Seismic Analysis and Parametric Study on Mitigation Measures of Shear Lag Effect in Frame Tube High-Rise Structures

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Abstract - *In modern development of tall building, there are various way to make structure efficient and effective during lateral loading as well as important to choose suitable structural system to satisfy all criteria.* Among many structural systems, tubular structural system provide most efficient structural concept by its configuration and combination with the other system are used world widely. *A G+44 story bare frame (BF) and frame tube (FT) structure with core wall are designed and analysed using response spectrum and time history analysis for zone V in ETABS 17 according to IS 1893:2016, IS 16700:2017. A parametric study is carried out to investigate existence of shear lag effect in terms of shear lag ratio (SLR) in bare frame and frame tube structure using varying column spacing, extra internal tube i.e. tube-in-tube and varying depth of beam to obtained optimised frame tube model for practical application for tall structures. Non-linear dynamic time history analysis is performed on optimised frame tube model using seven earthquake records and presented results in form of base shear, top floor displacement, time period and shear lag ratio to check the behaviour of frame tube structure during seismic action. It is observed that the varying parameters mitigate shear lag effect effectively and optimised frame tube system become structural solution for high-rise structures.*

***Key Words*: Frame Tube System, Tube-in-tube system, Shear Lag Effect**

1. INTRODUCTION

In modern development, high-rise structure developed intensively from decades by putting various configuration, splayed section or setbacks in building. Structural engineer matches architectural design in computer, which is revolutionary tool for today's stable analysis design of structure. Therefore, the necessity of knowledge about some of the less usual structural solution to implement on the structure. Strength, rigidity and stability are the three important basic concept for any design of building. In low-rise structures, the strength factor plays important role. The rigidity and stability are more important when height rises. Those requirements satisfied by two ways: first is to increase size of members beyond and above strength needed but it is uneconomical and not practically applicable. The second approach is to change the configuration into something innovative way to reduce deflection and increase stability.

Fazlur Khan firstly established tubular concept for modern high-rise structures. In recent years, the tallest building constructed with tubular system. The practical applications of tubular structures are the Standard Oil Building, the Sears tower and the Hancock Building in Chicago, old the World Trade Centre in New York. The amount of structural material required per m^2 space of tubular system is half the size as comparable to that used in conventionally frames hence tubular structures are most efficient and effective for high-rise structure.

1.1 Literature Survey

Bungale S. Taranath [1] introduces evolution of high-rise structures and its impact on size and location of structural elements and explained their seismic design and behaviour under lateral loading. Specifically, detailed design, behaviour and shear lag phenomenon of frame tube system were well explained by taking practical design of constructed high-rise structures. Author designed and analysed by taking various tall buildings such as 56-story office building in Dallas, 100-story John Hancock Center in Chicago, 56-story Bank of China Tower in Hong Kong, 443.5m high and 110-story Sears Tower having area 68.6m x 68.6m with combination of bundled tube for detailed understanding. As stated by author, for building taller than 50–60 stories the window opening should be made relatively narrow to reduce the shear lag.

Shreyans Rathod, Israr Khan, Keshav Sangle [4] presented optimization of structures using different structural system. A G+50 storey 32m x 32m in plan structure analysed using the tube in tube, shear wall and core out-trigger system in ETABS V9.7.4 software and compared the performance and behaviour of the considered systems. Top floor displacement and the story drift was less for tube in tube system while more for core and outrigger system. Story shear was minimum for tube in tube system while maximum for shear wall system. Time period was minimum for shear wall system while maximum for tube in tube system. Economically tube in tube was the cheapest.

K. K. Lee, H. Guan, Y. C. Loo [11] proposed method of minimum potential energy of framed-tube structures with multiple internal tubes. Based on minimum potential energy method the numerical model was prepared for frame tube with internal tube i.e. tube-in-tube. Three 40-storey frame tube structure with single, two and three internal tubes were analysed using proposed method in ETABS 1989. Column axial forces in flange frame panel of external and internal tubes were computed at 1st and 10th level. It was observed in external tube that effect of positive shear lag is greater at bottom of structure, whereas negative shear lag occurs at around ¼ of building height.

Yogesh D. Nagvekar, Dr. Mohankumar P. Hampali [13] gave analysis of shear lag effect in hollow structure. A 30-story 45m x 27m in plan structure was prepared to check the behaviour and shear lag effect in hollow tubular structure using ETABS software with lateral uniform load of 120 kN/m. The results obtained as the axial force in corner columns of 1st and 5th storey was maximum and in central columns were minimum, which is positive shear lag phenomenon. The results showed that at top of building negative shear lag was present on periphery columns.

1.2 Objective of Study

The following are objectives made for G+44 bare frame and frame tube structure with central core analysed using response spectrum and time history method:

1. To study analytical methods such as response spectrum method and time history analysis in ETABS 17 software for the analysis of tubular building system.
2. To evaluate percentage difference in total weight of structure by comparing tubular structure with bare frame to minimize material as well as weight of members to achieve sustainability and economy with maximum floor area.
3. To obtain optimised solution for mitigating shear lag effect in frame tube system by designing G+44 story frame tube structure with varying different parameters such as columns spacing at periphery, internal tube i.e. tube-in-tube, depth of beam.
4. To compare the results of frame tube structure with bare frame structure in terms of base shear, top floor displacement, time period, and shear lag effect in terms of shear lag ratio by using response spectrum method.
5. To investigate and study the behaviour of optimum model of frame tube structure by performing time history analysis for zone V.

2. TUBE SYSTEM

The tubular structures are in the category of exterior structures in which the lateral loads resisted by system situated at periphery of structure and minimises structural premium for lateral strength and stiffness, also architecturally designed for obstruction-free living area.

2.1 Frame Tube System

A frame tube structure is mainly composed of columns situated closely at the periphery of building link with the each other using deep beams. The frame tube structure 43-story apartment building in Chicago first established by Fazlur Khan. The other advantage of this system with respect to exterior cladding system costs minimise by closely spaced columns acts as a mullion. Partial or total removal of mullion of the curtain wall for window with the help of exterior columns. The another application of this system is the interior floor plan is kept obstruction-free of core bracing and large columns which increasing net leasable area for building. The structure has a tube like form which resist lateral loads at its periphery, thus its behaviour is much more complex than that of a solid tube so it is subjected to shear lag effects. The increase in axial stresses in the corner columns compared to in the inner columns of both the flange and the web panels as shown in figure 1 is called shear lag phenomenon. Every system has limitations so the aim is to reduce shear lag effect and make frame effective during seismic action.

2.2 Shear Lag Effect

The bending stresses will not be proportional to the distance from the neutral axis of the section during bending action hence the stress at the centre of the flanges "lags" behind the stress near the corners under lateral loading because of the lack of shear stiffness of the wall panel. The shear lag plays vital role in any frame tube structures. The axial stress concentration is more in corner columns than the inner columns and its behaviour is non-linear due lack of shear stiffness. Therefore from above, shear lag effect is represented in shear lag ratio (SLR) is the ratio of axial force distribution of corner columns to axial force of inner column at one edge of the exterior tube. The shear lag ratio is simply given as following expression:

$$\text{Shear Lag Ratio (SLR)} = \frac{\text{Axial Force in Corner Columns}}{\text{Axial Force in Middle Column}}$$

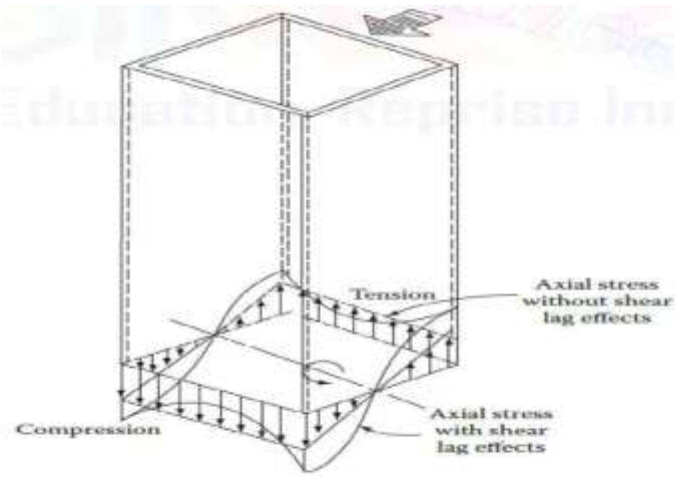

Fig - 1: Axial stress distribution with and without shear lag in hollow tube structure

2.3 Tube-in-Tube System

Additional columns required to support the gravity loads between the outer tube and inner core when the size of plan rises, because of too much prevention of the slab from bending. As the lateral loads become large to increase stiffness of frame tube, the extra internal tube system of closely spaced columns installed inside the structure named as tube-in-tube system. The 52-story One Shell Plaza of 1971 in Texas is the brilliant example of such system. The inner tube columns are connected with help of primary and secondary beams to the periphery columns for increase the stiffness of outer peripheral tube of columns as shown in figure 2.

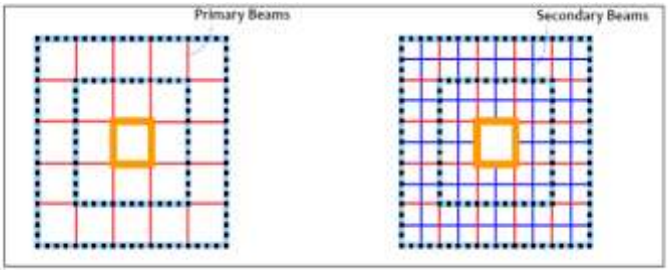

Fig - 2: Beam-Column plan of tube-in-tube system

3. STRUCTURAL MODELLING AND ANALYSIS

A G+44 story RC bare frame (figure 3) and frame tube (figure 4) buildings with core wall are considered for computation and analysis work. The structure is 135.5 m tall, and is 24.0 m wide and 24.0 m length square in plan. The ground story height is 3.5 m and other story height are 3m. Proposed slab thickness is 200 mm for all typical floors. The following are the properties of bare frame and frame tube model for designing and modelling system shown in table 1. The plan and 3D view of optimised model with large internal tube and 4m spacing as shown in figure 5. To have more thorough understanding of shear lag effect in frame tube building model, a parametric study of frame tube building with various arrangements as shown in table 4. The model is designed as per IS 456:2000 IS 16700:2017 and earthquake data considered as per IS1893:2016.

Table -1: Properties of bare frame and frame tube model

Material Properties	
Grade of Concrete	M40
Grade of Steel	Fe500
Ec	31622.78 MPa
Es	200000 MPa
Section Properties	
Beam size	Main Beam – 0.7 m x 0.9 m
	Core Beam – 0.4 m x 0.5 m
Column Size	Main Column= 0.9 m x 0.9m
	Core Column = 0.6 m x 0.6m
Load Consideration	
Floor Finish	1.5 kN/m^2
Core Wall Load	11 kN/m^2
Live Load	4 kN/m^2
Roof Live Load	1.5 kN/m^2
Seismic Properties	
Seismic zone	V
Response Reduction Factor	5
Importance Factor	1
Soil Type	II

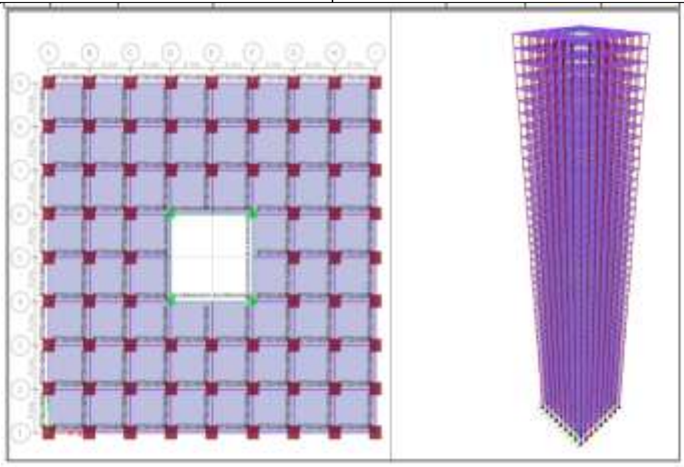

Fig - 3: Plan and 3D view of bare frame M1 model

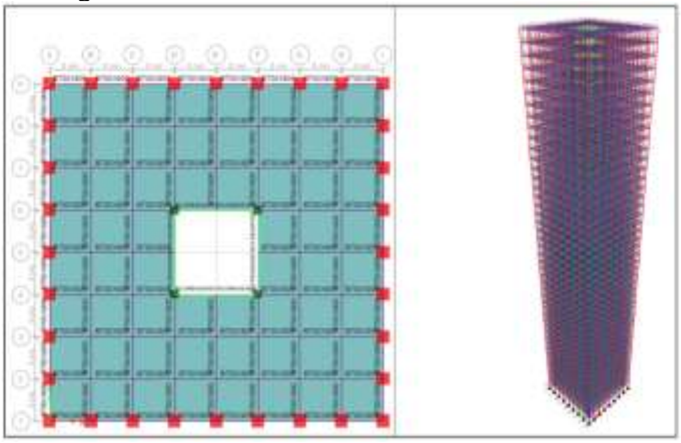

Fig - 4: Plan and 3D view of frame tube M2 model

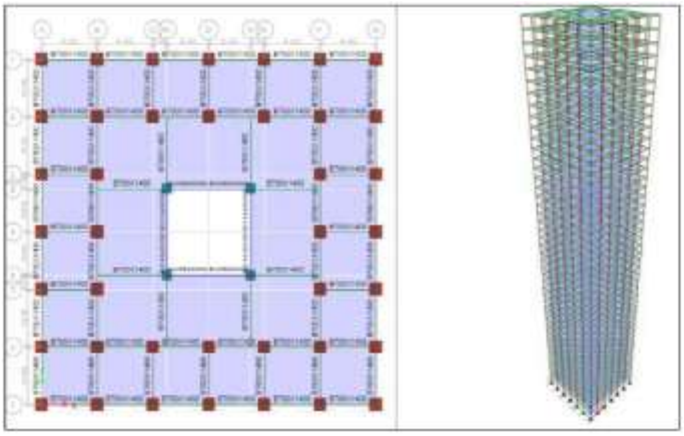

Fig - 5: Plan and 3D view of optimised FT M10 model

Table -2: Details of composed models

Sr. No.	Model No.	Parameter Studied	Specification
1.	M1		Bare Frame (BF) model
2.	M2		Frame Tube (FT) model
3.	M3	Column Spacing	FT with 2 m column spacing
4.	M4		FT with 4 m column spacing
5.	M5	Internal Tube	FT with smaller internal tube
6.	M6		FT with larger internal tube
7.	M7	Beam Depth	FT with 0.7 m beam depth
8.	M8		FT with 1.1 m beam depth
9.	M9		FT with 1.4 m beam depth
10.	M10	4m spacing, 1.4m beam depth	Optimised model

3.1 Response Spectrum Analysis

Response spectrum analysis is a means of using acceleration response spectra to determine the maximum forces and displacements in a structure that remains elastic when it responds to ground shaking. Response spectra are very useful tools of earthquake engineering for analysing the performance of structures and equipment in earthquakes.

3.2 Time History Analysis

The earthquake record in the form of acceleration time history is input at the base of the structure. The response of the structure is computed at each second for the entire duration of an earthquake. This method differs from response spectrum analysis because the effect of "time" is considered. For analysis purpose time histories with their Richter magnitude are selected as: San Fernando, Imperial Valley, Loma Prieta, Cape Mendocino, Joshua tree-Landers, Duzce-Turkey, Chuetsu-oki Japan.

4. RESULTS AND DSCUSSION

The weight and total number of elements used in the bare frame and frame tube structure are calculated to measure efficiency and economic considerations. The total structural weight for bare frame (M1) model is obtained as 527233.0155kN while for frame tube (M2) model is 418525.3566kN. The structural weight of frame tube (M2) model is reduced as compared to bare frame (M1) model by 20.62%. The reduction of main columns in frame tube (M2) model compared to bare frame (M1) model is 55.56%, which reduces total weight of frame tube (M2) model as calculated from table 3.

Table -3: Elements required for M1 and M2 models

Type of Frame	Pieces/Nos. of Elements			
	Main Column	Core Column	Main Beam	Core Beam
Bare Frame	3240	180	5940	360
Frame Tube	1440	180	5940	360

4.1 Results by Response Spectrum Analysis

1. Base shear

When compared to M1 model, the base shear is decreased by 33.8% for M2 model because the number of elements are more in M1 model than M2 therefore the weight of bare frame is more as shown in figure 6. Due to extra internal ring of columns, maximum beam depth in optimised M10 model the base shear value is increased by nearly 21% than FT M2 model.

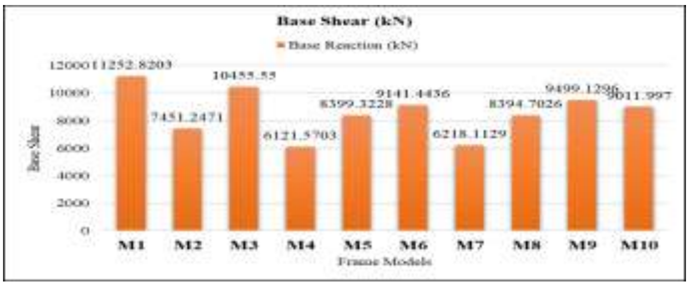

Fig - 6: Comparison of base shear of models

2. Top floor displacement

Tubular structure is efficient than bare frame structure as displacement of FT M2 model is reduced by 14.6% than BF M1 model as shown in figure 7. Due to extra internal ring of columns, maximum beam depth in optimised M10 model the displacement value is decreased by nearly 18.27% than FT M2 model.

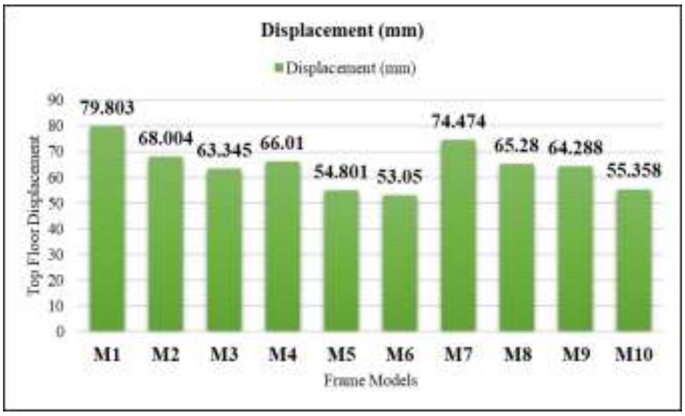

Fig - 7: Comparison of top floor displacement of models

3. Shear lag ratio

The non-linear axial stress distribution at periphery columns of all bare frame and frame tube models as shown in figure from 8 to 17. The SLR is calculated for G+44 story BF and FT building at 1st, 5th, 15th, 25th, 35 and 45-story level by using response spectrum analysis in ETABS 17. In all models the M4, M6 and M9 model mitigate shear lag effect.

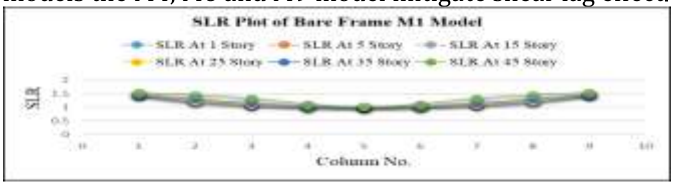

Fig - 8: SLR plot of bare frame M1 model

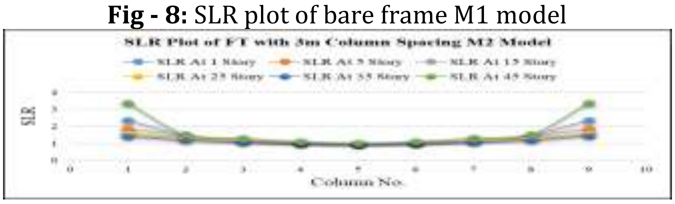

Fig - 9: SLR plot of frame tube M2 model

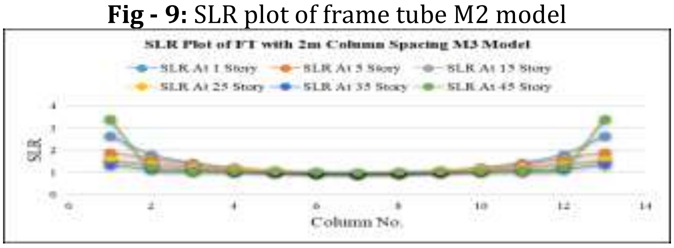

Fig - 10: SLR plot of FT with 2m spacing M3 model

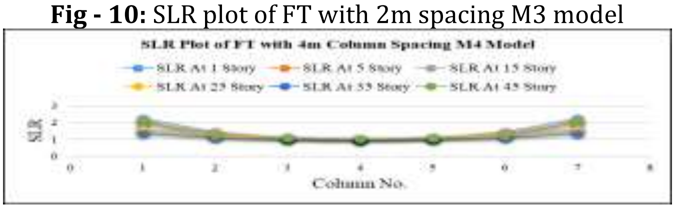

Fig - 11: SLR plot of FT with 4m spacing M4 model

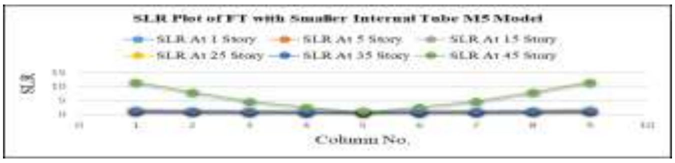

Fig - 12: SLR plot of FT with smaller tube M5 model

Fig - 13: SLR plot of FT with larger tube M6 model

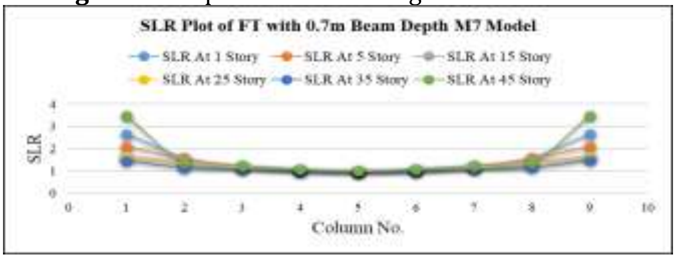

Fig - 14: SLR plot of FT with 0.7m beam depth M7 model

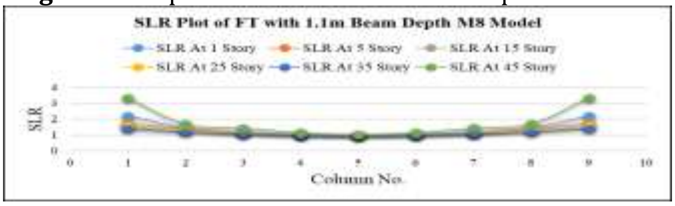

Fig - 15: SLR plot of FT with 1.1m beam depth M8 model

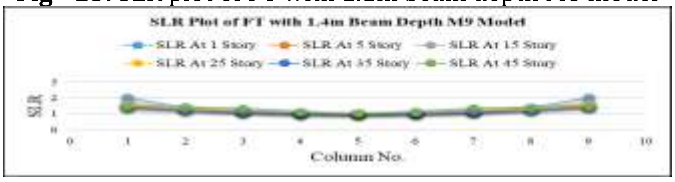

Fig - 16: SLR plot of FT with 1.4m beam depth M9 model

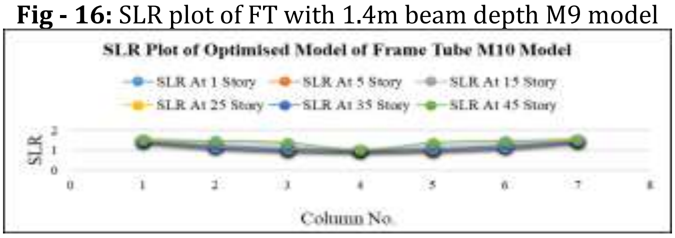

Fig - 17: SLR plot of optimised FT M10 model

Those all parameter models proved to more efficient in mitigating SLR than M2 and their respective model hence the SLR for optimised model are less.

4.2 Results by Time History Analysis of M10 Model

1. Base shear

The maximum base shear obtained along X-direction is 12444.8434 kN for San Fernando earthquake and along Y-direction is 12416.8096 for Chuetsu-oki Japan earthquake as shown in figure 18.

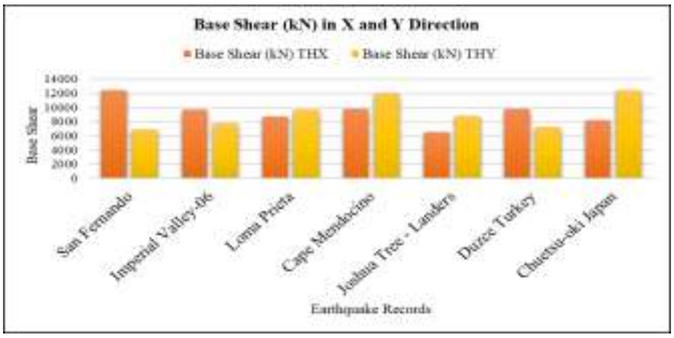

Fig - 18: Comparison of base shear of seven earthquake

2. Top floor displacement

The maximum displacement obtained along X-direction is 60.433mm San Fernando for earthquake and along Y-direction is 66.641mm for Loma Prieta earthquake as shown in figure 19.

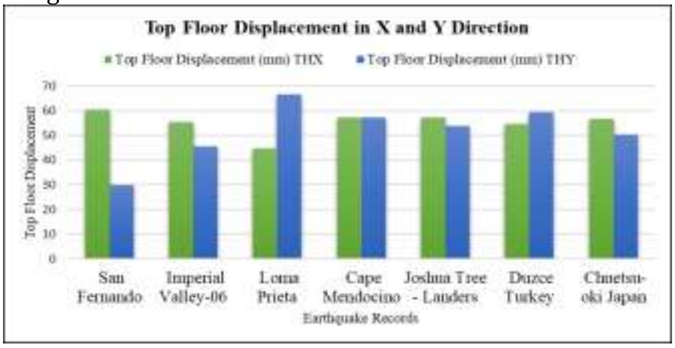

Fig - 19: Comparison of displacement of seven earthquake

3. Shear lag ratio

The slight nonlinearity observed for Loma Prieta and Cheutsu-oki Japan earthquake records. optimised FT M10 model satisfied with all seven earthquake records and practically applicable by reducing shear lag ratio as shown in figure from 20 to 26.

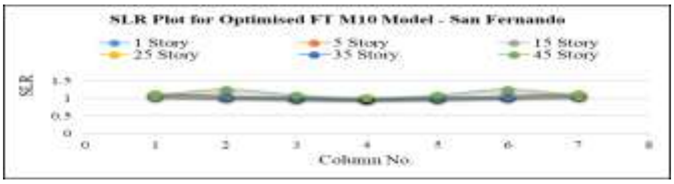

Fig - 20: SLR plot of FT M10 model-San Fernando

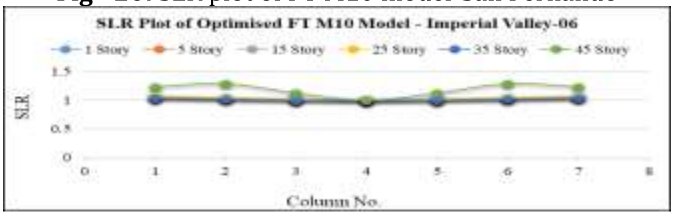

Fig - 21: SLR plot of FT M10 model-Imperial Valley

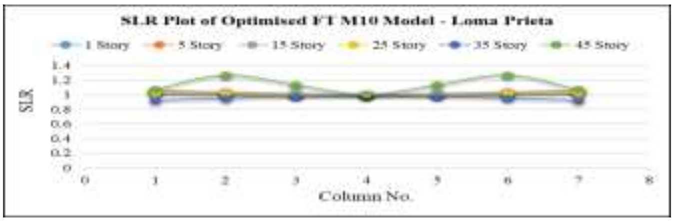

Fig - 22: SLR plot of FT M10 model-Loma Prieta

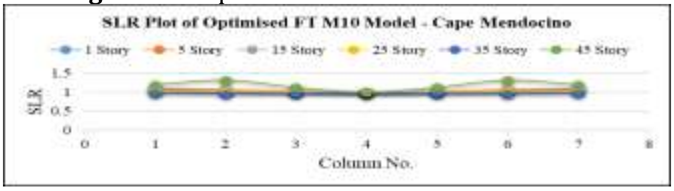

Fig - 23: SLR plot of FT M10 model-Cape Mendocino

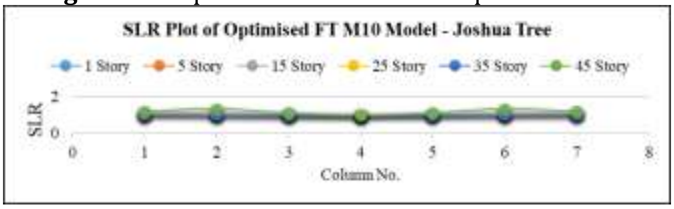

Fig - 24: SLR plot of FT M10 model-Joshua tree Landers

Fig - 25: SLR plot of FT M10 model-Duzce Turkey

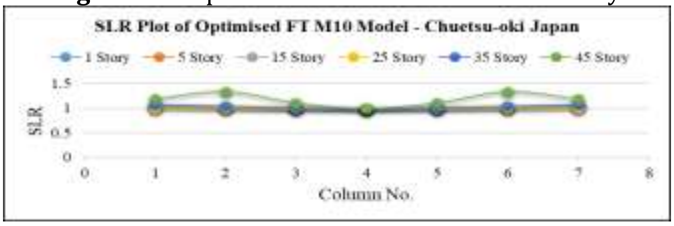

Fig - 26: SLR plot of FT M10 model-Chuetsu-oki Japan

4.3 Fundamental Time Period

1. When the percentage increase in stiffness because of increase in number of columns is larger than the percentage increase in mass, the natural period reduces. Hence, the usual discussion that increase in number of columns reduces the natural period of buildings, does not consider the simultaneous increase in mass. Buildings are said to have shorter natural periods with increase in number of columns. Stiffer buildings have smaller natural period.[3] After comparing bare frame BF M1 model with frame tube FT M2 model. The mass of BF M1 is higher than FT M2 model but time period is obtained as 2.7 sec and 3.706 sec. also in model M5 and M6 the time period is 2.994 sec and 2.858 sec implies that increment in stiffness of M6 reduces the time period as shown in figure 27.

2. Mass of a building that is effective in lateral oscillation during earthquake shaking is called the seismic mass of the building. Heavier buildings have larger natural period. This

kind of situation occurred in model M8 and M9 as the depth of beam increases the mass of structure hence M9 model has 3.618 sec marginally more time period than 3.608 sec of M8 model.

3. Value of T depends on the building flexibility and mass; more the flexibility, the longer is the T this type of situation present in M4 compared with M2 model. As the M4 model have less number of columns than M2 model as see in plan of M4 model results time period 4.207 sec which greater than M2 model time period. In the M7 model depth of beam reduced, the stiffness becomes flexible and therefore increases the time period 4.007 sec than M2 model.

4. In optimised FT M10 model has time period is 3.162 sec, which is between the different parameter frame tube models. In general, taller buildings are more flexible and have larger mass, and therefore have a longer T.

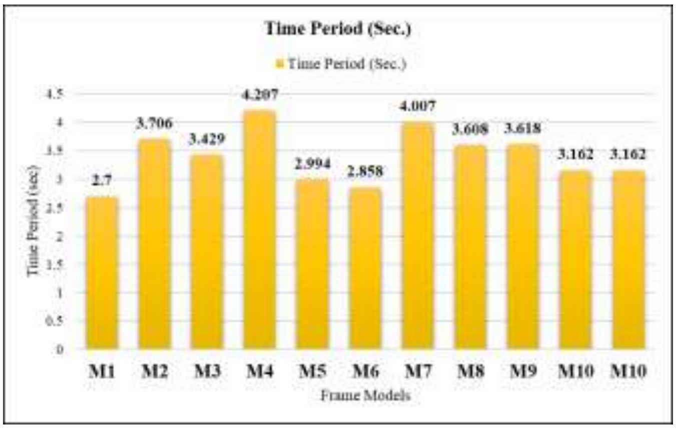

Fig - 27: Comparison of time period of all models

5. CONCLUSIONS

The following are the conclusions made after analysed various the models using response spectrum and time history analysis according to objective discussed earlier:

1. The structural weight of frame tube (M2) model reduced as compared to bare frame (M1) model by 20.62%. As the number of required for designing frame tube (M2) model are less as compared to bare frame (M1) model. The reduction of main columns in frame tube (M2) model compared to bare frame (M1) model found as 55.56%, which reduces total weight of frame tube (M2) model.

2. When compared to M1 model, the base shear is decreased by 33.8% for M2 model. The number of elements are more in M1 model than M2 therefore the weight and base shear of bare frame is more than frame tube model. Due to extra internal ring of columns, maximum beam depth in optimised M10 model the base shear value is increased by nearly 21% than FT M2 model.

3. Tubular structure is efficient than bare frame structure as displacement of FT M2 model found to be reduced by 14.6% than BF M1 model. For optimised FT M10 model compared M2 model the displacement reduced by 18.6%.

4. The 4m column spacing (M4 model), larger internal ring of columns (M6 model) and increased beam depth (M9 model) upto 1.4m proved to be effective in mitigating shear lag effect and thus those parameters taken to design optimised FT M10 model. The optimised FT M10 model resulted to be more efficient in mitigating shear lag effect as well as in seismic action.

5. The maximum base shear and displacement along X-direction obtained as 12444.8434 kN and 60.43mm for San Fernando earthquake and along Y-direction found to be 12416.8096 for Chuetsu-oki Japan and 66.64mm for Loma Prieta earthquake.

6. The time period obtained as different for different model because of effect of stiffness, mass and flexibility.

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