Evaluation of Structural Systems in Slender High-Rise Buildings

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Abstract

With the rapid population growth and scarcity of developable space, especially in large cities, there is a need for increased density in both commercial and residential housing, and hence a strong demand to maximise floor space by constructing not only tall, but also slender buildings. This study considers different structural systems available for constructing slender high-rise buildings and evaluates their feasibility in terms of the lateral deformation being one of the key governing design criteria for very tall buildings. To examine the performance of different structural systems in buildings of varying height and floorplan, this study applies finite element analyses in a parametric study to compare nine different building configurations under static loading with heights varying from 80m to 460m. The study shows that buildings with square footprints can achieve greater heights over rectangular footprints with the same area and that multiple towers when connected structurally at one or more levels can achieve even greater heights.

Keywords: *Slender High-Rise Buildings, Structural Systems, Large Cities, Building Footprint, Housing, Floor Space, Structural Performance*

1. Introduction

Creating tall structures first began as an expression of wealth, power and structural engineering advancement. However, with the rapid population growth and expanding urbanisation, tall structures remain highly relevant for both commercial and residential construction. In particular, slender buildings are becoming more commonplace as developers look to build higher in plots of lands that were previously considered too small to reach such heights. As indicated by Willis (2016), structural engineers generally consider skyscrapers with a minimum 1:10 or 1:12 ratio - the width of the building's base to its height - to be slender. However, many of the newest skyscrapers far exceed this ratio. For instance, "111 West 57th Street" tower in New York has a slenderness ratio of 1:24; this is more than twice as slender as what is required to be considered 'slender'.

A challenging design consideration of slender buildings to find the optimal compromise between usable floor space and structural performance is the arrangement of the vertical structural elements (columns and shear walls) within the building footprint. According to Khan (2004), the key structural performance criterion with creating taller and more slender structures is the excessive deflections under lateral wind loads. As buildings grow taller and thinner, gravity loads are no longer the critical loading case. Therefore, lateral wind loads become the dominate design case.

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Lateral sway deflections can cause discomfort to the building's occupants, especially on the higher levels and can increase the design action effects associated with geometric non-linearity. Several studies (e.g. Fatahi et al., 2011; Fatahi et al., 2014; Tabatabaiefar and Mansoury, 2016) have highlighted detrimental effects of excessive lateral sway deflections on performance level and overall stability of tall buildings. Developing an effective lateral load resisting system is therefore one of the greatest challenges for structural engineers designing tall slender towers. Traditionally, a large central concrete core is constructed to provide sufficient stiffness to minimise deflection (Ho 2016). To increase the slenderness of tall buildings, other innovative structural systems such as a 'trussed tube' can be utilised. Mitigation of deflection can be achieved through structural system modifications, auxiliary damping devices, and aerodynamic modifications (Tamura & Kareem 2013). This study is mainly concerned with static action effects and the impact that structural systems modifications can have on reducing maximum deflection and ensuring they remain within acceptable serviceability limits.

When considering the deformational response of tall buildings, inter-story drifts must be taken into account for the design of individual structural elements. However, based on empirical observations and theoretical dynamic response considerations, Scholl (1984) emphasised that the potential for drift related damage is highly variable, and is dependent on the structural and non-structural detailing provided by the designer. For this reason, a uniform structural design details were adopted for all buildings in this study and inter-story drift effects have not been included for comparing the deformational responses of different building systems. The maximum deflection was therefore chosen as it provides a single indicative parameter to comparing the global response of different building.

2. Comparative Study Overview

To investigate the structural performance of slender buildings, three common structural systems as shown in Figure 1 were examined. Each of those buildings has a total footprint area, which was chosen to be 676 m^2, which is slightly smaller than the 800m^2 footprint of 432 Park Avenue depicted in Figure 2 (Ho 2016); a square slender tower in New York that reached 426m, with a slenderness ratio of 1:15 (smallest width to height ratio). However, it is worth noting that in the design of 432 Park Avenue tower, a tuned mass damper was used to achieve the high slenderness ratio, which would not be feasible without the damping device.

2.1. Structural System Prototypes

As indicated in Figure 1, each of the buildings examined has either a square (26m × 26m) or a rectangular (40m × 16.9m) foot print configuration. For comparison purposes, each building design has an identical concrete core, housing four 3.5m × 2.95m lift shafts and uses a total of $51.8m^2$ cross-section area for shear walls and columns. Additionally, as will be presented later, a multiple tower concept was examined. All building prototypes were given the same cross section properties as far as possible. Dimensions and material properties adopted for all structural components were based on typical dimensions of similar high-rise buildings. All models use 60MPa high strength concrete. Tying the walls together are 800mm × 500mm (D × W) concrete beams and 200mm thick concrete slabs. The core and shear walls have a 500mm wall thickness. The total cross section area of all vertical structural elements, excluding the $32m^2$ core is constant on all floors to simplify comparison. Furthermore, a constant floor-to-floor height of 4m is maintained throughout.

The trussed tube prototype has the same configuration as both the shear wall and the framed tube prototypes, but with the inclusion of a truss placed on the external face of the buildings. The exterior truss uses round steel hollow sections with an outside diameter of 1000mm and a wall thickness of 100mm. Each exterior truss diagonal extends across 5 storeys and connects into large concrete corner columns. The finite element model with rectangular plan has the trusses included only on its shorter sides, to resist the lateral loads in the buildings weakest and most critical bending axis. The finite element model with square plan has the truss on all sides, as the critical bending axis is along the diagonal of the building.

2.2. Finite Element Models
The finite element models were created using CSI ETABS, a structural analysis software typically used in the analysis of high-rise buildings. All FE simulations have considered the combined actions of wind and gravity loading, as well as nonlinear P-Delta effects. Figures 3 to 8 depict finite element models of the different systems corresponding to the floor plans shown in Figure 1. All FE models depicted in Figures 3 to 8 were analysed for a range of the number of storeys varied from 20 to 70 and corresponding heights from 80m to 280m, respectively.

The ETABS models have each been created using the same design methodology and have a uniform floorplan throughout the superstructures. Each of the models depicted in Figures 3 to 8 were subjected to a uniformly distributed lateral load; and a preliminary validation of the models indicated that their maximum deflection was reasonably correlated to the deflection of an analogous fixed cantilever beam from first principals.

3. Structural Loading

Loads applied to all structural models were limited to gravity and wind actions as representative of the dominant loads affecting sway displacements in tall buildings. Other load conditions were considered not relevant for the purpose of investigating the lateral static deflections. Gravity loads applied to all floors were applied uniformly with typical values of 4 kPa and 2 kPa for dead and live loads respectively. Lateral wind forces were determined in accordance with AS/NSZ 1170.2 (2011) standards leading to the parameters listed in Table 1. A terrain Category 2 (Well-scattered obstructions having heights generally from 1.5 m to 10 m) was assumed as this is fairly conservative, and allows for a wider application for the results. The regional wind speed parameter was chosen to be 45m/s, which corresponds to a 500-year average recurrence interval, in the region of Sydney, Australia.

In the FE model, lateral (wind) forces were generated automatically by an in-built module of the ETABS software. The wind loads were simulated as resultants of the corresponding tributary façade area acting at each floor level, whereby floors were modelled to act as rigid 'diaphragms' in the horizontal plane that in turn distribute the loads to the vertical elements. As the framing plan is doubly symmetrical, the centre of stiffness coincides with the geometric centroid and hence twisting with respect to the vertical axis was not present. As an example, Figure 9 shows the force resultants applied at each floor level to both the narrow face and the wide face of a 70-storey building with rectangular footprint. Additionally, a load case representing diagonal wind exposure is applied in the FE simulation as a combination of directional forces acting simultaneously on the narrow and wide faces.

4. Parametric Study

As discussed earlier, the key structural performance criterion for tall slender buildings is limiting excessive deflections under lateral wind loads (Khan 2004). According to Section 2 of AS3600 (2009), the limiting lateral deflection allowed for a building is the Height/500 as expressed by Δ_{Limit} in Equation 1.

$$\Delta_{Limit} = \frac{H}{500} \tag{1}$$

The deflection limit of Equation 1 is therefore adopted as conservative criterion in order to determine the maximum possible building height of the different structural systems considered in this study.

4.1. Building Deflections, Height Limit and Slenderness Ratio

The approach used to identify the limiting height for a given structural system can be explained by referring to the examples of buildings with shear walls presented in Table 2 and Figure 10. As key parameter, the building height is varied by varying the number of storeys between 20 and 70 and a separate FE simulation was conducted in each case to establish the maximum lateral deflection of the building. In plotting the curves of both, the allowable deflection values (Δ_{Limit}) were determined based on Equation 1 while the maximum deflections (Δ_{max}) were obtained from the FE analysis as functions of number of storeys, the limiting height and corresponding slenderness ratio is able to be interpolated using the intersection of the two curves. In the example of Figure 10 for the case of the rectangular building with shear wall, the critical height reached is 176m which corresponds to a maximum of 44 storeys and a 1:10.7 slenderness ratio.

When the above approach is also applied to the building with the square footprint, the comparison in performance with the rectangular case can be easily established as shown in Table 3 and Figure 11.

4.2. Shear Wall Lateral Deflection Performance Comparison

From Figure 11 and Table 3, it can be seen that the square footprint model has a higher lateral stiffness and consequently performs significantly better in terms of its lateral deflection. Instead of a maximum possible height of 44 storeys, the square footprint design reached 62 storeys; a 41% improvement in performance.

5. Results and Discussion

The approach outlined above was applied to all other studied structural systems in order to compare their performance in terms of height while marinating the required lateral deflections limits under the same wind conditions. The results of individual building prototypes are given in Tables 4 to 7 and a summary is presented in Figure 12 and Table 8. It can be seen from Figure 12 that in all cases considered, the buildings with the square footprint perform better than the buildings with rectangular footprints. This difference is due to two major factors. The first is the critical wind exposure direction of the square tower with the loads acting in the diagonal direction, which has a smaller exposure width of 36.7m compared to the 40m critical exposure width of the rectangular tower's wide facade. The second reason is the square tower's larger effective moment of inertia around its diagonal axis compared with the weaker principal axis of the rectangular tower. It is also observed that the difference between the shear wall and framed tube systems considered in this study is minimal, due to a similar effective moment of inertia, while the trussed tube system shows the best results due to the additional lateral stiffness provided by the truss action.

5.1. Non-structural Consideration

While structural performance is essential for maximising building height and thereby floor space, other aspects not investigated in this study concerning cost, construction constraints and architectural function should also be considered as part of the design. For example, in order to facilitate comparison in this parametric study, the total cross-section area of vertical structural members (columns, shear walls and lift core) is kept constant over the entire height of the building, whereas in practice, these may be optimised to reduce cost of construction materials. It is also worth noting that for the trussed tube system, the erection of the steel trusses including complex steel to concrete connections can be costly and may extend the overall duration of construction.

Another aspect to consider is the amount of open vs blocked façade areas. An open façade is crucial for improving comfort for occupants, and usually has a positive financial return value attached to it. A comparison between different systems, in terms of open and blocked façade per floor, is provided in Table 9 and Figure 13.

The buildings with rectangular footprint have a total perimeter of 113.8m compared to 104m for the square floorplate design and hence a greater open façade area in comparison. The framed tube designs were the least obstructive to the façade area, with an average of 24% of the total perimeter per floor being blocked. More obstructive than the framed tube, was the shear wall structural systems, with an average of 39% of the façade area being blocked. Figure 13 shows that the shear wall structural systems block more of the available façade perimeter than the framed tube, limiting the openness of liveable building space. Even though a rectangular footprint gives a greater total perimeter, the square framed tube structural system was able to outperform the rectangular shear wall structural system by 9% or 6.2m in terms of open façade length per floor. The most obstructive structural system was the trussed tube structural system. While based on the framed tube models, the addition of the exterior trusses obstructed 25% of the façade on each floor; resulting in a 49% blocked façade on average. The aforementioned points emphasise the need for compromises between structural performance and architectural function.

6. Multiple Tower System

By structurally connecting two or more towers as indicated by the example of Figure 15b, it is assumed that their combined lateral stiffness will increase, thereby reducing deformation and consequently enabling the construction of taller towers compared with a standalone case

discussed earlier. To investigate this assumption, three different structural systems were modelled and analysed. The first model, as shown in Figure 14, has a square footprint (52m × 52m) with an area equal to the combined footprint area of four individual (26m × 26m) towers. The other two models simulate four towers with the layout shown in Figure 15b, which are connected by the trussed bridge structure that spans two storeys as depicted in elevation in Figure 15a. In the first model, the towers are linked between the 35th and the 37th floors while in the second model, a further connection is added between the 70th and 72nd floors. A round steel hollow sections with an outside diameter of 1000mm and a wall thickness of 100mm was adopted. Each truss comprised 34 sections in total, and is 8m high, 12m wide and 27.5m long.

The ground space between the towers may be allocated for roads or for 'green areas' as is often required by city planners. A further architectural advantage of dividing one tower into four slender towers, is the doubling of the total façade area.

6.1. Multiple Tower Wind Loading

Wind loads were established using the parameters of Table 1 and the approach applied to the standalone towers described earlier. Wind load profile and distribution of forces between the four towers was determined using a virtual wind tunnel simulation software module by Autodesk Robot Structural Analysis Professional.

From the wind simulation, it was determined that the critical wind was along the diagonal direction as indicated in Figure 14. In this scenario, the windward tower experiences the full loading that it would if it was to stand alone, however the leeward tower, somewhat sheltered from the wind pressures, experienced only approximately 40%, while the towers along the cross diagonal on the left and right experienced approximately 50% of the loading acting on the windward tower.

6.2 Multiple Tower lateral Deflection Performance Comparison

Results of the Finite Element analyses of the multiple towers leading to the maximum deflections given in Tables 10 and 11 are presented in Figure 16. The corresponding allowable tower heights are summarised in Table 12 and Figure 17. It can be seen that when multiple trussed tube towers are connected together; their lateral deflection performance is significantly improved; compared to standing alone.

When the individual towers become connected with trussed bridges at only the 35th storey, the maximum number of storeys increases by 23%; from 65 storeys to 80. However, when a second

set of steel trussed bridges is introduced at the 70th floor, the maximum number of possible storeys increases to 105 or 62% compared to the single tower. The 62% improvement is very significant, and gives the multiple tower concept great merit. This is assuming that the complexity and added construction and project development costs can be overcome. It is worth noting that combining the four buildings together into one large 52×52m tower will result in an even structurally superior design by achieving the greatest height of 464m with 116 storeys. However, with only 10% increase in number of storeys compared with the multiple towers, this design has only half the perimeter length per storey and therefore much reduced open façade area which may be less architecturally attractive.

7. Final Remarks

A summary of the results obtained from the nine structural systems investigated in this study is presented in Figure 18. It can be seen that the variation in maximum possible heights achieved for a given footprint by changing the structural systems is relatively small. The larger variations occur due to changing the aspect ratio of the floor plates, and therefore also the effective bending stiffness and the wind exposures. The rectangular building designs were only able to achieve approximately 70% of the height of their square counterparts; despite having an identical floorplate area. This was due to a combination of a higher critical wind exposure surface area, and a decreased moment of inertia around the weak principal bending axis of the rectangular buildings. While in terms of effective slenderness ratio, the rectangular designs were still able to outperform the square designs by approximately 10%, the square configuration enabled more storeys and hence more liveable floor space to be constructed on the same footprint area.

The multiple tower concept was able to significantly outperform the single trussed tube square tower that is used as the structural basis of the concept. This was mainly due to a larger combined lateral stiffness and the reduced wind pressures experienced by the leeward towers, due to the sheltering by the windward towers. This resulted in an average wind pressure 40% lower compared to a single exposed tower; assuming the structure is able to act as a single system.

8. Conclusion

Through this study, the structural response of nine different tall building systems was investigated. The structures were subjected to gravity and wind loads in order to determine the lateral deflection of the buildings and to establish the maximum possible height that would satisfy the serviceability requirement of height/500 as allowable deformation. Each of the

buildings examined, which had either a square (26m × 26m) or a rectangular (40m × 16.9m) foot print configuration, was analysed with different floorplan arrangements including a shear wall, a framed tube and a trussed tube configuration. Individual towers were analysed for heights varying between 80m and 280m while multiple towers that were connected structurally by truss bridges at one or two locations were analysed for heights varying between 280m and 464m. It was observed that the difference between the shear wall and framed tube systems considered in this study is minimal, while the trussed tube system showed the best results due to the additional lateral stiffness provided by the truss action. It was also found that buildings with a square footprint can achieve greater heights over rectangular buildings with the same footprint due to the rectangular building having in comparison a larger wind exposure façade area and weaker bending stiffness in the critical wind direction. Furthermore, multiple towers when connected structurally at one or more levels were found to achieve even greater heights than if they were not connected.

References

AS/NZS 1170.0. (2002) *Australian/New Zealand Standard and supplement, Structural Design Actions: General Principles*, Standard Australia, Sydney

AS/NZS 1170.1. (2002) *Australian/New Zealand Standard and supplement, Structural Design Actions – Part 1: Permanent, Imposed and Other Actions*, Standard Australia, Sydney

AS/NZS 1170.2. (2002) *Australian/New Zealand Standard and supplement, Structural Design Actions – Part 2: Wind Actions*, Standard Australia, Sydney

AS/NZS 3600. (2009) *Australian/New Zealand Standard and supplement, Plain and Reinforced Concrete – Code of Practice*

Fatahi, B., Tabatabaiefar, H.R & Samali, B. 2011, 'Performance Based Assessment of Dynamic Soil-Structure Interaction Effects on Seismic Response of Building Frame', *Proceedings of Georisk 2011 - Geotechnical Risk Assessment & Management (Geotechnical Special Publication No. 224)*, American Society of Civil Engineers (ASCE), pp. 344-351.

Fatahi, B., Tabatabaiefar, H.R & Samali, B. 2014, 'Soil-Structure Interaction vs Site Effect for Seismic Design of Tall Buildings on Soft Soil', *Geomechanics and Engineering*, vol. 6, no. 3, pp. 293-320, Techno Press.

Khan, Y. 2004, '*Engineering Architecture: The vision of Fazlur R. Khan*', Norton

Ho, G. 2016, '*Tall Building Structures: Analysis and Design'*, Council on Tall Buildings and Urban Habitat

Scholl, R. 1984, *Brace Dampers: An Alternative Structural System for Improving the Earthquake Performance of Buildings*, Prentice Hall, pp1017

Tabatabaiefar, H.R. & Mansoury, B. 2016, 'Detail Design, Building and Commissioning of Tall Building Structural Models for Experimental Shaking Table Tests', *The Structural Design of Tall and Special Buildings*, vol. 25, no. 8, pp. 357–374, Wiley-Blackwell.

Tamura, Y. & Kareem, A. 2013, '*Advanced Structural Wind Engineering*', Springer Japan, pp378-407

Willis, C. 2016, '*Singularly Slender: Sky Living in New York, Hong Kong, and Elsewhere*', Council on Tall Buildings and Urban Habitat.
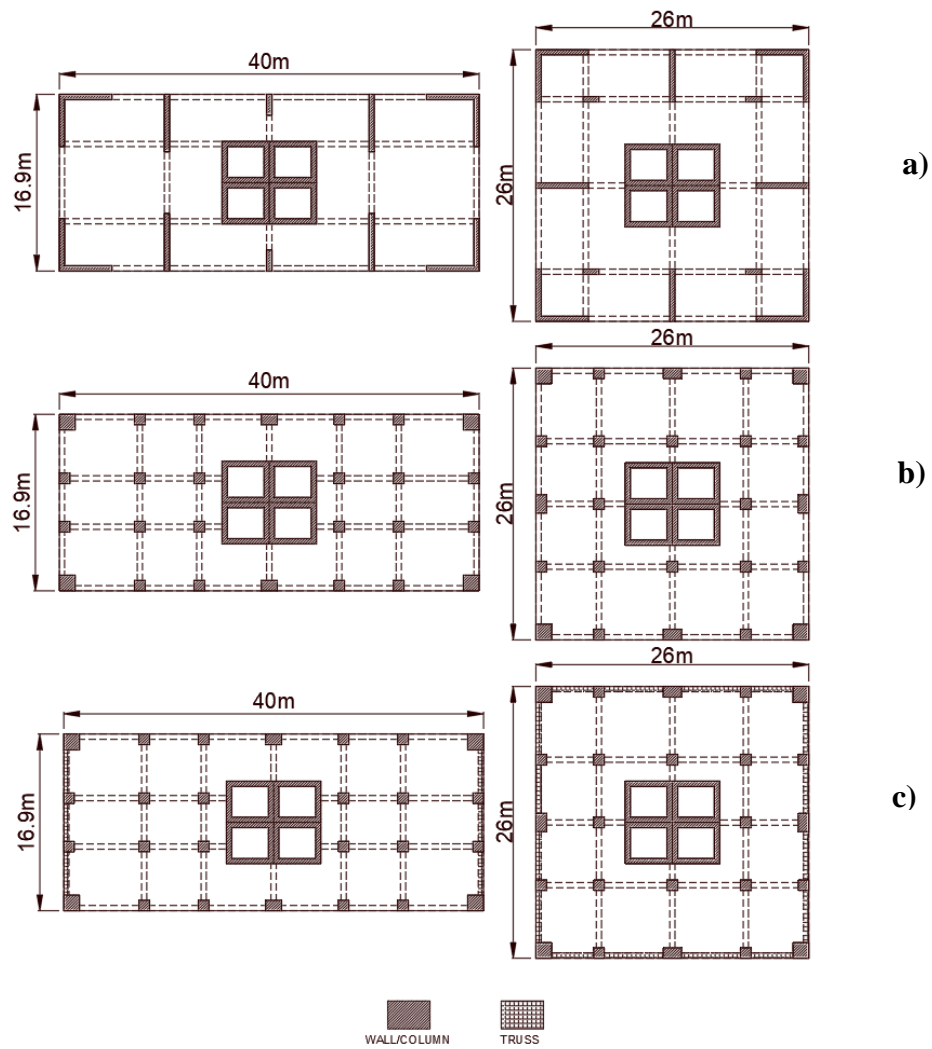
Figure 1: Building Footprints; (a) Shear Wall system; (b) Framed Tube system; (c) Trussed Tube system
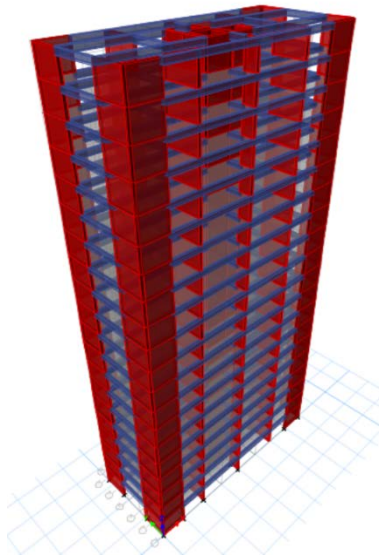
Figure 2: 432 Park Avenue (Ho 2016)

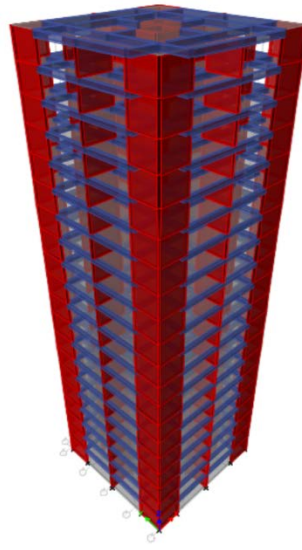Figure 3: Rectangular shear wall finite element model

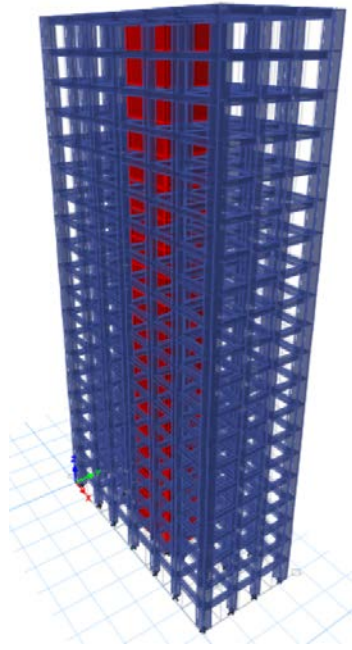Figure 4: Square shear wall finite element model
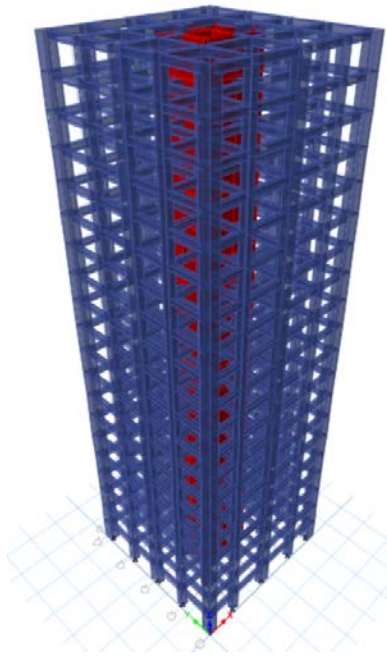
Figure 5: Rectangular framed tube finite element model
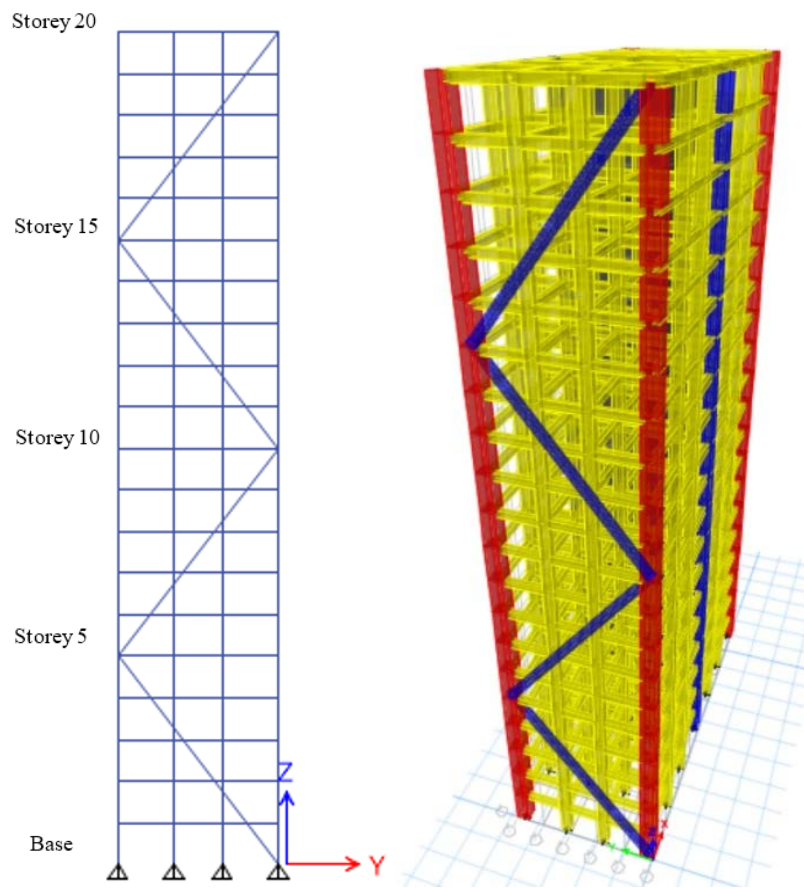
Figure 6: Square framed tube finite element model
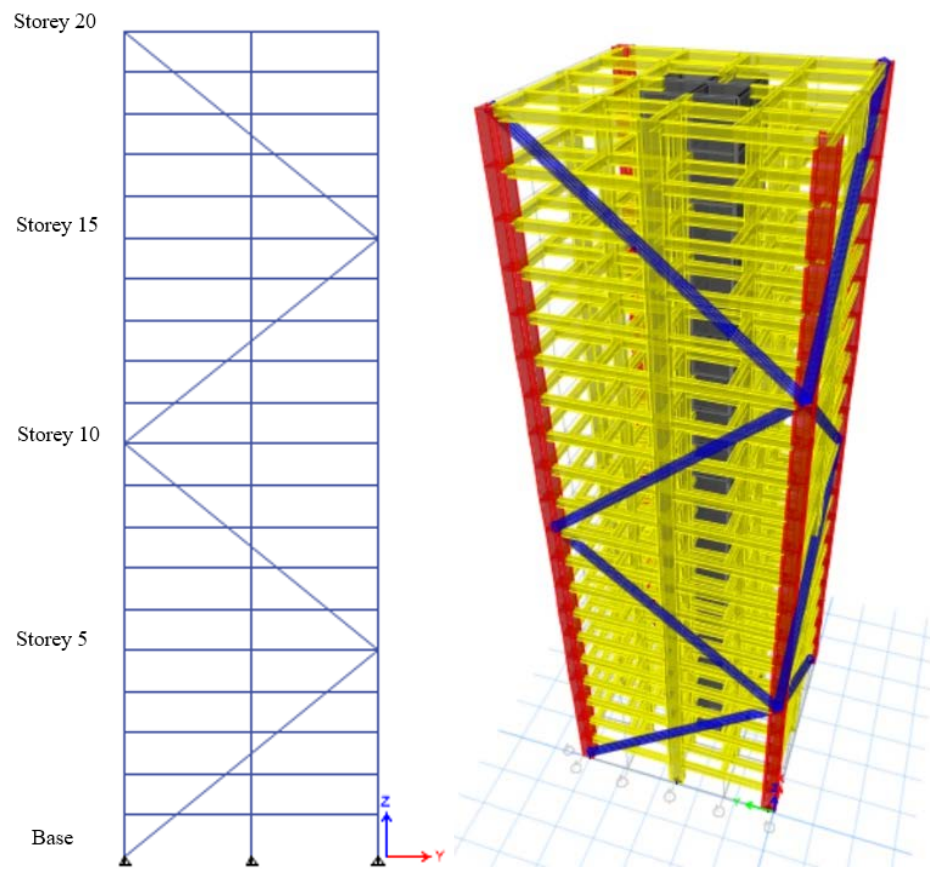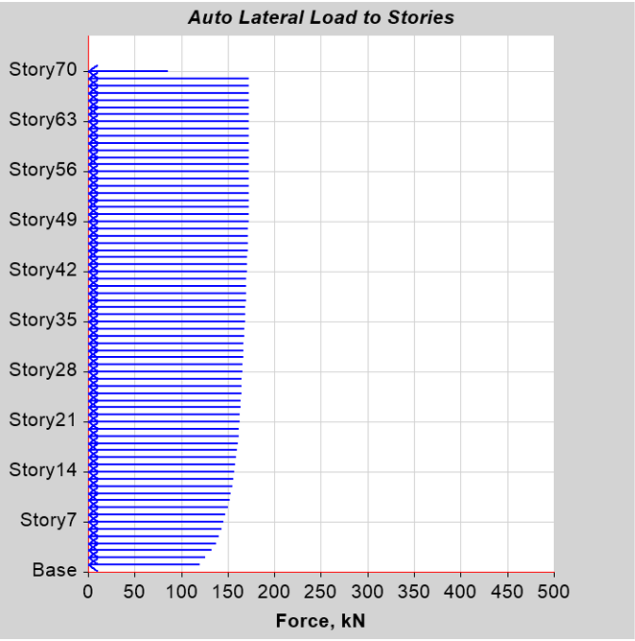
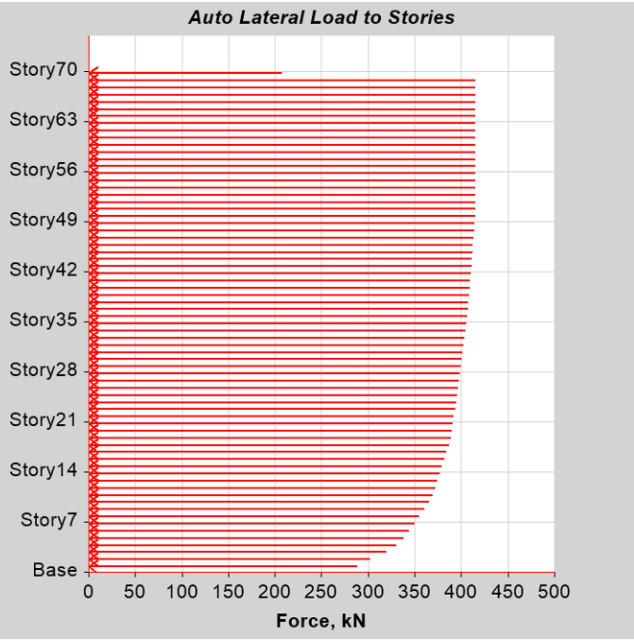Figure 7: Rectangular trussed tube finite element model

Storey 20

Storey 15

Storey 10

Storey 5

Base

Figure 8: Square trussed tube finite element model

Figure 9: Example of lateral loads of a 70 storey rectangular building; (a) Narrow face; (b) Wide face
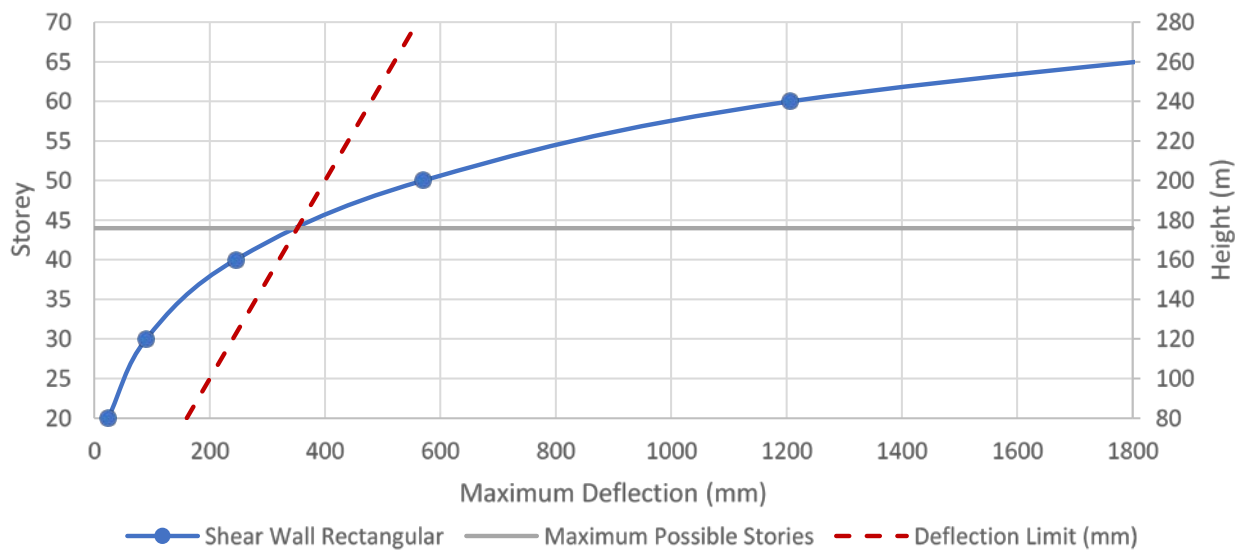
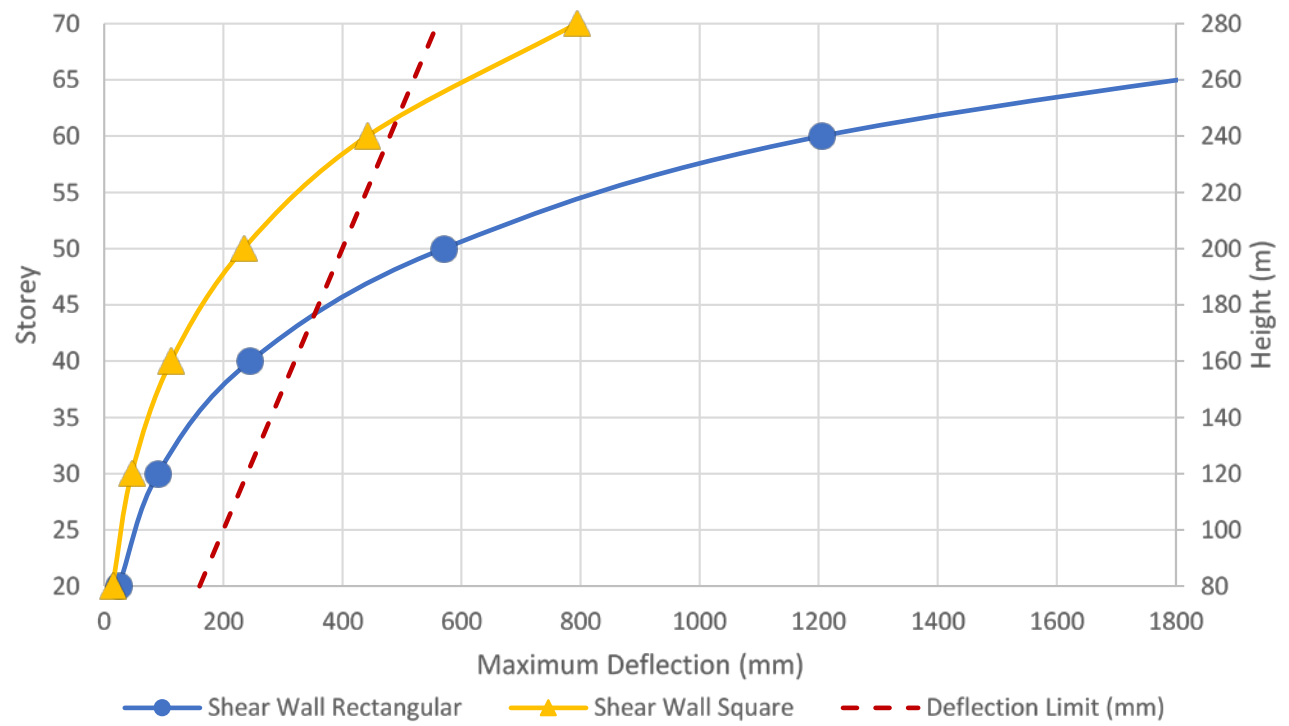Figure 10: Rectangular shear wall maximum possible storeys

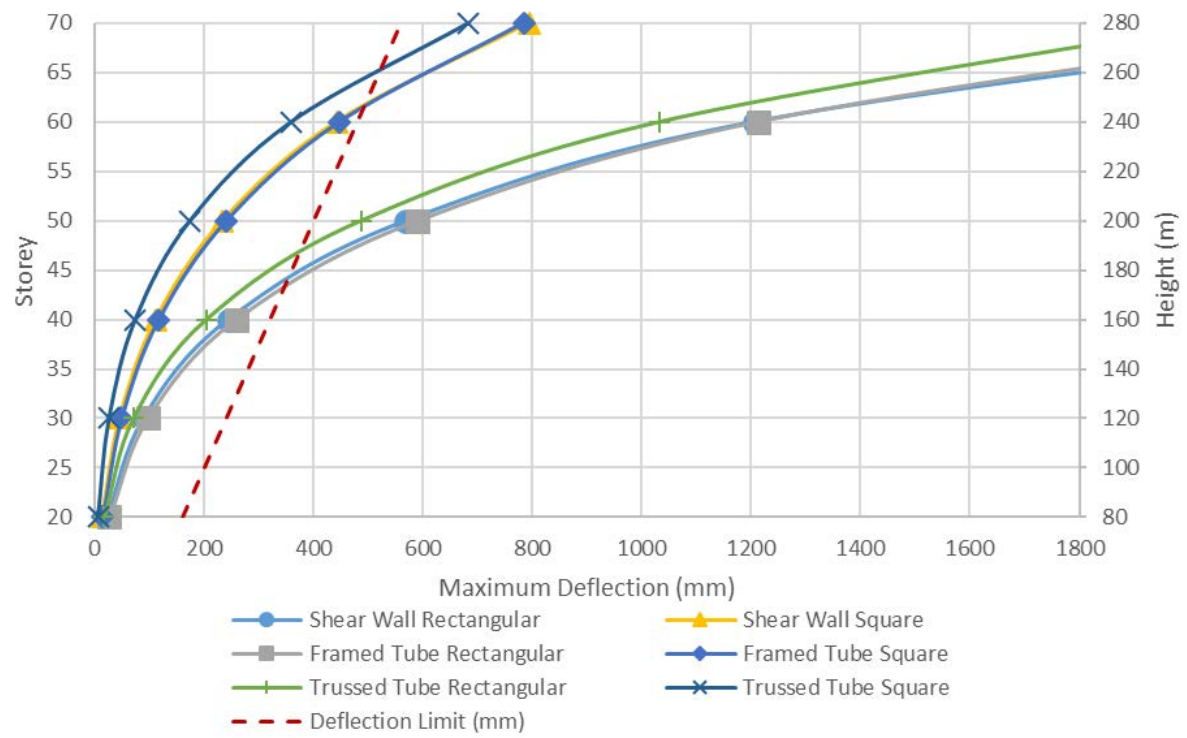Figure 11: Rectangular and square shear wall maximum possible storeys

Figure 12: Comparison of structural systems lateral deflection performance

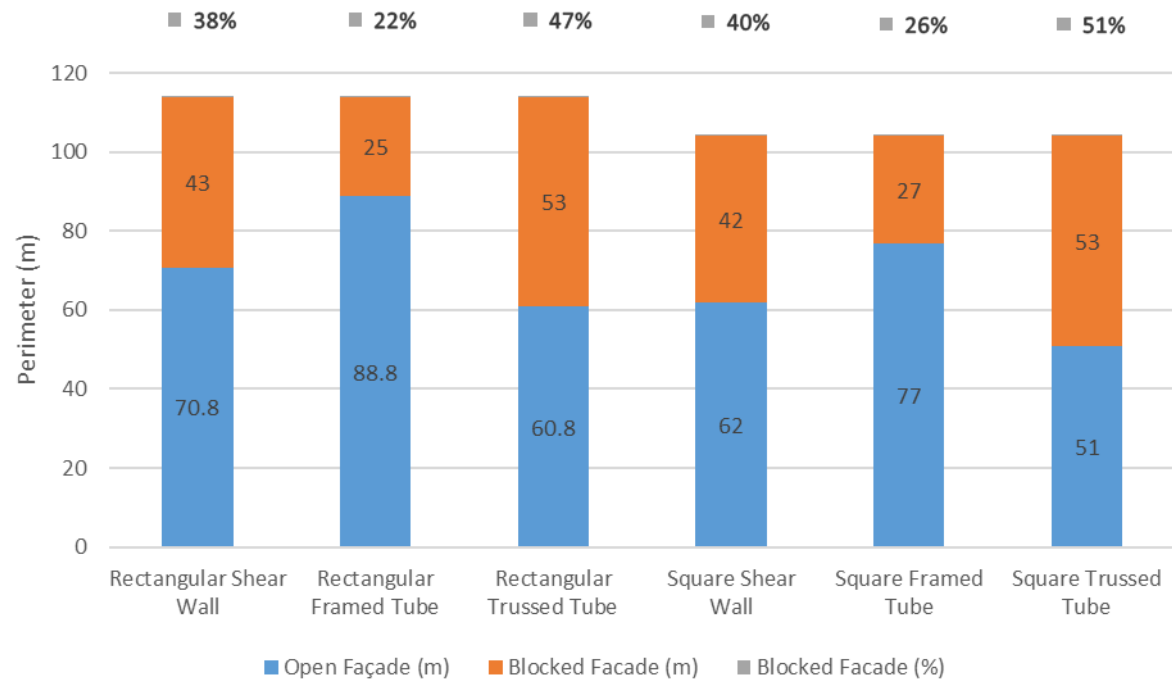Figure 13: Façade openness of structural systems (per floor)
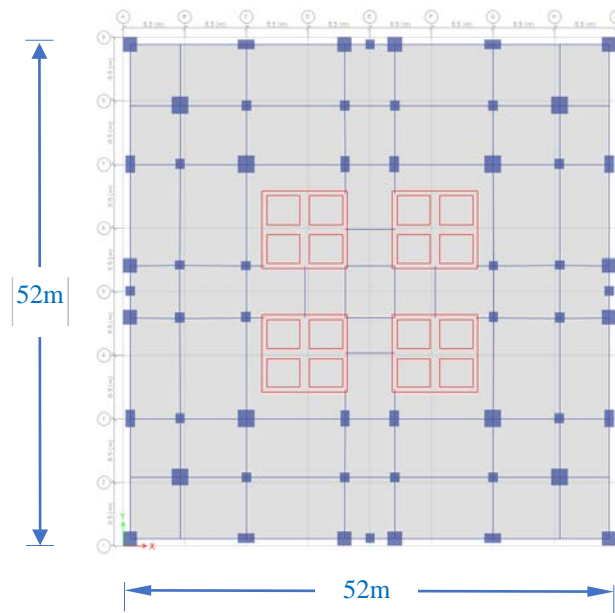
Figure 14: 52m × 52m single tower plan view
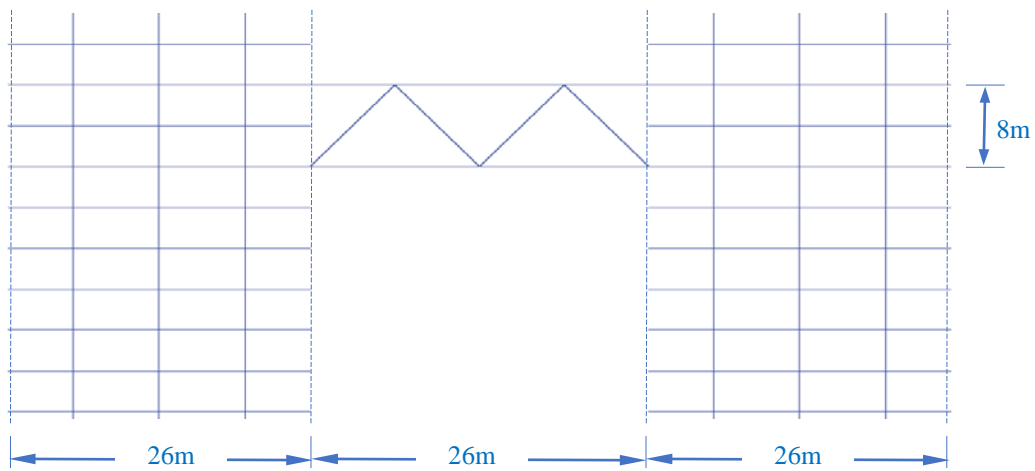
a)
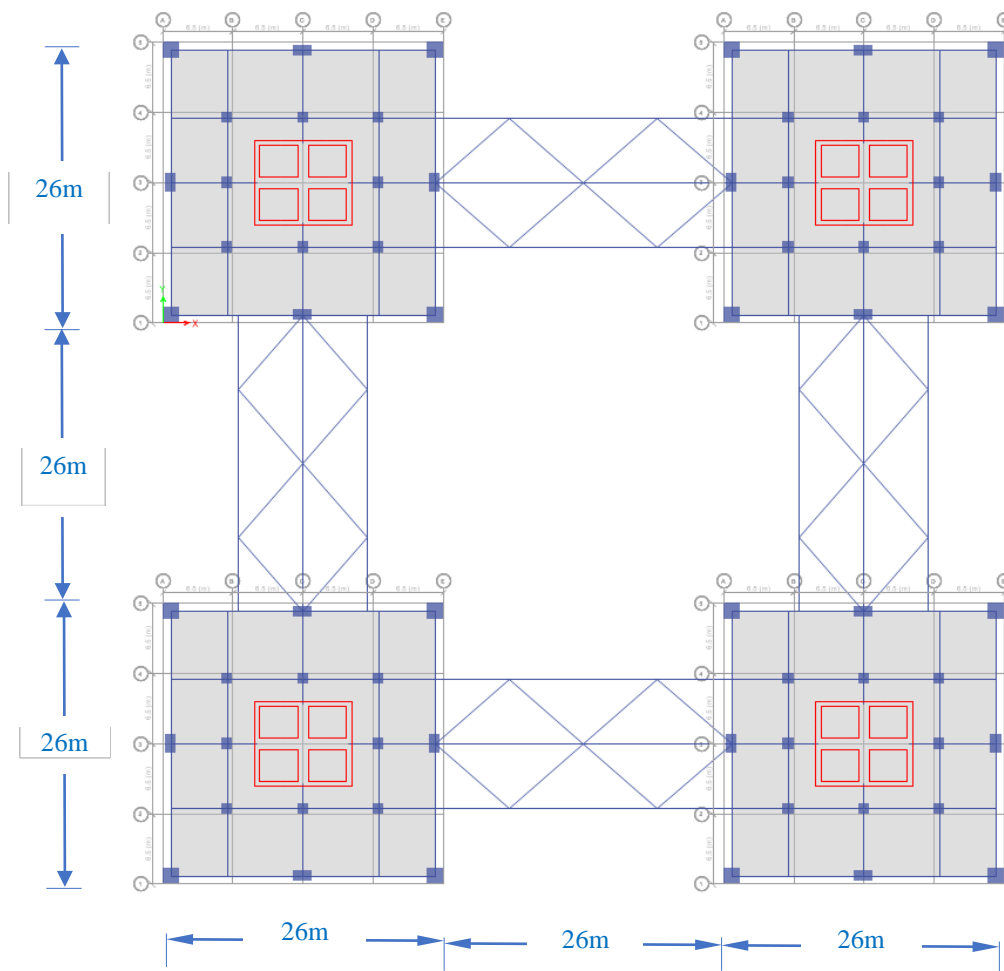
b)

Figure 15 : (a) Trussed bridge elevation; (b) Trussed bridge plan view
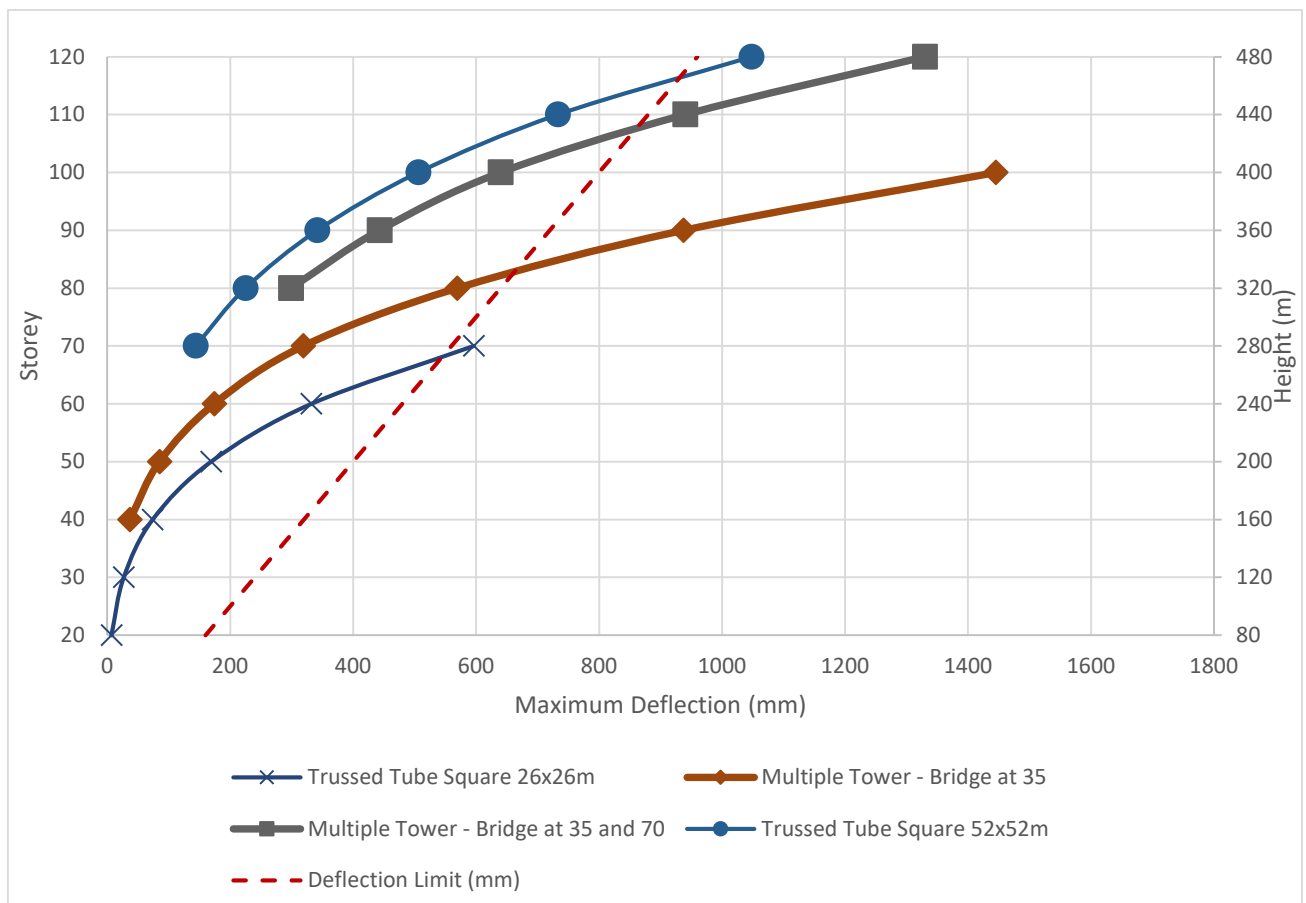
Figure 16: Comparison of structural systems lateral deflection performance
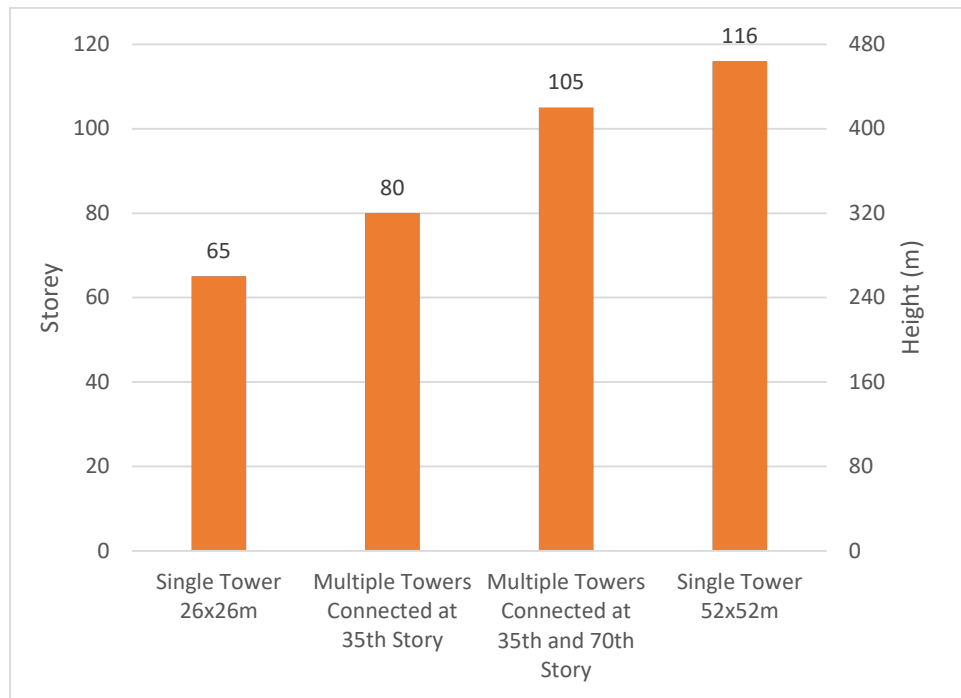
Figure 17: Maximum possible heights of structural systems
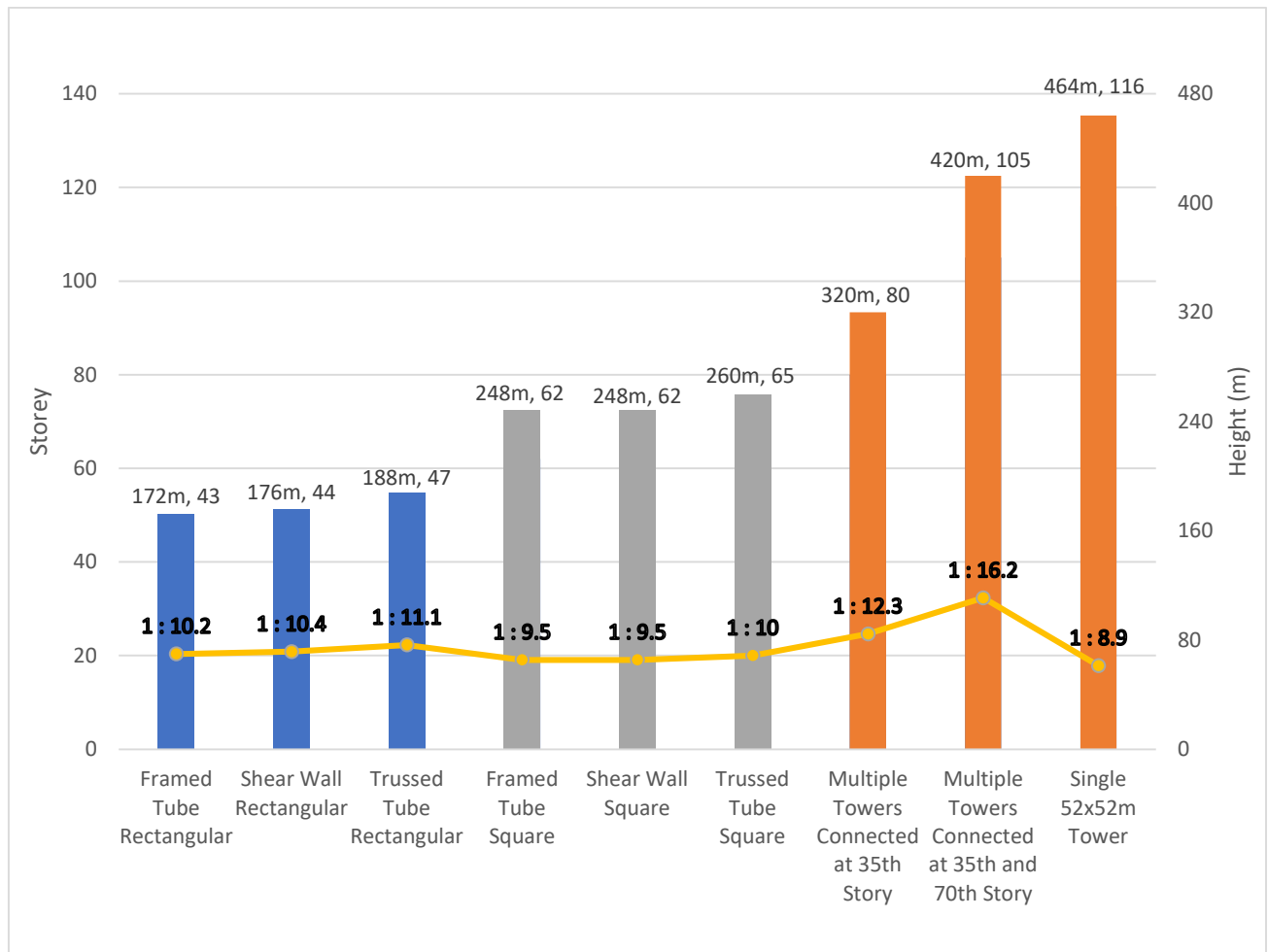
Figure 18: Maximum possible heights of structural systems (slenderness ratio in bold)

Table 1: AS/NZS 1170.2 (2011) wind loading parameters

Windward Coefficient, C_p	0.8
Leeward Coefficient, C_p	0.5
Regional Wind Speed, V_r (m/s)	45
Terrain Category	2

Table 2: Rectangular Shear Wall Storey vs Max Deflection

Shear Wall Rectangular

Storey	Max Deflection (mm)	Deflection Limit (mm)	Slenderness Ratio	$1-\Delta_{max} / \Delta_{Limit}$ (%)
20	24	160	1:4.7	85
30	90	240	1:7.1	63
40	245	320	1:9.5	23
50	570	400	1:11.8	-43
60	1206	480	1:14.2	-151
70	2485	560	1:16.6	-344

Table 3: Rectangular and square shear wall performance in lateral deflection

Maximum possible values	Rectangular Shear Wall	Square Shear Wall
Number of Storeys	44	62
Maximum Height (m)	176	248
Maximum Slenderness Ratio	1:10.4	1:9.5

Table 4: Rectangular framed tube performance in lateral deflection

Framed Tube Rectangular

Storey	Max Deflection (mm)	Deflection Limit (mm)	Slenderness Ratio	$1-\Delta_{max}/\Delta_{Limit}$ (%)
20	27	160	1:4.7	83
30	97	240	1:7.1	60
40	259	320	1:9.5	19
50	591	400	1:11.8	-48
60	1213	480	1:14.2	-153
70	2364	560	1:16.6	-322

Table 5: Square framed tube performance in lateral deflection

Framed Tube Square

Storey	Max Deflection (mm)	Deflection Limit (mm)	Slenderness Ratio	$1-\Delta_{max}/\Delta_{Limit}$ (%)
20	15	160	1:3.1	91
30	49	240	1:4.6	80
40	117	320	1:6.2	63
50	241	400	1:7.7	40
60	448	480	1:9.2	7
70	785	560	1:10.8	-40

Table 6: Rectangular trussed tube performance in lateral deflection

Trussed Tube Rectangular

Storey	Max Deflection (mm)	Deflection Limit (mm)	Slenderness Ratio	$1-\Delta_{max}/\Delta_{Limit}$ (%)
20	18	160	1:4.7	89
30	71	240	1:7.1	70
40	204	320	1:9.5	36
50	487	400	1:11.8	-22
60	1033	480	1:14.2	-115
70	2056	560	1:16.6	-267

Table 7: Square trussed tube performance in lateral deflection

Trussed Tube Square

Storey	Max Deflection (mm)	Deflection Limit (mm)	Slenderness Ratio	$1-\Delta_{max}/\Delta_{Limit}$ (%)
20	7	160	1:3.1	96
30	27	240	1:4.6	89
40	75	320	1:6.2	77
50	175	400	1:7.7	56
60	360	480	1:9.2	25
70	684	560	1:10.8	-22

Table 8: Summary of Maximum Height and Slenderness Ratio

Structural System	Maximum possible Number of Storeys	Maximum Possible Height (m)	Maximum Possible Slenderness Ratio
Rectangular Shear Wall	44	176	1:10.4
Rectangular Framed Tube	43	172	1:10.2
Rectangular Trussed Tube	47	188	1:11.2
Square Shear Wall	62	248	1:9.5
Square Framed Tube	62	248	1:9.5
Square Trussed Tube	65	260	1:10

Table 9: Open and blocked façade for structural systems

	Rectangular Footprint			Square Footprint		
	Shear Wall	**Framed Tube**	**Trussed Tube**	**Shear Wall**	**Framed Tube**	**Trussed Tube**
Total Façade Perimeter (m)	113.8	113.8	113.8	104	104	104
Blocked Façade (m)	43	25	53	42	27	53
Open Façade (m)	70.8	88.8	60.8	62	77	51
Blocked Façade (%)	38%	22%	47%	40%	26%	51%
Open Façade (%)	62%	78%	53%	60%	74%	49%

Table 10: Multiple tower performance in lateral deflection (Bridge at 35th floor)

Multiple Tower – Bridge at 35th floor

Storey	Max Deflection (mm)	Deflection Limit (mm)	Slenderness Ratio	$1-\Delta_{max}/\Delta_{Limit}$ (%)
70	348	560	1:10.8	38
80	619	640	1:12.3	3
90	1050	720	1:13.8	-46
100	1687	800	1:15.4	-111

Table 11: Multiple tower performance in lateral deflection (Bridge at 35 and 70)

Multiple Tower – Bridge at 35th and 70th floors

Storey	Max Deflection (mm)	Deflection Limit (mm)	Slenderness Ratio	$1-\Delta_{max}/\Delta_{Limit}$ (%)
90	465	720	1:13.8	35
100	693	800	1:15.4	13
110	1030	880	1:16.9	-17
120	1499	960	1:18.5	-56

Table 12: Structural systems performance in lateral deflection

Structural System	Maximum Possible Number of Storeys	Maximum Possible Height (m)	Maximum Possible Slenderness Ratio
Single Tower 26×26m	65	260	1:10
Multiple Towers Connected at 35th Storey	80	320	1:12.3
Multiple Towers Connected at 35th and 70th Storey	105	420	1:16.2
Single Tower 52×52m	116	464	1:8.9