A Simplified Approach for Optimization of Tube System in Tall Buildings

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Abstract: In this paper, the superstructure of 30, 40 and 50 storeyed composite framed tube and tube-in-tube structure tall buildings are analysed by using SAP 2000 V.14 software and dual system building, which is the combination of moment resisting frame and shear wall, is analysed until it obtains the same stiffness values with that of tube structures in order to compare the effectiveness of the structural systems. If the stiffness values of tube structure buildings are not the same with that of the dual system buildings, the model is analysed again by changing the modification factor. In this paper, the modification factors are represented in term of the modulus of elasticity of steel and concrete used as structural material in the buildings and stiffness of the building is exemplified by maximum displacement of that building. Then, analysis results are evaluated based on the stiffness of the buildings. Finally, modification factor is produced for simplified analysis of dual system to represent framed tube and tube-in-tube system tall buildings. By introducing this proposed system, it can be transformed from dual system building design into framed-tube building or tube-in-tube building design by multiplying an optimization factor.

Key Words: Frame tube, Tube-in-Tube, Modification Factor, Stiffness, Shear Lag Effect, Maximum Displacement, Base Shear, Weight.

Introduction:

Structural systems for tall buildings have undergone a dramatic evolution throughout the previous two decades and into the 2010s. Developments in structural form have historically been realized a response to emerging architectural trends in high-rise building design. The development of the original tubular systems for tall buildings was indeed predicated upon an overall building form of constant or smoothly varying profile [1]. As the number of different high-rise structures in existence expands every year, there is an increase in the possibility of damage due to earthquake or other hazards. In the event of such damage it is important to be able to correlate damage intensity with the particular tall building system used. Of the various alternatives, a framing-oriented scheme is selected as a means of classifying structural systems. The fundamental systems within it are bearing wall, core, tube, and frame, together with the appropriate mixtures of these systems. For a proposed building there is no right or wrong way for a structure to carry gravity loads to the foundation or resist lateral loads. However, there are structurally efficient solutions, economic solutions and other radical, unique, and challenging solutions [2]. Tall buildings are highly sophisticated engineering projects. Due to the complexity of the structures, the most advanced engineering design techniques are needed in tall buildings. To develop these techniques, new and existing research and empirical studies need to be documented in usable and accessible form [3]. Hopefully, this paper will aid in developing a pragmatic way to generate efficient structural design of tube structure buildings solutions that offer economy, performance and elegance.

Methodology: The decision about using the method in analysing building structure is no less important than choosing an appropriate modelling technique. Linear and nonlinear analysis is the two basic methods in analysing structures. Linear elastic analysis is generally used for multi-storey structures due to its simplicity. Linear elastic analysis of building structures can be performed by using static or dynamic approaches. Briefly, static analysis is performed by considering the building structure as stationary and the loads acting on the structure as constant and not time dependent. The effects of all kinds of loads are idealized and simplified in this approach. In contrast to static analysis, dynamic analysis is based on the behaviour of the structural system in a time domain. The model superposition method and the time history method are the dynamic analysis methods most commonly suggested by earthquake codes [4].

1. Equivalent Static Lateral Force Method

According to UBC 97, the static lateral force is obtained by using the following steps:

- Consider all applied loads (gravitational loads including deal load and live load and lateral loads including wind and seismic loads).
- Estimate the first-mode natural period T.

$$T = C_t (h_n)^{3/4} \qquad \text{Equation (1)}$$

- Choose the appropriate seismic base shear coefficient C_a, C_v.
- Calculate the seismic design base shear (V) of the model.

$$0.11 C_a I W \le V = \frac{C_v I}{RTW} \le \frac{2.5 C_a I}{R} W \qquad \text{Equation (2)}$$

where, I = Importance Factor
R = Response modification factor
W = Total Seismic Dead Load
C_t = 0.35 for steel moment- resisting frame
C_t = 0.03 for reinforced concrete moment resisting frames and eccentrically braced frames
C_t = 0.02 for all other buildings
h_n = Height from the base to nth level [5]

2. Dynamic Response Spectrum Method

The response spectrum method is a procedure for dynamic analysis of a structure subjected to earthquake ground motions. In a conceptual sense, it reduces dynamic analysis to a series of static analysis [1]. The actual elastic response of the structure under earthquake force is obtained by superposing the evaluated individual solutions. One of the most important concepts in this method is the combination of the individual solutions. The basic steps of the modal superposition method are as follows:

- Selection of design spectrum.
- Determination of mode shapes and periods of vibration.
- Determination of the level of response from the design spectrum for the period of each of the modes considered.
- Calculation of the participation of each mode corresponding to the single degree of freedom response read from the curve.
- Addition of the effects of modes to obtain combined maximum response.
- Conversion of combined maximum response into shears and moments.
- Analysis of the building for resulting moments and shears in the same manner as for static load.

A response spectrum is the graphic representation of maximum response i.e. displacements, velocity and acceleration of a damped single degree freedom system to a specified ground motion, plotted against the frequency or modal periods. In the response spectrum analysis, the distribution of seismic lateral force on the building is based on the deformed shapes of natural modes of vibration, which is determined from the distribution of mass and stiffness of the structure. From the response spectrum, a specified spectra value can be read. This value is used to calculate the theoretical maximum seismic force (V) acting on a structure.

$$V = \frac{W S_a}{g} \qquad \text{Equation (3)}$$

where, S_a = Spectral Acceleration read from Spectrum
g = Acceleration due to Gravity (9.81ft/s^2) [6]

3. Structural Systems for Proposed Buildings

The basic design philosophy in all of framed tube forms has been to place as much as possible of the load carrying material around the external periphery of the building to maximize the flexural rigidity of the cross section. The tube structure offers a relatively efficient, easily constructed, and appropriate for use up to the greatest of heights. By using framed tube and tube-in-tube structural system, wide column free space can also be achieved.

A. Framed-Tube System

The framed-tube system in its simplest form consists of closely spaced exterior columns tied at each floor with relatively deep spandrel beams, thereby creating the effect of a hollow concrete tube.

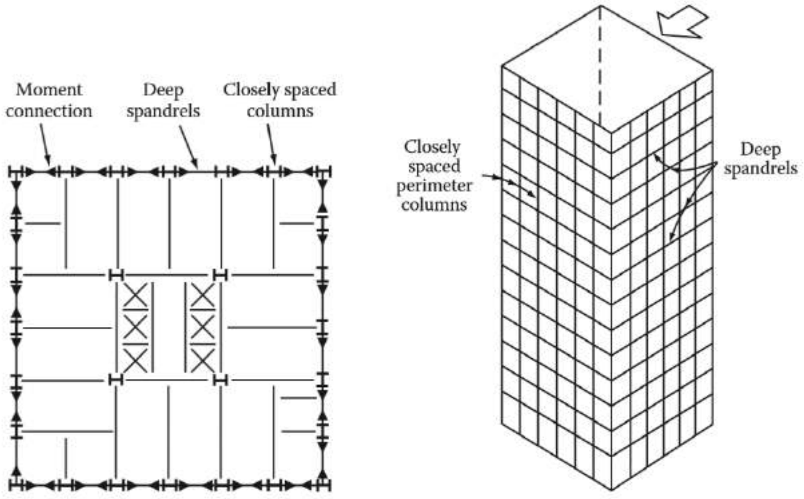


Figure 1. Plan and 3D View of Framed-Tube Structure Building
Source [6]

This structural system is referred to as “Frame Tube”, since it simulates a hollow tube using perimeter of closely spaced frame elements. The centre to centre spacing of the exterior columns in the system is generally from 7ft to 13ft. The spandrel beams interconnecting the closely spaced columns generally vary from 2ft to 4ft in depth with widths from 1ft to 3ft [6].

B. Tube-in-Tube Structural System

A tube-in-tube system is a variation of the framed tube created by the shear walls, and the outer tube consisting of the closely spaced column system. It has the advantage of both the framed tube structures and the shear wall type structures. These buildings have interior cores but, since the cores are not designed to resist lateral loads they act as hollow tubes. The stiffness of a framed tube system is very much improved by using the core to resist lateral loads [7].

C. Dual System

Shear wall-frame systems (Dual Systems) consist of reinforced concrete frames interacting with reinforced concrete shear walls. According to UBC 97, dual system is defined as a structural system with following features:

- An essentially complete space frame provides support for gravity loads.
- Resistance to lateral load is provided by shear walls or braced frames and moment resisting frames. The moment resisting frames shall be designed to independently resist at least 25 percent of the design base shear.
- The two systems, moment resisting system and lateral force resisting system, shall be designed to resist the total design base shear in proportion to their relative rigidities considering the interaction of the dual system at all levels [5].

4. Shear Lag Effect in a Framed Tube Building

The effect of shear lag on the tube action results in non-linear pressure distribution along the column envelope; the columns at the corners of the building are forced to take a higher share of the load than the column in between.

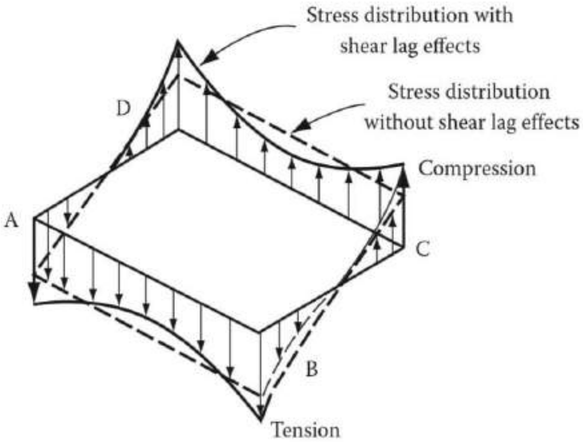


Figure 2. Axial stress distributions of Shear Lag Effect
Source [6]

Furthermore, the total deflection of the building does not resemble a true cantilever tube, as shear mode deformation becomes more significant. The ratio of axial force in the corner column to that in the central column of the flange was chosen as the measure of shear lag. A value of f greater than unity represents positive shear lag and that less than unity represents negative shear lag. The level at which f is unity represents the level of shear-lag reversal. The shear lag effect in framed tube buildings varies along height and changes its direction at a certain level [7].

Analysis: The structures selected for this study is 30, 40 and 50 storeyed composite framed-tube structure buildings, tube-in-tube structure buildings and dual system buildings which were built with reinforced concrete slabs, steel beams and composite columns. Based on the structural concepts of the tube system, the parameter columns were placed 7 feet between centres to centres and joined by deep spandrel beams at the perimeter of the structure. For dual system buildings, an essentially complete space frame supports for gravity loads. Resistance to lateral load was provided by shear walls and moment resisting frame. As the proposed models were tall buildings, special moment resisting frame (SMRF) was applied.

1. Case Study

Nine case studies for square-shaped framed-tube structure, tube-in-tube structure and dual system buildings were made for the analysis in this paper. For making the comparison of analysis results, 30 storeyed, 40 storeyed and 50 storeyed tube structure buildings and dual system buildings were applied. Structural steel used in this building is A992-Grade 50 steel and compressive strength of concrete is 4 ksi. Wide flange sections have been used for beams and composite tube sections have been used for columns. Floor slabs have been used as reinforced concrete slab system. The structural elements are designed according to AISC-LRFD 93. As lateral loadings, earthquake loading in zone 2B was considered and for gravity loading, dead load, superimposed dead load, wall load and live load were included. Earthquake load (both static and dynamic analysis) was based on UBC-1997. Floor plan and 3D view of framed tube, tube-in-tube and dual system buildings are shown in figure 4 and figure 5.

Table1. Model Information for Tube Structure buildings and Dual System buildings

Group	No. of Storey	Structural System	Plan Configuration	Dimension (ft)			Aspect Ratio	
				L	B	H	L/B	H/B
1	30	Framed Tube	Square	126	126	368	1	2.92
		Tube-in-Tube						
		Dual System						
2	40	Framed Tube	Square	126	126	488	1	3.87
		Tube-in-Tube						
		Dual System						
3	50	Framed Tube	Square	126	126	608	1	4.83
		Tube-in-Tube						
		Dual System						

2. Input Data for Proposed Buildings

Material properties used for purposed tube structure buildings are:

Analysis Properties Data

- Weight per unit volume of concrete : 150 pcf
- Modulus of elasticity of concrete : 4.4152×10^6 psi
- Modulus of elasticity of steel : 29×10^6 psi
- Poisson’s ratio : 0.2
- Coefficient of thermal expansion : 5.5×10^{-6}

- Design Properties Data
  - Reinforcing yield stress (f_y) : 50 ksi
  - Concrete cylinder strength (f_c') : 4 ksi

Data for earthquake loads which are used in structural analysis are as follows:

Seismic zone = 2B
Seismic zone factor = 0.2
Soil type = S_D
Importance factor, I = 1
Response modification factor, R = 0.85
Numerical coefficient, C_t = 0.02
Seismic coefficient, C_v = $0.4N_v$
Seismic coefficient, C_a = $0.28\ N_a$
Near source factor, N_a = 1
Near source factor, N_v = 1

3 Implementation Programme

In this study the following implementation programme was carried out.

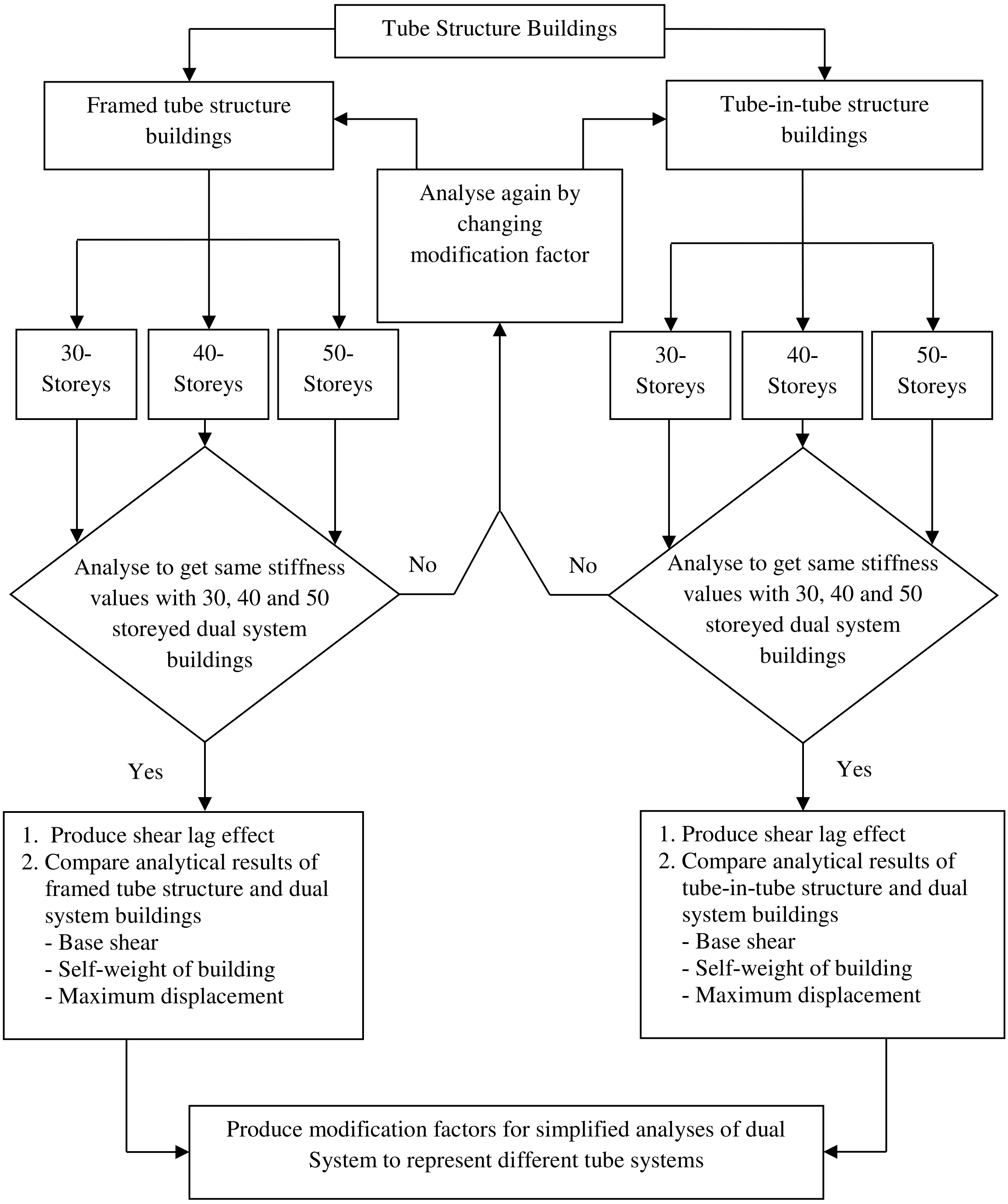
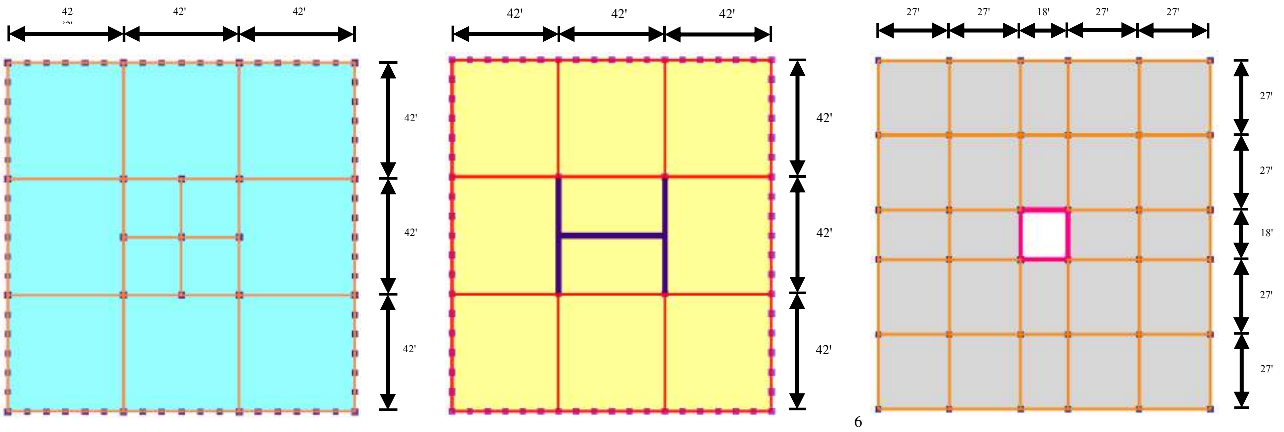
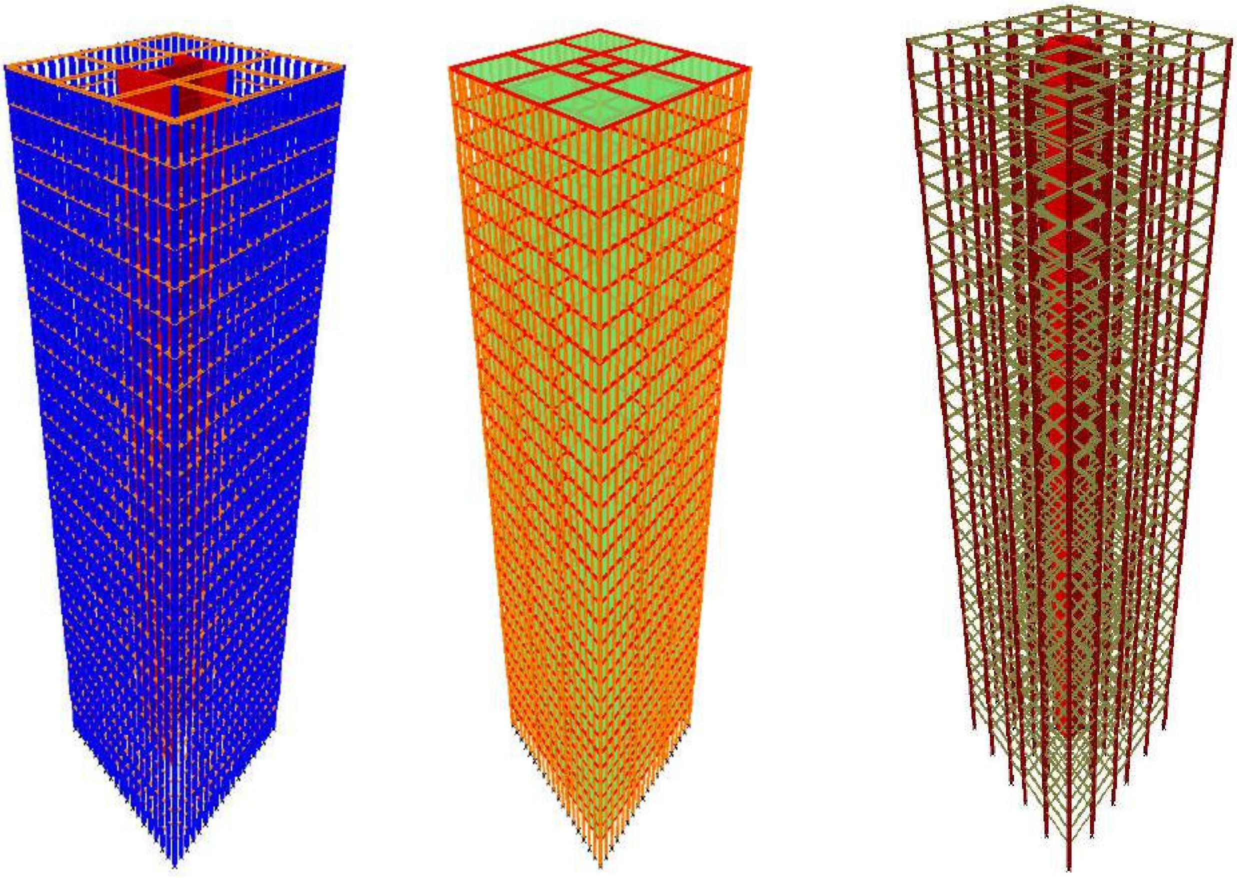


Figure 3. Implementation programme



(a) Framed Tube (b) Tube-in-Tube (c) Dual

Figure 4. Floor Plan of Proposed Buildings



(a) Framed Tube (b) Tube-in-Tube (c) Dual

Figure 5. 3D View of Proposed Buildings

4. Assumption

Modelling for analysis, an effort to analyse a tall building and account correctly for all aspects of performance of all the constituents and materials, even if their sizes and properties were known, would be virtually intolerable. Simplifying assumptions are obligatory to reduce the problem to a viable size. The assumptions in this study are as shown.

(a) Materials – The material of the structures and the structural components are assumed to be linearly elastic. The linear methods and their solution by computer software have finished it possible to analyse large multipart statically indeterminate structures.

(b) Participating Components – Only the principal structural elements take part in the overall performance.

(c) Floor Slabs – Floor slabs are supposed to be rigid in plane. Therefore, the number of unidentified displacements to be calculated in the analysis is greatly reduced.

Result: For tube structure buildings, the results of shear lag effect in flange and web frames were presented from dynamic response spectrum analysis. The maximum displacement at the top of the tube structure buildings was determined from the dynamic response spectrum analysis. Then the modification factors of tube structure buildings from dual system buildings were evaluated for earthquake load in dynamic analysis. Finally, the base shear, total self-weight of buildings and maximum displacement at the top of the building of tube structure buildings were compared with that of dual system building. To compare the shear lag effects of framed tube structure buildings due to earthquake load, axial force distribution for both flange and web frames of 40 storeyed framed tube structure building were illustrated below.

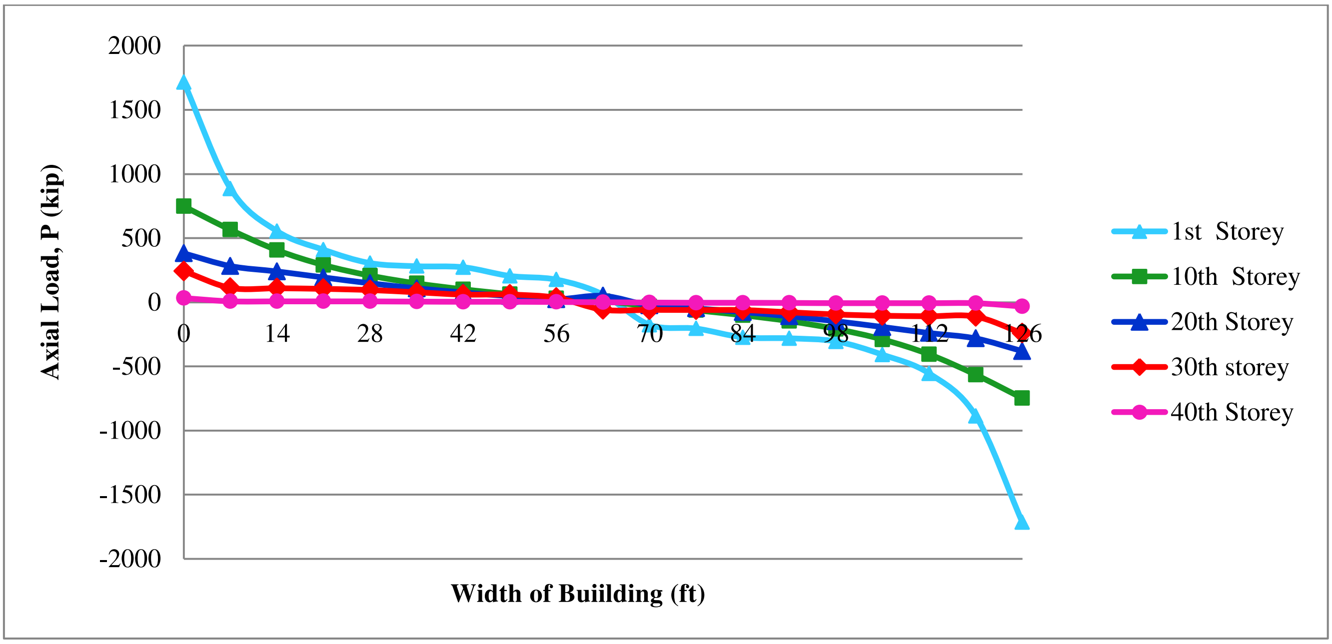


Figure 6. Shear Lag Effect of Flange Frame at every 10th Floor of 40 Storeyed Framed-Tube Structure Building

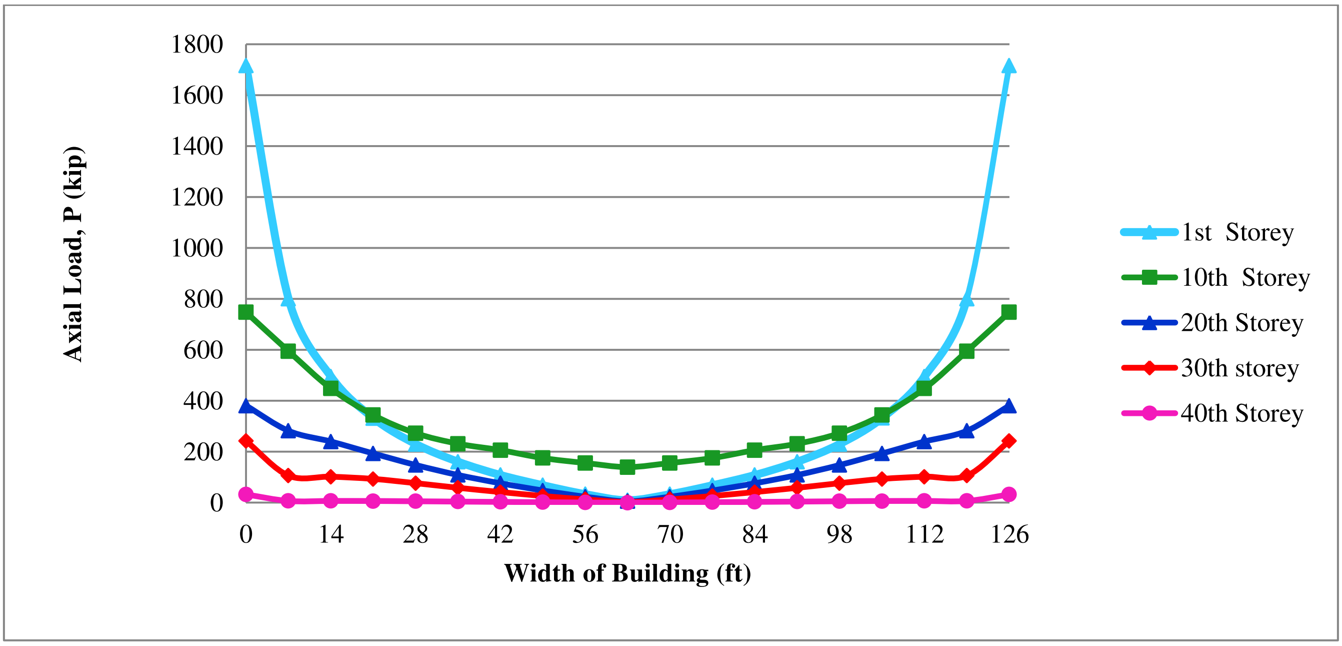
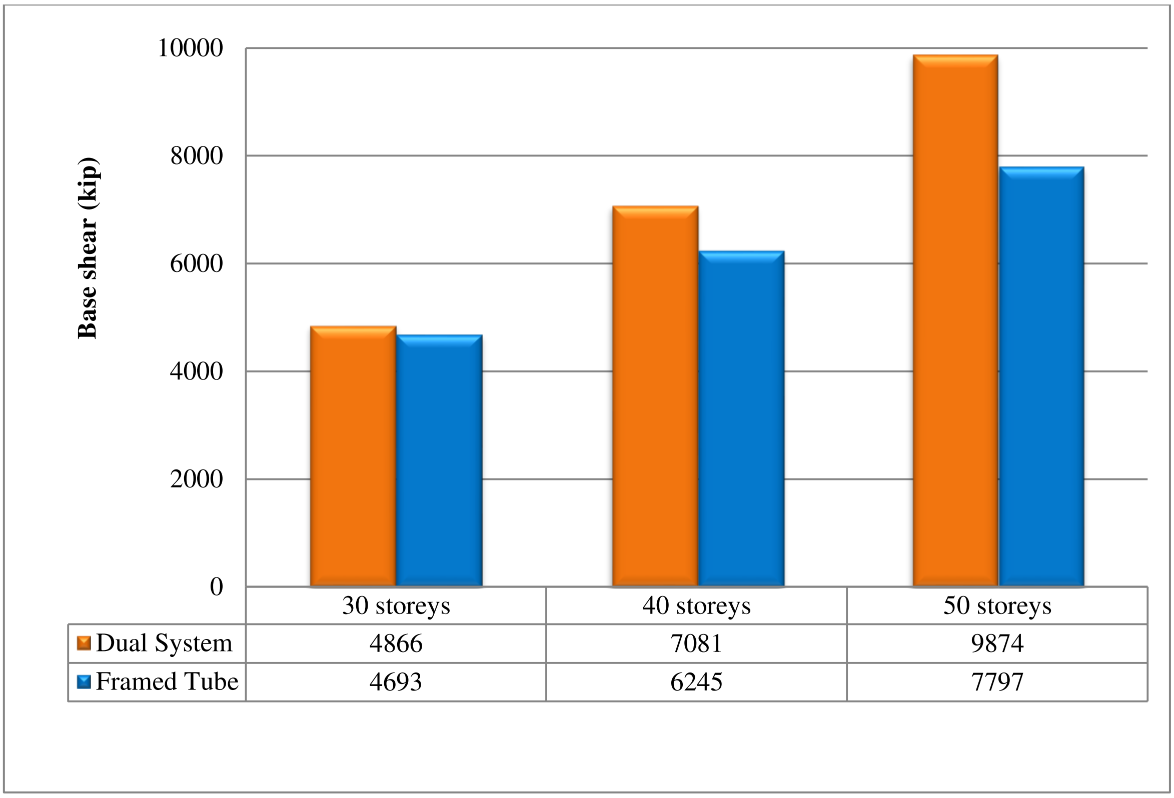


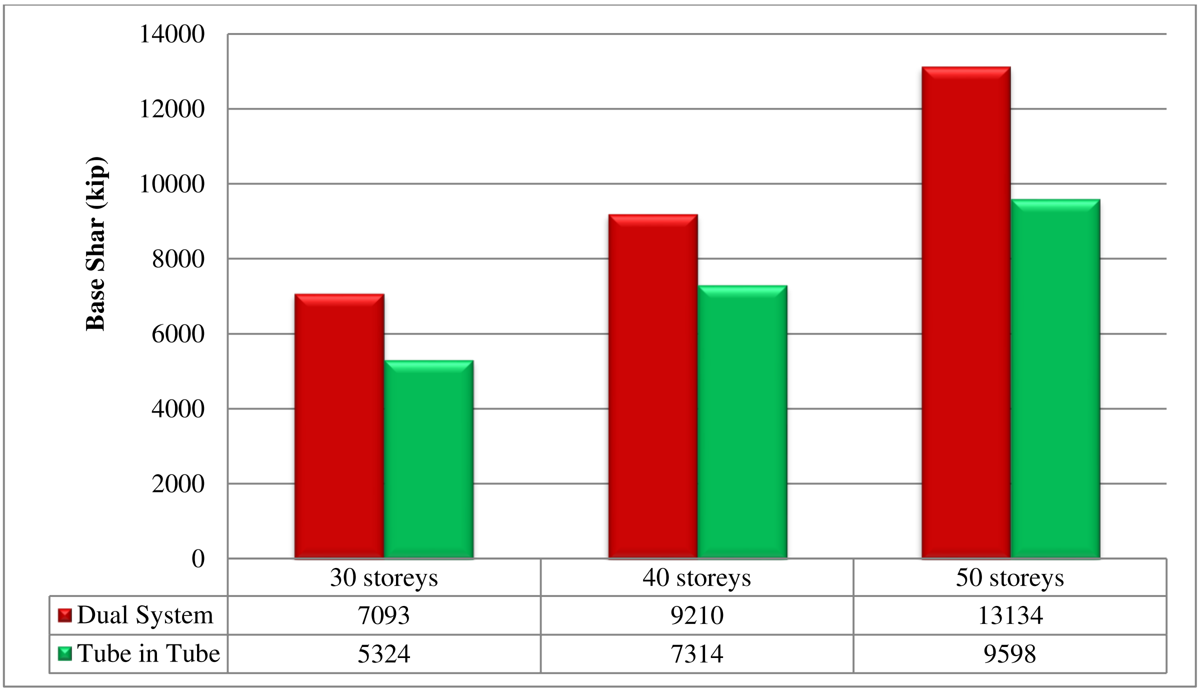
Figure 7. Shear Lag Effect of Web Frame at every 10th Floor of 40 Storeyed Framed-Tube Structure Building

When lateral loading is applied to the tube structure buildings, different axial loads are occurred in the column of the perimeter of the buildings. The frames parallel to the lateral load act as the “webs” of the perforated tube cantilever, while the frames normal to the lateral load act as the “flanges” [6]. According to Figure 6 and Figure 7, the axial load distribution is larger in outer columns and decreased dramatically in inner columns. These effects are more significant in lower storeys than upper ones because of the accumulation of axial load to the lower storeys.



	30 storeys	40 storeys	50 storeys
🟧 Dual System	4866	7081	9874
🟦 Framed Tube	4693	6245	7797

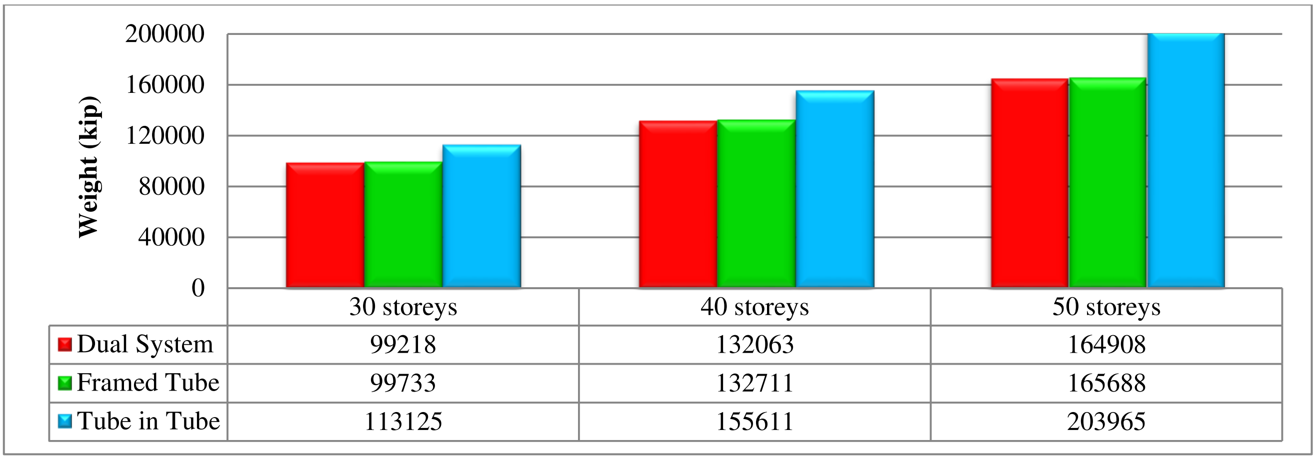
Figure 8. Comparison of Base Shear between 30, 40 and 50 Storeyed Framed-Tube Structure Buildings and Dual System Buildings (multiplying with Modification Factor)



	30 storeys	40 storeys	50 storeys
🟥 Dual System	7093	9210	13134
🟩 Tube in Tube	5324	7314	9598

Figure 9. Comparison of Base Shear between 30, 40 and 50 Storeyed Tube-in-Tube Structure Buildings and Dual System Buildings (multiplying with Modification Factor)

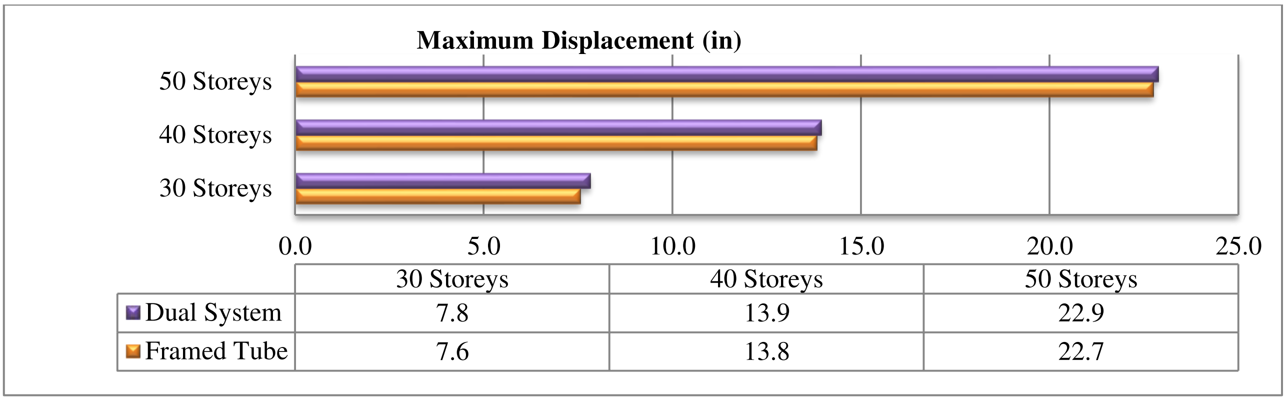
According to the base shear results from figure 8 and figure 9, the values of base shear in both of the dual system (multiplying with modification factor) and framed-tube structure buildings are slightly different in 30 storeys. But these values are much different in higher storey buildings. The values of base shear in dual system buildings are greater than that of framed tube structure buildings because the dual system is optimized by the modification factor to get the same stiffness value with that of framed tube structure building.



	30 storeys	40 storeys	50 storeys
🟥 Dual System	99218	132063	164908
🟩 Framed Tube	99733	132711	165688
🟦 Tube in Tube	113125	155611	203965

Figure 10. Comparison of Self- weight of building between 30, 40 and 50 Storeyed Tube Structure Buildings and Dual System Buildings (multiplying with Modification Factor)

According to the results from Figure 10, Self-weight of dual system buildings (multiplying with modification factor) and framed-tube structure buildings are approximately the same in all cases although the dual system building contains the shear wall. This shows that, the framed-tube structure buildings are reliable like dual system buildings even it does not contain the definite shear wall as the dual system buildings (multiplying with modification factor). In tube-in-tube structure buildings, the self-weight of building is larger than the others because it contains not only framed-tube structure building but also H-section shear wall inside the buildings.



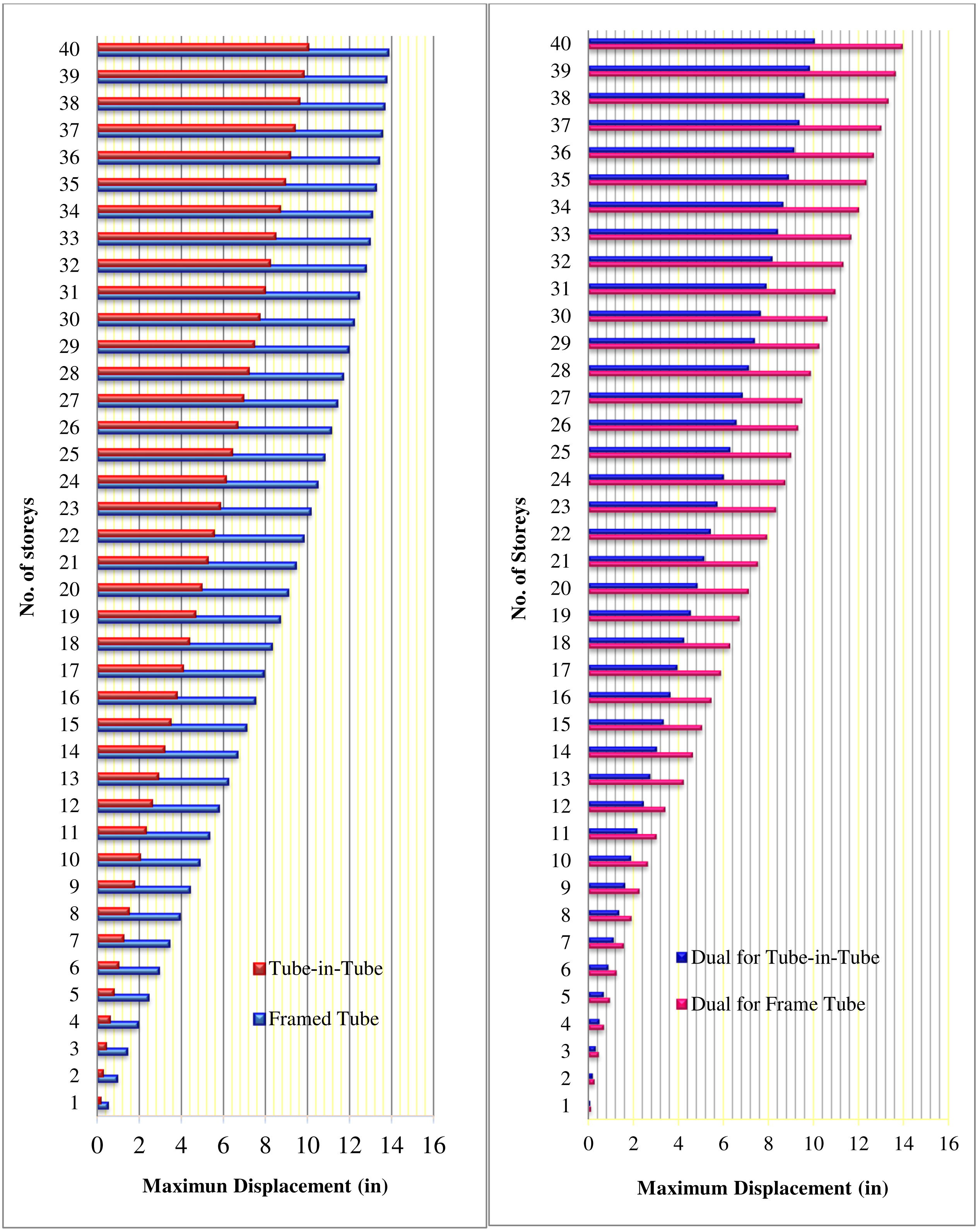
	30 Storeys	40 Storeys	50 Storeys
🟪 Dual System	7.8	13.9	22.9
🟧 Framed Tube	7.6	13.8	22.7

Figure 11. Comparison of Maximum Displacement between 30, 40 and 50 Storeyed Framed-Tube Structure Buildings and Dual System Buildings (multiplying with Modification Factor) in X direction

	30 Storeys	40 Storeys	50 Storeys
🟩 Dual System	5.0	10.0	16.3
🟨 Tube-in-Tube	4.8	10.0	16.2

Figure 12. Comparison of Maximum Displacement between 30, 40 and 50 Storeyed Tube-in-Tube Structure Buildings and Dual System Buildings (multiplying with Modification Factor) in X direction

According to the results of two analyses in Figure 4.30 and 4.31 shown below, the maximum displacements of tube structure buildings and dual system buildings (multiplying with modification factor) are almost the same in order to get the same stiffness value when multiplying by the modification factors respectively.



(a) Framed tube and tube-in-tube (b) Dual for framed tube and dual for tube-in-tube

Figure 13. Comparison of Maximum Displacement at Each Floor Level of 40 Storeyed Tube Structure Buildings (multiplying with Modification Factor) in X Direction

For framed tube structure building, the maximum displacement at each floor level increase steadily throughout the height of building as shown in figure 13(a). For tube-in-tube structure building the same increase steadily up to the three quarter of the total height of building. After that, it increases in curved shape up to the topmost floor of the building. According to the Figure 13(b), for the dual system which is the same stiffness with that of tube-in-tube structure building, the pattern of maximum displacement at each floor level throughout the height of building is the same as that of framed tube structure building because of same structural configuration.

After analysis results are evaluated based on the stiffness of the buildings, modification factor is produced for simplified analysis of dual system to represent framed-tube and tube-in-tube structure tall buildings.

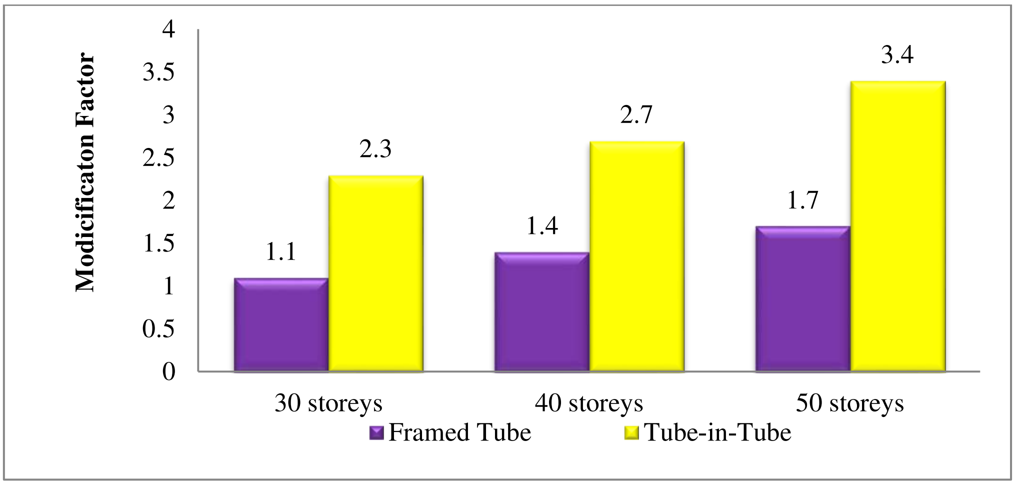


Figure 14. Comparison of Modification Factor between 30, 40 and 50 Storeyed Tube Structure Buildings and Dual System Buildings (multiplying with Modification Factor)

According to Figure 14, the modification factors of tube-in-tube structure buildings are approximately twice that of framed-tube structure buildings when optimizing from dual system to tube system tall buildings. Therefore tube-in-tube system is better than framed-tube system because of presenting of core shear wall.

Recommendations: In this paper, the superstructure of 30, 40 and 50 storeyed tube structure buildings and dual system buildings were analysed with dynamic response spectrum analysis for zone 2B by using SAP 2000 design software. Dual system building is also analysed until it can get the same stiffness value with that of framed tube and tube-in-tube structure tall buildings. When the dual system gets the same stiffness value with that of above two types of buildings, the modification factors are evaluated based on the stiffness of the buildings. Based on this study, a further research should be carried out as follows:

1. It should be investigated to minimize shear lag effect in tube system.
2. Further research should be carried out for more severe seismic zones such as zone 3 and zone 4.
3. Other tube structures such as bundled tube and braced tube should be analysed and designed.
4. Building should be analysed and designed with non-linear time history dynamic analysis.

Conclusion: From the analyses results of the sample buildings, the following conclusions can be made.

1. The effect of shear lag on the tube action as it causes non-linear pressure distribution along the column envelope is observed also in the sample framed-tube buildings and tube-in-tube structure buildings.
2. For 30 storeyed buildings, the modification factor for framed-tube and tube-in-tube structure buildings are 1.1 and 2.3. Likewise, for 40 storeyed buildings, the modification factors are 1.4 and 2.7 and for 50 storeyed buildings, these factors are 1.7 and 3.4.
3. The modification factors of tube-in-tube structure buildings are approximately twice that of framed-tube structure buildings when optimizing from dual system to tube system tall buildings.

By introducing this approach system, there can be transformed easily from dual system building design to framed tube building or tube-in-tube building design by multiplying a modification factor.

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