

OPTIMAL DESIGN OF TUBE IN TUBE SYSTEMS

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ABSTRACT

The primary objectives of this study are to investigate effects of varying design parameters on the tube action and shear lag behavior of a typical reinforced concrete tube in tube building, and propose optimal design approaches for similar tube in tube structures. A parametric study was conducted with selected key design variables on the performance of a 40 story building. The design variables considered for the parametric study include the column depth, beam depth, interior walls of the moment frames. The performance of each model was assessed in terms of overall and critical (maximum) story drifts, and shear lag behavior. Overall, the effects of the column depth on the tube action and shear lag behavior were more prominent than the other member dimensions.

Keywords: ????

INTRODUCTION

A building framed-tube system is considered one of the most efficient lateral force-resisting systems. Modern high-rise buildings of the framed-tube system exhibit a considerable degree of shear-lag with consequential reduction in structural efficiency. These buildings are usually equipped with service cores or internal tubes that are often designed to provide added lateral stiffness to the building. The internal tubes also interact with each other as well as with the external tube. Framed-tube structures with multiple internal tubes, or tubes-in-tube structures, can be assessed as a system capable of maximizing the structural efficiencies.

The use of multiple internal tubes reduces the effect of shear lag in the tubes, induces more effective participation of internal columns in resisting lateral forces and offers additional lateral stiffness to the structure. Figure 1 shows the stress distribution of the bottom story of a typical framed-tube structure under lateral loading. The true behavior of the tube structure is influenced by shear-lag arising from the tube action which results in a nonlinear stress distribution.

The tube-tube interaction coupled with the existence of the negative shear-lag in the tubes complicates the estimation of the structural performance and the accurate analysis of tubes-in-tube structures. Tubular structures have proved to be efficient for high-rise building construction. It is no wonder that a significant amount of research work has been done on the shear-lag phenomenon in framed tubes. Kristek and Bauer (1993), Singh and Nagpal (1995) and Lee *et al.*, (2002) extended the study to examine the shear lag behavior of single and multiple framed-tube buildings. In a framed-tube system, columns play a role in making up discontinuous segments of the building tube section that are potentially available for the tube action, and the role of spandrel beams is to effectively engage the discontinuous section segments together, so that they can be fully utilized for the tube action. Therefore, the tube action can be improved by adjusting column and spandrel beam sizes, and/or perimeter column spacing. Lee *et al.*, (2002) conducted a parametric study by changing the axial and bending stiffness properties of columns and beams, and reported that the axial stiffness of the columns was the most influential factor on the tube action as well as the shear lag behavior, while the bending stiffness of the columns and beams were of little impact perhaps due to the tube-to-tube interaction. However, the variables used in this parametric study appear to be unreasonable from a practical standpoint, because changing one stiffness property of a member typically accompanies changes in other stiffness properties of the member (and even other members in some cases) in real design, which was not taken into account in Lee *et al.*, (2002). For example, varying the column sectional dimension parallel to the frame direction affects not only the stiffness of the column, but also the stiffness of the beams framing into the column (by reducing the clear span length of the beams).

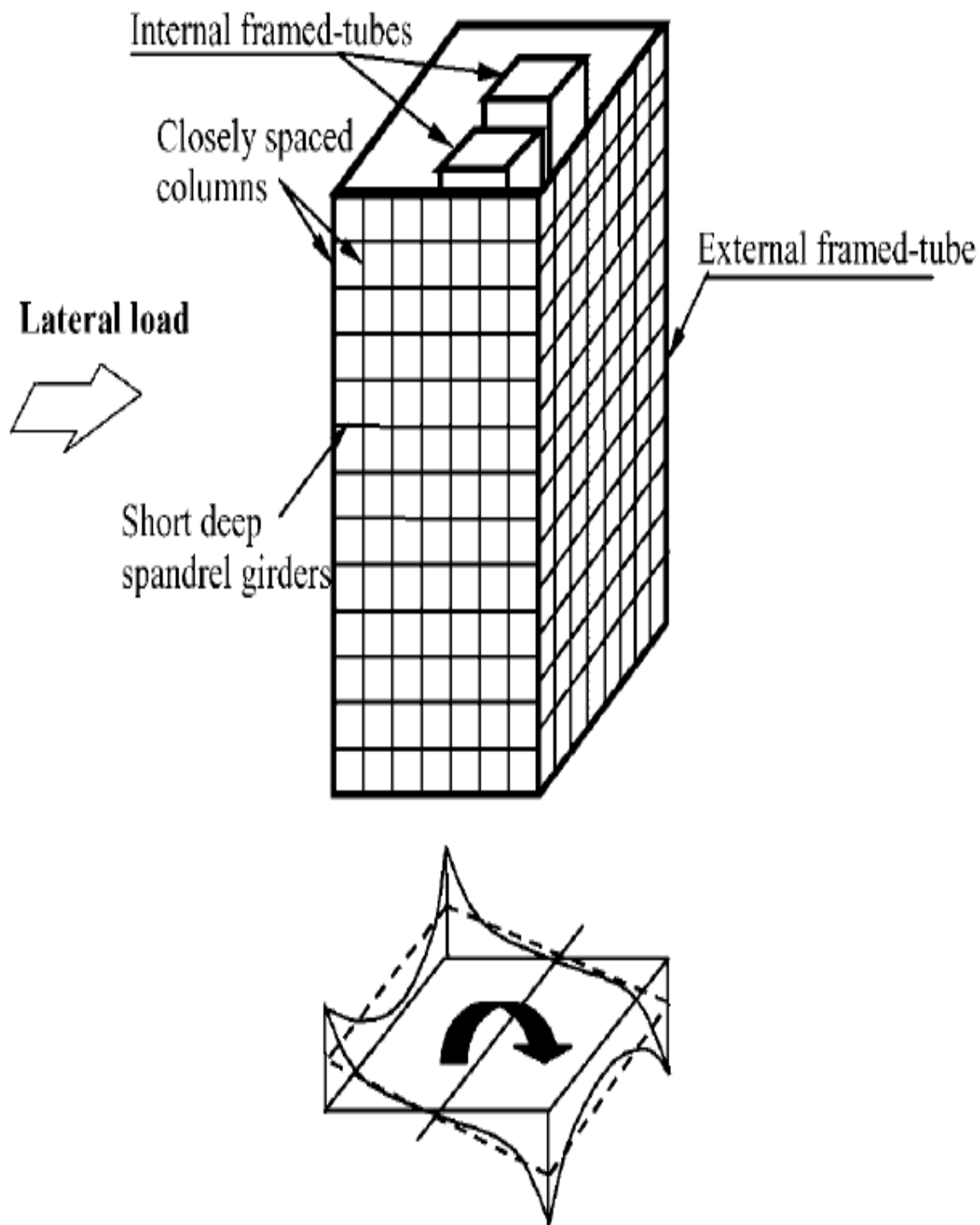


Figure 1: Stress distribution in the external frame of the bottom story of a framed-tube structure

Structural System of the Case Study Building

Figure 2 illustrates a 40-storey concrete and wall layouts and slab edges building. The structure is approximately 147.4 tall, and is 21.6 wide and 43.2 length. The story height is 4 m at the first story and 3.6 m at the upper story. Proposed slab thickness is 200 mm for all typical floors. The concrete compressive strengths 350(kg/cm²) were used for corresponding members.

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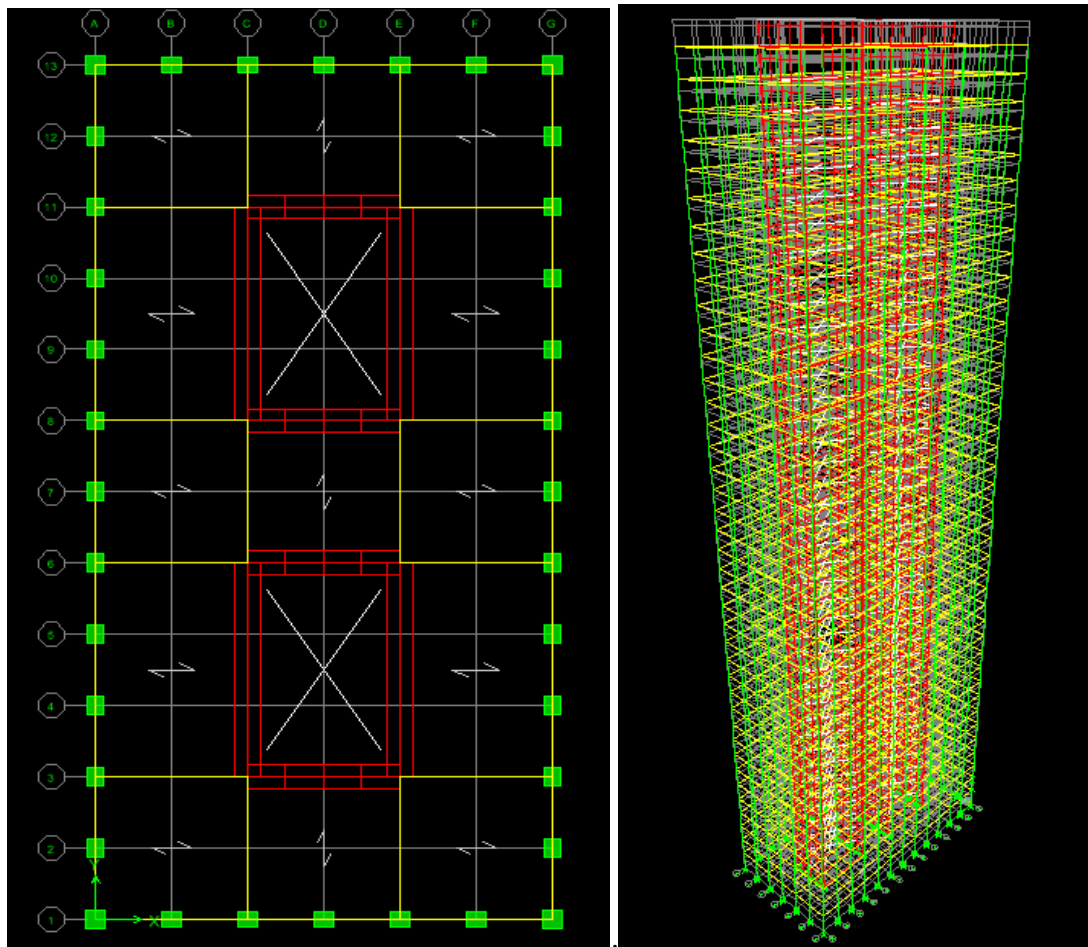


Figure 2: Column and wall layouts, ETABS model of the case study building

Design Variables for Parametric Study

The primary goal of this study is to propose design approaches towards the optimal design of tube in tube structures that are similar to the case study building. The performance of each model was assessed in terms of overall building and critical (maximum) story drifts, as well as force distributions among various lateral force-resisting members (e.g., between the flange and web members of the tube structure, and among the flange columns). Also, the degree of shear lag for each model was evaluated as one of the important performance indicators.

Design variables used for this study include sectional dimensions of the exterior moment frame members: the depth of columns (h_c), depth of beam (h_b), width of columns (b_c), shear wall thickness (t_w) and width of beams (b_b). In each model, an identical set of sectional dimensions are given to all columns, beams and shear wall at all typical floors for simplicity and in each model section of corner column 0.9×0.9 m Considered. Table 1 summarizes model design variables and their relative ratios for all investigated models.

Varying any of the design variables affects multiple sectional stiffness properties of the member at the same time; for example, axial (EA), flexural (EI) and shear (GA) rigidities, where A is the sectional area, I is the moment-of-inertia, E is the modulus of elasticity and G is the shear modulus.

Also, it should be noted that the larger column depth not only increases the column stiffness, but also increases the beam stiffness by reducing the clear distance between the columns (i.e., beam clear span length). Similarly, the larger beam depth affects the column stiffness as well as the beam stiffness. Given this, the direct effects of column flexural rigidity may be assessed only in an approximate way by

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comparing pairs of models with the same axial and shear rigidities but two different flexural rigidities for the columns. Also, the direct effects of beam flexural rigidity may be roughly evaluated in a similar way. All other design values, including the center-to center distance between the columns, are kept constant among all models. Although the spacing between the exterior columns of a tube structure, along with the member dimensions and the plan aspect ratio, is one of the most influential factors on the tube action, the column spacing is typically selected by architectural requirements; thus, it is excluded from the current investigation. The spacing between exterior columns is 3.6 m.

Table 1: Model design variables and descriptions

model	bc	hc	bb	hb	tw
v00	0.75	0.9	0.75	0.95	1.2
v01	0.75	0.9	0.75	1.05	1.4
v02	0.75	0.9	0.75	1.15	1.65
v03	0.75	0.9	0.75	1.25	1.9
v10	0.75	1.1	0.75	0.95	0.8
v11	0.75	1.1	0.75	1.05	0.85
v12	0.75	1.1	0.75	1.15	1
v13	0.75	1.1	0.75	1.25	1.15
v20	0.75	1.3	0.75	0.95	0.45
v21	0.75	1.3	0.75	1.05	0.55
v22	0.75	1.3	0.75	1.15	0.65
v23	0.75	1.3	0.75	1.25	0.7
v30	0.75	1.5	0.75	0.95	0.55
v31	0.75	1.5	0.75	1.05	0.4
v32	0.75	1.5	0.75	1.15	0.4
v33	0.75	1.5	0.75	1.25	0.5
v40	0.75	1.7	0.75	0.95	0.8
v41	0.75	1.7	0.75	1.05	0.55
v42	0.75	1.7	0.75	1.15	0.4
v43	0.75	1.7	0.75	1.25	0.35
v40-A	0.75	1.7	0.75	0.95	1.2
v40-B	0.75	1.7	0.75	0.95	1.6
v30-A	0.75	1.5	0.75	0.95	1
v30-B	0.75	1.5	0.75	0.95	1.4
v30-C	0.75	1.5	0.75	0.95	2
v20-A	0.75	1.3	0.75	0.95	0.85
v20-B	0.75	1.3	0.75	0.95	1.25
v10-A	0.75	1.1	0.75	0.95	1.2
v10-B	0.75	1.1	0.75	0.95	1.6
v00-A	0.75	0.9	0.75	0.95	1.6
v00-B	0.75	0.9	0.75	0.95	2

bc, column width; hc, column depth; bb, beam width; hb, beam depth and tw, shear wall thickness

Modelling and Analysis Assumptions

ETABS building analysis and design software has been used for the modelling and analysis of this study. Figure 3 illustrates the 3-dimensional ETABS model. Several important modelling and analysis approaches used for the parametric study are summarized in the following:

- (1) Joints between the beams and columns (parts of both the beams and columns belonging to their common regions) are assumed rigid. Note that varying the column (or beam) depth of the frames changes the beam (or column) length between the column faces, so as to also affect the beam (or column) stiffness due to this assumption.
- (2) The contribution of the slab to the beam stiffness (i.e., T-beam action) is ignored.
- (3) The concrete floors are modelled with rigid diaphragm constraints for lateral force analysis.

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(4) P-delta effects are taken into account by an approximate method imbedded in ETABS (CSI, 2005).

(5) The flexural stiffness of uncracked shear walls is assumed to correspond to 100% of the gross section properties, while the flexural stiffness of all spandrel beams and coupling beams is taken as 50% based on ACI 318-08, Section 8.8 (ACI 318, 2008).

It has been verified from the models that the shear walls are expected not to undertake cracking at all stories under the lateral forces used for this study. Detailed discussions for the finite element modelling of cracked shear walls can be found elsewhere.

Discussions for Parametric Study

When the beam and/or column sizes increase in the case study building, the participation of the frames in overall behavior generally becomes greater.

In a framed-tube system, columns play a role in making up the tube section, that is, column sections are discontinuous segments of the entire tube section. On the other hand, the primary role of spandrel beams is to tie columns together and transfer lateral forces between adjacent columns.

Thus, varying the column size affects the moment-of-inertia of the entire building plan that is potentially available for the tube action, while varying the beam size affects the quality of the force transfer (e.g., the distribution of axial forces) among the web and/or flange columns.

The effects of the design variables on each of the performance indices, such as story drifts are compared with respect to relative ratios for each of the design variables, as well as to their absolute changes. Also, different impacts of each design variable are observed and discussed.

Story Drifts

Figure 3 shows story drifts (a) and overall building drift (b) along the building height for five companion models with different column depths under the service-level seismic forces. For lateral force resistance, the structure mainly uses the exterior column, and a combination of the moment frames and the interior shear walls.

The level of the story showing the maximum drift lowered when the column depth became larger in both directions, as more tube action affected the overall behavior (see Figure 3).

The sensitivity of the overall building drift to the change in the column size was much greater than the sensitivity to the change in the beam size; this can be observed by comparing the slopes of the curves shown in Figure 3 (a).

This also happened with varying each of the other two design variables (column depth and beam depth). Figure 4 depicts effects of the column and beam depths on the (a) maximum (critical) story drift and the (b) overall building drift.

The effects of the beam depth (h_b) on the drifts were very small. However, the effects of the column depth (h_c) were quite significant and these prominent effects were almost identical for all different beam depths.

For lateral force resistance, the structure mainly uses the exterior column and interior shear walls had Secondary role to resistance lateral forces. Lateral drifts can be most effectively reduced by increasing the column depth.

This is likely attributable to the increased flexural rigidity of the building plan (i.e., the tube section), as well as the reduced beam clear span that increases the beam stiffness against relative transverse displacements between the beam ends caused by shear lag.

The results presented in this subsection provide quantitative assessment for the impact of change in each sectional dimension of the frame members on the lateral displacement.

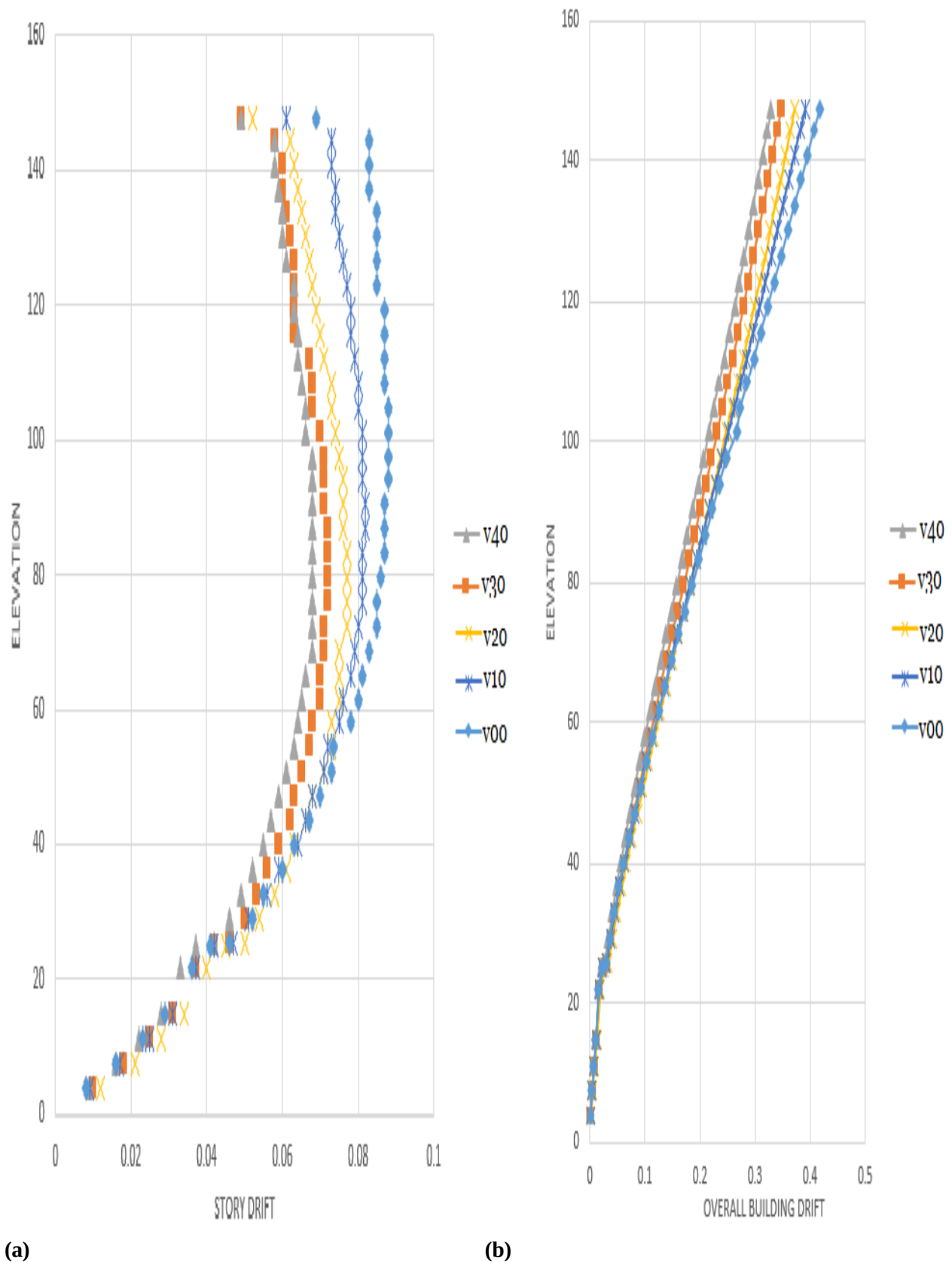
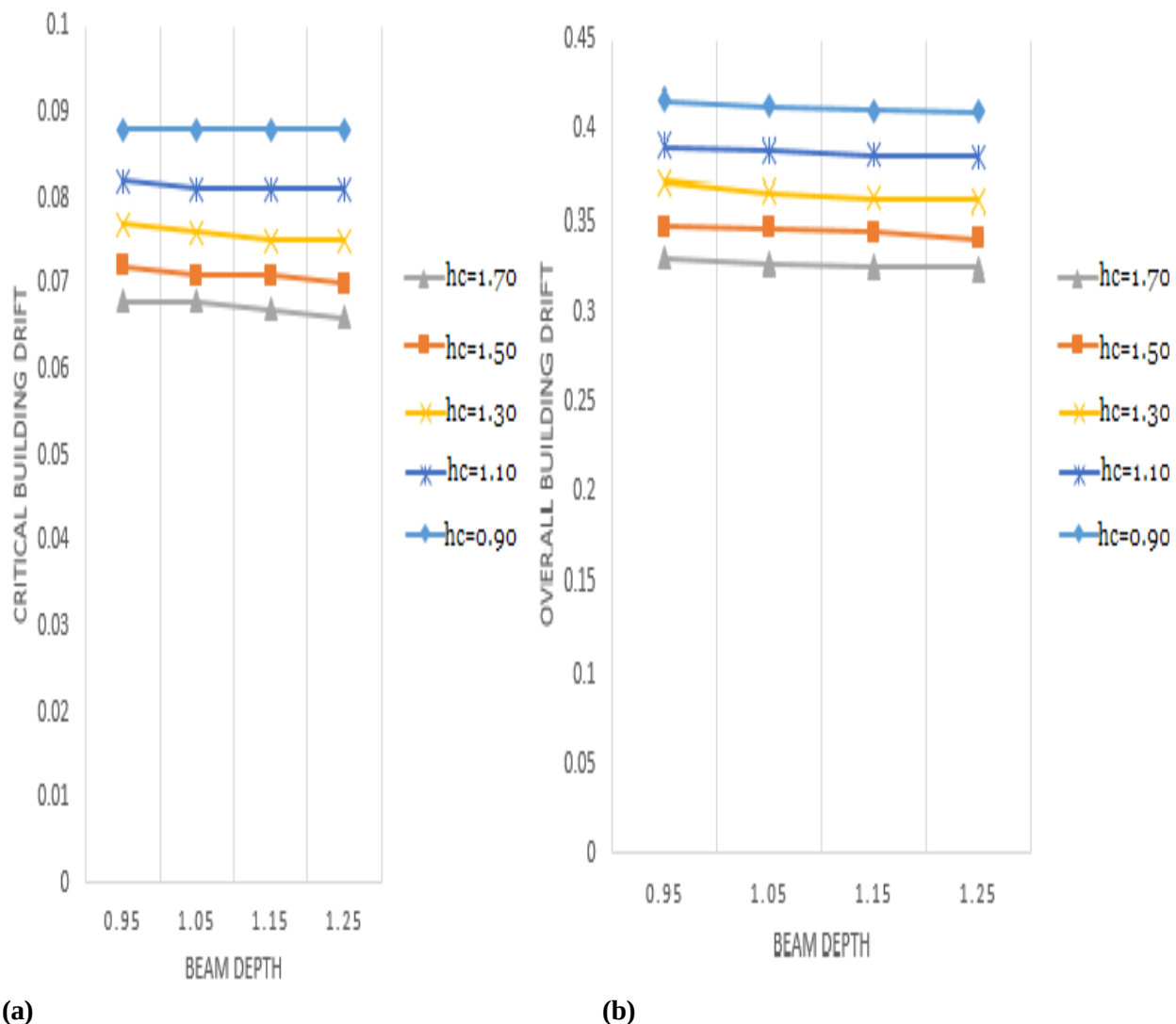


Figure 3: Story drifts (a) and (b) overall building drift

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(a) **(b)**
Figure 4: (a) Maximum (critical) story drift and (b) overall building drift under service seismic forces

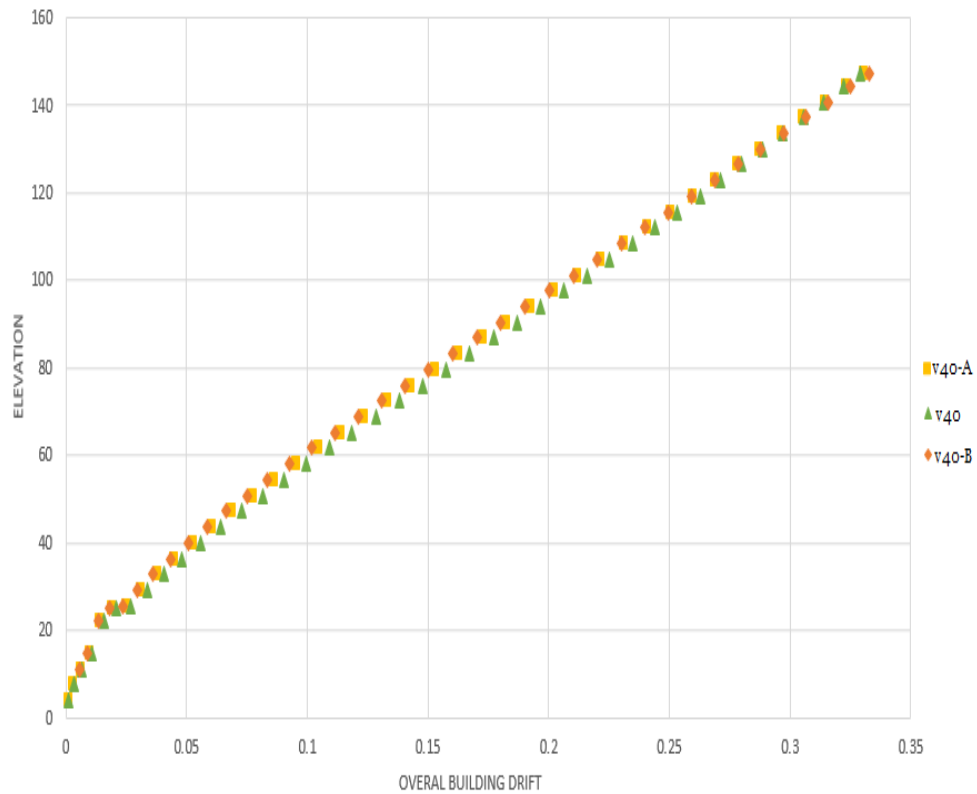
Effects of Interior Walls on Story Drifts

Figures 5 (a) until (k) comparing story drift and overall building drift models with constant column and beam depth with varying Thickness of interior walls. In Models v40, v40-A and v40-B with 1.70 cm column depth, gradual increase of thickness interior walls lead to increase overall building drift. In v30, v30-A, v30-B and v30-C models gradual increase of interior walls thickness firstly lead to reduction overall building drift but with further increase thickness of interior walls the overall building drift increase.

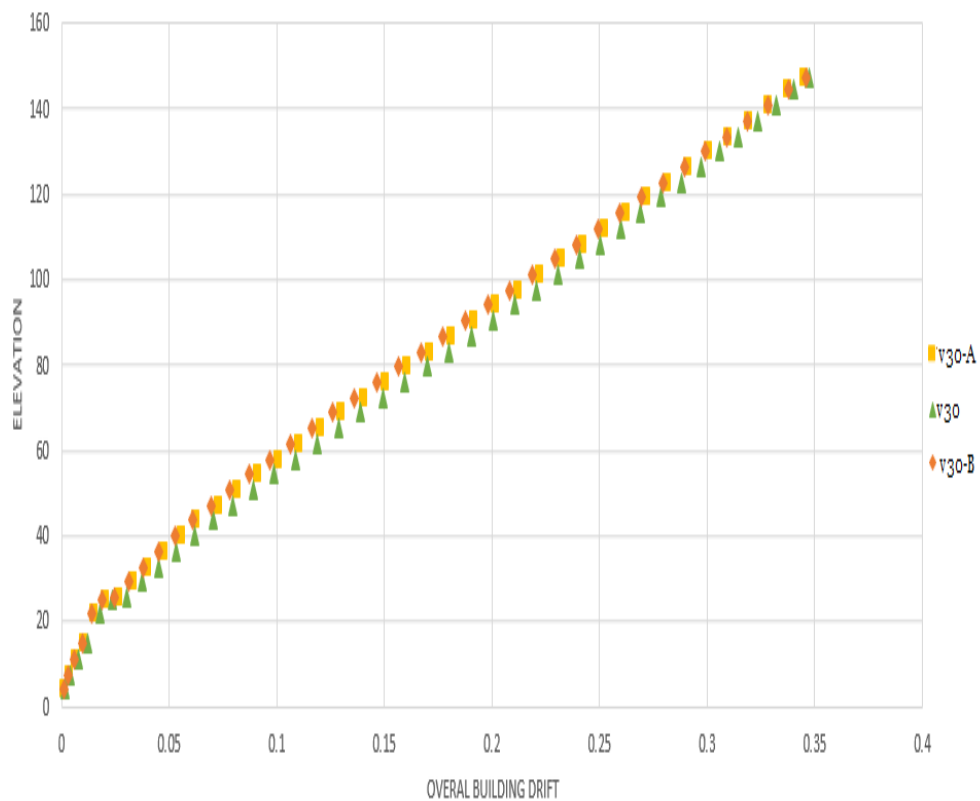
In models with lesser column depth with increase thickness of interior walls structure will have behavior almost same behavior of v30, v30-A, v30-B and v30-C models.

In this case increase column depth lead to increase exterior frame lateral stiffness, it seems when the exterior frame have high lateral stiffness increase thickness of interior walls lead to rapid increase overall building drift. Frame with smaller column depth have lesser lateral stiffness and increase thickness of interior walls in this frames firstly decrease overall drift but with further increase thickness of interior wall the overall building drift increase. Figure 6 describes relation between overall building drift and thickness of interior walls in this case.

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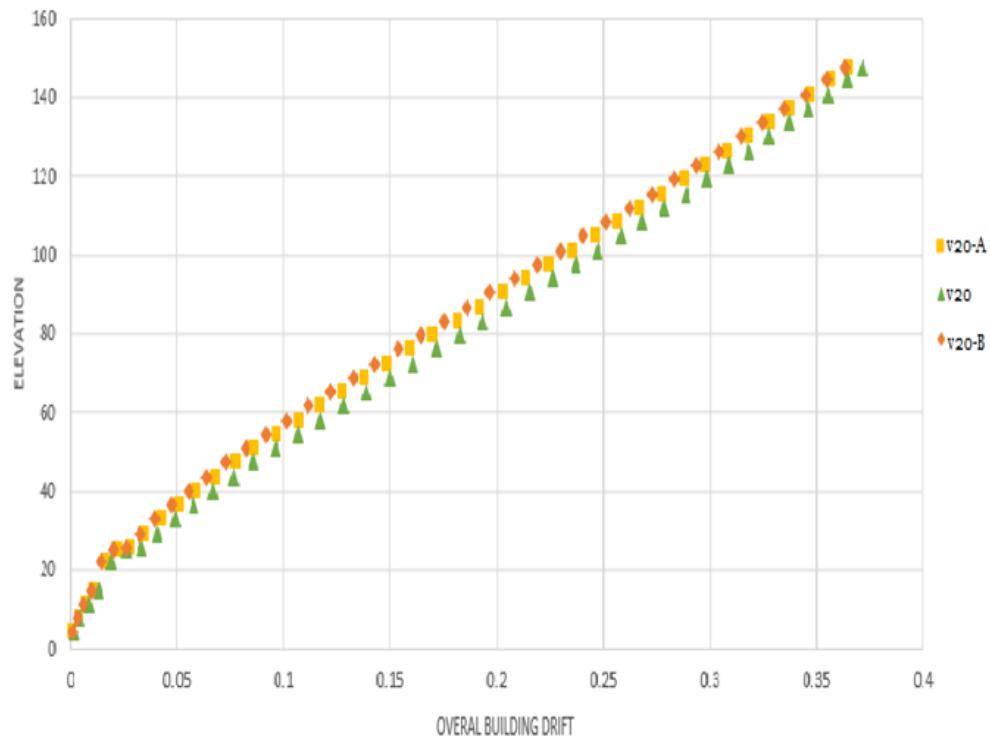


(a)

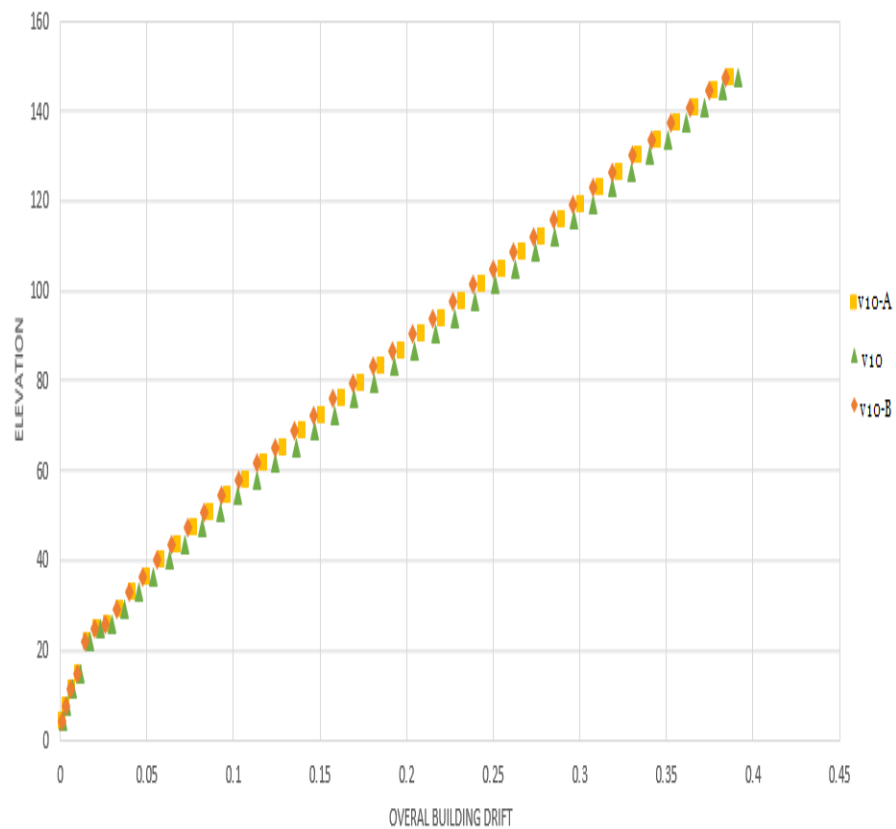


(b)

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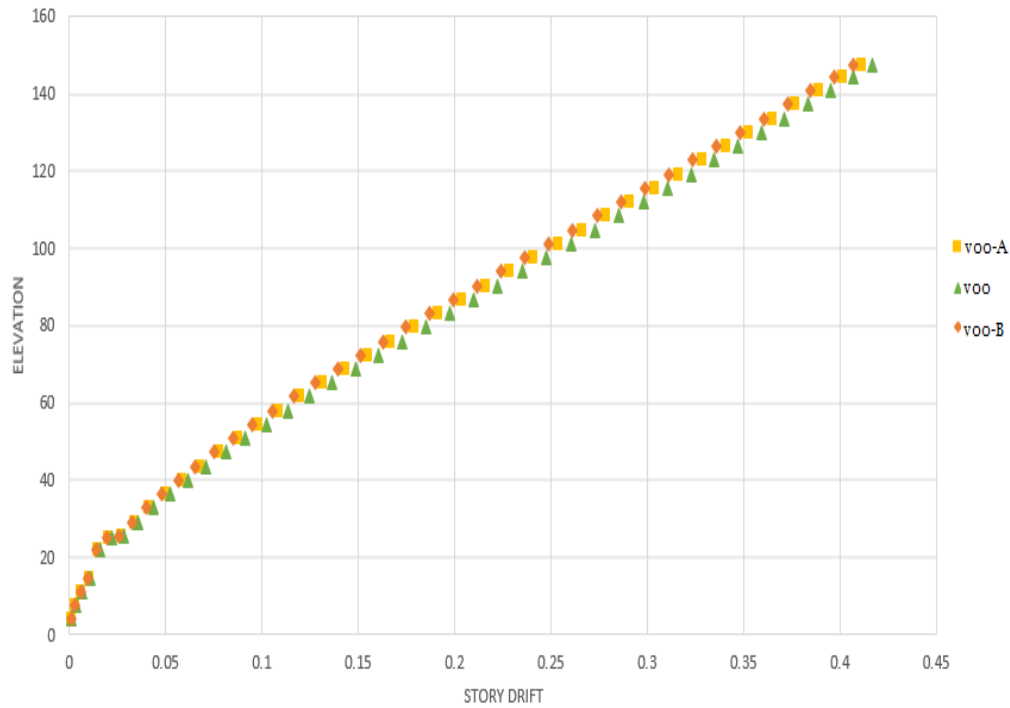


(c)

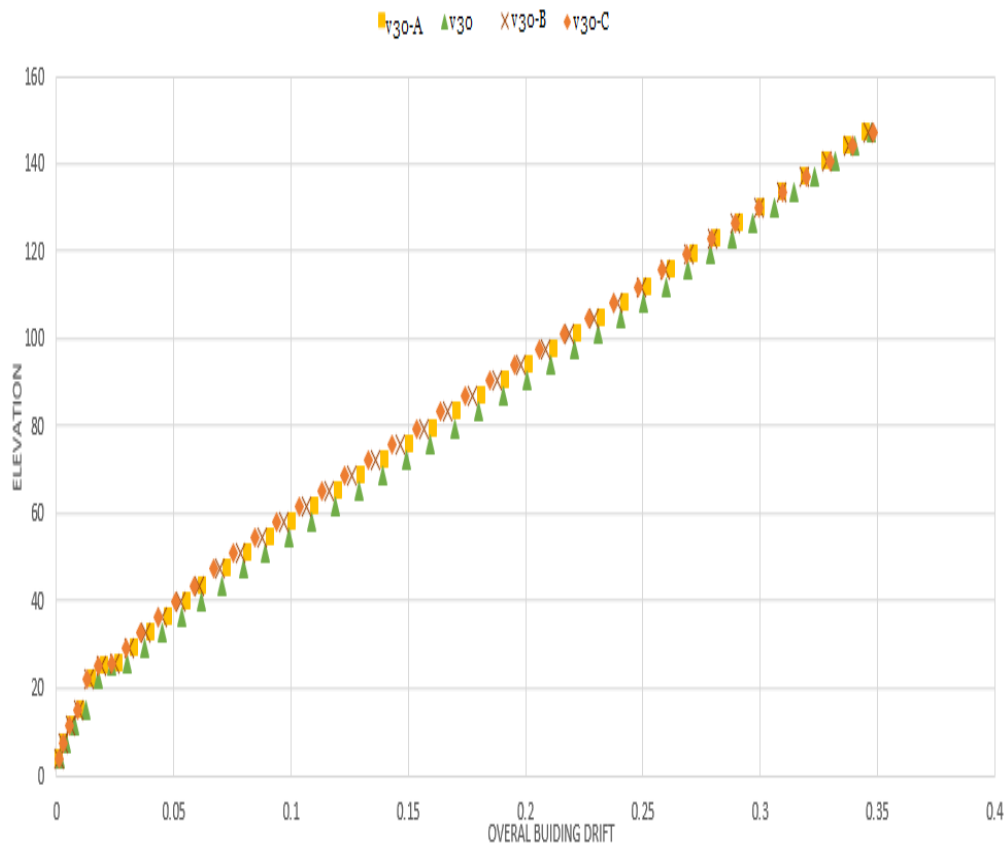


(d)

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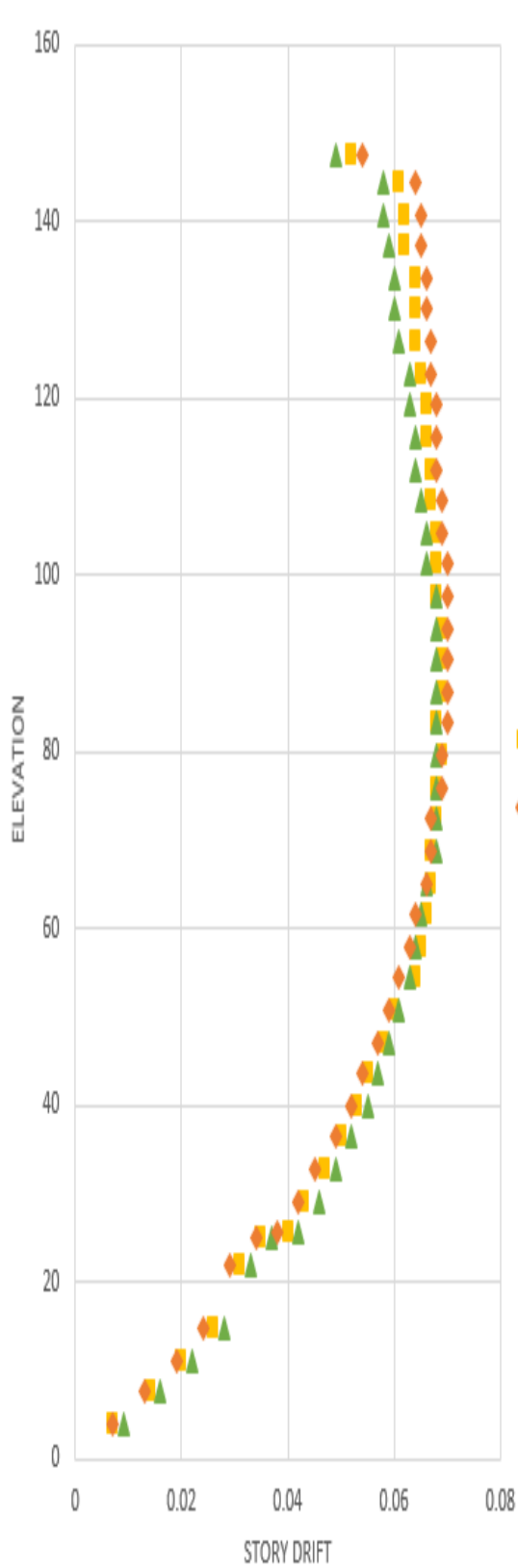


(e)

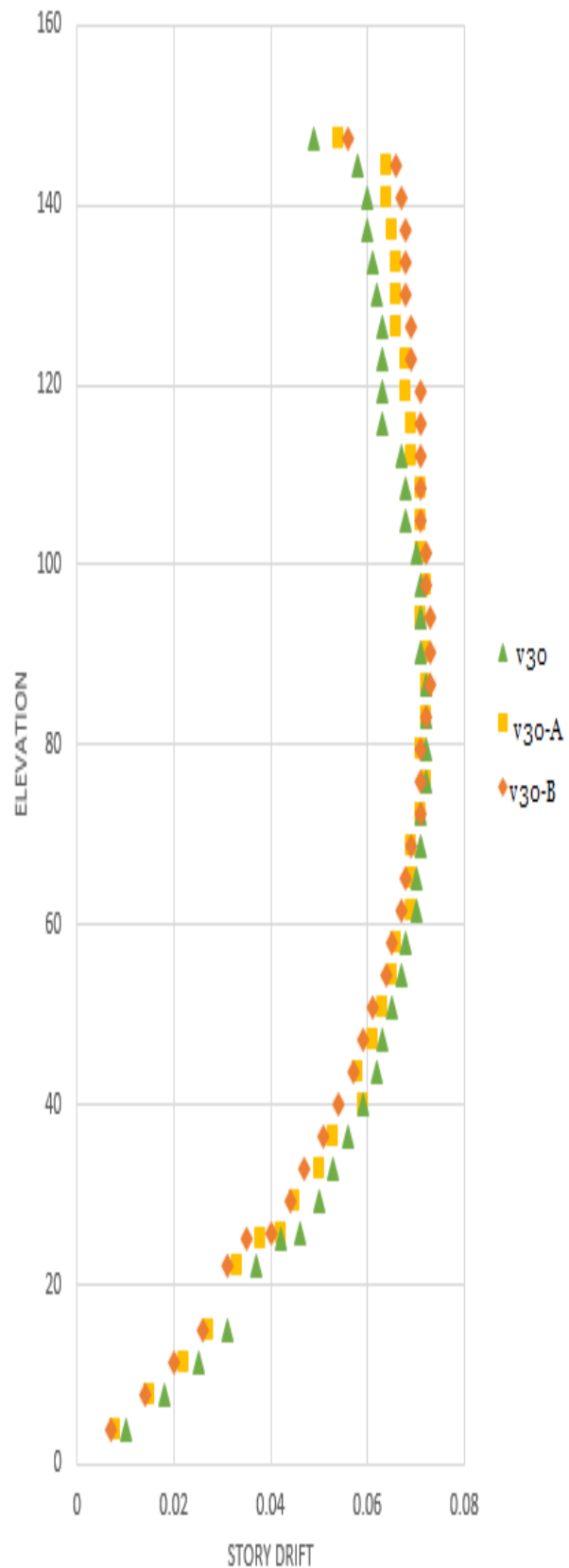


(F)

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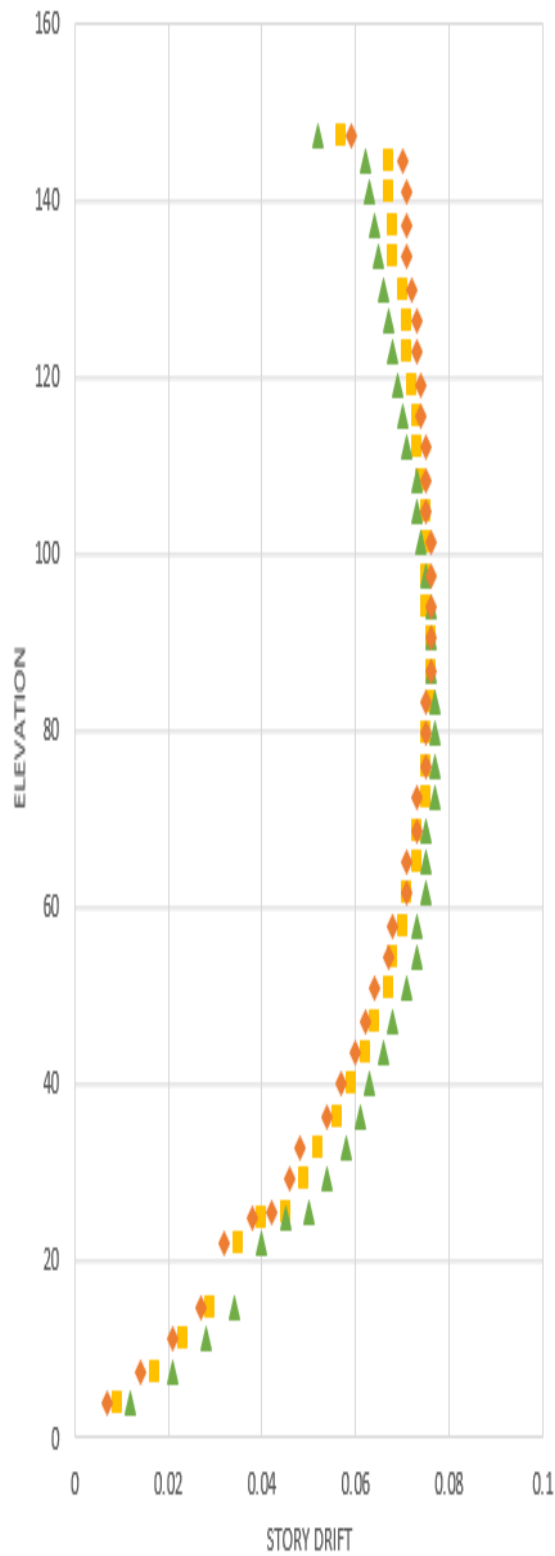


(g)



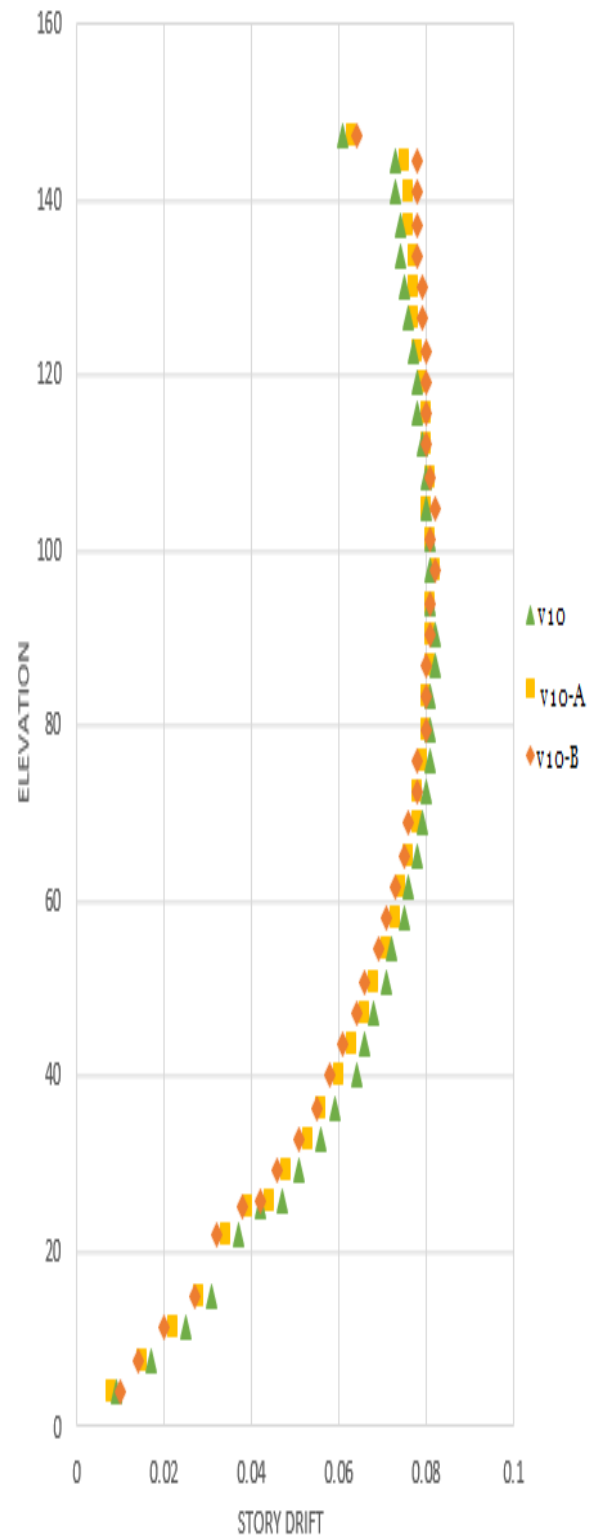
(h)

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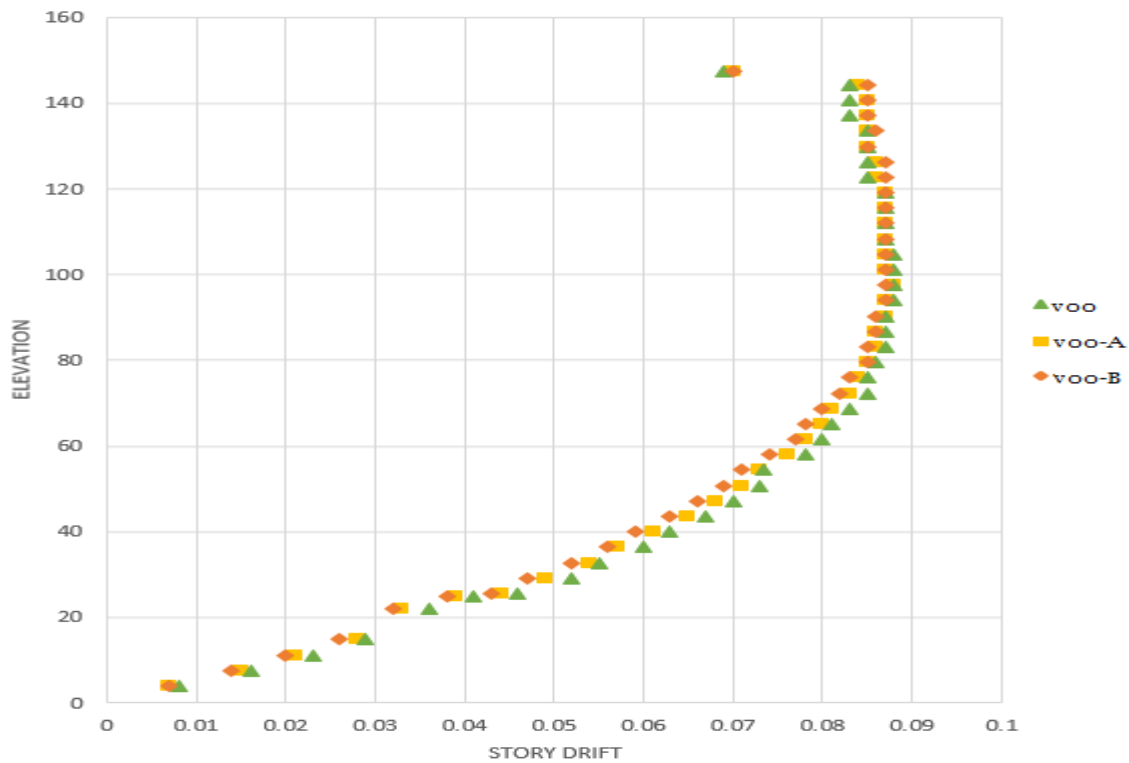


(i)

(j)



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(k)

Figure 5: Overall building story drift (a) ,(b) ,(c) ,(d) ,(e) and (f) ,story drift (g) ,(h) ,(i) ,(g) and (k)

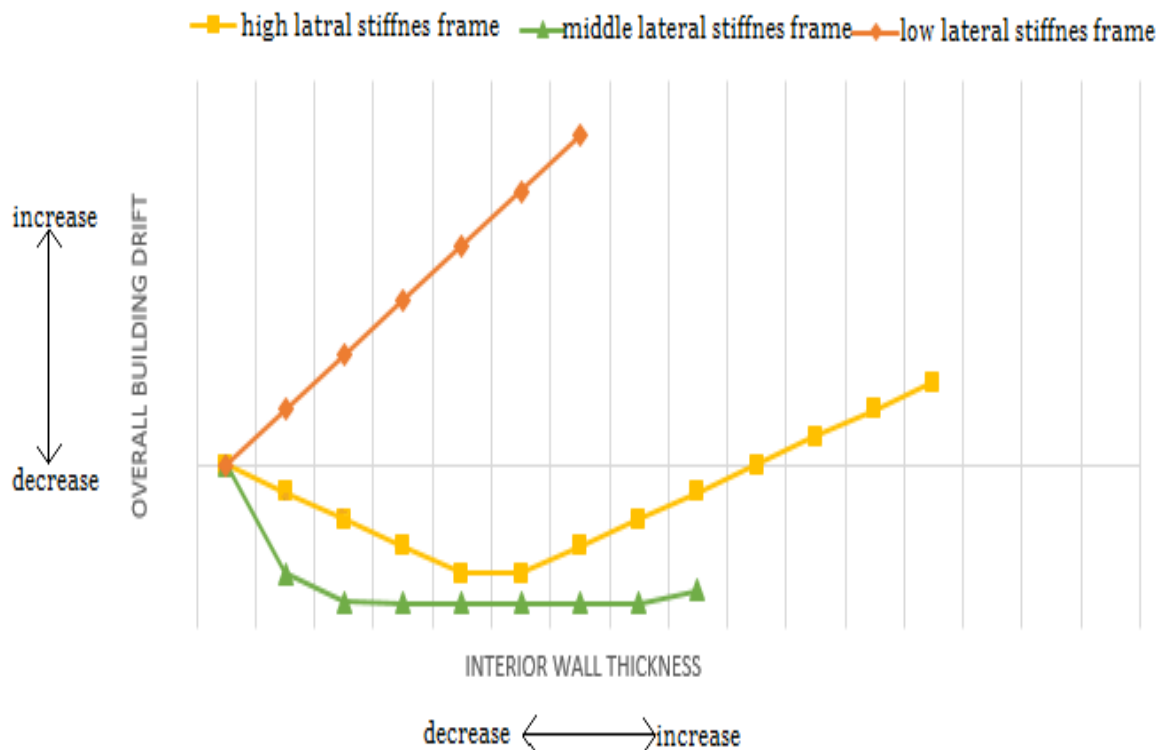


Figure 6: Relation between overall building drift and thickness of interior walls

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Distribution of Column Axial Forces and Stresses

Figure 7 illustrates column axial force of first story for flange and web of structure. For the web seismic load exerted in X direction and for flange of structure seismic load exerted in Y direction. Figure 7 (a) and (b) showing axial force of first story column for five models with different column depth and constant beam depth. Comparing the five models with different column depths showing middle columns take gradually increasing forces when the column depth increases. On the other hand, forces of the corner columns change only by slight amounts. Figure 8 showing columns axial force at 20th story for web and flange of building, the results of column axial force for 20th story was approximately similar the first story. In v40 observe axial force of column that located next corner column is more than corner columns, this is probable occur because clear span of beam become smaller and then stiffness of beam become larger. Of the two beams with an identical shear area, the beam with a larger depth has the greater moment-of-inertia and consequently the greater stiffness, which better ties the middle and corner columns together. Figure 9 comparing column axial force of web and flange of structure with constant column depth and vary beam depth. With respect to the effects of the beam depth illustrated in Figure 9, the larger beam depth results in larger forces in the middle columns with larger forces in the corner columns, generally increases beam depth lead to unbalanced distribution column axial force (more shear lag state).

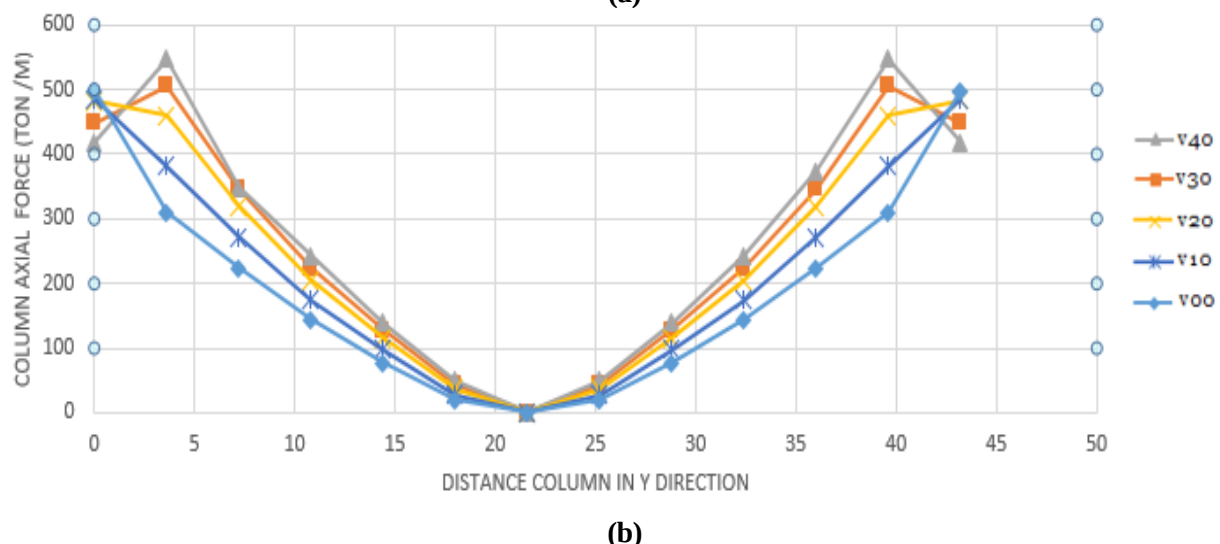
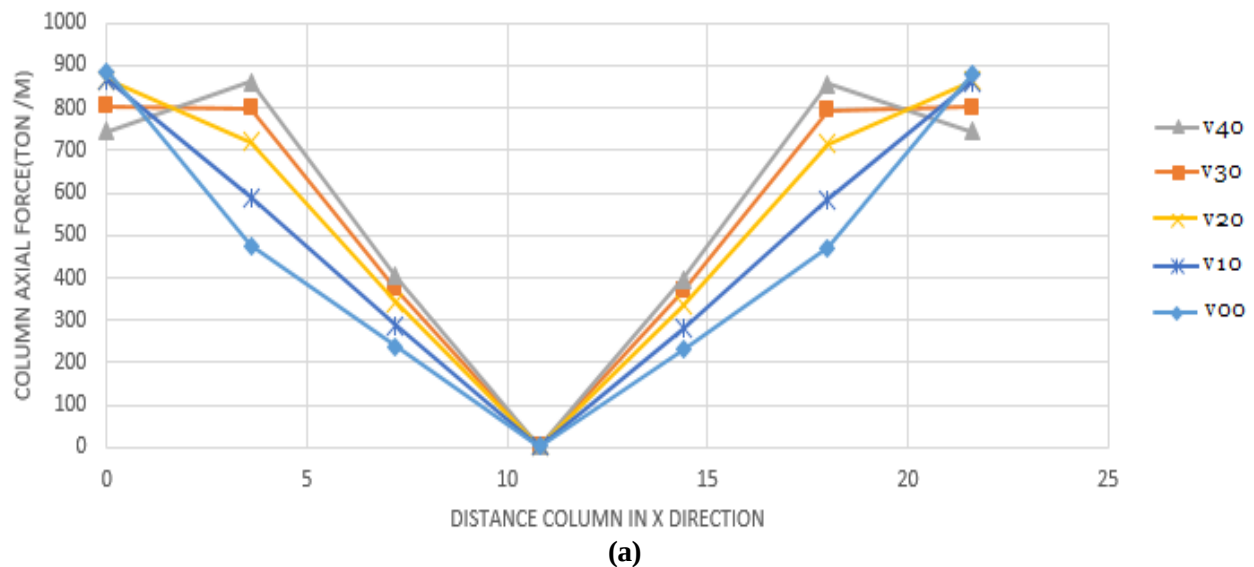
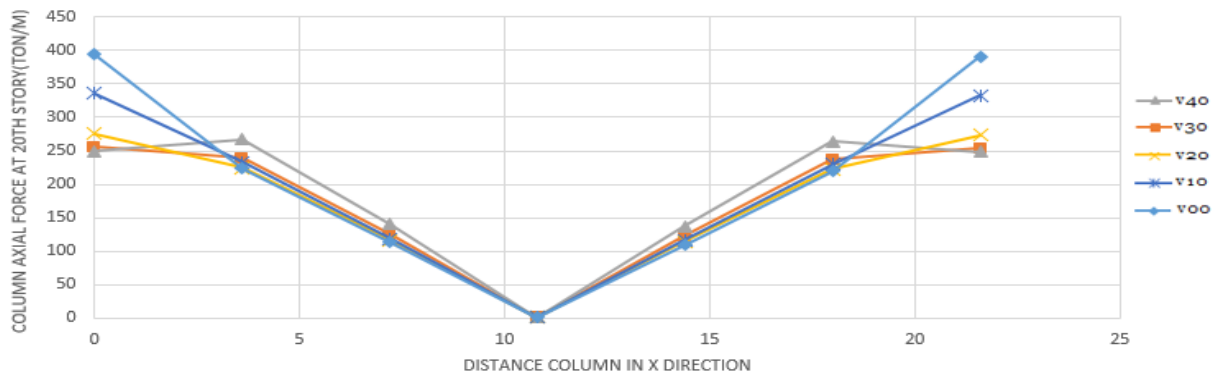
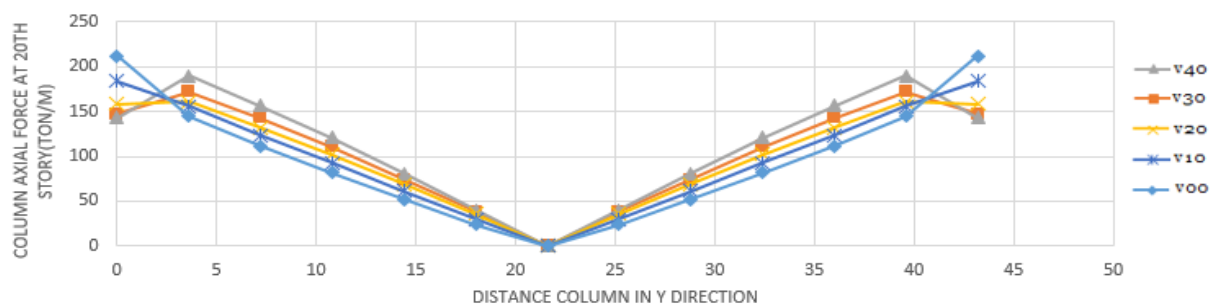


Figure 7: First story column axial force (web) (a) and (b) first story column axial force (flange)

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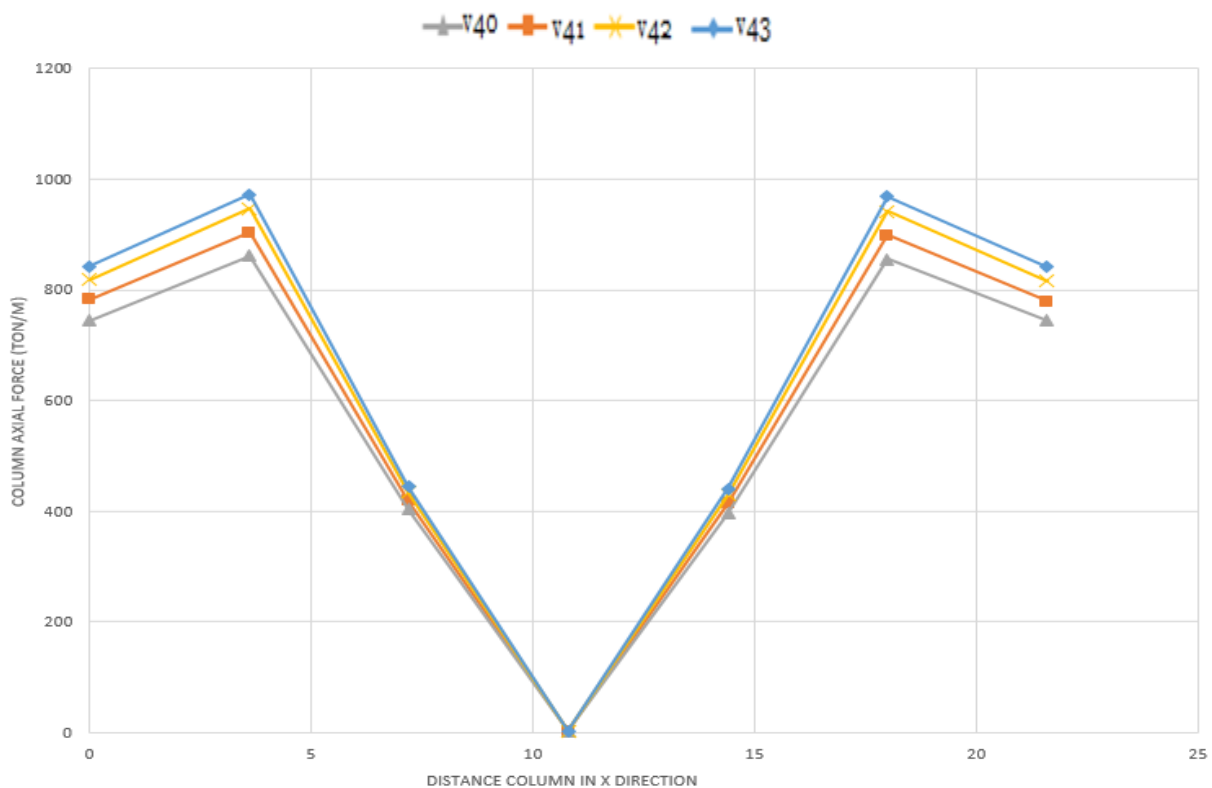


(a)

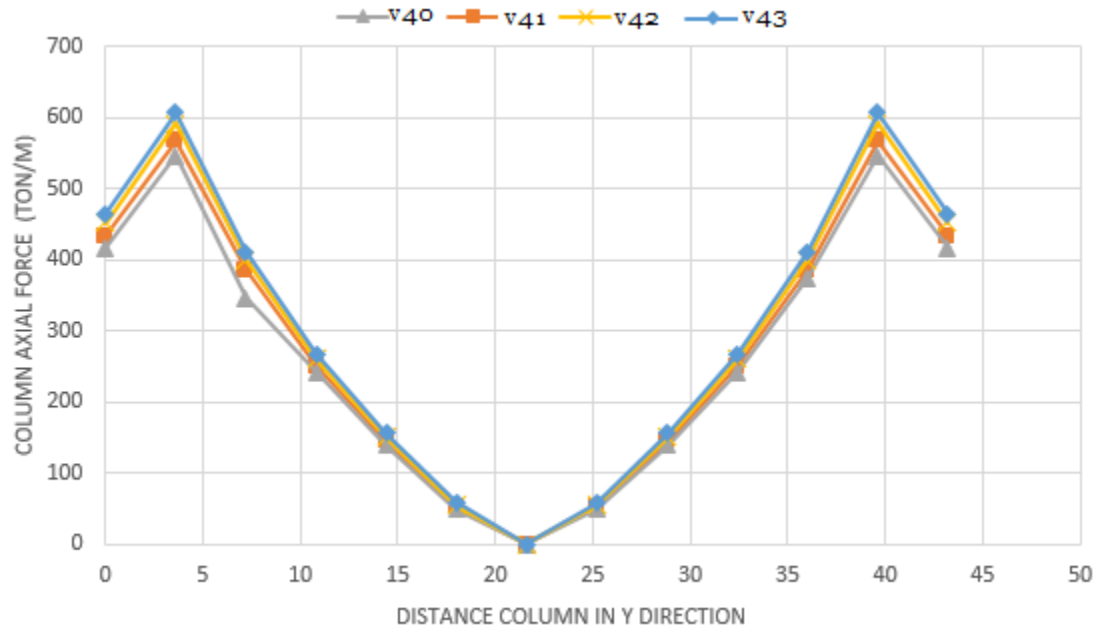


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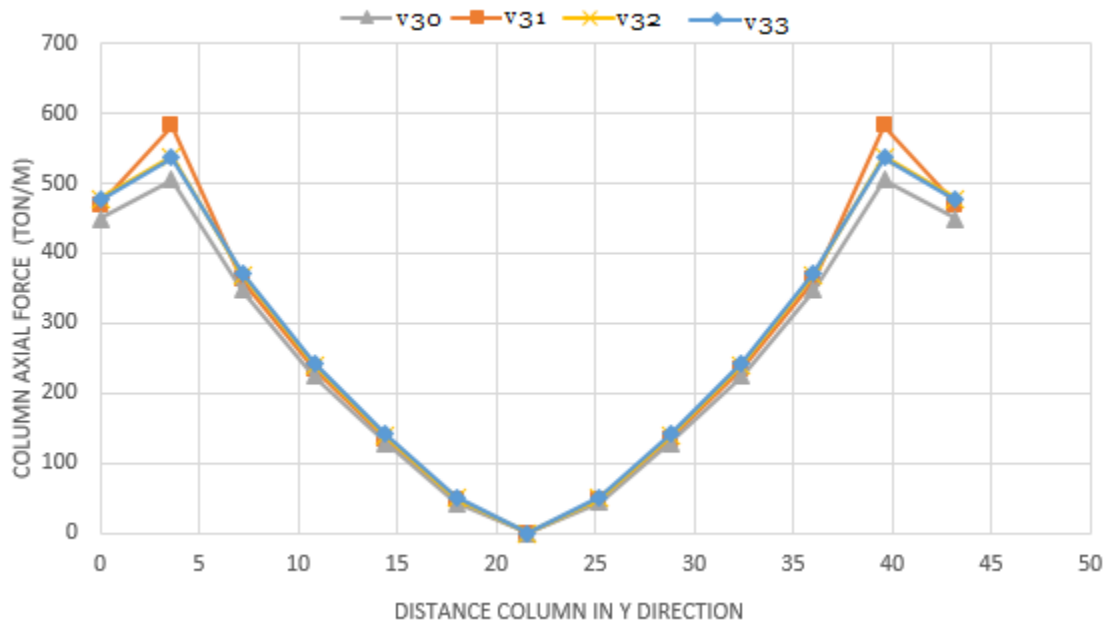
Figure 8: 20th story columns axial force (web) (a) and (b) 20th story columns axial force (flange)



(a)



(b)



(b)

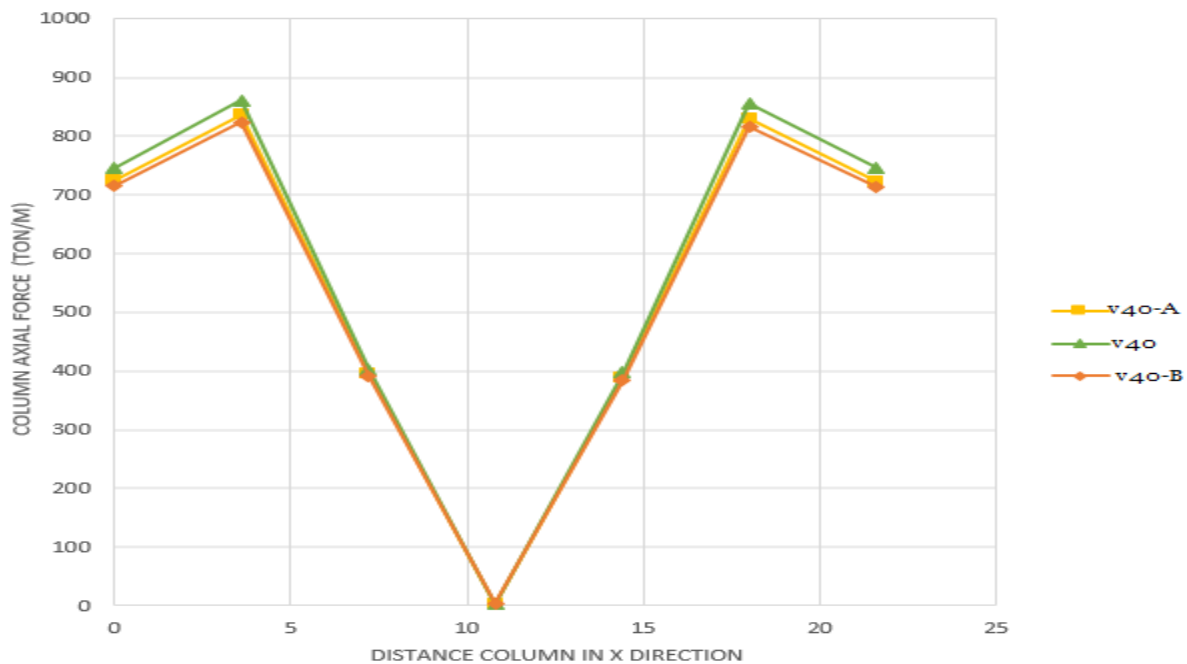
Figure 9: Column axial force with constant column depth and vary beam depth (web) (a) and (b) flange

Effect of Interior Walls on Column Axial Force

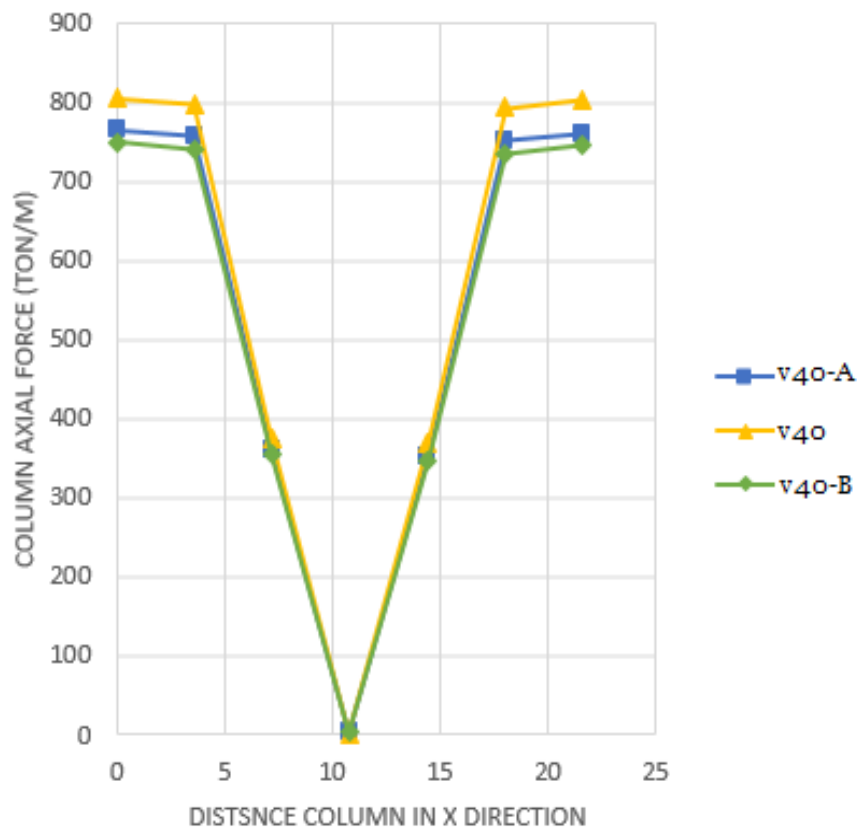
Figures 10 comparing column axial force models with constant column and beam depth with varying Thickness of interior walls. In all of models for both web and flange increases thickness interior walls lead to decrease corner columns axial force and increase middle columns axial force. With increase thickness interior walls distribution axial force between corner and middle columns more balanced and

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closer to the ideal state (less shear lag). Increase thickness interior walls had greatest effects on models with 1.30 cm column depth and lesser effects on models with 1.70 cm column depth observed.

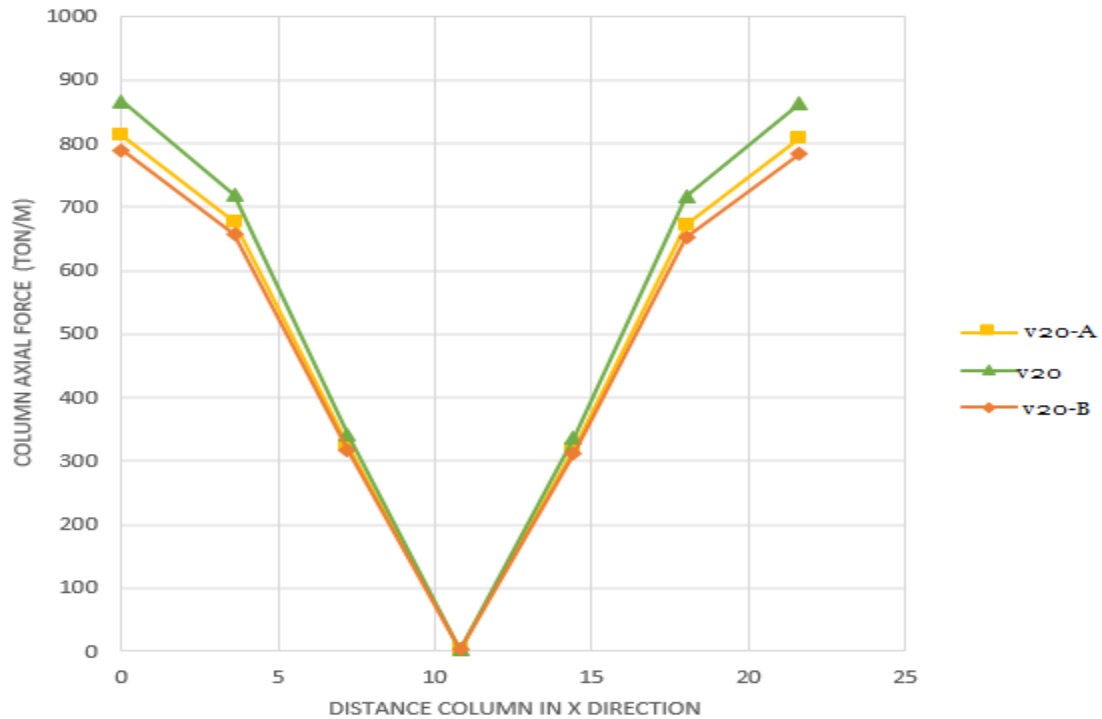


(a)

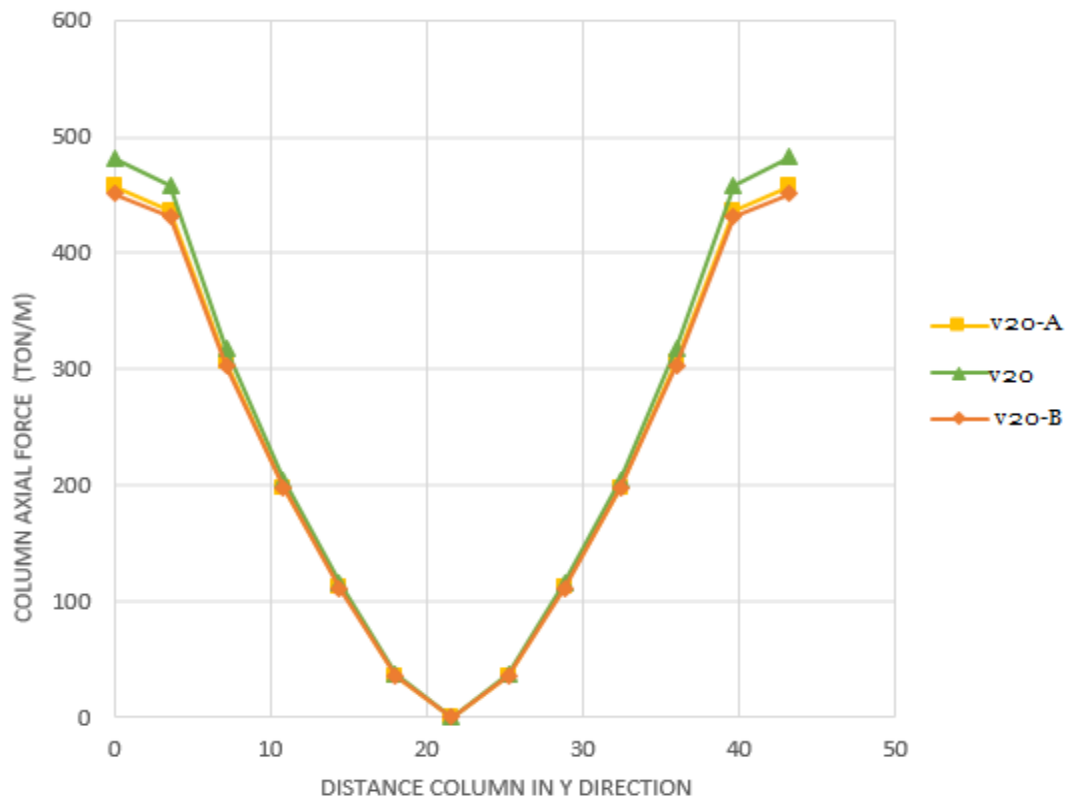


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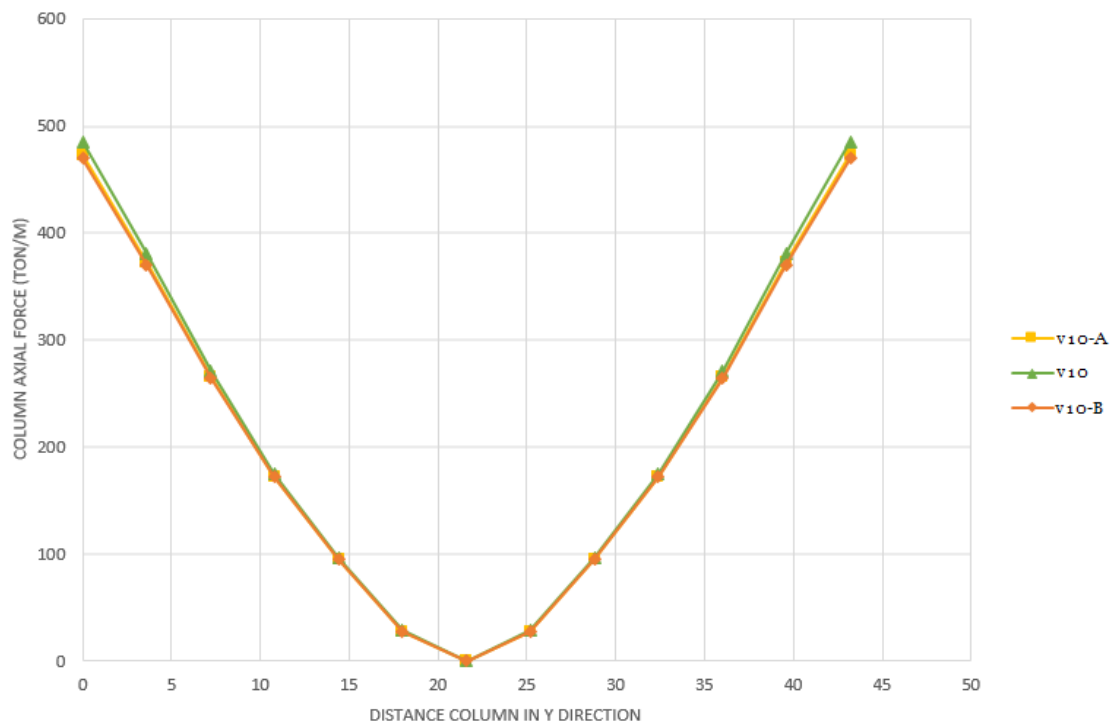


(c)



(d)

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(e)

Figure 10: Column axial force models(web) (a) ,(b) , (c) and (d) ,(e) flange

Summary and Conclusion

In this paper, an extensive parametric study was conducted to investigate the contribution of tube action to the lateral stiffness and strength of an RC tube in tube building to propose optimal design approaches for similar high-rise tube systems. Based on the parametric study, the following conclusions can be drawn:

- (1) Overall building drifts or story drifts of a structure similar to the case study building can be effectively reduced by increasing the stiffness properties of flange and web frame members, on other hand increase column depth had most effects on overall building and story drift.
- (2) Increase beam depth graduate reduction overall building drifts. Effect of beam depth on critical story drift is more than overall building drifts. On other hand increase beam depth reduction critical building more than overall building drifts.
- (3) Increase thickness of interior walls in models with high lateral stiffness(column with large depth) ,increase overall buildings rapidly, Increase thickness of interior walls in models with middle lateral stiffness (column with average depth) firstly decrease overall building and with further increase thickness of interior walls, increase overall building drifts and increase thickness of interior walls in models with low lateral stiffness(column with small depth) firstly reduction overall building drifts and Later with increase thickness interior walls to the high degree , overall building increases.
- (4) Increase column depth, decreases corner columns axial force and increases middle columns axial force and subsequently distribution of axial forces become closer to the ideal state. Note that increase columns depth to much, decrease clear beam bay and subsequently stiffness of beam increase to high degree.
- (5) Increase beam depth lades to increase corner columns axial force and increase middle columns axial force. In this case study increase beam depth, away column axial force from ideal state.
- (6) Increase thickness interior wall lead to decrease corner columns axial force and increase middle columns axial force, in this way columns axial force closer to ideal state.

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