BEHAVIOUR OF SHEAR LAG OF PERIPHERAL T-SHAPED SHEAR WALL IN FRAMED TUBE STRUCTURES

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ABSTRACT

The framed tube concept is an effective framing technique. This structural system comprises tightly spaced peripheral columns connected by deep spandrel beams. The whole system works as a giant vertical cantilever, and its high efficiency is due to the considerable distance between windward and leeward columns. In a framed tube structure under lateral load, the stress distribution of the flange wall panels is nonuniform and nonlinear, and in the web wall panels, it is called "shear lag." The most important structural system features that determine tall building behaviour are plan geometry, body shape, height-to-width ratio, and stiffness for wind and seismic load transmission. Reinforced concrete structural walls provide substantial lateral strength and stiffness to limit damage when structures are subjected to ground shaking. In this paper, T-shear walls replace the peripheral columns in framed tube structures to get better performance by reducing the shear lag effect. The flange shear lag factor of square-shaped framed tube structures having peripheral T walls is reduced from 4% to 57% compared to structures with peripheral columns. The shear lag factor decreases with height in a building, reaching zero at specific stories and then converting to negative. The shear lag factor depends on the structure's height. The buildings with lower height have a higher shear lag factor than the buildings with higher height.

Keywords: *Framed tube, T shear walls, Shear lag.*

1. INTRODUCTION

Framed tube structures have significant advantages over traditional building designs, particularly in terms of structural integrity and sustainability. These structures are increasingly favored in high-rise construction due to their superior seismic performance, efficient material use, and innovative design capabilities. This structural system comprises tightly spaced peripheral columns connected by deep spandrel beams. The whole system works as a giant vertical cantilever, and its high efficiency is due to the considerable distance between windward and leeward columns (Moghadasi et al., 2020). Framed tube structures are recommended for high-rise constructions due to their high resistance against lateral and seismic forces, offering significantly higher structural resistance than other systems (Nassani & Kamiran, 2020). Framed tube structures exhibit enhanced seismic resistance compared to traditional shear wall systems. They demonstrate reduced displacements, higher drift ratios, and improved structural ductility, making them suitable for tall buildings in seismic regions (Sutar & Patil, 2023). These structures also perform well under wind loads, with tube-in-tube systems providing stability against both lateral and gravity loads, enhancing the building's overall stability (Wadde & Awari, 2022).

Reinforced concrete walls have traditionally had rectangular cross-sections, but composite cross-sections like T-shaped walls are becoming more common (Rojas et al., 2021). T-shaped walls exhibit varied seismic performance under different conditions and configurations. Research on full-scale T-shaped precast concrete superposed shear walls with cast-in-place boundary columns and special boundary elements shows that these walls can achieve seismic performances comparable to or even superior to traditional cast-in-place walls, especially when using novel vertical joint designs and higher axial compression load ratios (Gu et al., 2022; Singhal et al., 2021). The coupling of bidirectional horizontal ground motions significantly impacts T-shaped walls, intensifying cracking and damage, reducing bearing and deformation capacities, and accelerating energy dissipation, with L-shaped walls showing more pronounced effects than T-shaped walls (Yan et al., 2022). Additionally, T-shaped walls exhibit enhanced displacement ductility and energy dissipation capacities, particularly with higher vertical reinforcement ratios, although they also show higher stiffness degradation rates than rectangular walls (Liu et al., 2022). T-shaped walls exhibit better seismic behavior than rectangular ones, with improved shear capacity, decreased shear span ratio, increased concrete compressive strength, flange width, and axial load ratio (Ke et al., 2023; Wang et al., 2023).

In a framed tube structure under lateral load, the stress distribution of the flange wall panels is nonuniform and nonlinear in the web wall panels. This anomaly that reduces the structures' efficiency is called "shear lag" (Guan et al., 2000). This factor is the axial force ratio of the corner column to the center column. The shear lag is positive when the stresses in the corner columns of the flange frame panels exceed those in the center columns. However, in certain situations, the stress in the center columns surpasses that in the corner columns, a condition known as negative shear lag. The shear lag effect affects tubular structure design, lateral deflection, and stability. It decreases with height in tall buildings, reaching zero at specific stories and converting to negative shear lag (Gaur & Goliya, 2015).

The shear lag phenomenon, characterized by uneven axial stress distribution, can significantly impact the performance of these structures under lateral loads such as wind and earthquakes. Different research has been conducted to mitigate the shear lag effect in framed tube construction. The integration of shear links and spandrel beams significantly improves the energy dissipation capacity and inelastic behavior of framed tube structures, thereby reducing the adverse effects of shear lag (Zhang et al., 2023). Mashhadiali et al. (2021) demonstrated that altering the configuration of tube-type structural systems can influence shear and bending deformations, suggesting that strategic design modifications can minimize shear lag effects. Implementing exoskeleton structures can effectively reduce shear lag by optimizing the location of openings and enhancing the structural system's overall stiffness. This approach has been shown to significantly decrease the shear lag effect, particularly in buildings with varying aspect ratios (Aramesh & Kheyroddin, 2021). The geometry of the building plan plays a critical role in shear lag mitigation. Studies have shown that hexagonal plan shapes exhibit the least shear lag compared to rectangular and triangular shapes, especially under wind loads

(Mashhadiali et al., 2021). The shear lag factor for the ground floor of square-shaped framed tube structures varies from 4% to 56% for different structural heights (D Mallick and MAA Siddique, 2025). Integrating composite action through RC slabs and utilizing replaceable shear links in steel-framed tube structures can significantly improve structural performance. This approach enhances the initial stiffness and load-carrying capacity, thereby reducing shear lag. Adjusting the span-to-depth ratio of spandrel beams and incorporating T-shaped connectors can delay the separation of RC slabs, which mitigates shear lag effects (Lian et al., 2024).

These findings emphasize the significance of mitigating the shear lag effect to enhance the performance of frame tube constructions. However, no research is available in the literature for peripheral T-shaped shear walls in frame tube construction, considering the Bangladesh National Building Code, BNBC 2020.

Therefore, the objective of this research is to study the behavior of the shear lag effect due to lateral loads considering T-shaped shear walls at the periphery of framed tube structures instead of columns, according to BNBC 2020, and also compare the behavior due to the variation of the height.

This research has modeled and analyzed six reinforced concrete framed tube buildings with different heights and peripheral members. These are divided into two groups of structures with (a) square columns at the periphery and (b) T-shaped shear walls at the periphery. A regular plan with square-shaped framed tube structural systems with 20, 40, and 60-storied total heights of 81.5 m, 161.5 m, and 241.5 m, respectively, has been considered. All structures have been modeled and analyzed using commercial finite element software ETABS. The Bangladesh National Building Code, BNBC 2020, was used to design different building models. The dead load consists of two parts: its self-weight, and has been considered 4 kPa for the partition wall and floor finish weight. Moreover, the live load has been assumed to be 3 kPa.

2. MODEL VALIDATION

Bhavanishankar and Vinod (2021) investigated the performance of the conventional moment-resisting frame with and without a central core, tubed frame structures. They compared the performance in modal time periods, base shear, story displacement, story drift, and story acceleration. They used commercially available software, ETABS, for their analyses. Those frame models were considered for model validation in the present study. The three-dimensional (3D) models of a tubed frame structure for Zone-II and Zone-V, according to IS: 1893-2016, have been considered, and the results obtained have been compared. The considered model was the tubed frame structure having a plan dimension of 30 m x 30 m and a height of 63 m. Each story height is 3 m for 21 stories. The floor height was kept the same. The responses are obtained from applied gravity and seismic loads as per IS 1893:2016. The present study of base shear, time period, maximum story displacement, and maximum story drift ratio varies -12.2%, 5.9%, 6.4%, 7.1% for zone II, and -12.2%, 5.9%, 7.1%, 7.7% for zone V from the Bhavanishankar and Vinod study. The value obtained from the current investigation indicates good agreement with those from the reference analysis.

3. NUMERICAL ANALYSIS

In this paper, six reinforced concrete square-shaped framed tube buildings with different heights and peripheral members have been modeled, analyzed, and designed according to BNBC (2020). Table 1 illustrates the parameters considered in these models.

Table 1: Modeling parameters for the considered buildings

Model ID	SMC-1	SMS-1	SMC-2	SMS-2	SMC-3	SMS-3
Story	20	20	40	40	60	60
Height (m)	81.5	81.5	161.5	161.5	241.5	241.5
Concrete strength (MPa)	34.48	34.48	41.38	41.38	48.28	48.28
Rebar strength (MPa)	500	500	500	500	500	500

Model ID	SMC-1	SMS-1	SMC-2	SMS-2	SMC-3	SMS-3
Thickness of slab (mm)	175	175	175	175	175	175
Peripheral beam (mm)	450 x 900	300 x 600	1000 x 1000	450 x 1050	1350 x 1350	750 x 900
Main beam (mm)	300 x 600	300 x 600	375 x 600	375 x 600	375 x 600	375 x 600
Peripheral column (mm)	600 x 600	-	750 x 750	-	1350 x 1350	-
Peripheral corner column (mm)	600 x 600	-	1250 x 1250	-	1800 x 1800	-
Main column (mm)	650 x 650	650 x 650	1050 x 1050	1050 x 1050	1200 x 1200	1500 x 1500
Peripheral T-shaped wall thickness (mm)	-	300	-	375	-	450
Corner L-shaped wall thickness (mm):	-	300	-	500	-	600

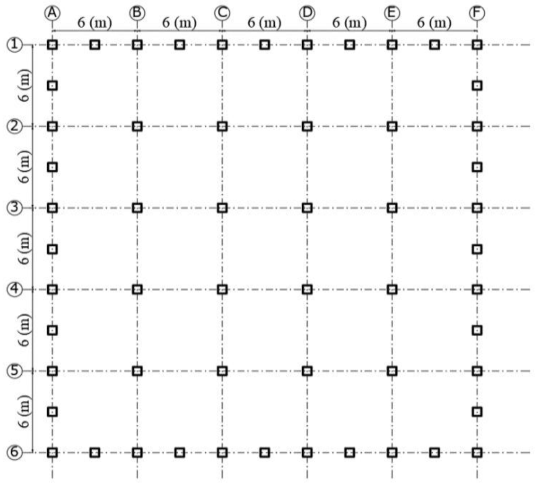

Figure 1: Plan view of models SMC 1, 2, 3

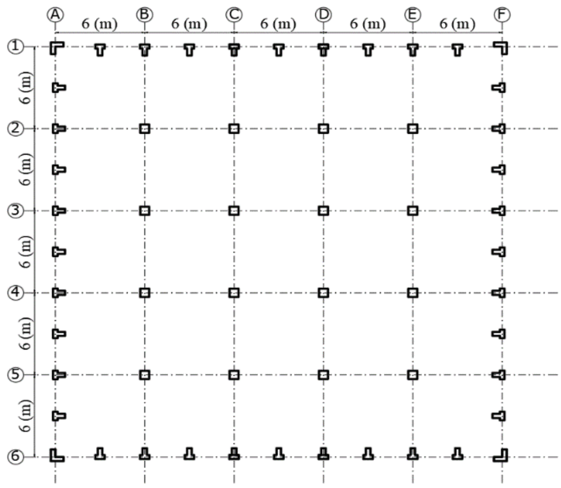

Figure 2: Plan view of models SMS 1, 2, 3

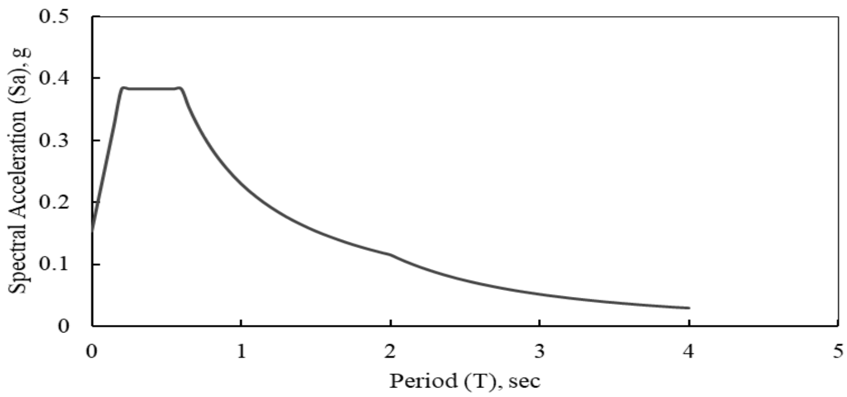

Figure 3: The response spectrum curve for the considered data according to BNBC 2020

Figures 1 and 2 represent the plan view of frame tube structures having peripheral square columns and T walls for 20, 40, and 60 stories, respectively. The structures are square-shaped, having a dimension of 30 m x 30 m. The peripheral columns/ T walls are spaced closely, with 3m intervals for tubular action. The inner columns are spaced 6m center to center. The grid dimensions of 20, 40, and 60-storied structures are kept identical to obtain the results in height variation. Table 2 represents the load intensities used in the study.

All models are analyzed and designed according to BNBC 2020. Response spectral analysis was performed on earthquake loads. As per BNBC 2020, all load combinations are considered when designing the models. Figure 3 illustrates the response spectrum curve.

Table 2: Lateral loads and intensities used in this study

Description	**Intensities**	
	With Peripheral Columns	**With Peripheral T walls**
Design Category	Intermediate Moment Resisting Frame (IMRF)	Dual System with Ordinary Wall
a) Seismic Load Parameters		
Zone factor	0.20 (Zone II)	0.20 (Zone II)
Importance factor	1.0	1.0
Response reduction factor	5	5.5
Overstrength factor, Ω_0	3	2.5
Deflection amplification factor, C_d	4.5	4.5
0.2-sec Spectral Accl, S_s	0.5	0.5
1-sec Spectral Accl, S_1	0.2	0.2
Soil type	SC	SC
Site coefficient, Fa	1.15	1.15
Site coefficient, Fv	1.725	1.725
b) Wind Load Parameters		
Wind Speed, mph	147	147
Exposure type	A	A
Importance factor	1	1
Topographical factor, K_{zt}	1	1
Gust factor, G	0.85	0.85
Directionality factor, K_d	0.85	0.85

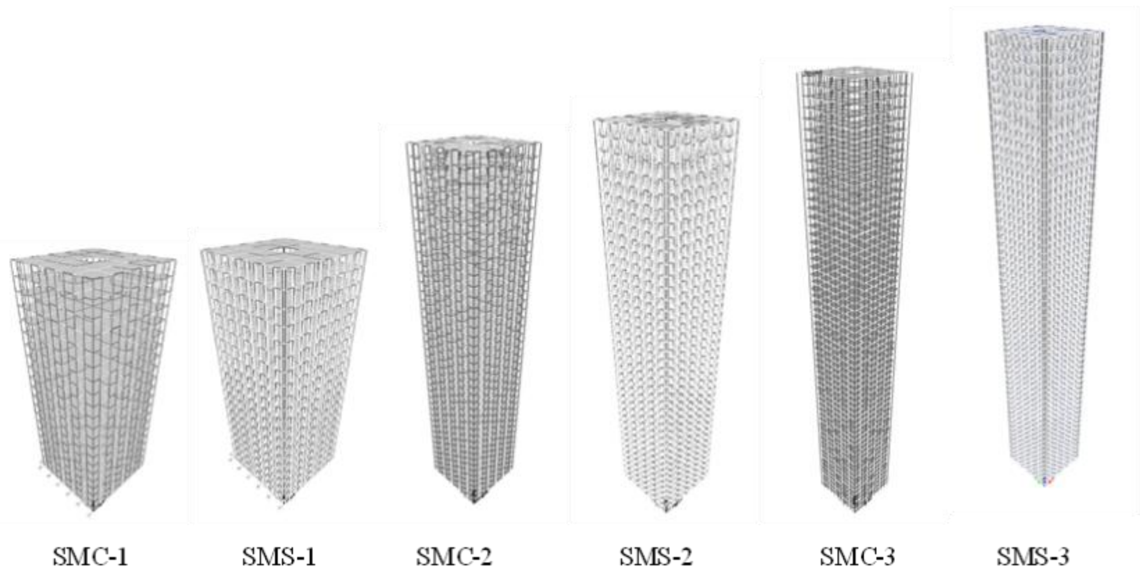

Figure 4: 3D views of all models considered in the study

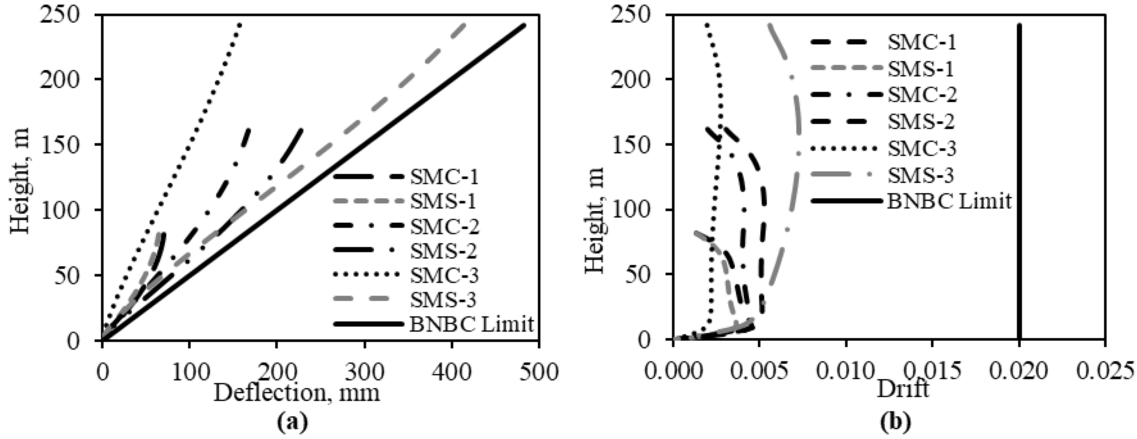

Figure 5: (a) Displacement under wind load, and (b) inter-story drift ratio for the considered buildings

All considered buildings' serviceability criteria according to BNBC 2020 have been checked, and these are illustrated in Figures 5(a) & 5(b). Figure 5(a) illustrates the comparative displacement, and Figure 5(b) represents the comparative seismic inter-story drift for all considered buildings. All the parameters of all models are within the BNBC 2020 limit.

4. RESULTS AND DISCUSSION

All the results and outputs from numerical analysis regarding the shear lag factor have been discussed for response spectrum analysis of all models with different criteria, plan configurations, and heights. The flange shear lag factor at different stories for square-framed tube structures with peripheral T-walls is less than that of structures having peripheral columns under both the wind and earthquake loadings. The reduction of the shear lag factor is 4% to 57% for earthquake and wind loads. The decreasing phenomenon of the shear lag factor with height due to lateral loading is a polynomial of different orders for both the building models with peripheral T-shaped walls and the columns.

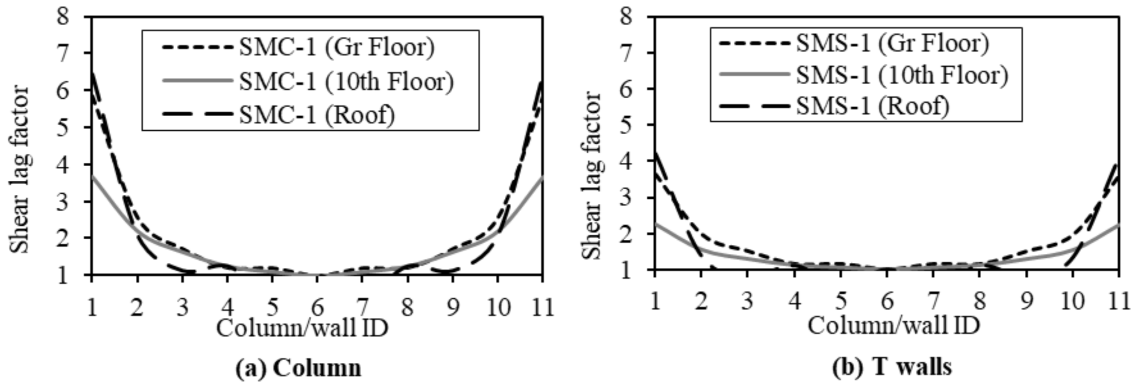

Figure 6: The shear lag factor of 20-storied buildings for seismic loading with peripheral (a) column and (b) T walls

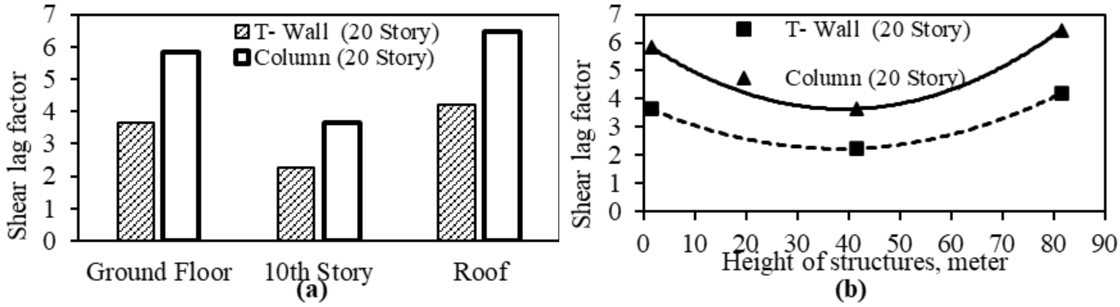

Figure 7: (a) Comparative flange shear lag factors, and (b) variation of the flange shear lag factor with the height of 20-storied buildings for seismic loading

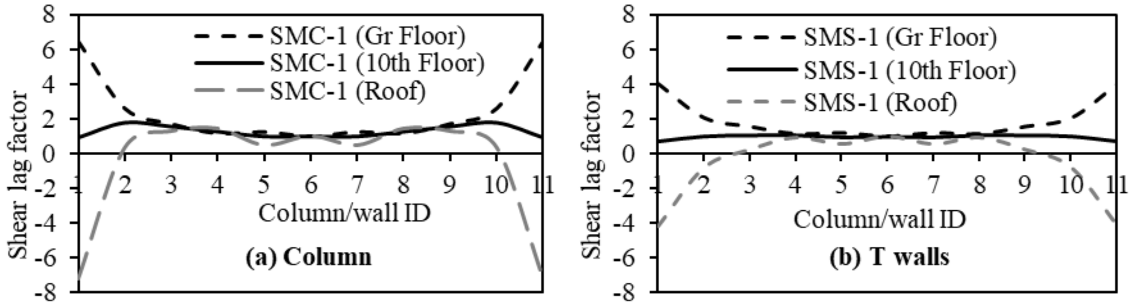

Figure 8: The shear lag factor of 20-storied buildings for wind loading with peripheral (a) column and (b) T walls

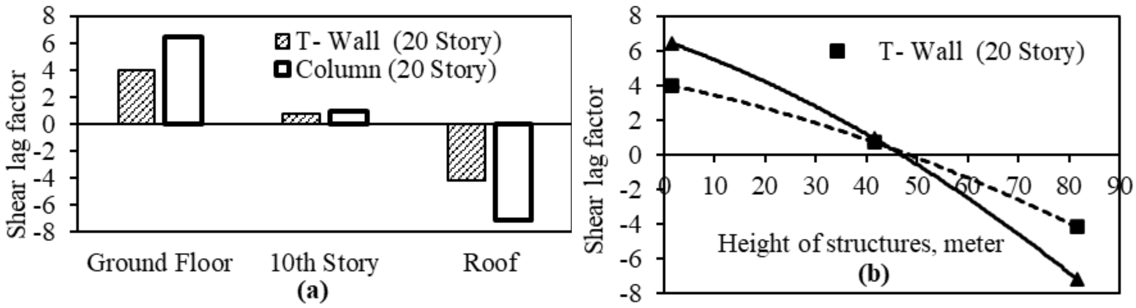

Figure 9: (a) Comparative flange shear lag factors, and (b) variation of the flange shear lag factor with the height of 20-storied buildings for wind loading

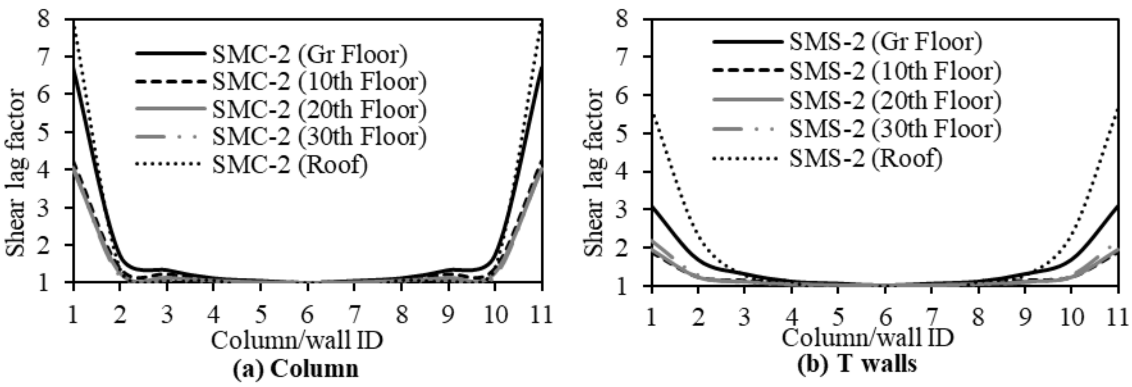

Figure 10: The shear lag factor of 40-storied buildings for seismic loading with peripheral (a) column and (b) T walls

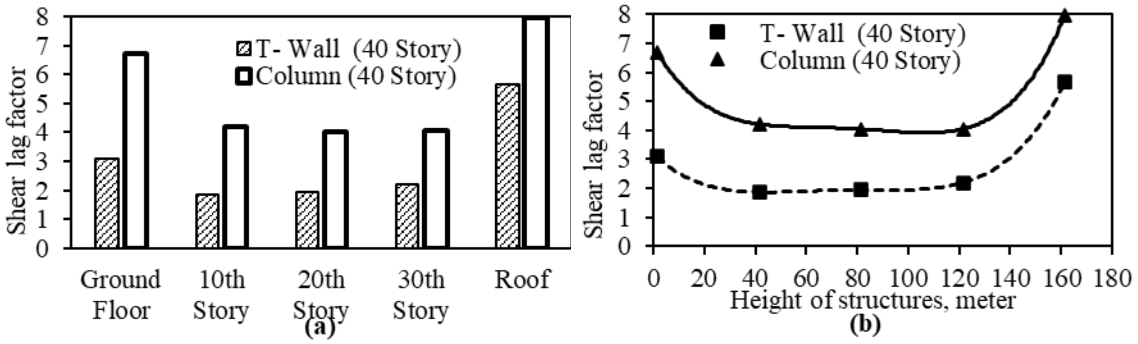

Figure 11:(a) Comparative flange shear lag factors, and (b) variation of the flange shear lag factor with the height of 40-storied buildings for seismic loading

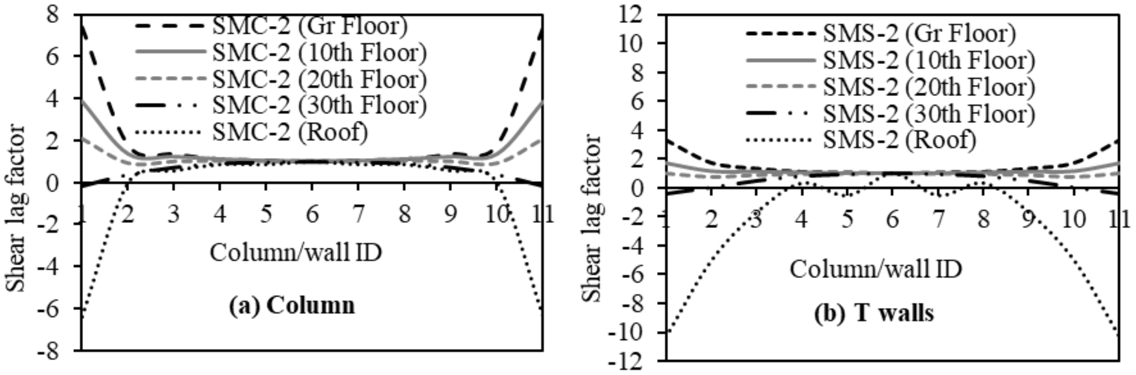

Figure 12: The shear lag factor of 40-storied buildings for wind loading with peripheral (a) column and (b) T walls

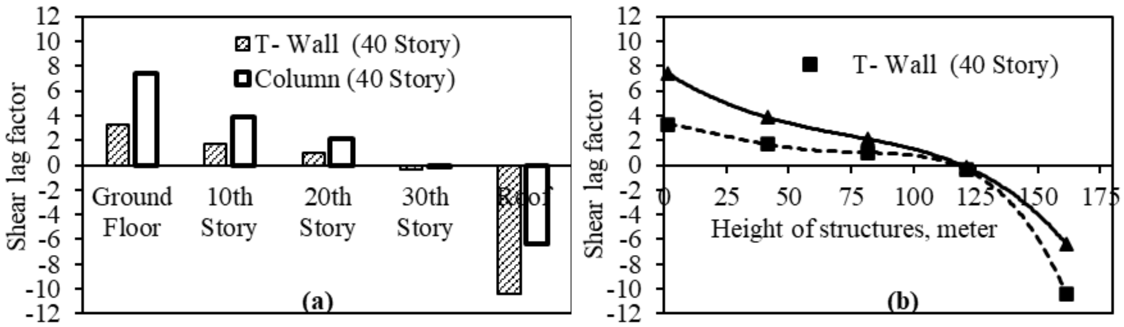

Figure 13: (a) Comparative flange shear lag factors, and (b) variation of the flange shear lag factor with the height of 40-storied buildings for wind loading

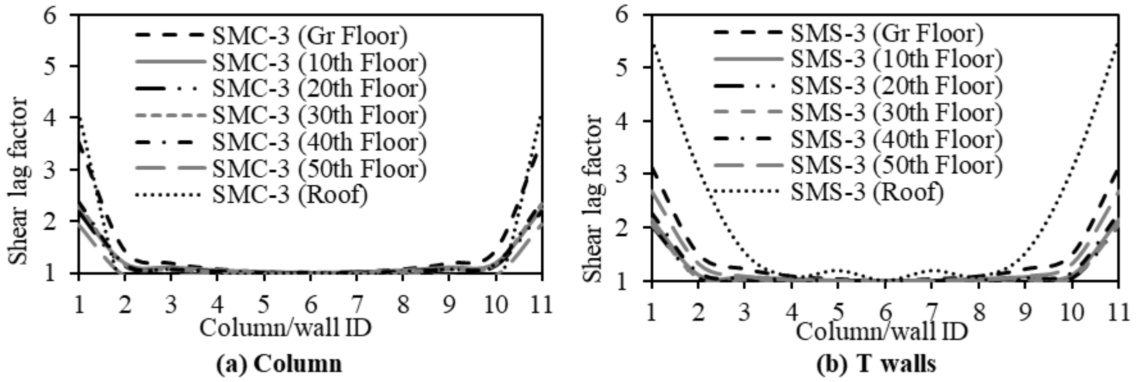

Figure 14: The shear lag factor of 60-storied buildings for seismic loading with peripheral (a) column and (b) T walls

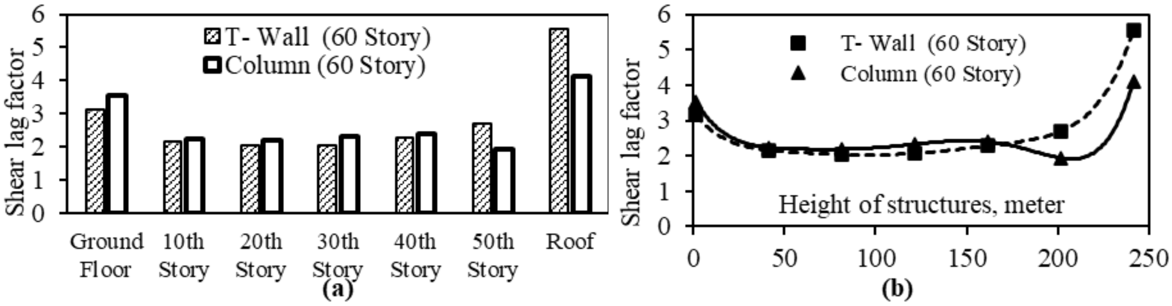

Figure 15: (a) Comparative flange shear lag factors, and (b) variation of the flange shear lag factor with the height of 60-storied buildings for seismic loading

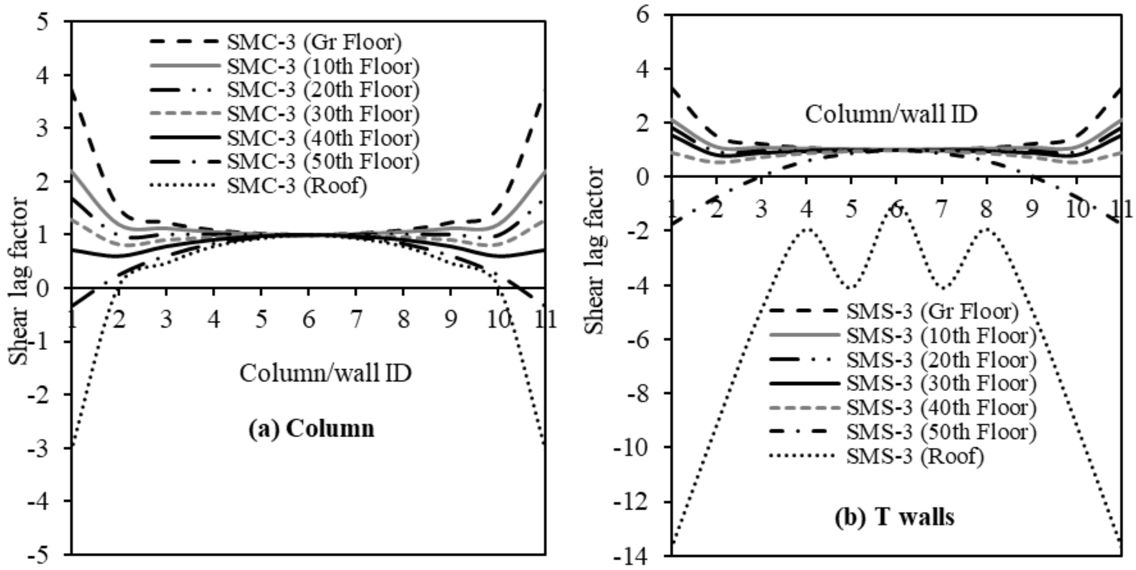

Figure 16: The shear lag factor of 60-storied buildings for wind loading with peripheral (a) column and (b) T walls

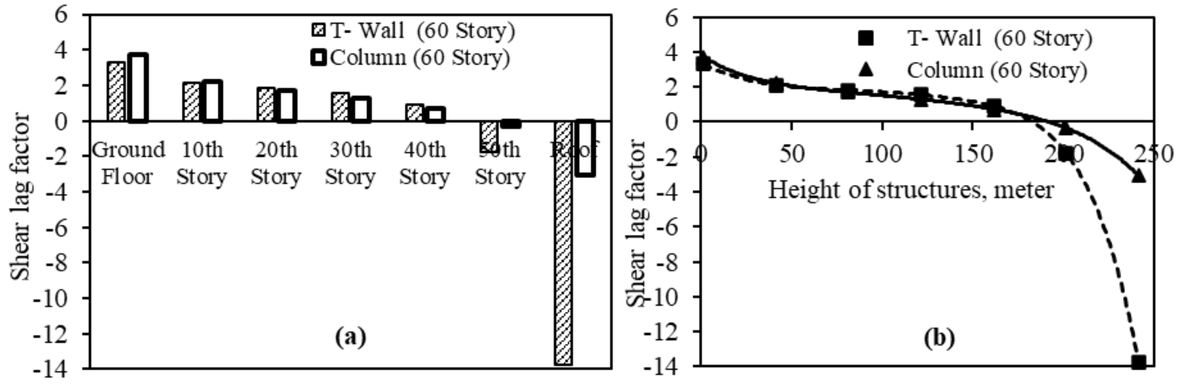

Figure 17: (a) Comparative flange shear lag factors, and (b) variation of the flange shear lag factor with the height of 60-storied buildings for wind loading

From Figures 6 to 17, it can be summarized that the flange shear lag factor due to dynamic seismic loading at different floors of 20, 40 & 60-storied buildings having peripheral T walls is 35%-38%, 29%-56%, and 4%-11%, respectively, less compared to the buildings with peripheral columns. Due to wind loading, the flange shear lag factor at different floors of 20, 40 & 60-storied buildings having peripheral T walls is 23%-42%, 52%-57%, and 5%-11%, respectively, less compared to the buildings with peripheral columns. For certain storied buildings, both for peripheral T walls and columns, the flange shear lag factor decreases with the increase in height. For wind loading, the shear lag factor decreases with height in a building, reaching zero at specific stories and then converting to negative values. The average flange shear lag factor of 20-storied buildings is higher than that of 40-storied & 60-storied buildings. Thus, the average flange shear lag factor decreases with the structure's story height.

5. CONCLUSION

This paper conducted numerical analysis on six reinforced concrete framed tube buildings of different heights and two different peripheral members, such as T-shaped walls and square columns. A regular plan with square-shaped framed tube structural systems with 20, 40, and 60-storied buildings has been considered, and the buildings have been designed as per BNBC 2020. Based on the results obtained from numerical analyses, the main conclusions of this research study are stated as follows:

- The flange shear lag factor for the ground floor of 20, 40, and 60-storied square-framed tube structures with the peripheral column is higher than that with peripheral T-shaped walls. The shear lag factor for T walls decreases from 4% to 57% for the considered buildings.
- The decreasing phenomenon of the shear lag factor with height due to lateral loading is a polynomial of different orders for both the building models with peripheral T-shaped walls and the columns.
- For certain storied buildings, both for peripheral T walls and columns, the flange shear lag factor decreases with the increase in height.
- For wind loading, the flange shear lag factor decreases with height in a building, reaching zero at specific stories and then converting to negative for framed tube buildings having both peripheral T walls and columns.
- For response spectrum analysis, the flange shear lag factor is always positive for buildings with T-shaped walls and square columns.

Overall, the performance for mitigating the shear lag effect of the peripheral T-shaped shear walls in frame tube construction is much better than that of conventional buildings with peripheral square columns.

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