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A Comparative Study of The Dynamic Earthquake Behaviour of Braced Tube, Diagrid, Tube-in-tube, and Shear Wall-frame Structures

Grant Oduor*, Silvester Abuodha , Siphila Mumenya
Department of Civil and Construction Engineering, University of Nairobi, Kenya
***Corresponding author, e-mail: isagrnt@gmail.com**

Abstract— Recent trends show that tubular systems are already widely used for tall buildings in most regions of the world; the shear wall-frame system is also dominant in other parts of the globe. This study aimed at comparing the dynamic earthquake behaviour of braced tube, diagrid, tube-in-tube, and shear wall-frame structures. This research study used ETABS software to model, analyze, and design 12 building models, whereby every structural system had 12-, 24-, and 36-story models. The constant model parameters were as follows: the floor slab depth and area, the service area, the plan dimensions, the story heights, and materiality. Furthermore, the research used modal response spectrum analysis per EN 1998-1-1:2004 for the Nairobi city area in Kenya to obtain the fundamental periods of vibration, top drifts, seismic base shears, and top floor accelerations of the braced tube, diagrid, tube-in-tube, and shear wall-frame models. In addition, this study illustrates the dynamic earthquake behaviour of the aforementioned lateral systems with different heights and highly recommends using diagrid systems for seismic load resistance in 12-, 24-, and 36-story buildings with regular plan geometry.

Keywords: Fundamental period of vibration, top drift, seismic base shear, top floor acceleration, modal response spectrum analysis, tall buildings.

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1. Introduction

Earthquakes occur when there is a sudden rupture of geological faults, resulting in the dissipation of the elastic strain energy that radiates from the fault rupture as seismic waves [1]. Earthquakes can cause the collapse of buildings and infrastructure, resulting in several casualties and huge losses [2]. Therefore, the design of structures should ensure that they remain in safe conditions after seismic actions and allow the occupants to be evacuated safely [3].

The predominant lateral structural system before 1960 was the moment-resisting frame. However, innovations have led to tubular, core, and outrigger systems [4]. Tubular systems are already widely used for significantly tall structures [5]. Tubular systems include framed tubes, braced tubes, trussed tubes, tube-in-tubes, and bundled tubes. The diagrid system, a more recent trussed tube, improves the structure's stability by offering maximum resistance to overturning moments and torsion [3]. The use of shear wall-frame structural systems is a common practice for lateral load resistance in tall buildings [6]. For example, most tall buildings in Kenya are predominantly shear wall-framed structures. Therefore, there is a need to compare and identify the most effective system concerning earthquake behaviour.

The braced tube system is also called a trussed-tube system [3]. As the name implies, the braced tube system incorporates braces into the conventional framed tube. The fascia diagonal interacts with trusses on the perpendicular faces, resulting in three-dimensional behaviour that eliminates shear lag in the frames, thereby enabling wide column spaces [5], [6]. The braces also help propagate the gravity loads, acting as inclined columns [4], [5].

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The term "diagrid" originates from the mashup of the words "diagonal" and "grid". The triangulation of the diagonals enables the diagrid structures to achieve incredible in-plane stiffness [5]. The diagonal pattern also significantly influences the structural responses of diagrid systems [7]. There are two classes of diagrids: uniform and varying angle diagrids. The uniform angle diagrid consists of the optimal angle maintained throughout the building height, while the varying angle diagrid system has steeper angles towards the structure's base [4].

The tube-in-tube system is a structural system that uses an exterior tube and an inner core [8]. The inner core is usually a steel-braced tube or a concrete core wall connected to the outer tube by a floor diaphragm [6]. The outer tube bears more lateral forces [3]. The diagrid system, braced tube system, or framed tube system constitutes the exterior tube, while the concrete core comprises the inner tube [4].

The shear wall-frame system is a structural system where both the shear walls and the rigid frame function jointly to resist lateral loads. This horizontal interaction depends on the shear wall's and the moment frame's stiffness [5]. If well designed, the shear wall-frame system can effectively realize the lateral stiffness of the shear wall and frame despite the two having different deformation properties, thereby improving the lateral load resistance of the building [6]. This research study considered the steel plate shear wall, which has several advantages over the traditional reinforced concrete shear wall, including lower structural mass, easier and faster construction, and it occupies a smaller floor area [9]. The steel plate shear walls also have considerable strength and ductility to ensure good performance against lateral loads [10].

Some recent studies on tubular and shear wall systems [11], [12] have assessed analytical methods that can be useful in the determination of natural frequencies of tall buildings during the preliminary design stage. The methods are comparable to the results from the finite element method. Other studies have evaluated the dynamic responses of different tubular systems to help structural designers with system selection. For brevity, this section expounds on two of these studies.

In one study [13], the diagrid system, a trussed tube system, was comparatively studied with an exterior braced frame system. The model adopted was a 24-story building, and the diagrids had an angle of 70º. The study used two square plan models with a square diagrid system, two rectangular models with a circular diagrid system, a square plan model with an exterior braced system, and a rectangular plan with an exterior braced system. The seismic analysis considered Zone III, soil type II, and a response reduction factor of five per the Indian Standard code. ETABS software helped with the analysis. The basis of comparison was on the following values: the period of vibration, stiffness, base shear values, and lateral displacements. The conclusion was that the diagrid system performs better than the exterior braced frame systems based on its lower displacements and periods of vibration. In addition, its stiffness and the corresponding base shear values were also higher than those of the exterior braced frame system.

Another study [14] assessed different tubular systems for tall buildings against dynamic wind and earthquake effects. The systems investigated were the tube-in-tube, braced bundled tube, and bundled tube systems. The case study model was an existing 58-story building in Dallas, USA. The earthquake analysis was per the Uniform Building Code 94 design spectrum, while the wind analysis was by equivalent static and time history methods. The basis of comparisons were the values of displacement indexes and shear lag. The tube-in-tube system attained the lowest displacement index for wind and earthquake loads. Regarding the shear lag and resultant structural weight, the braced bundled tube performed better than the other systems.

This research study aimed at comparing the dynamic earthquake behaviour of braced tube, diagrid, tube-in-tube, and shear wall-frame structures. The dynamic seismic parameters of interest were the fundamental periods of vibration, top drifts, seismic base shears, and top floor accelerations. Previous comparative research studies [13], [14] never studied the top floor accelerations, which is an

essential dynamic parameter. There is a need to study the top floor accelerations because they control the comfort of the building occupants on the top floors in a seismic event. Moreover, different seismic areas have different peak ground accelerations that affect the design spectral accelerations and, ultimately, the modal response spectrum values, hence the need to understand the dynamic behaviour of structures in different seismic regions.

2. Method

This study compared the dynamic earthquake behaviour of braced tube, diagrid, tube-in-tube, and shear wall frame structures. The compared dynamic parameters comprised the fundamental periods of vibration, top drifts, seismic base shears, and top floor accelerations obtained by modal response spectrum analysis per EN 1998-1-1:2004. This research work also adopted 12 building models, whereby every structural system comprised 12-, 24-, and 36-story models. The story difference of 12 accounts for the least common multiple of 6- and 4-story modules for the braced tube and diagrid models, respectively. The investigated seismic zone was the Nairobi city area in Kenya.

The following model parameters were constant for all 12 models: the floor slab depth and area, the service area, the plan dimensions, the story heights, and materiality. The building models also complied with the ultimate limit and damage limitation states to meet the seismic design requirements. The limiting inter-story drift of all 12 building models for the damage limitation states was h/100 per EN 1998-1-1:2004. Table 1 shows the building model data, while Table 2 shows the parameters for modal response spectrum analysis used in every building model.

Table 1. Building model data

Model feature	**Description**
Plan dimensions	36m by 36m
Service area	12m by 12m
Typical story heights	3.6m
Diagrid angle	67.38^0
Diagrid story-module	4
Brace type	Overall X-braces connected with columns at intersections
Brace angle	30.96^0
Braced tube's X-brace story-module	6
Interior braced tube's X-brace angle and story module (Tube-in-tube models)	30.96^0, 2
Exterior diagrid tube's angle and story module (Tube-in-tube models)	67.38^0, 4
Shear wall type (for Shear wall-frame models)	Unstiffened steel plate shear-walls
Grade of solid concrete deck slabs	C25/30
Grade of wide-flange steel sections	S355
Grade of hollow structural steel sections	S355H
Grade of unstiffened infill steel plates	S275
Importance class	II
Building location	Nairobi, Kenya
Seismic zone	VII
Method of seismic analysis	Modal response spectrum analysis per EN 1998-1-1:2004
Density of concrete	25 KN/m^3 per EN 1991-1-1:2002
Density of structural steel	78.5 KN/m^3 per EN 1991-1-1:2002
Typical floor live load	1.5 KN/m^2 per EN 1991-1-1:2002
Roof floor live load	2.5 KN/m^2 per EN 1991-1-1:2002
Typical floor finishes load	1 KN/m^2 per EN 1991-1-1:2002

Table 2. Modal response spectrum parameters per EN 1998-1-1:2004

Parameter	Value
Peak ground acceleration	0.12g
Spectrum type	1
Ground type	A
Soil factor, S	1
Spectrum period, T_b	0.15
Spectrum period, T_c	0.4
Spectrum period, T_d	2
lower bound factor, β	0.2
Behaviour factor, q	3
Damping ratio	0.05

This study utilized ETABS software, and the primary modelling assumption was that the horizontal floor slabs are infinitely stiff and therefore act as rigid diaphragms. The control of steel sections was necessary to minimize the impact of sectional differences on the seismic behaviour of each model (see Appendix File 1). All the models had solid deck slabs with a thickness of 150 mm. The floor plans of all the building models were double symmetrical about the X and Y axes, as shown in Figure 1. Appendix File 1 provides the detailed floor plans of the models. Figure 2 depicts the elevations of the building models.

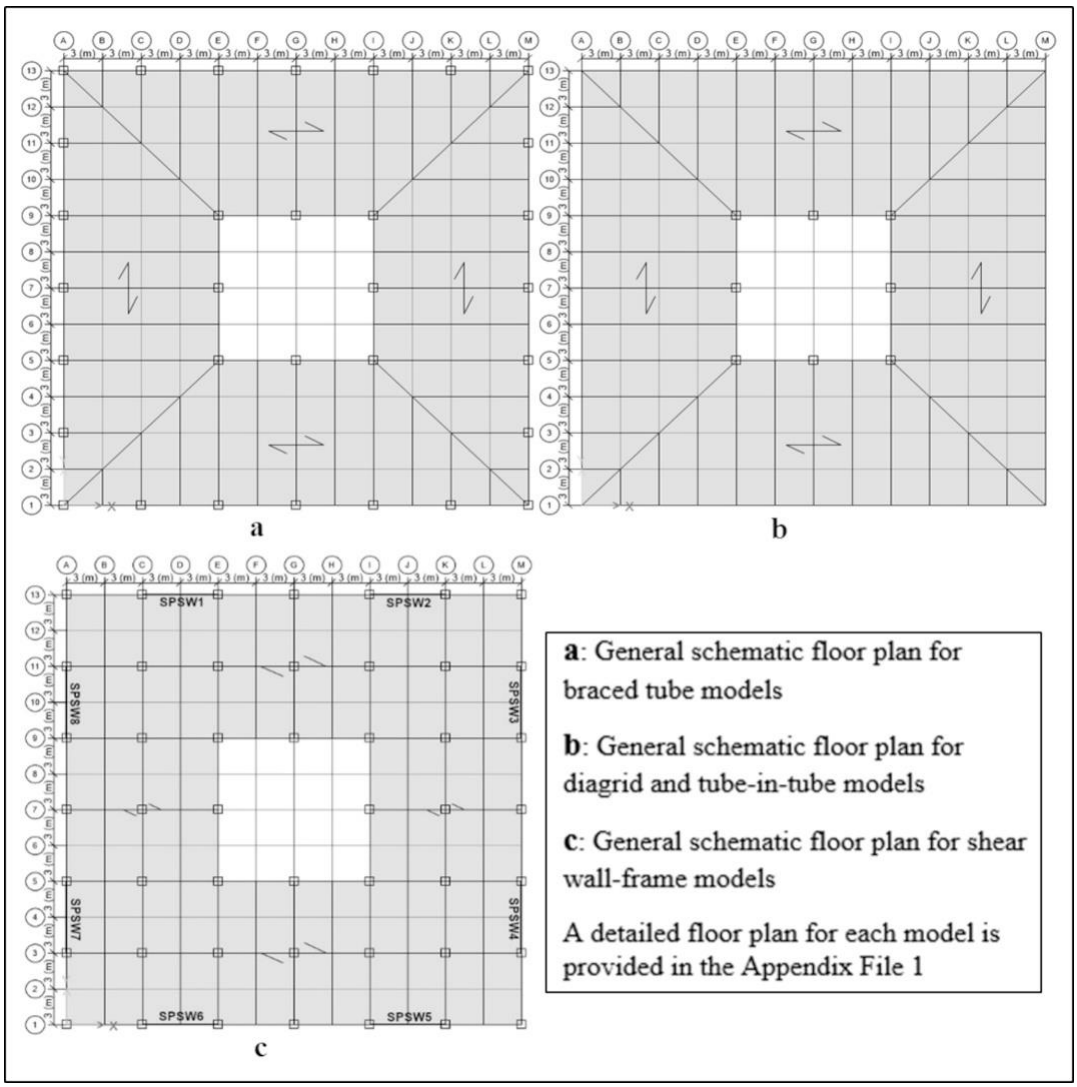


Figure 1. General schematic floor plans for the building models

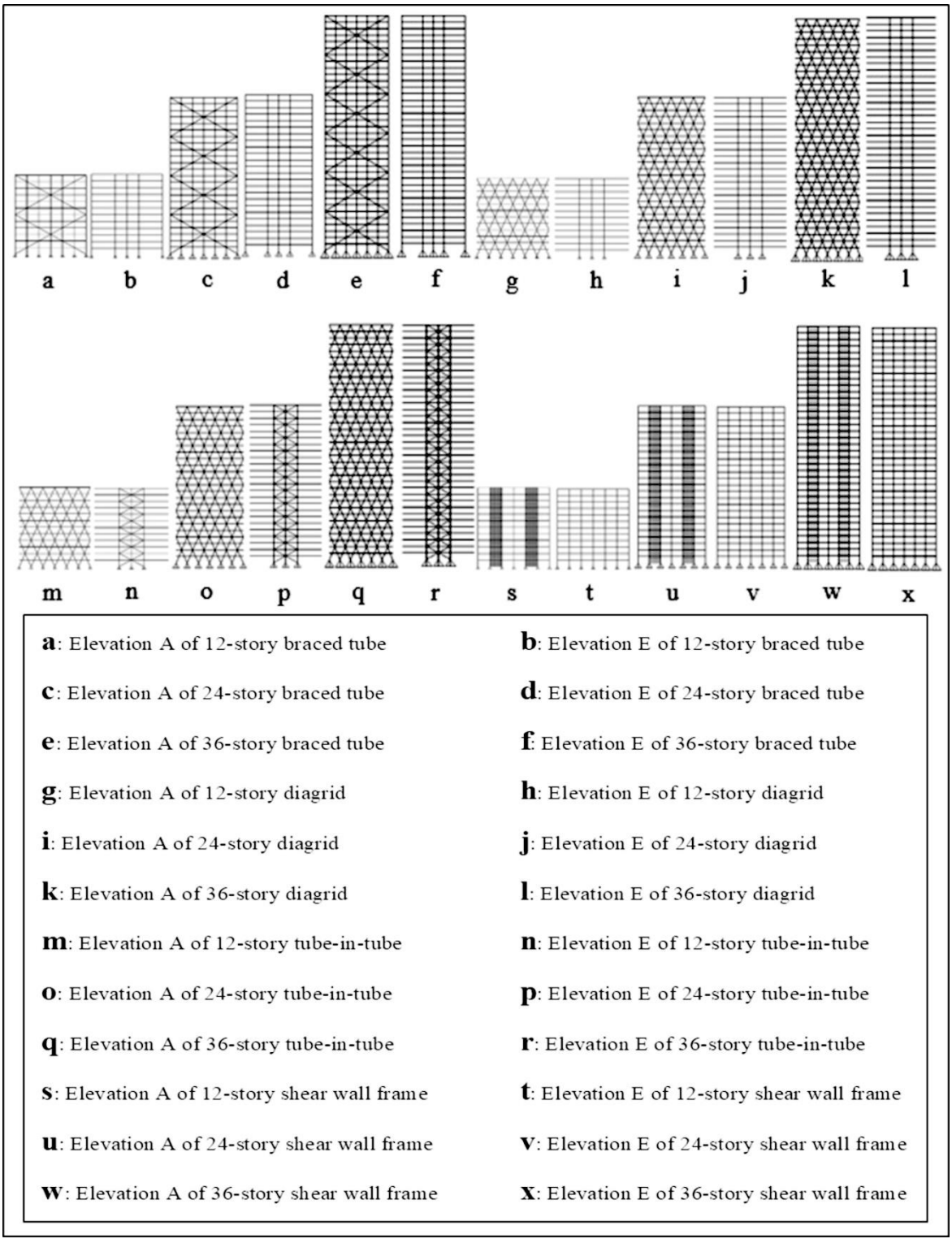


Figure 2. Elevations of the building models

For the braced-tube structure models, all the structural steel elements were pin-connected. Therefore, the lateral load propagation was through the axial forces induced in the diagonal bracings. Additionally, the overall X-braces adopted had 6-story modules, which satisfied the successive column connection requirement for optimal behaviour proposed by Gaur and Goliya [15]. The bracings had pinned connections with columns at intersections. The resulting angle between the diagonal bracings and the horizontal plane was 30.96º. Moreover, the structure models had pinned base connections.

Regarding the diagrid structure models, all the structural steel elements were pin-connected. Consequently, the lateral load propagation was through the axial forces induced in the diagonal members (inclined columns). As Isaac and Ipe [16] proposed, the diagrid module used was the 4-story module with a uniform and optimum angle of 67.38º. The structure models also had pinned base connections.

Concerning the tube-in-tube structure models, all the structural steel elements were also pin-connected. As a result, the axial forces induced in the diagonal members (inclined columns) propagated a significant portion of the lateral load. On the other hand, the axial forces generated in the internal bracing resisted a minor part. Furthermore, the exterior tube adopted was the diagrid since it is more effective than the framed or braced tube. The interior tube adopted was the braced tube instead of a core wall since materiality was an independent variable in this study. The exterior diagrid tube had 4-story modules with diagonal angles of 67.38º, as proposed by Isaac and Ipe [16], while the interior braced tube had 2-story modules with diagonal angles of 30.96º. Diagonals of the interior braced tube were connected to successive columns, hence satisfying the optimal behaviour proposed by Gaur and Goliya [15]. In addition, the structure models had pinned base connections.

For the shear wall-frame structure models, the structural steel elements (girders and columns) had rigid connections, and the expected lateral load propagation was through shear wall-frame interaction. Additionally, the secondary beams had pinned connections. This study adopted unstiffened steel plate shear walls instead of the traditional concrete walls since materiality was an independent variable in this study. Moreover, these walls had a constant thickness and strategical positions along the perimeter of the building models to eliminate the twisting of the buildings. The structure models had pinned base connections. A method known as the orthotropic membrane model, initially proposed by Sabelli and Bruneau [17], was adopted to analyze the steel plate shear walls.

3. Result and Discussion

3.1 Comparisons of 12-story models

Figure 3 shows the results for the fundamental periods of vibration from the modal response spectrum analysis. From observation, the 12-story tube-in-tube model recorded the lowest fundamental period of vibration, while the 12-story shear wall-frame model recorded the highest value. These results imply that the 12-story tube-in-tube and shear-wall frame models had the highest and the lowest overall lateral stiffness, respectively. Furthermore, the superiority of diagrid systems over braced tubes at controlling vibration periods is consistent with the research findings of Sarvaswini, Ranjith, and Sanjith [13].

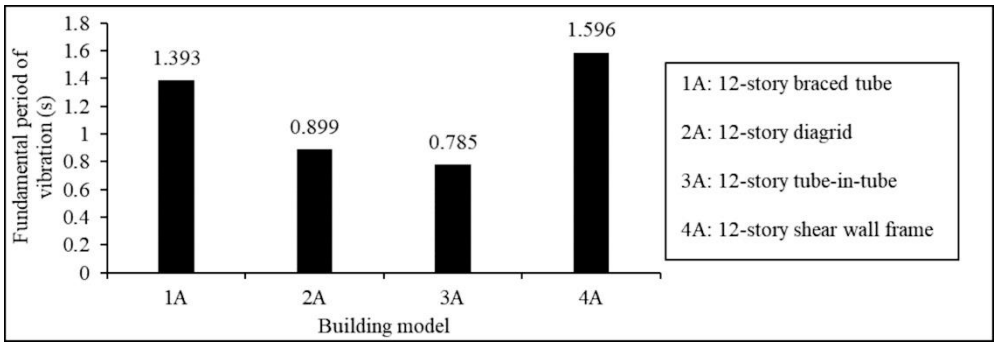


Figure 3. Fundamental periods of vibration for 12-story models

Figure 4 shows the top-floor accelerations for the 12-story models from the modal response spectrum analysis, which included a directional combination. As observed, the 12-story diagrid model recorded the lowest top floor acceleration, while the 12-story tube-in-tube model recorded the highest top floor acceleration. These results imply that the product of the participation factors, mode shape

values and modal spectral accelerations was lowest for the 12-story diagrid model and highest for the 12-story tube-in-tube model. Moreover, the lowest period of vibration, recorded earlier, for the 12-story tube-in-tube model significantly increased its modal spectral accelerations, resulting in the highest top-floor accelerations compared with the other study models.

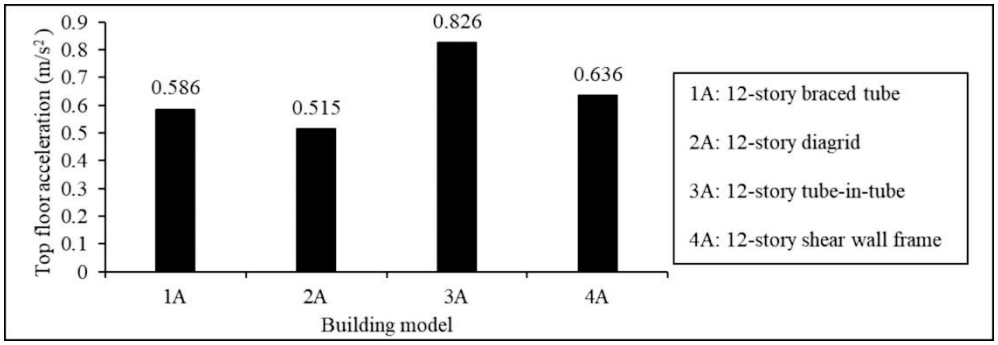


Figure 4. Top-floor accelerations for 12-story models

Figure 5 depicts the seismic base shears for the 12-story models from the modal response spectrum analysis, which included a directional combination. The 12-story shear wall-frame model had the lowest seismic base shear, while the seismic base shear for the 12-story tube-in-tube model was the highest. The findings imply that the product of effective mass values and modal spectral accelerations was lowest for the 12-story shear wall-frame model and highest for the 12-story tube-in-tube model. Additionally, the periods of vibration discussed earlier imparted the modal spectral accelerations and hence the seismic base shear values. The short and long periods of vibration resulted in high and low seismic base shears, respectively.

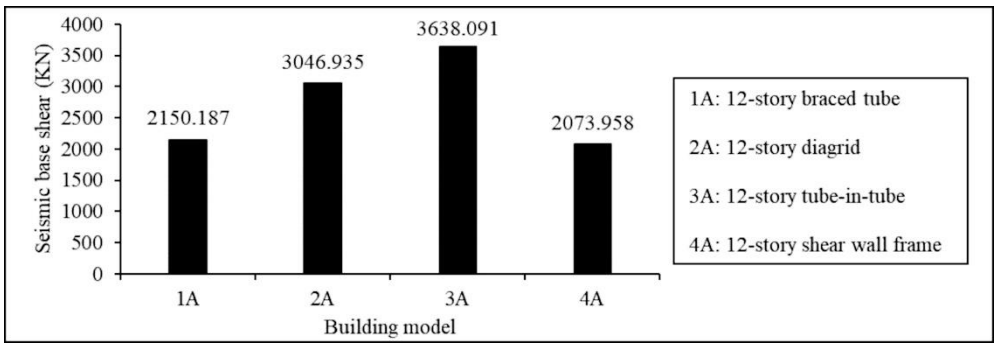


Figure 5. Seismic base shears for 12-story models

Figure 6 shows the top drifts for the 12-story models from the modal response spectrum analysis, which included a directional combination. Note that the design displacements per EN 1998-1-1:2004 would be the product of these MRSA values and the behaviour factor [18]. The 12-story diagrid model had the lowest top drift, while the top drift for the 12-story shear wall-frame model was the highest. These findings suggest that the 12-story diagrid model had the highest overall lateral stiffness, while the 12-story shear wall-frame model had the lowest. Furthermore, the results imply that the product of participation factors, mode shape values, modal spectral accelerations, and the square of the periods of vibrations was lowest for the 12-story diagrid model and highest for the 12-story shear wall-frame model. However, the 12-story tube-in-tube model did not record the lowest top drift despite having the lowest period of vibration because of the significant impact of its high modal spectral acceleration values in this story. The outstanding property of diagrid systems being very effective at controlling lateral displacements is consistent with the findings of Sarvaswini, Ranjith, and Sanjith [13].

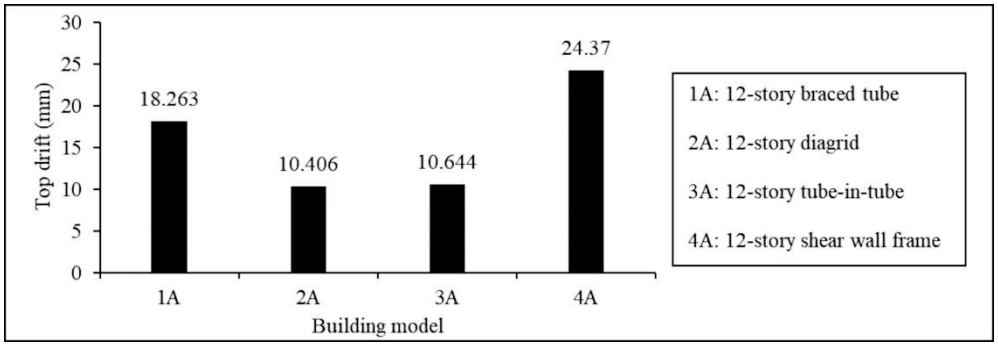


Figure 6. Top drifts for 12-story models

3.2 Comparisons of 24-story models

Figure 7 shows the results for the fundamental periods of vibration from the modal response spectrum analysis. The 24-story tube-in-tube model had the lowest fundamental period of vibration, while the 24-story shear wall-frame model recorded the highest. These results imply that the 24-story tube-in-tube model had the highest overall lateral stiffness, while the 24-story shear wall frame model had the lowest overall lateral stiffness. Furthermore, the superiority of diagrid systems over braced tubes at controlling vibration periods is consistent with the findings of Sarvaswini, Ranjith, and Sanjith [13].

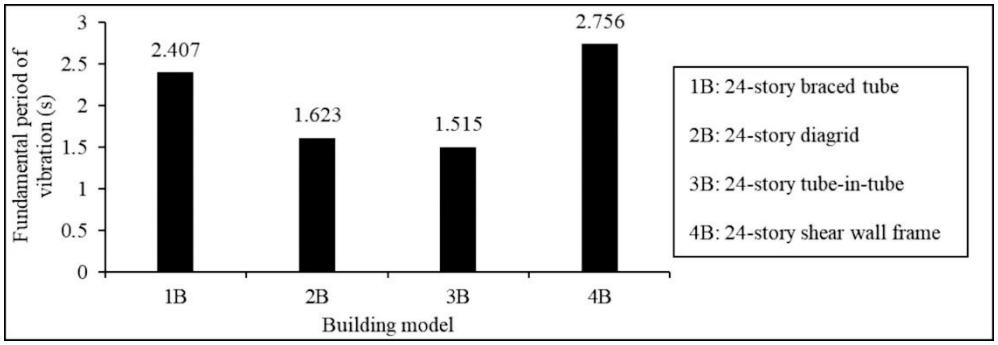


Figure 7. Fundamental periods of vibration for 24-story models

Figure 8 shows the top-floor accelerations for the 24-story models from the modal response spectrum analysis, which included a directional combination. As observed, the 24-story diagrid model recorded the lowest top floor acceleration, while the 24-story tube-in-tube model recorded the highest top floor acceleration. These results imply that the product of the participation factors, mode shape values and modal spectral accelerations was lowest for the 24-story diagrid model and highest for the 24-story tube-in-tube model. Moreover, the lowest period of vibration, recorded earlier, for the 24-story tube-in-tube model significantly increased its modal spectral accelerations, resulting in the highest top-floor accelerations compared with the other study models.

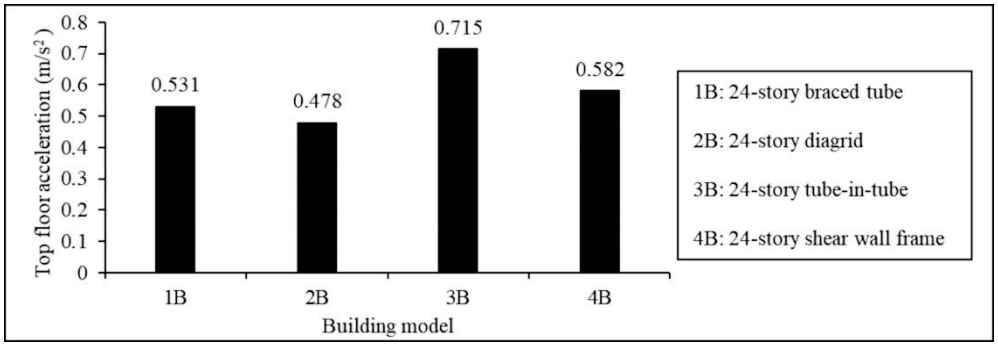


Figure 8. Top-floor accelerations for 24-story models

Figure 9 shows the seismic base shears for the 24-story models from the modal response spectrum analysis, which included a directional combination. From observation, the 24-story braced tube model recorded the lowest seismic base shear, while the 24-story tube-in-tube model recorded the highest seismic base shear. The results suggest that the product of the effective mass values and modal spectral accelerations was lowest for the 24-story braced tube model and highest for the 24-story tube-in-tube model. Additionally, the periods of vibration discussed earlier imparted the modal spectral accelerations and hence the seismic base shear values. However, the 24-story shear wall-frame model did not record the lowest seismic base shear despite having the highest period of vibration because of the significant impact of its high effective-mass value in this story.

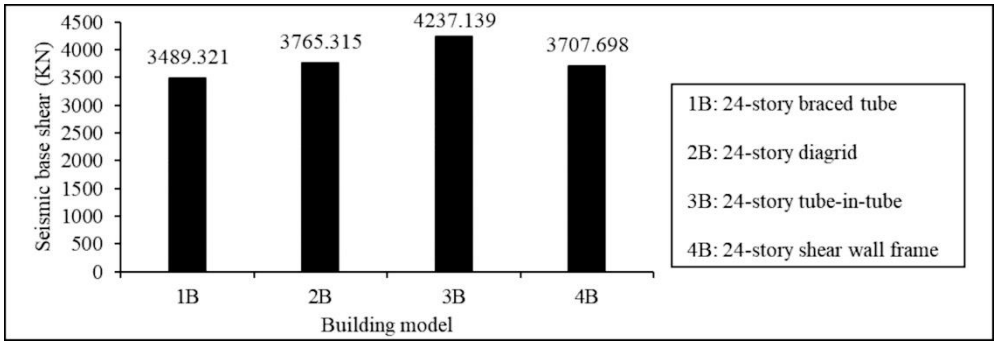


Figure 9. Seismic base shears for 24-story models

Figure 10 shows the top drifts for the 24-story models from the modal response spectrum analysis, which included a directional combination. Note that the design displacements per EN 1998-1-1:2004 would be the product of these MRSA values and the behaviour factor [18]. By observation, the 24-story tube-in-tube model recorded the lowest top drift, while the 24-story shear wall-frame model recorded the highest top drift. These results suggest that the 24-story tube-in-tube model had the highest overall lateral stiffness, while the 24-story shear wall-frame model had the lowest overall lateral stiffness. Moreover, the results also imply that the product of the participation factors, mode shape values, modal spectral accelerations, and the square of the periods of vibrations was lowest for the 24-story tube-in-tube model and highest for the 24-story shear wall-frame model. This superior property of tube-in-tube systems being very effective at controlling lateral displacements is consistent with the findings of Ghanbari, Salajegheh, Khojastehfar, and Salajegheh [14].

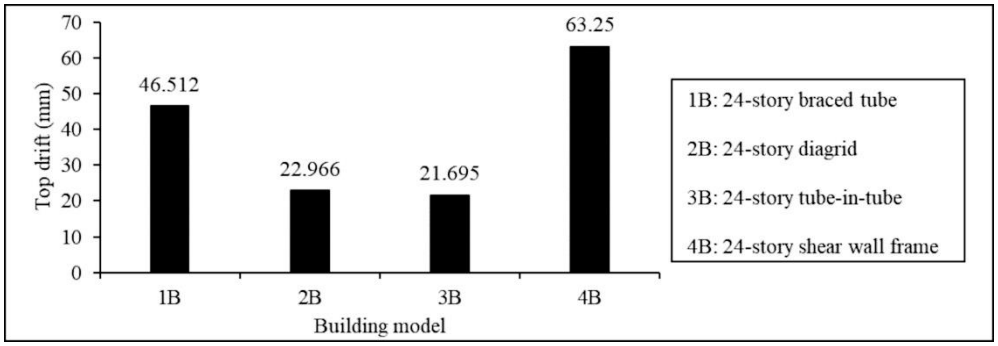


Figure 10. Top drifts for 24-story models

3.3 Comparisons of 36-story models

Figure 11 shows the results for the fundamental periods of vibration from the modal response spectrum analysis. Again, the 36-story tube-in-tube model had the lowest fundamental period of vibration, while the shear wall-frame model recorded the highest value. These results imply that the 36-story tube-in-tube and shear-wall frame models had the highest and lowest overall lateral stiffness, respectively. Furthermore, the superiority of diagrid systems over braced tubes at controlling vibration periods is consistent with the findings of Sarvaswini, Ranjith, and Sanjith [13].

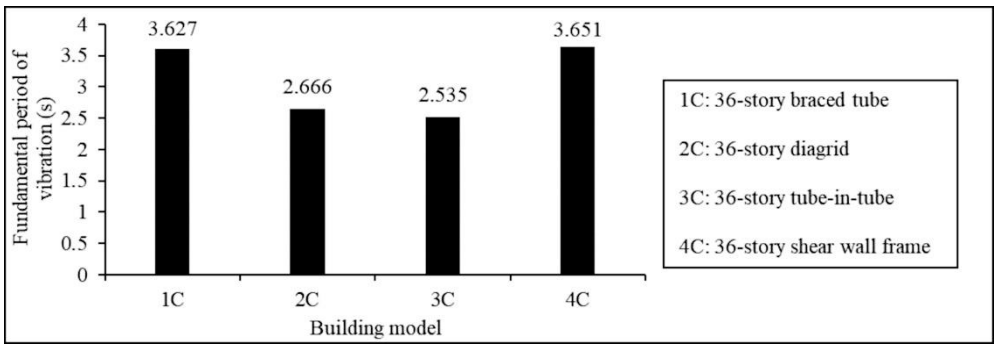


Figure 11. Fundamental periods of vibration for 36-story models

Figure 12 shows the top-floor accelerations for the 36-story models from the modal response spectrum analysis, which included a directional combination. From observation, the 36-story braced tube model had the lowest top floor acceleration, while the top floor acceleration of the 36-story tube-in-tube model was the highest. These results imply that the product of the participation factors, mode shape values and modal spectral accelerations was lowest for the 36-story braced tube model and highest for the 36-story tube-in-tube model. Moreover, the lowest period of vibration, recorded earlier, for the 36-story tube-in-tube model significantly increased its modal spectral accelerations, resulting in the highest top-floor accelerations compared with the other study models.

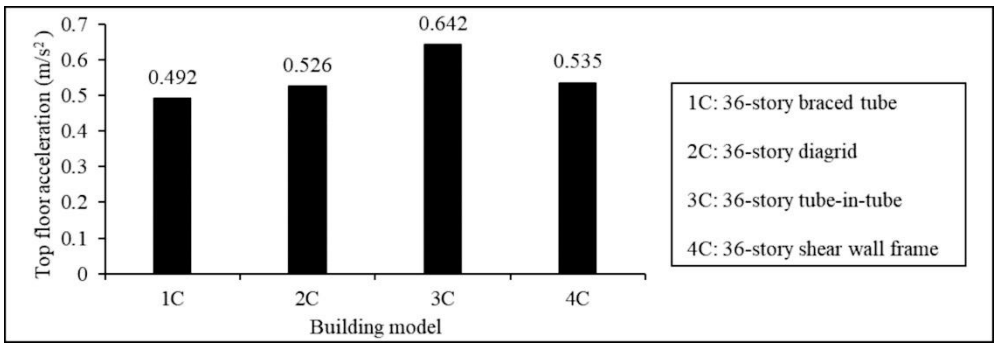


Figure 12. Top-floor accelerations for 36-story models

Figure 13 shows the seismic base shears for the 36-story models from the modal response spectrum analysis, which included a directional combination. The 36-story braced tube model had the lowest seismic base shear, while the seismic base shear for the 36-story shear wall-frame model was the highest. These results imply that the product of the effective mass values and modal spectral accelerations was lowest for the 36-story braced tube model and highest for the 36-story shear wall-frame model. Additionally, the periods of vibration discussed earlier imparted the modal spectral accelerations and hence the seismic base shear values. However, the 36-story shear wall-frame model did not record the lowest seismic base shear despite having the highest period of vibration because of the significant impact of its very high effective mass value in this story.

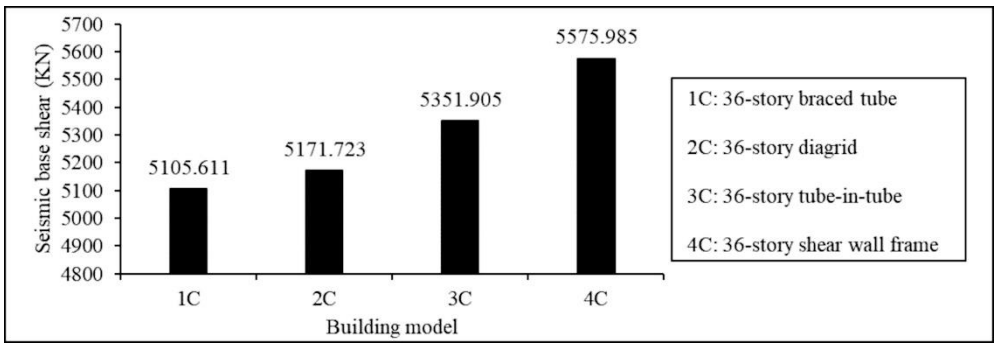


Figure 13. Seismic base shears for 36-story models

Figure 14 shows the top drifts for the 36-story models from the modal response spectrum analysis, which included a directional combination. Note that the design displacements per EN 1998-1-1:2004 would be the product of these MRSA values and the behaviour factor [18]. By observation, the 36-story tube-in-tube model recorded the lowest top drift, while the 36-story shear wall-frame model recorded the highest top drift. These results suggest that the 36-story tube-in-tube model had the highest overall lateral stiffness, while the 36-story shear wall-frame model had the lowest overall lateral stiffness. Moreover, the results also imply that the product of the participation factors, mode shape values, modal spectral accelerations, and the square of the periods of vibrations was lowest for the 36-story tube-in-tube model and highest for the 36-story shear wall-frame model. This superior property of tube-in-tube systems being very effective at controlling lateral displacements is consistent with the findings of Ghanbari, Salajegheh, Khojastehfar, and Salajegheh [14].

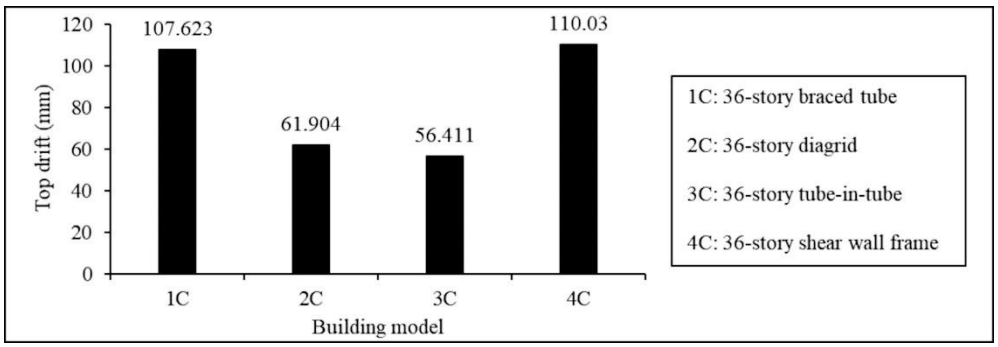


Figure 14. Top drifts for 36-story models

4. Conclusion

This study draws the following conclusions: Concerning the fundamental periods of vibration, the 12-story diagrid model was 56% and 65% of the 12-story shear wall-frame and braced tube models, respectively, but 15% more than the 12-story tube-in-tube model. Additionally, the 24-story diagrid model was 59% and 67% of the 24-story shear wall-frame and braced tube models, respectively, but 7% more than the 24-story tube-in-tube model. Finally, the 36-story diagrid model was 73% and 74%

of the 36-story shear wall-frame and braced tube models, respectively, but 5% more than the 36-story tube-in-tube model. These differences imply that the 12-, 24-, and 36-story diagrid and tube-in-tube models had the highest overall lateral stiffness, with the latter being slightly ahead.

Concerning the top floor accelerations, the 12-story diagrid model was 62%, 81%, and 88% of the 12-story tube-in-tube, shear wall-frame, and braced tube models, respectively. Additionally, the 24-story diagrid model was 67%, 82%, and 90% of the 24-story tube-in-tube, shear wall-frame, and braced tube models, respectively. Finally, the 36-story diagrid model was 82% and 98% of the 36-story tube-in-tube and shear wall-frame models, respectively, but 7% more than the 36-story braced tube model. These differences suggest that the diagrid system was the most effective at controlling the top-floor accelerations for the 12- and 24-story models and was close behind the 36-story braced tube model, which implicates its low product of participation factors, mode shape values, and modal spectral accelerations.

Concerning the seismic base shears, the 12-story diagrid model was 84% of the 12-story tube-in-tube model but 42% and 47% more than the 12-story braced tube and shear wall-frame models, respectively. Additionally, the 24-story diagrid model was 89% of the 24-story tube-in-tube model but 2% and 8% more than the 24-story shear wall-frame and braced tube models, respectively. Finally, the 36-story diagrid model was 93% and 97% of the 36-story shear wall-frame and tube-in-tube models, respectively, but 1% more than the 36-story braced tube model. Therefore, the shear wall-frame model had the highest seismic base shear limitation among the 12-story models, while the braced tube model had the highest seismic base shear limitation among the 24- and 36-story models. This seismic behaviour implicates the low product of the effective mass values and modal spectral accelerations that these two systems, as mentioned above, recorded.

Concerning the top drifts, the 12-story diagrid model was 43%, 57%, and 98% of the 12-story shear wall-frame, braced tube, and tube-in-tube models, respectively. Additionally, the 24-story diagrid model was 36% and 49% of the 24-story shear wall-frame and braced tube models, respectively, but 6% more than the 24-story tube-in-tube model. Finally, the 36-story diagrid model was 56% and 58% of the 36-story shear wall-frame and braced tube models, respectively, but 10% more than the 36-story tube-in-tube model. These results imply that the 12-, 24-, and 36-story diagrid and tube-in-tube models had the highest overall lateral stiffness, with the latter being slightly ahead.

The diagrid system is highly recommended, followed by the braced tube, tube-in-tube, and shear wall-frame systems, respectively, for seismic load resistance in 12-, 24-, and 36-story buildings with regular plan geometry. It is important to note that this study used a constant behaviour factor of 3 for all the lateral systems. Further studies can adopt nonlinear seismic methods such as pushover and time history analyses. Nevertheless, the findings of this study will be helpful to structural engineers when selecting between braced tube, diagrid, tube-in-tube, and shear wall-frame structural systems, particularly during the preliminary design stage.

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