PERFORMANCE OF PERIPHERAL T-SHAPED SHEAR WALL IN FRAMED TUBE STRUCTURES IN CONTEXT OF DHAKA CITY

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ABSTRACT

Bangladesh is a small country with a high population density. Due to the demand for massive urbanization, it needs to construct more high-rise buildings in major cities. For this case, the framed tube structural system can be an effective framing technique. This system comprises tightly spaced peripheral columns connected by deep spandrel beams. The total system works as a giant vertical cantilever. Reinforced concrete structural walls provide substantial lateral strength and stiffness to limit damage when structures are subjected to ground shaking. In this paper, T-shaped shear walls replace the peripheral columns with an aim to obtain better performance. The reduced cost of columns, walls, and beams of square-shaped framed tube structures with peripheral T-shaped wall compared to the column is in the range of 8-18%. The shear lag factor for the ground floor of square-shaped framed tube structures is also reduced from 4% to 56% for different structural configurations. The concrete quantity of columns, walls, and beams of square-shaped framed tube structures with peripheral T-walls is reduced in the range of 6-19%. The longitudinal reinforcement quantity of columns, walls, and beams is also reduced in the range of 12-25%. The reaction force for the foundation design of square-shaped framed tube structures with peripheral T-shaped walls lies between 2% and 11% less than the square-shaped framed tube structures with peripheral columns.

Keywords: *Framed tube, T-shaped shear walls, Shear lag, Cost, Reaction force*

1. INTRODUCTION

Bangladesh is one of the world's most densely populated countries. According to UN World urbanization prospects: The 2014 revision, 56% of the population will be in urban areas by 2050, with Dhaka's population growing to 27.4 million. Urbanization has reached a critical point, surpassing infrastructure and services supply. The demand for vertical expansion in Dhaka city has increased due to land scarcity and urban migration, making horizontal settlement expansion complex (Alam, 2018). Various research works show that taller buildings increase the demand for structural systems to resist lateral loads, leading to increased material consumption for buildings beyond 20-30 stories (Ali, 2001). In such cases, framed tube structures are usually recommended for high-rise constructions due to their high resistance against lateral and seismic forces, offering significantly higher structural response compared to other systems (Nassani et al., 2020). The framed tube structure is a suitable alternative for high-rise buildings in seismic zones, with better seismic resistance in terms of displacement, drift ratio, base shear, and ductility of the structure (Sutar et al., 2023). In a framed-tube structure under lateral load, the stress distribution in the flange wall panels is nonuniform and is nonlinear in the web wall panels. This anomaly that reduces the structures' efficiency is called "shear lag" (Lee et al., 2000). The shear lag effect affects tubular structure design, affecting lateral deflection and stability. It decreases with height in tall buildings, reaching zero at specific stories and converting to negative shear lag (Gaur et al., 2015).

Shear walls are structural systems that resist in-plane lateral pressures like wind and earthquakes, providing stability and ductility. They are reinforced braced systems, ensuring load-carrying capacity in tall structures. The dimensions, height, and geometry of the shear wall system are crucial for structural advantages (Krishnan et al., 2023). Shear wall buildings have been extensively constructed in many earthquake-prone countries and regions worldwide providing high strength, stiffness, and adequate safety margin against excessive damage or collapse (Cando et al., 2020). Reinforced concrete walls have traditionally had rectangular cross-sections, but now composite cross-sections like T-shaped walls are becoming more common (Rojas et al., 2021). T-shaped walls exhibit better seismic behavior compared to rectangular ones, with improved shear capacity with decreased shear span ratio and increased concrete compressive strength, flange width, and axial load ratio (Ke et al., 2023 and Wang et al., 2023). However, no such research works are available in the literature for buildings designed by BNBC 2020. Therefore, the main objective of this research is to assess the performance of peripheral T-shaped shear walls in frame tube construction analyzed and designed as per BNBC 2020.

In this research work, 06 reinforced concrete framed tube buildings with different heights and peripheral members have been modeled and analyzed. 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 having a total height of 81.5 m, 161.5 m, and 241.5 m, respectively, have been considered. All structures have been modeled and analyzed in commercial finite element software ETABS. The Bangladesh National Building Code, BNBC 2020, was used to design different building models. The dead load consisted of two parts as its self-weight and will be considered 4 kPa for partition wall and floor finish weight named as superimposed dead load. Moreover, the live load has been assumed as 3 kPa. The structures were analyzed by response-spectral linear dynamic analysis to achieve an authentic and accurate structural analysis. The earthquake and wind loads as well as load combinations have been applied based on BNBC 2020.

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 terms of 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 both Zone-II and Zone-V according to IS: 1893-2016 have been considered and the obtained results are 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. Table 1 shows the summary of the present analysis compared to those of the results by Bhavanishankar and Vinod (2021). The value obtained from the current investigation indicates good agreement with those from the reference analysis.

Table 1: Summary of comparison of results

Sl. No.	**Description**	**Parameters**	**Present analysis**	**Bhavanishankar and Vinod (2021)**	**% Variation**
1	Time period, sec	1st mode	1.97	1.86	5.9%
		2nd mode	1.97	1.86	5.9%
		3rd mode	1.44	1.56	-7.7%
2	Base shear, kN	Zone II	3478	3962	-12.2%
		Zone V	12520	14262	-12.2%
3	Maximum story displacement, mm	Zone II	27.66	26	6.4%
		Zone V	99.58	93	7.1%
4	Maximum story drift ratio (*10^{-6})	Zone II	546	510	7.1%
		Zone V	1967	1827	7.7%

3. BUILDING MODELS CONSIDERED IN THE PRESENT STUDY

In this paper, 6 (six) reinforced concrete square shape framed tube buildings with different heights and peripheral members have been modeled, analyzed, and designed according to BNBC 2020. Table 2 illustrates the parameters considered in these models. Figs. 1 and 2 show the plan view with peripheral square columns and T-shaped walls, respectively. Tables 2 and 3 present the modeling parameters and load intensities, respectively, used in the study.

Table 2: Modelling 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
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

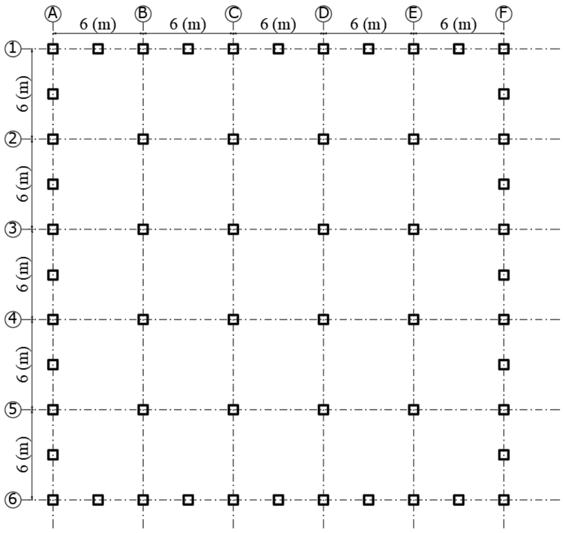

Figure 1: Plan view of models SMC 1, 2, 3

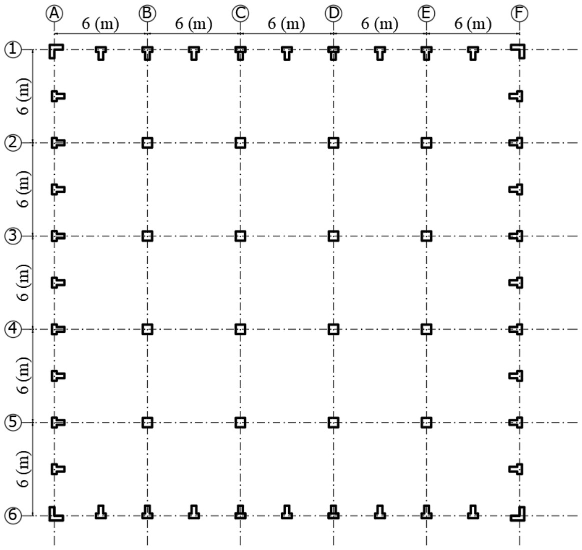

Figure 2: Plan view of models SMS 1, 2, 3

Table 3: 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

All models are analyzed and designed according to BNBC 2020. Response spectral analysis has been performed for earthquake loads. All load combinations as per BNBC 2020 are considered to design the models. Figure 3 illustrates the response spectrum curve used in this study. Fig. 4 shows the 3D views of the considered buildings. SMC refers to buildings with columns and SMS refers to buildings with T-shaped walls.

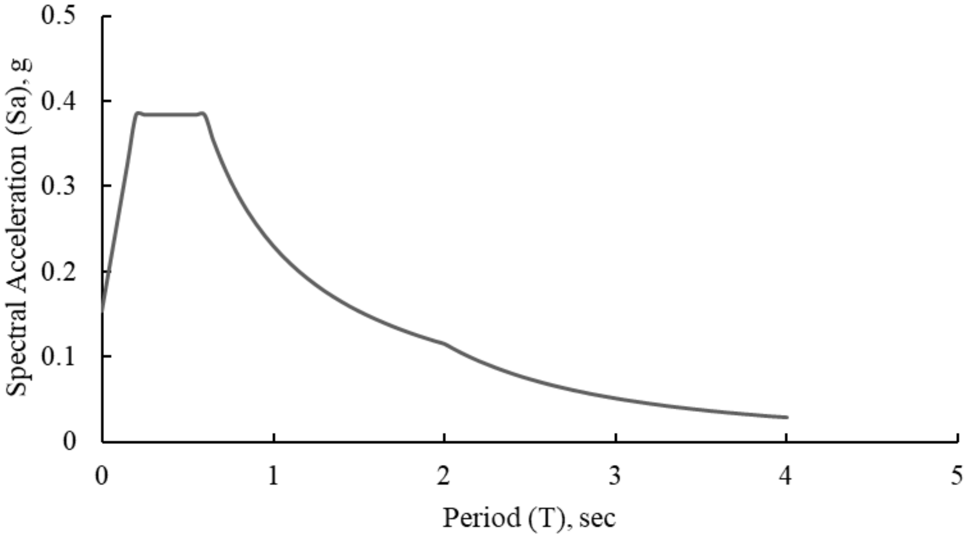

Figure 3: Response spectrum curve

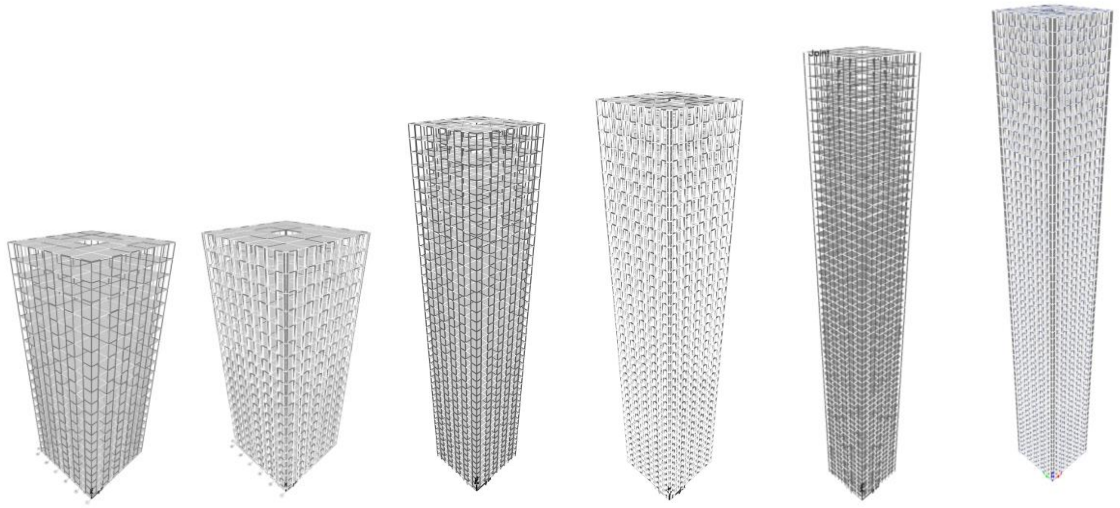

Figure 4: 3D views of all models considered in the study

4. RESULTS AND DISCUSSION

4.1 Serviceability

The total displacement and the drift ratio of all the models are within the service limit of BNBC 2020. Figures 5 to 7 illustrate the comparative total displacement and drift ratio under wind load and earthquake loads, respectively, and compared with the allowable limits according to BNBC 2020.

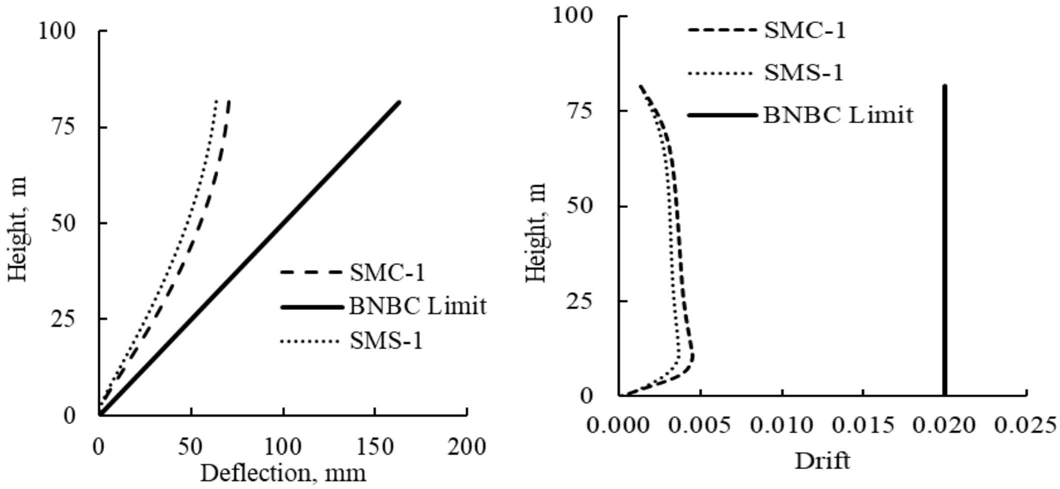

Figure 5: Displacement under wind and inter-story drift under earthquake load for 20 storied buildings

Figure 5 illustrates the comparative displacement along the height under wind load and inter-story drift under earthquake loads for SMC-1 and SMS-1 buildings. It is shown that SMS-1 gives better performance than that of the SMC-1. In addition, both models satisfied BNBC 2020 requirements.

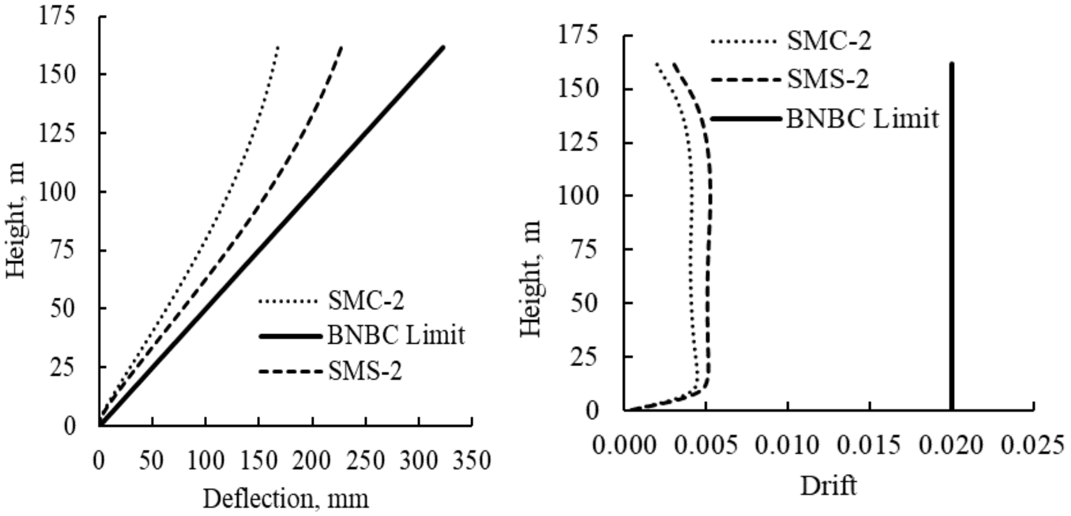

Figure 6: Displacement under wind and inter-story drift under earthquake load for 40 storied buildings

Figure 6 represents the comparative wind displacement along the height and seismic inter-story drift for SMC-2 and SMS-2 buildings. It is evident that the wind displacement along the height and inter-story drift of the SMC-2 building model is less than that of the SMS-2 model. However, the parameters of both models are within the BNBC 2020 limit.

Figure 6 shows the comparative wind displacement along the height and inter-story drift ratio under earthquake loads for 60-storied buildings. From this figure, it is also evident that displacement under wind load and inter-story drift ratio of SMC-3 are lesser than those of the SMS-3 building. However, In this research work, 06 reinforced concrete framed tube buildings with different heights and peripheral members have been modeled and analyzed. 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 having a total height of 81.5 m, 161.5 m, and 241.5 m, respectively, have been considered. All structures have been modeled and analyzed in commercial finite element software ETABS. The Bangladesh National Building Code, BNBC 2020, was used to design different building models. The dead load consisted of two parts as its self-weight and will be considered 4 kPa for partition wall and floor finish weight named as superimposed dead load. Moreover, the live load has been assumed as 3 kPa. The structures were analyzed by response-spectral linear dynamic analysis to achieve an authentic and accurate structural analysis. The earthquake and wind loads as well as load combinations have been applied based on BNBC 2020.

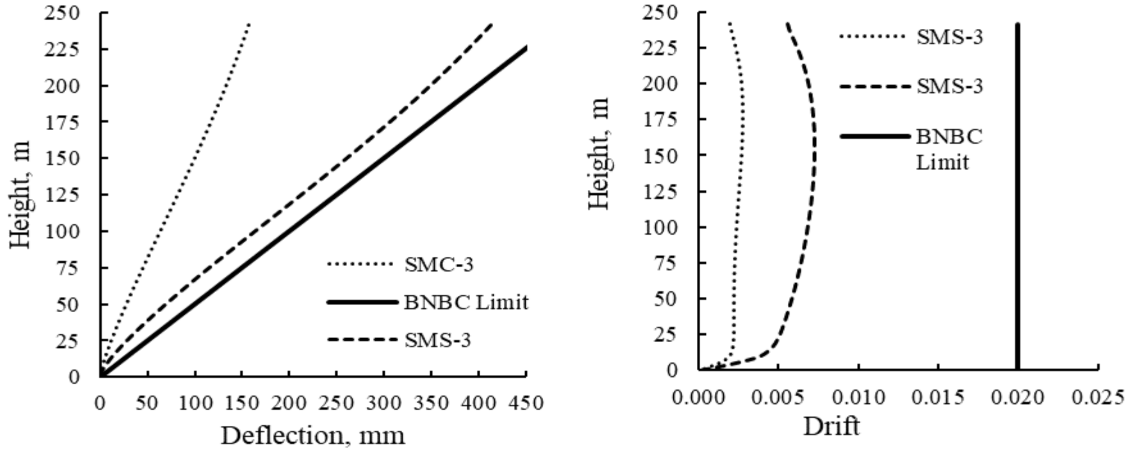

Figure 7: Displacement under wind and inter-story drift under earthquake load for 60 storied buildings

4.2 Shear Lag Effect

The flange shear lag factor of the ground floor for square-framed tube structures with peripheral T-walls is less than structures having peripheral columns under both the wind and earthquake loadings. The reduction of the shear lag factor is 4% to 54 %, and 11% to 56% for earthquake and wind loads, respectively. The decreasing phenomenon of the shear lag factor with height due to lateral loading is a polynomial 2nd order equation for both the building models with peripheral T-shaped walls and the columns.

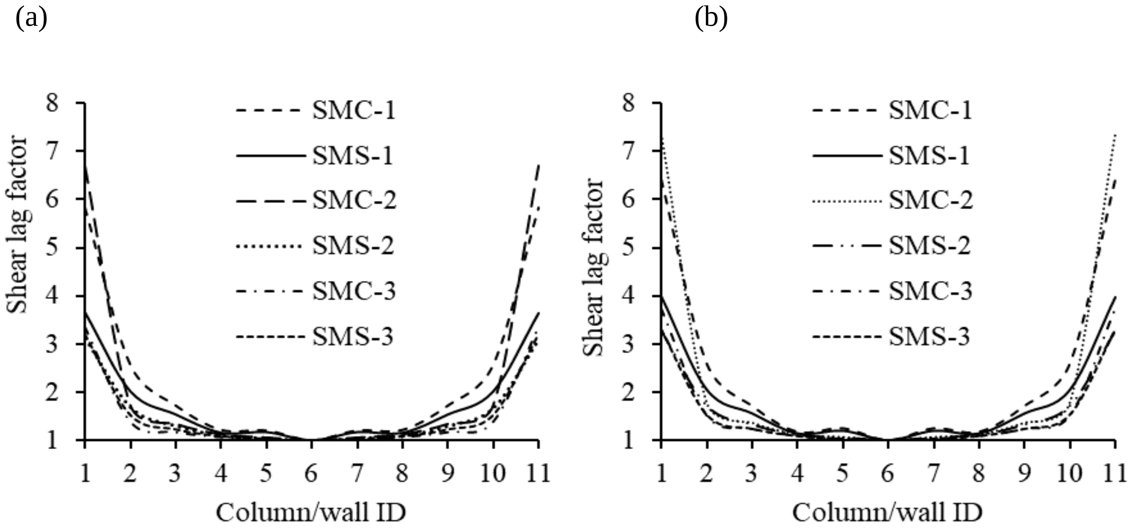

Figure 8: Flange shear lag factor for the ground floor elements (a) Seismic load and (b) Wind load

Figure 8 illustrates the comparative flange shear lag factor of the ground floor structural members of all building models for seismic and wind loadings. The shear lag factor of square-framed tube structures having T-shaped walls at the periphery is less than that of the models with square columns at the periphery.

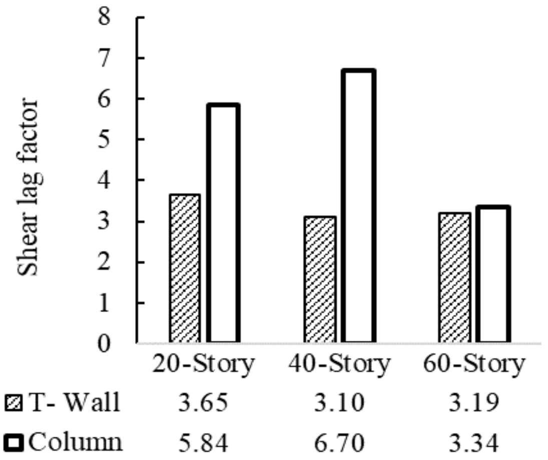

Figure 9: Comparative flange shear lag factors of ground floor elements under earthquake load

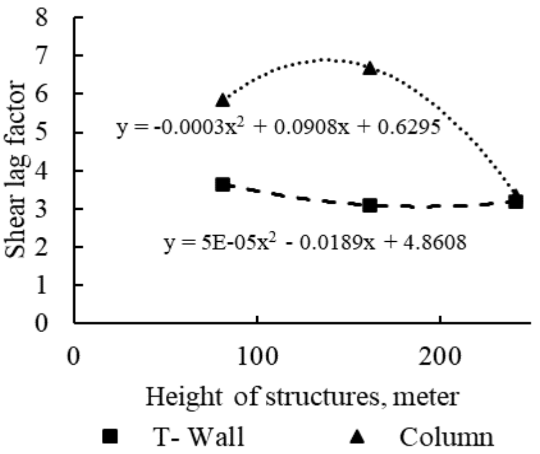

Figure 10: Variation of the flange shear lag factor of the ground floor with the height of the buildings

Figure 9 shows the bar chart of the flange shear lag factor of the ground floor structural elements of all building models under seismic loading. The shear lag factor of square framed tube structures having T-shaped walls at the periphery is less than the structures having square columns at the periphery. The reduction of shear lag factor is 38%, 54%, & 4% for 20, 40, and 60-storied buildings, respectively. Figure 10 represents the variation of the shear lag factor with height for both the structures having T-shaped walls and columns.

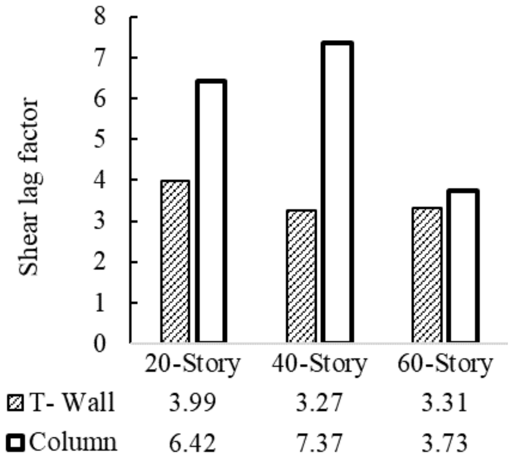

Figure 11: Comparative flange shear lag factor of ground floor elements under wind

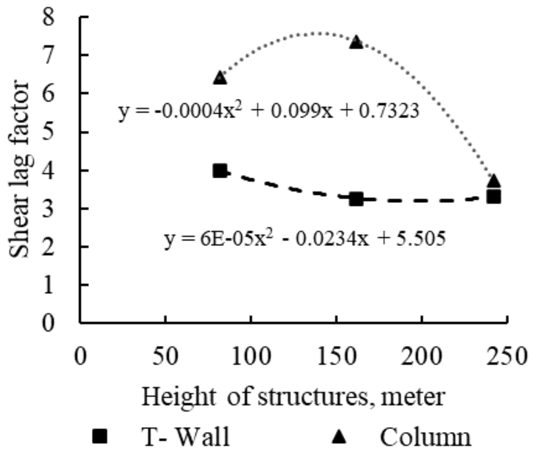

Figure 12: Variation of flange shear lag factor of ground floor elements along the height

Figure 11 represents the bar chart of the flange shear lag factor at the ground floor levels of all buildings under wind loading. The shear lag factor of square framed tube structures having T-shaped walls at the periphery is less than the structures having square columns at the periphery. The reduction of shear lag factor is 38%, 56%, and 11% for 20, 40, and 60 storied buildings, respectively. Figure 12 represents the variation of shear lag factor with height for both the structures having T walls, and columns.

4.3 Reaction Force for Foundation Design

The reaction force at the foundation of square framed tube structures with peripheral T-shaped walls is lesser than that of the structures having peripheral columns. The reduction of the force ranges from 2% to 11%.

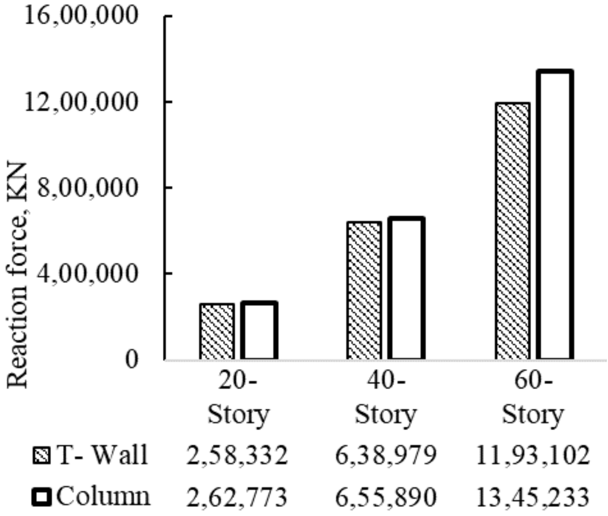

Figure 13: Comparative base reaction force

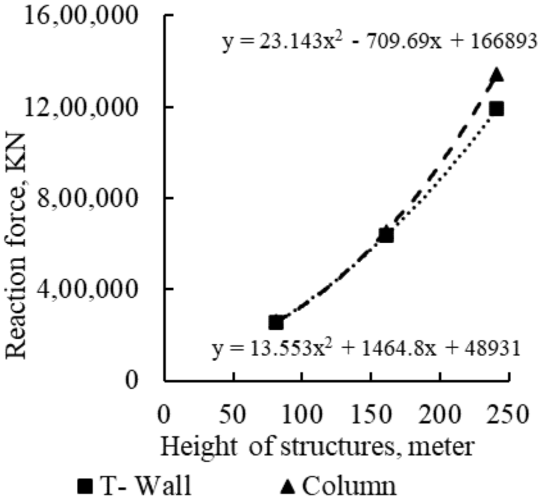

Figure 14: Variation of reaction force with height

Figure 13 illustrates the bar chart of reaction force for the foundation design of all buildings. The reaction force of the square framed tube structures having T-shaped walls at the periphery is less than that of the buildings having square columns at the periphery. The reduction of reaction force is 2%, 3%, and 11% for 20, 40, and 60 storied buildings, respectively. Figure 14 represents the variation of the reaction forces with respect to the height of the building.

4.4 Concrete Quantity

The concrete quantity of beams, columns, and walls of the square framed tube structures with peripheral T-shaped walls is less than that of the building with peripheral columns. The reduction of the quantity varies from 6% to 19%.

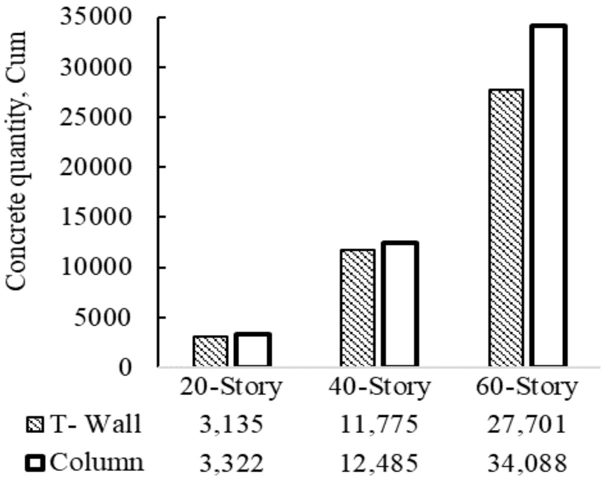

Figure 15: Comparative concrete quantity

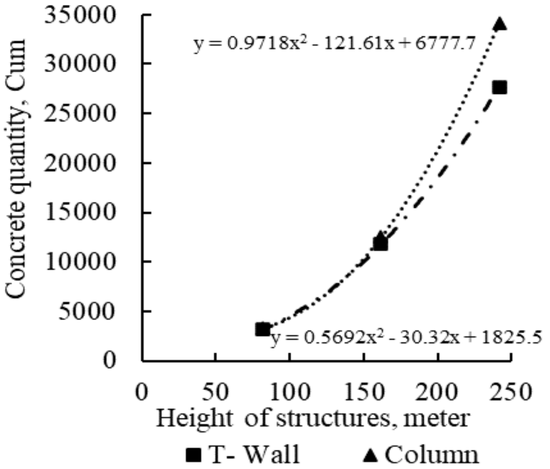

Figure 16: Variation of concrete quantity with the height of the buildings

Figure 15 shows the variation in the concrete quantity of beams, columns, and walls of all buildings. The concrete quantity of square framed tube buildings with T-shaped walls is lesser than that of the square columns at the periphery. The reduction of concrete quantity is 6%, 6%, and 19% for 20, 40, and 60-storied buildings, respectively. Figure 16 presents the variation of concrete quantity with height for both structures.

4.5 Longitudinal Reinforcement Quantity

The longitudinal reinforcement quantity of beams, columns, and walls of square framed tube structures with the peripheral T-walls is reduced from 12% to 25%.

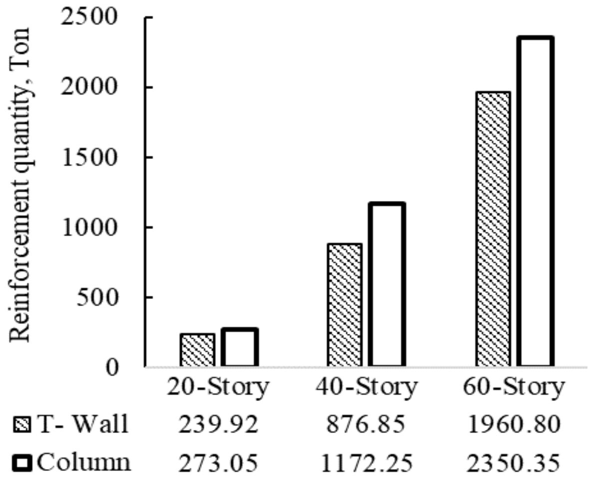

Figure 17: Comparative reinforcement quantity

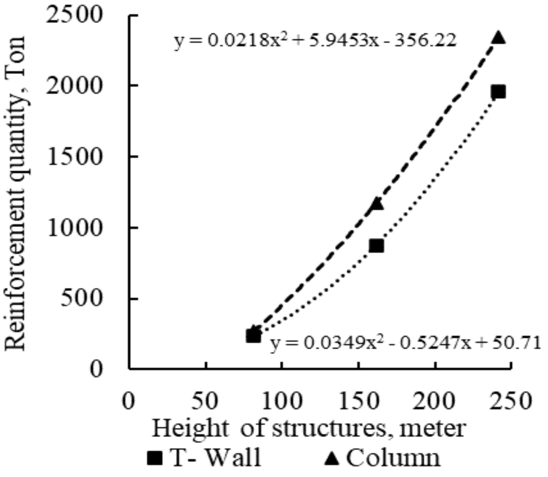

Figure 18: Variation of reinforcement quantity with the height of the building

Figure 17 presents the variation of the longitudinal reinforcement quantity of beams, columns, and walls of all buildings. The reinforcement quantity of square framed tube structures having T-shaped walls is lesser than the structures having square columns at the periphery. The reduction of reinforcement quantity is 12%, 25%, and 17% for 20, 40, and 60-storied buildings, respectively. Figure 18 represents the variation of reinforcement quantity with different heights of the buildings.

4.6 Cost

The cost based on concrete and longitudinal reinforcement quantity of beams, columns, and walls of squared-shaped framed tube structures with peripheral T-shaped walls is calculated based on the PWD Schedule of Rate, 2022, GoB.

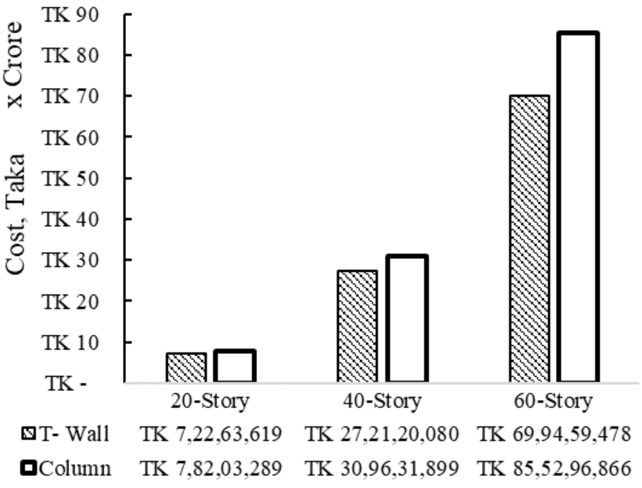

Figure 19: Comparative cost

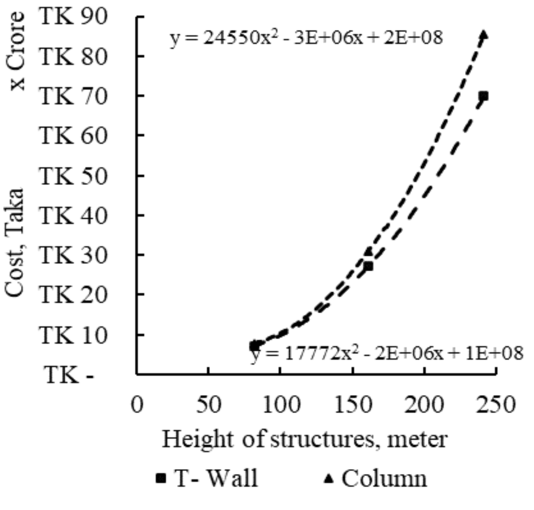

Figure 20: Variation of cost with height

From Figure 19, the cost of square framed tube structures having T-shaped walls at the periphery is less than that of the buildings with square columns. The reduction of reinforcement quantity is 8%, 12%, and 18% for 20, 40, and 60-storied, respectively. From Figure 20, the cost variation for T-shaped walls and square columns is shown.

5. CONCLUSIONS

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

i) The flange shear lag factor for the ground floor of 20, 40, and 60-storied square-framed tube structure with the peripheral column is higher than the structure with peripheral T-shaped walls. The shear lag factor for T walls decreases from 4% to 56% for the considered buildings.

ii) The reaction force of the square framed tube structure with the peripheral T-shaped walls is less than the structure with peripheral columns for designing the foundation. This reduction shows 2% to 11% for different heights of the buildings.

iii)The concrete, and longitudinal reinforcement quantity of beam, column & wall of the square-framed tube structure with the peripheral T-walls is 6% to 19% and 12% to 25% less than the structures with the peripheral columns. In terms of cost, a framed tube structure with peripheral T-shaped walls results in 8% to 18% lower than that of square columns at the periphery.

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

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