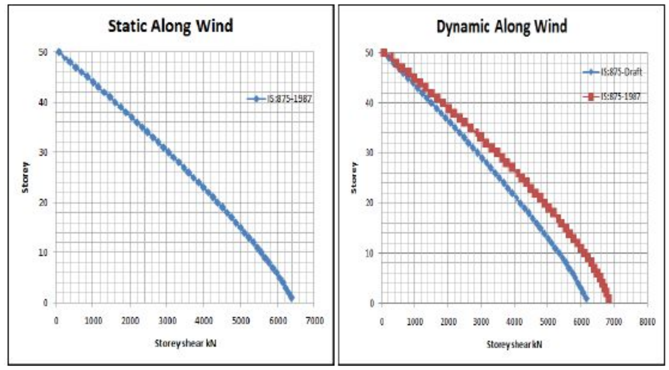
Location : Ahmedabad
Basic wind speed: 39 m/sec
Terrain category : III
Class : C

Parameters for static wind loading are specified in ETABS. Dynamic along wind loading is calculated as per IS: 875(III)-1987(Gust factor method) [7] and IS: 875 Draft code [8]. Across wind equivalent static load is also calculated. Base shear for static along wind, dynamic along wind and across wind loading is shown in Table I.

TABLE I
TOTAL WIND LOAD ON BUILDING

Sr. No	Loading		Base shear (kN)
1	Static wind	IS:875(III)-1987	6387.59
2	Dynamic wind	IS:875(III)-1987	6803.85
3		IS:875(III)-Draft	6119.76
4	Across wind IS:875 (III)-Draft		4866.31

Fig 1 shows the variation of static and dynamic storey shear in the direction of wind along the height of building. Comparison of dynamic along wind load calculated by Gust factor and IS:875-Draft code is presented in Fig 1(b). Gust factor method of IS:875(III)-1987 gives the higher dynamic along wind load compared to IS:875-Draft code. Dynamic along wind (IS: 875(III)-1987) and across winds are applied simultaneously to the building for analysis.



(a) (b)

Fig. 1. Storey shear considering along wind loading

Variation in storey shear due to across wind load along the height of building is shown in Fig 2.

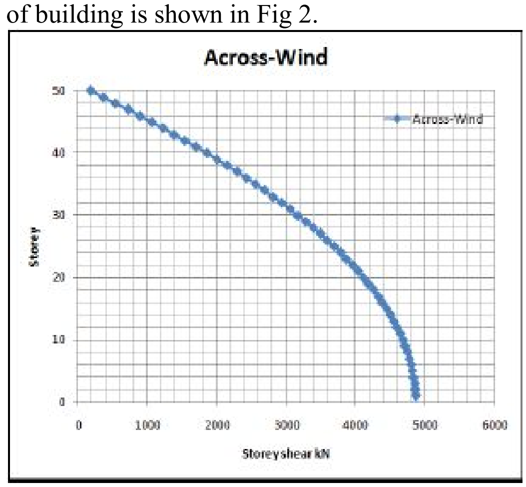


Fig. 2. Storey shear considering across wind loading

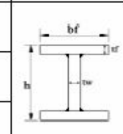
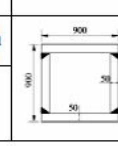
Load combinations for the design are as per clause 3.5 with appropriate partial safety factors given in Table 4 of IS: 800-2007 [9]. The design of critical members are carried out as per IS:800-2007 for governing load case.

C. Structural Systems Considered

1) Moment Resisting Frame

Typical floor plan and elevation of 50 storey moment resisting frame is shown in Fig 3. Hollow steel columns are provided at internal and at periphery of the building. The sizes of various members are shown in Table II.

TABLE II
SIZES OF STRUCTURAL MEMBERS OF MOMENT RESISTING FRAME BUILDING

Slab	S_1	150mm thick composite slab	
Beams	B_1	Built-up (h=600, b_f=250, $t_f = t_w$=25)	
	B_2	Built-up (h=600, b_f=300, $t_f = t_w$=25)	
	B_3	ISMB500	
Column	C_1	1200 × 1200 × 60 × 60 Periphery column	
	C_2	900 × 900 × 60 × 60 internal column	

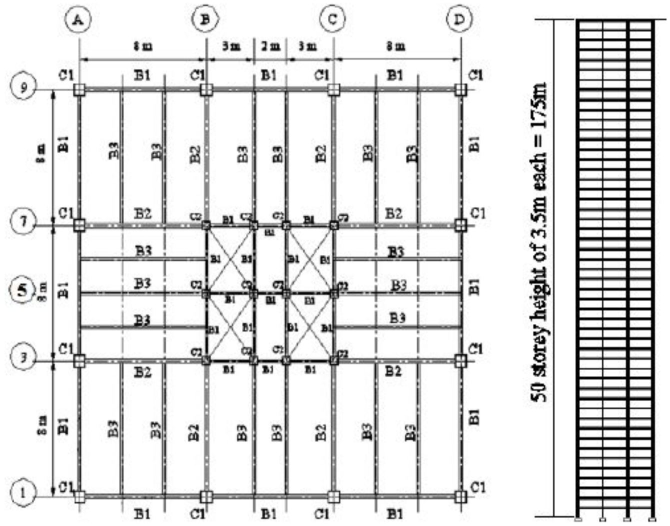


Fig. 3. Moment Resisting Frame (Typical floor plan and elevation)

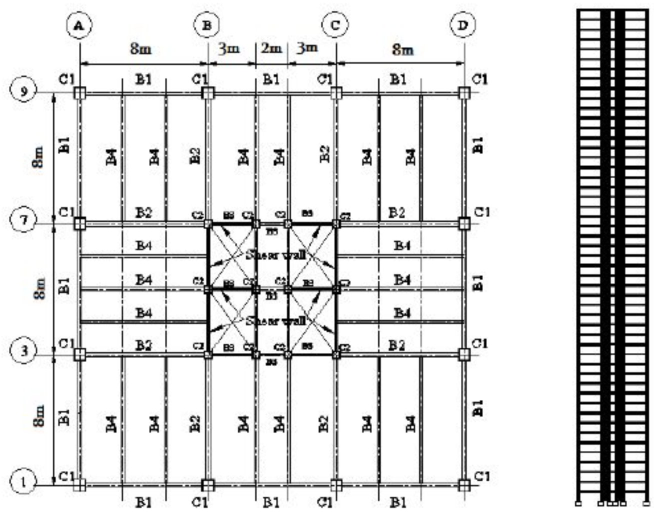


Fig. 4. Shear-Wall Frame structure (Typical floor plan and elevation)

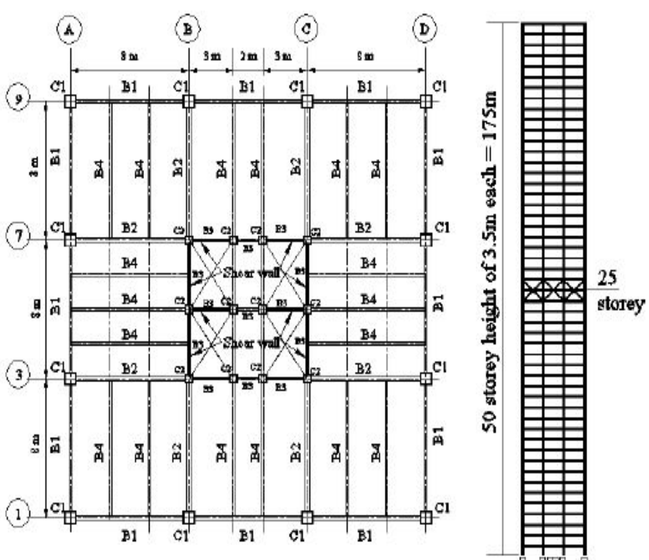


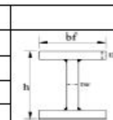
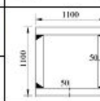
Fig. 5. Outrigger structural system. (Typical floor plan and elevation)

2) Shear-Wall Frame Structure

Typical floor plan and elevation of 50 storey Shear-wall frame building is shown in Fig 4. The central core consists of unstiffened steel plate shear wall with columns as vertical boundary element and beams as horizontal boundary element. The sizes of various members are shown in Table III.

TABLE III

SIZES OF STRUCTURAL MEMBERS OF SHEAR WALL FRAME BUILDING

Slab	S_1	150mm thick composite slab	
Beams	B_1	ISMB600	
	B_2	Built-up (h=600, b_f=250, $t_f = t_w$=25)	
	B_3	ISMB450	
	B_4	ISMB500	
Column	C_1	1100 × 1100 × 50 × 50 Periphery column	
	C_2	750 × 750 × 60 × 60 Core column	
Shear Wall	30mm	thick steel plate	

3) Outrigger structural system

Typical floor plan and elevation of 50 storey Outrigger structure is shown in Fig 5. The outrigger and belt-truss of two storey height is provided at mid height of building. The sizes of various members are shown in Table IV.

TABLE IV

SIZES OF STRUCTURAL MEMBERS OF OUTRIGGER BUILDING

Member type	Overall height mm	Flange width mm	Flange thickness mm	Web thickness mm
Beam B1	ISMB600			
Beam B2,B3	600	250	25	25
Beam B4	ISMB500			
Outrigger Diagonals	600	400	50	50
Outrigger Beams	1000	600	50	50
Column C1	900	900	50	50
Column C2	750	750	50	50
Steel Plate shear wall thickness				30mm

III. RESULTS AND DISCUSSION

The response of the different structural system depends on its behavior and load transfer mechanism. All the three buildings are modeled and analysed in ETABS software. The design of structural members is carried out manually as per IS:800:2007. The analysis results, considering appropriate designed section, for three structural systems are compared [10]. The comparison of time period, top storey displacement in X direction and in Y direction, maximum drift in X and in Y direction for Moment Resisting Frame, Shear-Wall Frame and Outrigger Structure are shown in Table V.

The variation of Time period for different structural system is shown in Fig 6. The Time period is minimum for Outrigger structural system compared to Moment resisting frame and Shear-wall frame system. This indicates more stiffness of outrigger structural systems.

The variation in the maximum displacement at top storey in X and Y direction are shown in Fig. 7 and Fig 8 respectively. The top storey displacements in X and Y directions are minimum for Outrigger structure.

TABLE V
COMPARISON OF RESULTS OF STRUCTURAL SYSTEMS

Parameters		Moment Resisting Frame	Shear Wall Frame	Outrigger Structure
Time period (sec)		5.553	5.370	4.929
Top Storey Displacement (m)	X	0.345	0.358	0.329
	Y	0.352	0.292	0.285
Maximum Drift (mm)	X	2.556	2.620	2.262
	Y	2.687	2.040	2.033

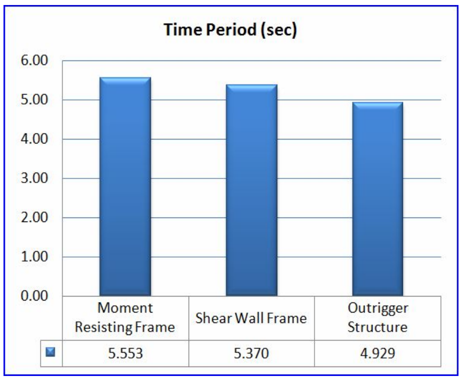


Fig. 6. Comparison of Time Period

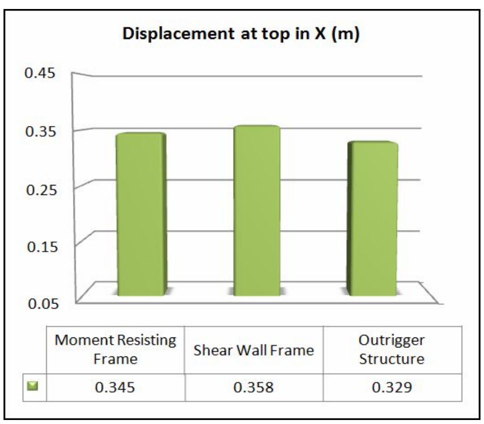


Fig. 7. Comparison of Top Storey displacement in X dir

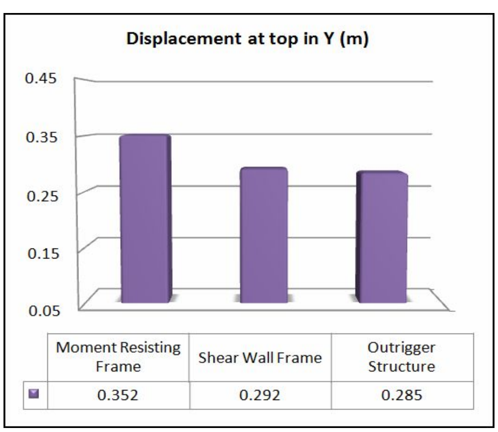


Fig. 8. Comparison of Top Storey displacement in Y dir

The variation in maximum drift in X and Y direction are shown in Fig 9 and Fig 10 respectively. Outrigger structural system has minimum inter-storey drift compared to moment resisting frame and shear wall frame structure.

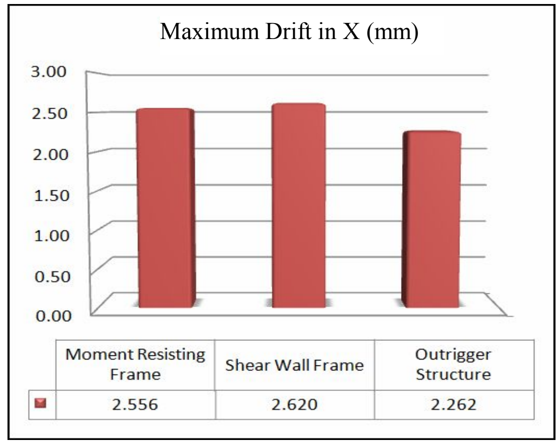


Fig. 9. Comparison of Maximum storey drift in X dir.

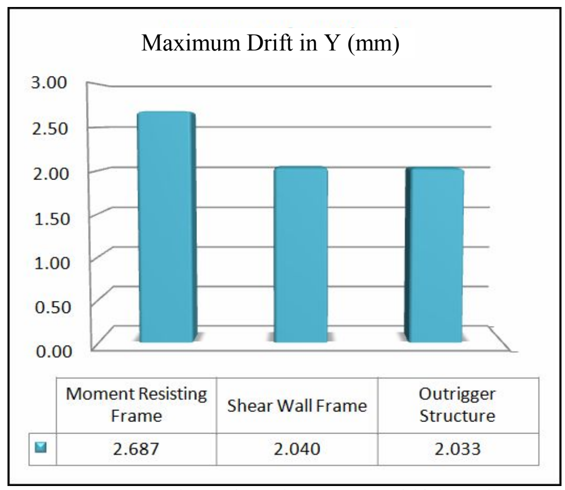


Fig. 10. Comparison of Maximum storey drift in Y dir.

The percentage reduction in Time period, Top storey displacement and Maximum drift for Shear-wall frame and Outrigger system in comparison with Moment resisting frame are shown in Table VI.

TABLE VI
COMPARISON OF RESULTS IN TERMS OF PERCENTAGE REDUCTION

Parameters		Shear Wall Frame	Outrigger Structure
Time period		3.30	11.24
Top Storey Displacement	X	-3.77	4.64
	Y	17.05	19.03
Maximum Drift	X	-2.50	11.50
	Y	24.08	24.34

In case of Shear-wall frame structure Time period is reduced by 3%, Top storey displacement is reduced by 17% in Y direction and Maximum drift is reduced by 24% in Y direction compared to Moment resisting frame. The displacement and drift in X direction increase by 4% and 2.5% respectively due to less stiffness. The Outrigger structure reduced the Time period by 11%, Top storey displacement in X direction by 4%, in Y direction by 19%, Maximum drift in X direction by 11.5% and in Y direction by 24%.

Storey displacements variation in X and Y direction along the height of building are presented in Fig 11 and Fig 12 respectively. Variation in storey drift in X and Y direction along the height of building are presented in Fig 13 and Fig 14 respectively.

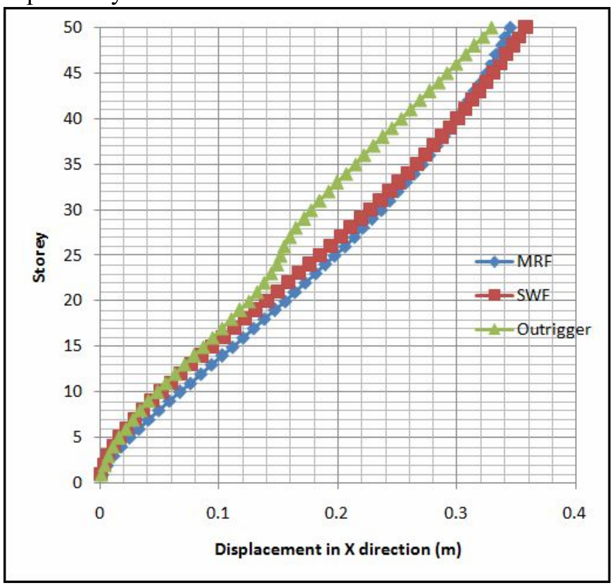


Fig. 11. Storey displacement variation along height in X dir.

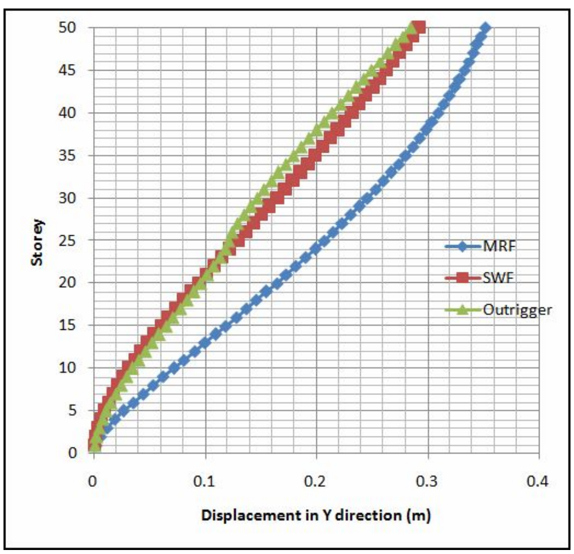


Fig. 12. Storey displacement variation along height in Y dir.

From the design of 50 storey building with all the three structural systems requirement of steel is estimated. The total quantity of steel required for Moment Resisting frame, Shear-wall Frame and Outrigger structure is presented in Table VII.

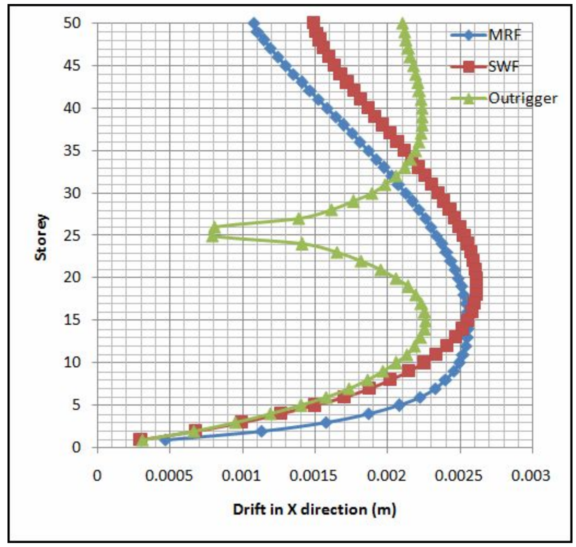


Fig. 13. Storey drift variation along the height in X dir.

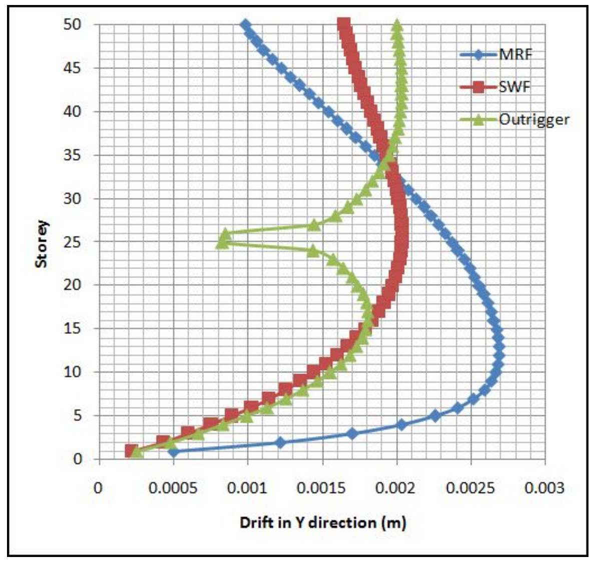


Fig. 14. Storey drift variation along the height in Y dir.

TABLE VII
REQUIRED QUANTITY OF STEEL

Item	Weight (Tonne)		
	Moment Resisting Frame	Shear-Wall Frame	Outrigger Structure
Slab (Deck Sheet)	296.660	296.660	296.660
Column	7817.115	6178.679	5099.549
Beam/Outrigger	2497.485	1860.559	2457.173
Diagonal	-	-	216.564
Shear Wall	-	1398.263	1398.263
Total quantity of structural Steel	10611.26	9734.17	9468.21
% reduction	-	8.27	10.77

In case of Shear-wall frame total quantity of steel required is 8% less while in case of Outrigger system 10% less steel required compared to Moment resisting frame. Kyoung Sun Moon [5] pointed the amount of steel used in The Empire State building, John Hancock Center, World Trade Center NY and Sears Tower. He also presented the material-saving strategies which can be used for the design of tall structure. Table VIII shows the comparison of the amount of steel required for different well known structure with the present study.

TABLE VIII
AMOUNT OF STEEL REQUIRED PER SQUARE FOOT OF FLOOR AREA

Building	Year	Stories (Height/ Width)	Structural System	Steel Usage	
				psf	Tonne/ m^2
Empire State Building, NY	1931	102 (9.3)	Braced Rigid Frame	42.2	0.21
John Hancock Center, Chicago	1968	100 (7.9)	Braced Tube	29.7	0.15
World Trade Center, NY	1972	110 (6.9)	Framed Tube	37.0	0.18
Sears Tower Chicago	1974	109 (6.4)	Bundled Tube	33.0	0.16
Present Study	2011	50 (7.29)	Rigid Frame	74.7	0.36
			Shear-Wall Frame	68.5	0.34
			Outrigger System	66.7	0.33

It is observed that the structural system play an important role in the design of tall structure. The higher values of steel consumption in present study are observed due to uniform member sizes throughout the height. The steel consumption can be reduced by varying sizes of structural members along the height.

IV. Summary and Conclusions

The comparisons of the Moment resisting frame, Steel plate shear-wall frame and Outrigger structural systems are carried out in terms of building response like time period, top storey displacement, drift and analysis results. The total steel required for different structural systems considered for 50 storey high rise regular building is also compared. Analysis results show that the outrigger system is most effective and economical.

- The shear-wall frame structure reduces the time period by 3%, top storey displacement by 17% and maximum drift by 24% in Y direction, top storey displacement increased by 4% and maximum drift increased by 2.5% in X direction respectively.
- The outrigger system reduces the time period by 11%, top storey displacement by 4% in X direction and 19% in Y direction, Maximum drift by 11.5% in X direction and 24% in Y direction compare to Moment resisting frame.
- The Shear-wall frame structure requires 8% less steel compared to Moment resisting frame.
- The Outrigger structural system requires 10% less steel compared to Moment resisting frame.

V. References

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