CHAPTER 6

DESIGN ASPECTS OF FRAMED TUBE BUILDINGS SUBJECTED TO SLP

6.1 INTRODUCTION

The load resisting capacity of the beam and column depend on the flexural rigidity. It the structure it is assumed that stronger structural element sustains more actions (load, bending moment) than the weaker structural element. The relative strength can be understood in terms of stiffness of the respective structural element.

In the framed tube structure, the beam and column joints are assumed rigid. The primary function of floor and roof system is to support the gravity load and to transfer these loads to other structural system such as beam, column and wall. Under the influence of lateral load, the beam-column and slab interactions have significant impact on distribution of lateral load to peripheral column of the tubular structures. The slab also transfer shear force from peripheral structural elements to the internal structural elements and vice-versa. The variation of bending stresses along with the height is also irregular. The value of bending stresses changes from compressive to tensile somewhere at a point along the height of the column. The point where the bending stress changes it sign is called the point of inflection. It is stated that the inflection point lies after quarter height from the support for a cantilever box girder [Chang and Zheng 1987]. Also, the additional bending moment generated in the tubular building is analyzed as it is analyzed by Chang and Zheng (1987) in the box girder bridges.

In this chapter, the study has been presented regarding the effect of beam-column and slab interaction on the shear lag phenomenon (SLP) in tubular buildings and to estimate the design aspect regarding this phenomenon. The various aspects considered are relative stiffness of beam and columns; axial forces in the columns; base bending moment; additional bending moment; deflections; estimation of critical columns and to find the position of the point of inflection in each column. These aspects are essential to deciding the preliminary dimension of the structural elements. The tubular buildings are analyzed by using STAAD Pro. v8i (2007).

6.2 HIGH RISE STRUCTURES

A 40-storeys tubular structure is analyzed in this section. The specifications of the tubular building are given in chapter 4, as basic tubular structure. In addition, the slab thickness is assumed 200 mm (Kwan 1994). To study the influence of relative stiffness of beam and column on shear lag phenomenon, the slab thickness is ignored. The result obtained is presented in the following sections.

6.2.1 Variation of Axial Forces

The variations of axial stress in the flange and web panels along the height of the tubular structure have been presented. The axial stress and hence the axial forces in the leeward direction are plotted at every level i.e. storey wise of the structure.

(a) **Variation of axial force in flange panel:** Axial force in columns of compression flange panel has been plotted for every ten storeys in each plot so that one can realize the effect the shear lag on design axial force of columns behavior along the height.

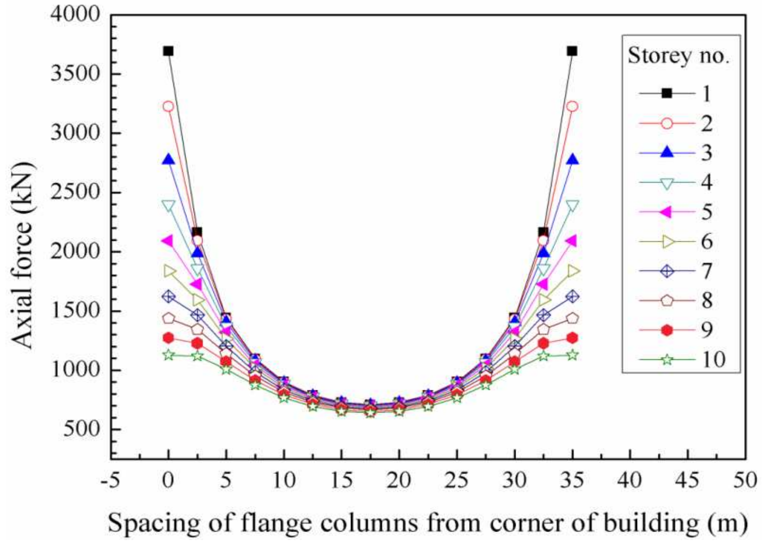


Fig. 6.1. Axial force in flange panel's column (1-10 Storeys)

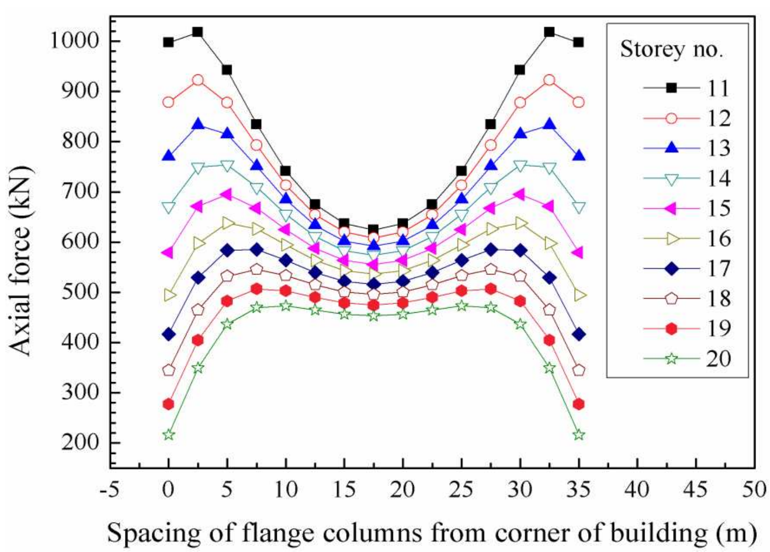


Fig. 6.2. Axial force in flange panel's column (11-20 Storeys)

Axial force in corner columns (C1 and C15) are the maximum and central column (C8) is subjected to minimum axial force shown in Fig. 6.1. This is a case of a positive shear lag phenomenon as the corner columns of flange panels are subjected to more force than the central column. With increasing in the height of the building axial force in corner columns is decreasing with respect to the central column. For the 10^{th} storey, axial forces in corner columns are lesser than immediately adjacent inner columns. For upper storeys, this trend becomes more prominent as shown in Fig. 6.2-6.4. This trend indicates the occurrence of negative shear lag at higher storeys. In the 16th storey, the axial force in corner column is lesser than the central column. This is a negative shear lag phenomenon as central column has more axial force than corner column. Axial forces in corner columns are now decreasing faster as the height increases. The point of maximum axial force is shifting towards the center. Above 24th storey, axial forces are maximum in central column and corner columns have the axial force of opposite nature. This is negative shear lag phenomenon as the central columns are experiencing more force than corner columns. From the plots of axial forces in columns of flange panel, it can be concluded that axial forces in corner columns decrease and changes sign with the increase in the height of the building. Due to negative shear lag axial force in central columns increases and there is decrease for corner columns for upper storeys. Axial force distribution, which was concave upward at the base, becomes concave downward at the top.

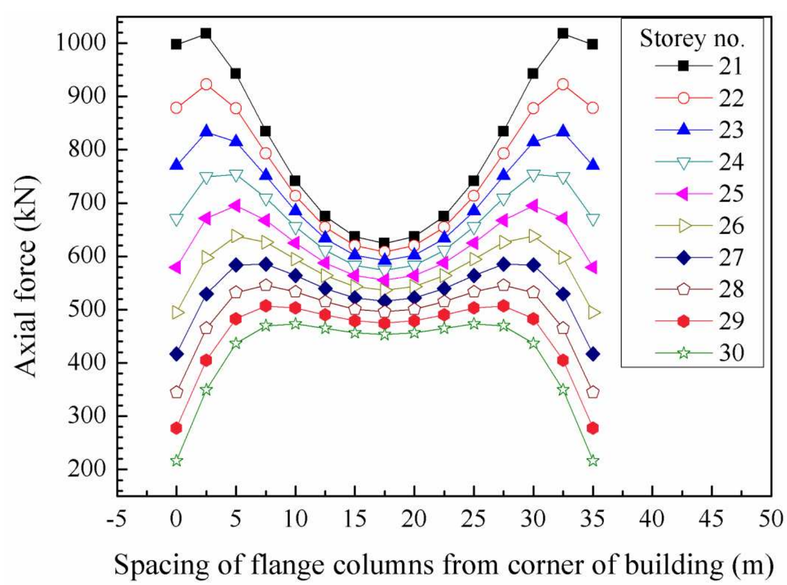


Fig. 6.3. Axial force in flange panel’s column (21-30 Storeys)

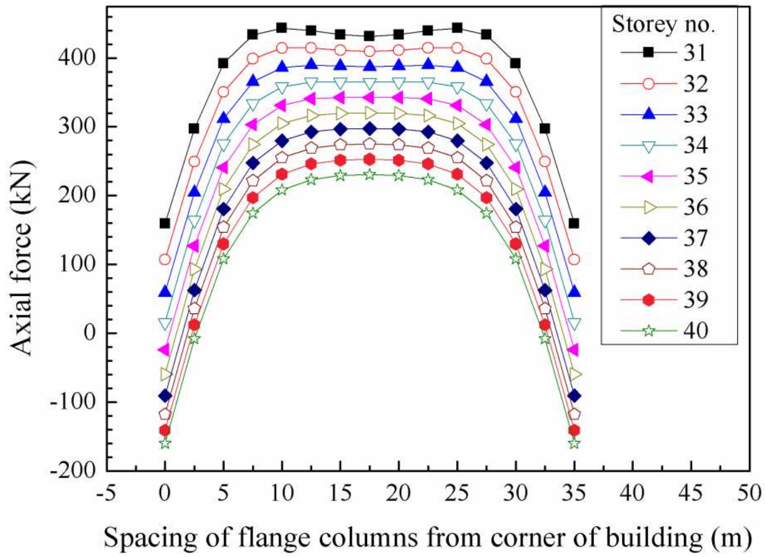


Fig. 6.4. Axial force in flange panel's column (31-40 Storeys)

This distribution of axial force clearly shows the positive shear lag at the base and negative shear lag at the top. This distribution of axial force was observed by Singh and Nagpal (1994). Designer should be careful about this behavior as some columns at upper storeys may be subjected to tension also.

(b) Variation of axial force in web panel: To study the pattern of axial force distributions in the web panel's columns and to see the variation of it with the height of the building, axial force in columns of web panel for every ten storeys have been plotted in each plot (Fig. 6.5-6.8), so that comparison can be made on the basis of height. For the five storeys as shown in Fig. 6.5, the axial force in web panel is almost linear for the middle half portion of the web panel and it is approximately straight for the 5th storey. As the height increasing, axial force in corner columns is reducing. Axial force in other columns is not much affected with height. As the height increasing, axial force in columns adjacent to corner column is increasing and has attended greater magnitude after 12th storey. Column subjected to maximum axial force is shifted to immediately adjacent to corner column, i.e., column C2 and C14. Axial force in columns C3 and C13 are maximum after 24^{th} storey, it

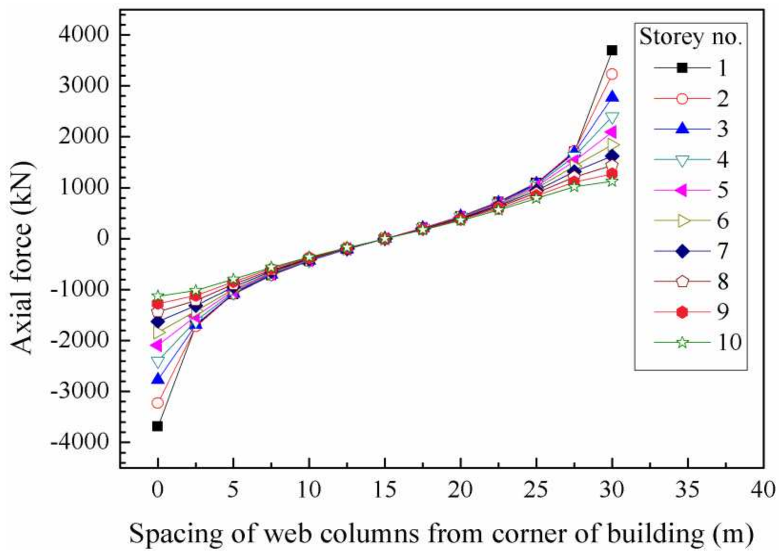


Fig. 6.6. Axial force in web panel's column (1-10 Storeys)

means point of maximum axial force is shifting towards the center of the web panel. From the plots of axial forces in columns of web panel, it is clear that as the height of the building increases, the point of maximum axial force shifts towards the center of the web from either end but does not reach to the central column. It is interesting to note that as the height increases; axial force in corner columns decreases and after a certain height it again increases but the nature of the force is different from the previous. In other words, columns those are under compression in lower storeys gets tensile forces in upper storeys. It is also interesting to note that axial force in corner columns, which is maximum at the base reduces and axial force in adjacent columns increases with height but after a certain height axial forces in corner columns again starts increasing but nature is tensile and axial force in adjacent columns reduces up to the top of the building.

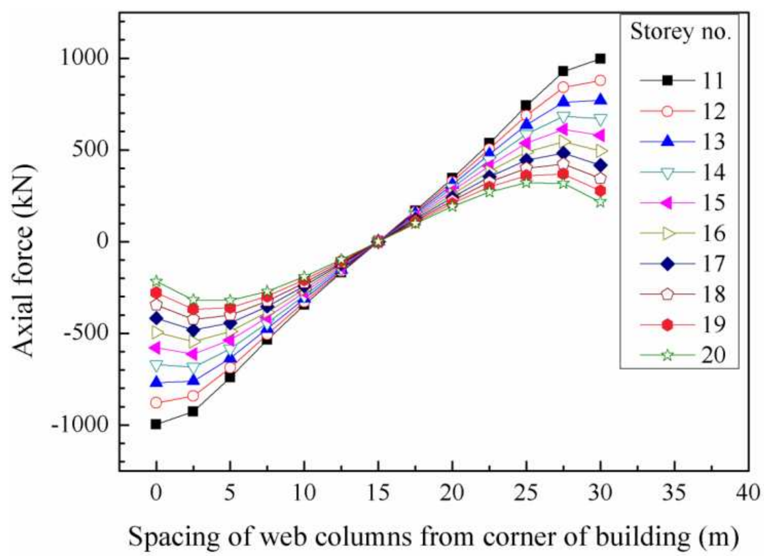


Fig. 6.6. Axial force in web panel’s column (11-20 Storeys)

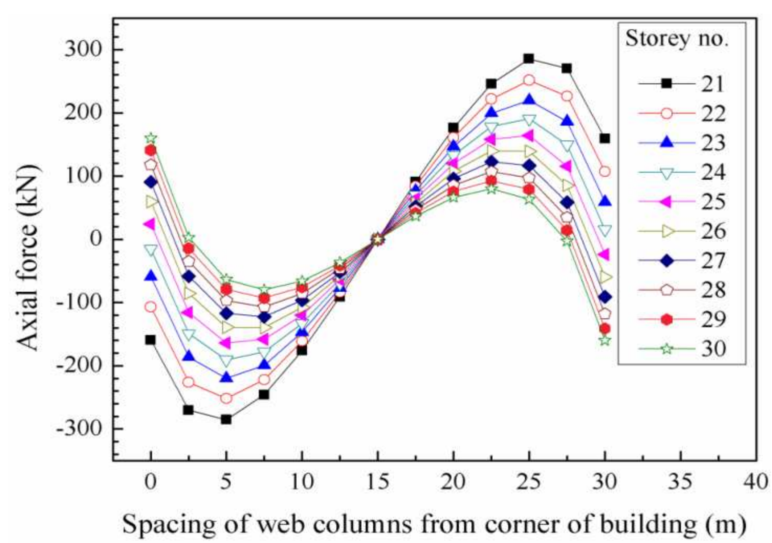


Fig. 6.7. Axial force in web panel’s column (21-30 Storeys)

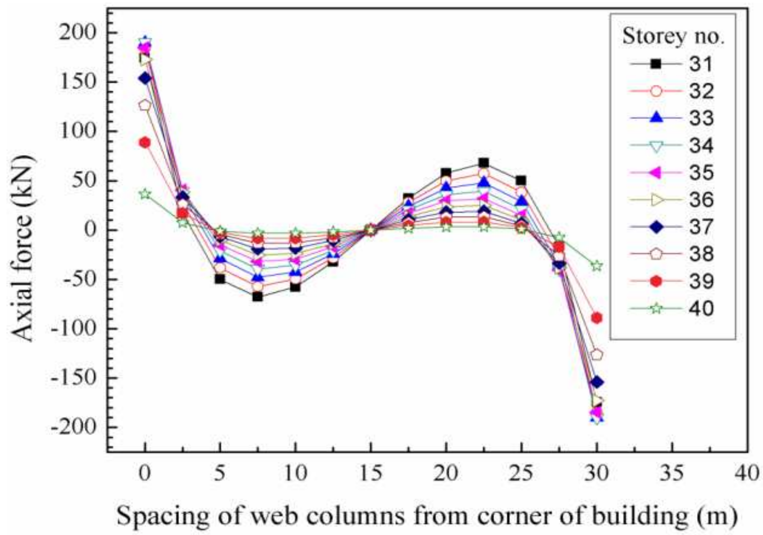


Fig. 6.8. Axial force in web panel's column (31-40 Storeys)

6.2.2 Lateral Displacement

Lateral displacement of all nodes at particular storey level is same as the semi-rigid diaphragms are considered at each floor level. The maximum displacement of the structure is 129 mm at the top of the building. Displacement of the structure is almost linear with the height of the building.

6.2.3 Additional Bending Moment and Location of Inflection Point

For comparison between box beam and framed-tube structure, a plot of additional axial force for columns C1 to C8 of flange panel to study the inflection point, as plotted for the additional bending moment of box beam by Chang and Zheng (1987), have been plotted in Fig. 6.9.

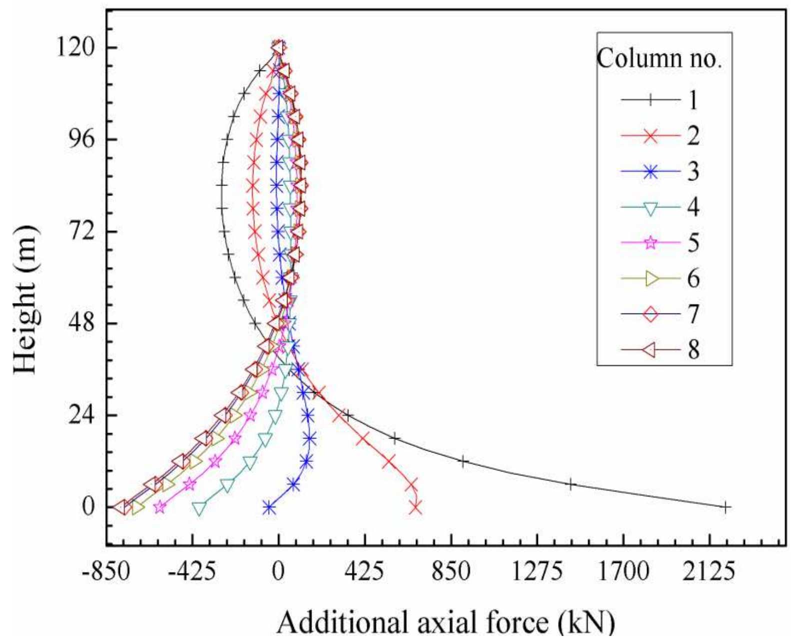


Fig. 6.9. Additional axial force vs. height of the building

From Fig. 6.9, it can be said that inflection point varies between 27 m to 72 m from the fixed end which is 0.225 to 0.60 from the support whereas in box girder inflection point generally occurs approximately at $1/4^{th}$ span from the support [Chang and Zheng 1987]. In Table 6.1, one can see that for corner column the inflection point is at 0.34^{th} of the height of the building from support. This is close to the above range of Chang and Zheng (1987).

6.3 EFFECT OF RELATIVE STIFFNESS OF BEAM AND COLUMN ON AXIAL FORCE IN COLUMNS

Variation in the axial force, base bending moments and lateral deflection in the column of tubular buildings have been analyzed & critically studied here. A tubular building model (Fig. 4.1) is analyzed for varying stiffness of the beam and column in terms of cross section and moment of area of the beam and column. The moment of area of the beam and column has been varied from I to 2I and 3I. These changes have been made by increasing the depth of beam and column for a constant width. The depth of beam and column for the moment of area I, 2I and 3I are 0.8 m, 1.0 m and 1.15 m respectively.

Table 6.1. Location of inflection points for different columns in the flange

Column No.	Level of Inflection Point	Height from base (m)
C1	14th storey	39.10 m
C2	16th storey	47.61 m
C3	24th storey	69.36 m
C4	10th storey	27.09 m
C5	14th storey	41.50 m
C6	16th storey	47.18 m
C7	17th storey	49.61 m
C8	17th storey	50.24 m

To understand the effect of relative stiffness of beams and columns on the shear lag phenomenon in tubular buildings, it is to be noted that the same has been analyzed in STAAD. Pro in two cases as Case 1: the column stiffness is kept constant, i.e. I, and the beam stiffness varied form I, 2I and 3I & Case 2: the beam stiffness is kept constant i.e. I, and column moment of area varied from I to 2I and 3I, respectively.

6.3.1 Effect of Varying Beam Stiffness

Figs. 6.10-6.12 presented the variation in axial forces for case 1, wherein only the cross section and moment of area of beams have been varied. It is observed that axial forces in the flange columns increase with increasing beam rigidity. The observed increment in axial forces in the flange columns is less when beam moment of area increases from 2I to 3I, in comparison with increment from I to 2I.

At the quarter height, i.e., 30 m from the base, axial forces in the corner column also decrease more, when the stiffness of beam increases from 2I to 3I compared to that from I to 2I. Also, the maximum axial force does not occur always in the corner column (Fig.

6.11). It shifts towards the adjacent column from the corner in the flange for every increment in beam moment of area at this level. Regardless of the above variation, there is reverse variation in other intermediate columns in the flange. In the web column, axial force always decreases in every case but the magnitude of reduction is marginal.

At the mid-height of the building, i.e., 60 m from the base, a reverse trend is observed in the flange column, where, the axial force in the middle of flange column increases. Reduction in axial force in web column is observed up to the centre of the web (Fig. 6.12). When beam moment of area varies from I to 3I, contrary to Figs.6.10-6.11, the axial force in the flange column at 60 m from base level is also increasing, where; the axial force is minimum in the corner column for the beam stiffness as I. The maximum axial force in the flange column is in the 4th column from the corner.

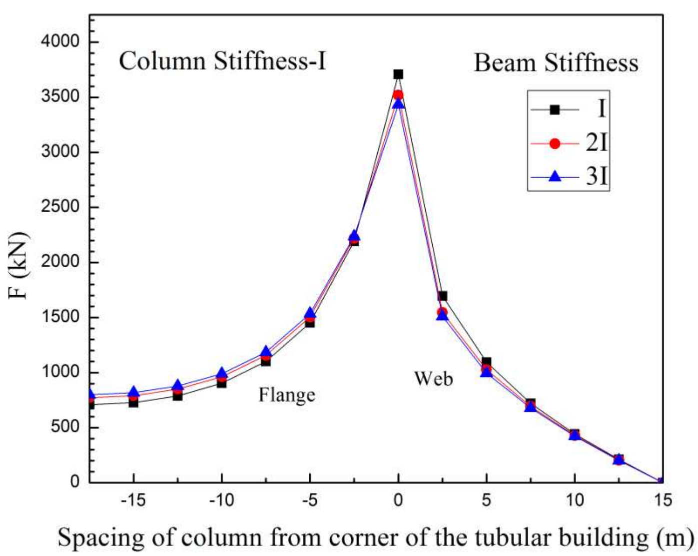


Fig. 6.10. Axial forces in columns at the base level for increasing stiffness of beams

Also, the position of the column of maximum axial force in the flange is shifted towards the centre of the flange, if the beam stiffness increases from I to 2I and 3I. Maximum axial force in the web column occurs in 2nd column. This reverse trend in variation of axial forces is well known in literature as negative shear lag phenomenon.

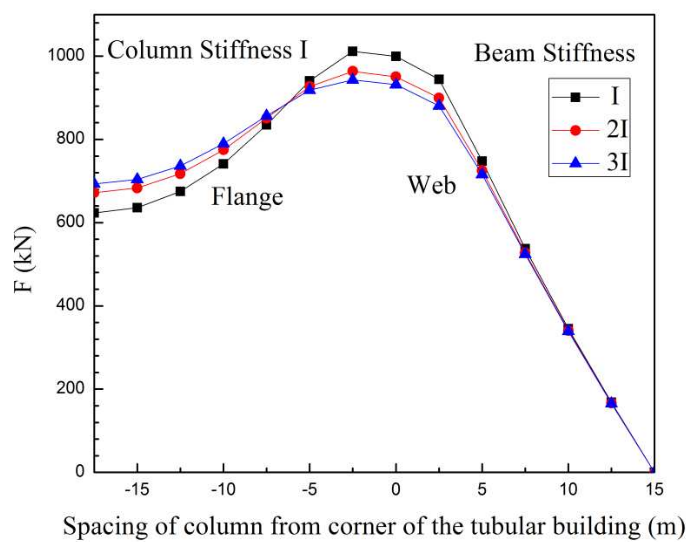


Fig. 6.11. Axial forces in columns at height 30 m from base level for increasing stiffness of beams

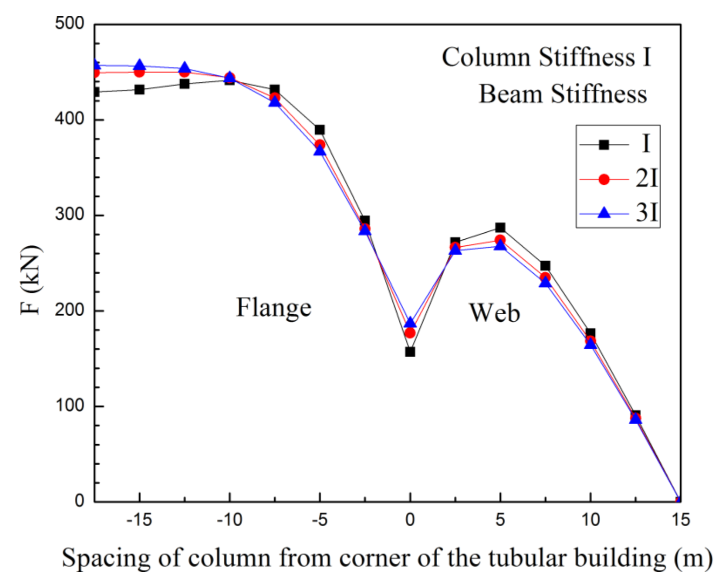


Fig. 6.12. Axial forces in the columns at height 60 m from base level for varying stiffness of beams

6.3.2 Effect of Varying Column Stiffness

The effect of variation in the column moment of area is significant from I to 2I, but the high stiffness, i.e., 3I, results in significant suppression in the axial force at the base level (ref. Fig. 6.13). In the web columns, axial force decreases in every column when moment of area of column increases from I to 2I and for 2I to 3I. An abrupt variation is observed as axial force increases from 2nd to 3rd column which indicates some instability. A negligible variation in the axial force in the flange and web column occurs at the height 30 m from base level (ref. Fig. 6.14).

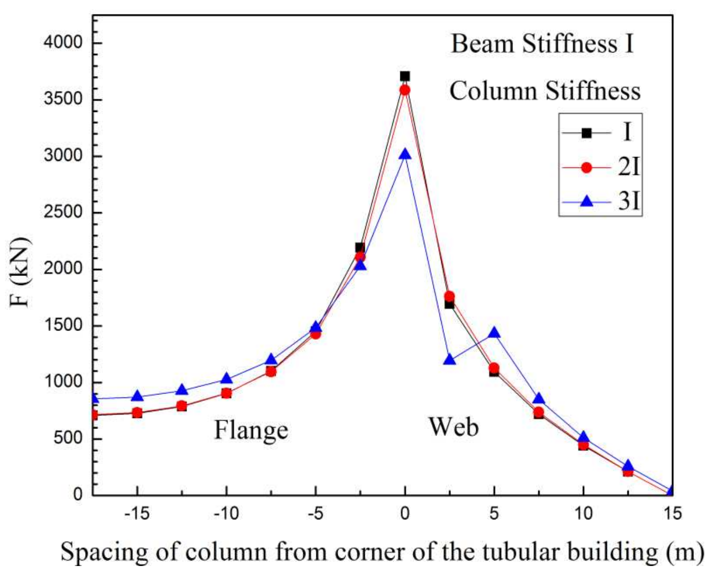


Fig. 6.13. Axial forces in the columns at the base level for varying stiffness of columns

At the height 60 m from the base level, the axial force in the flange column increases and in the web column decreases when the column moment of area increases from I to 2I.When the column stiffness is 3I, the axial force in the corner column increases and axial force in the web column decreases (Fig. 6.15).

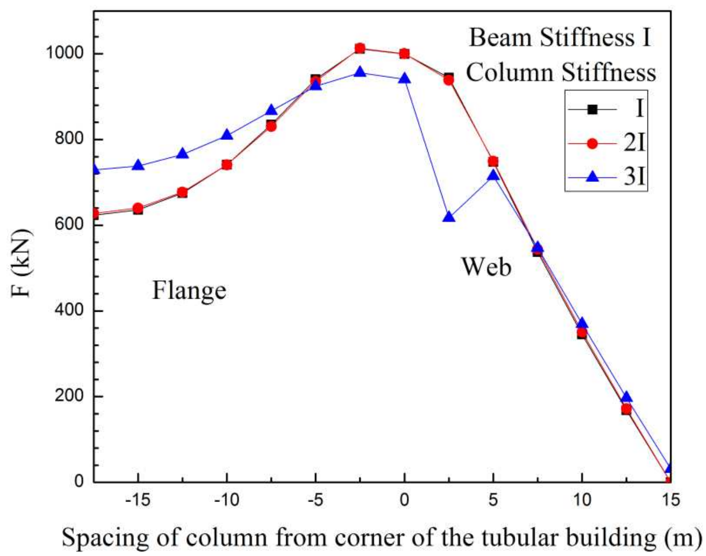


Fig. 6.14. Axial forces in the columns at height 30 m from base for varying stiffness of columns

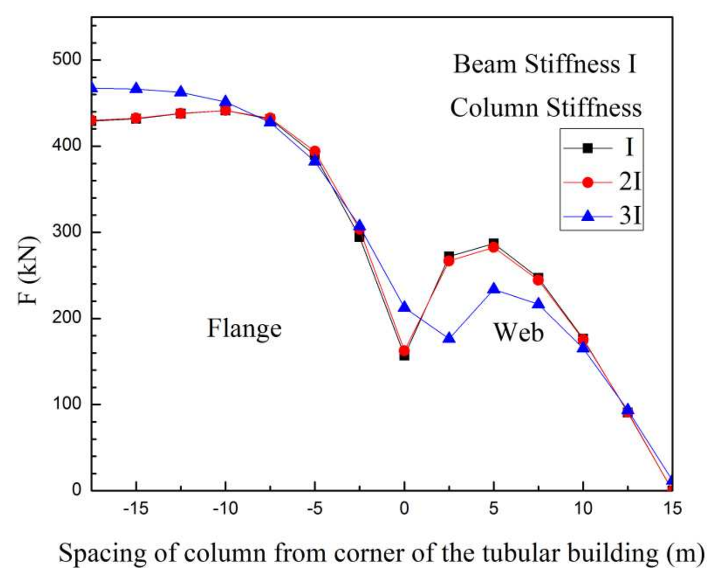


Fig. 6.15. Axial forces in the columns at height 60 m from base for varying stiffness of columns

6.3.3 Influence of Relative Stiffness of Column and Beam on Lateral Deflection and Base Bending Moments (BBM)

It is well known that a building deflects more with decreasing flexibility giving rise to higher base bending moment. The same can be observed in Figs. 6.16 -6.19. The effect of varying beam and column moment of area on the lateral deflection of the tubular building has been presented in Figs. 6.18-6.19. The corresponding maximum lateral deflections for beam moment of area I, 2I and 3I are 129.17 mm, 109.58 mm and 101.91 mm respectively. Similarly, for column moment of area increasing from I, 2I and 3I are 129.17 mm, 100.96 mm and 88.05 mm. It is observed that the column moment of area has more influence on controlling the lateral deflection of the tubular buildings than the beam moment of area.

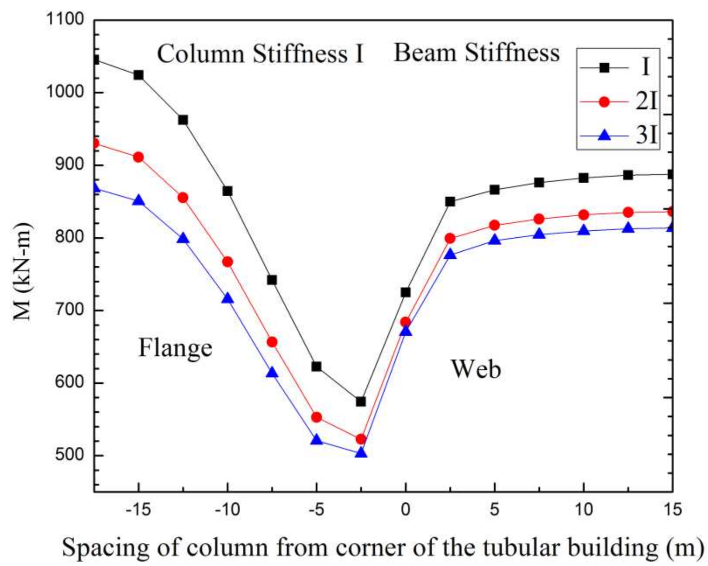


Fig. 6.16. Bending moment at base level of tubular building for varying stiffness of the beams

The increased value of the moment of area of the beam from I to 3I decreases the base bending moments in the flange as well as in the web columns (Fig. 6.16). The minimum bending moment occur at the adjacent column in the flange from the corner column. The relative reduction is higher in first increment (from I to 2I) than second increment (2I to 3I).

For increasing column stiffness (from I to 2I), the bending moment in both flange & the web column increases (Fig. 6.17).

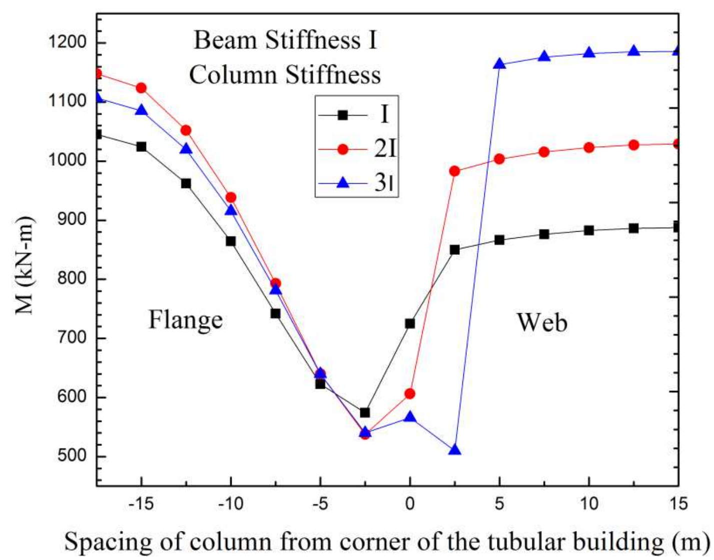


Fig. 6.17. Bending moment at base level of tubular building for varying stiffness of the columns

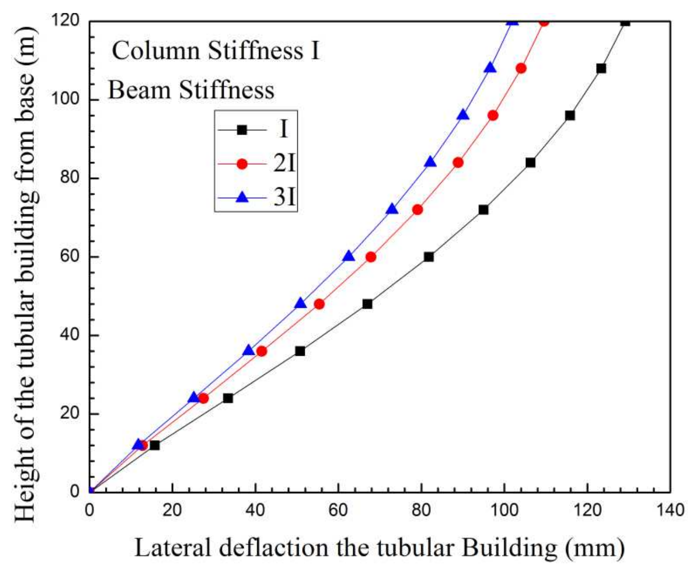


Fig. 6.18. Lateral deflection of the tubular building for varying stiffness of beams

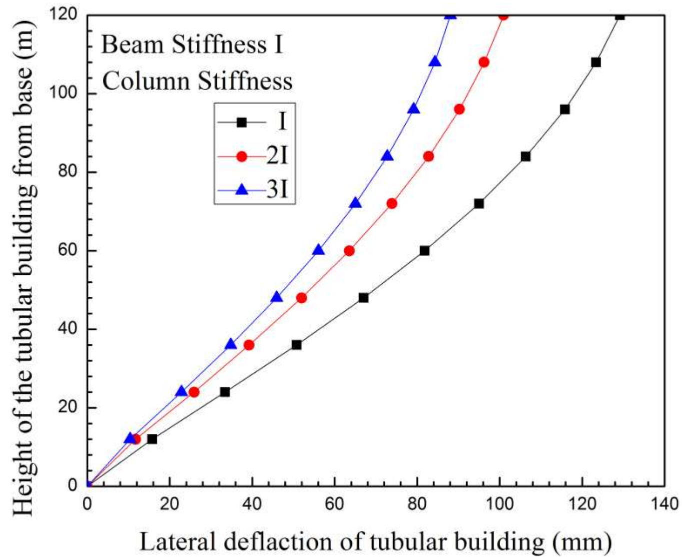
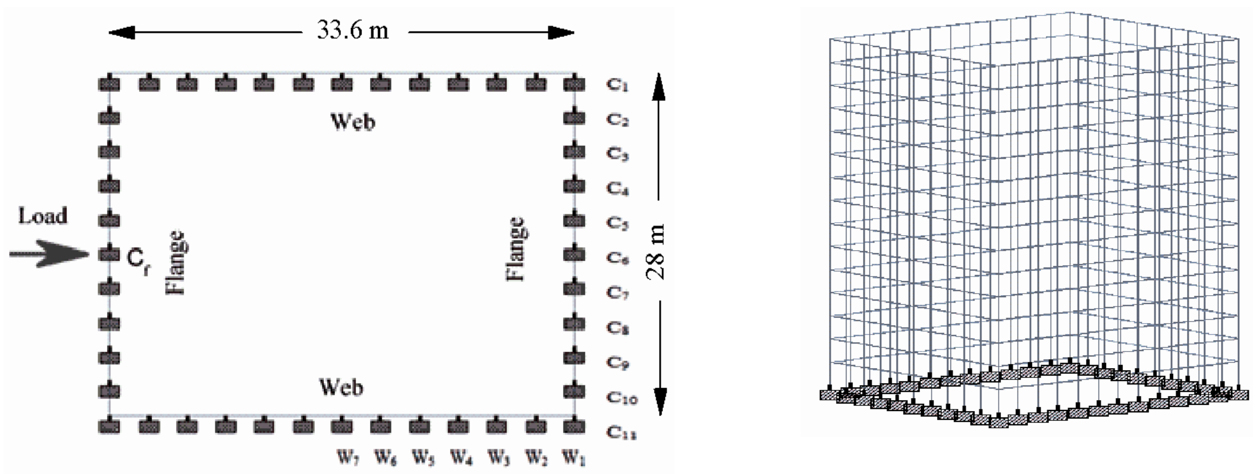


Fig. 6.19. Lateral deflection of the tubular building for varying stiffness of columns

6.4 LOW RISE STRUCTURES

A 15 storey steel tube building has been examined in this section. The shear lag phenomenon is closely reinvestigated. The structure is firstly analysed by Kwan (1994). The input data for the analysis are: height of the building - 48 m; storey height-3.2 m; column spacing-2.8 m center to center; all the beam and column members are made of a standard section Universal Beam as per British Steel Table with 610 mm × 305 mm × 238 kg/m (I = 207,571 cm^4; A = 303.8 cm^2; As = 117.7 cm^2); modulus of elasticity-20 GPa and shear modulus-8 GPa. A triangularly distributed lateral load of intensity150 kN/m at the top and zero intensity at the bottom is applied in the shorter side to the structure in central column line (Fig. 1). The parameters studied are the axial forces in web and flange columns and their relative variation resulting into positive or negative shear lag and plotted for better understanding. It is interesting to note that the results are close to that of Kwan (1994). The results of Kwan (1994) were based on approximate hand method to estimate the shear lag for preliminary design purpose.



Plan Elevation

Fig. 6.20. Plan and elevation of 15 toreys steel building

The tubular building mentioned has been analyzed for the lateral load with the semi-rigid slab in terms of the plate at each floor level as Kwan (1994). Plate thickness assumed for the slab is 0.2 m. The variations of axial force in flange and web panel for each storey and the displacement of the structure have been reported herein to see the effect of the shear lag phenomenon.

6.4.1 Variation of Axial Forces

(a) Axial force in flange panel: Axial force in flange columns in leeward direction has been plotted. The variations of axial forces depicted in Figs. 6.21-6.23. The variations of axial forces clearly represented the effect of shear lag. The transition of shear lag behavior from positive to negative can also be analyzed accordingly. The corner columns of flange panels are subjected to more axial force than the central column. This phenomenon is well known as the positive shear lag. Along the height of building, degree of concavity of axial force distribution decreasing and flattening. It is interesting to note that axial force in the column of middle half portion of the flange panel have no appreciable change. It is almost same for the five storeys (Fig. 6.21). However, for quarter portion from the either end, the column of flange panel suffers more variation in axial forces.

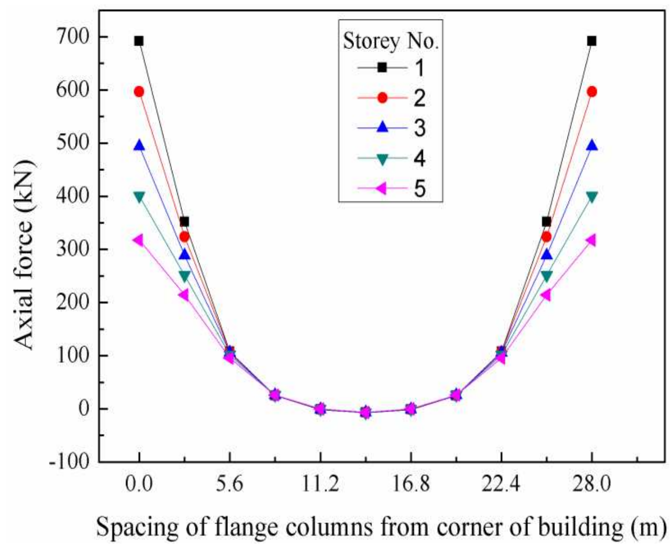


Fig. 6.21. Axial force in flange panel (1-5 Storeys)

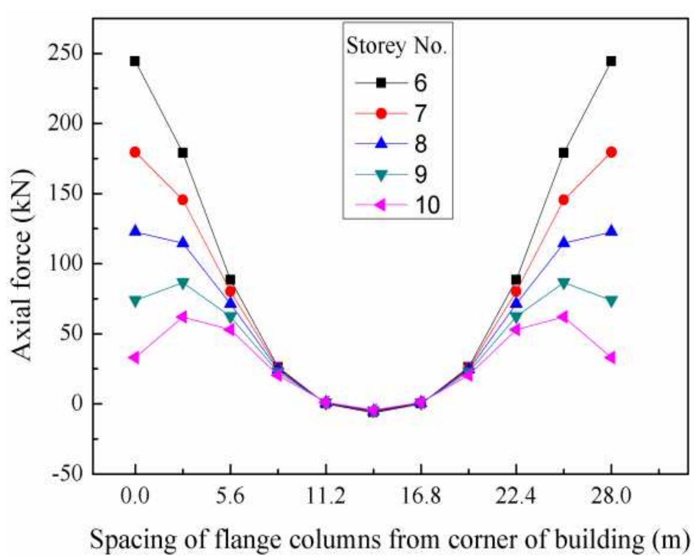


Fig. 6.22. Axial force in flange panel (6-10 Storeys)

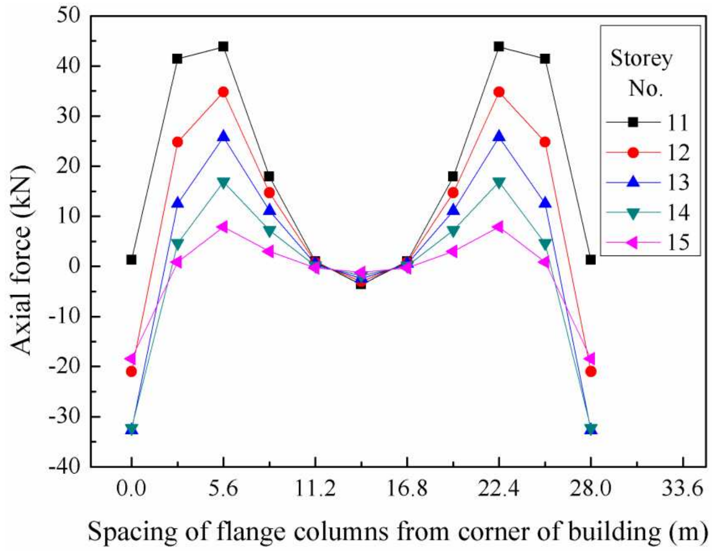


Fig. 6.23. Axial force in flange panel (11-15 Storeys)

For storey no 6 to 10, axial forces of corner columns are reducing with increasing floor level. The axial force in columns located between corner and centre of the flange starts increasing. Axial force of central column is not much affected with the height of the building. At 8th storey, the axial force in corner column and column immediately adjacent to it, are almost equal. It is concluded that rate of shear flow for corner column decreases and increases for column immediately adjacent to corner column.

In the flange column above 11th storey, tensile forces in corner columns are increasing along with the height of the building. The discontinuity of the structure affects the trend for the top storey.

(b) Axial force in web panel

The shear lag phenomenon in web panel columns is not as prominent as flange columns. Nevertheless, it would be interesting to investigate the same, similar to flange columns as above. Axial force in web columns has also been studied to see the pattern of axial stress distribution at different floor level of the building (Figs. 6.24-6.26).

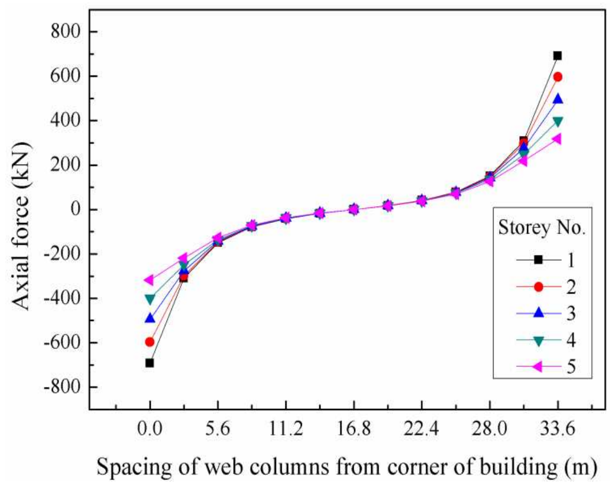


Fig. 6.24. Axial force in web panel (1-5 Storeys)

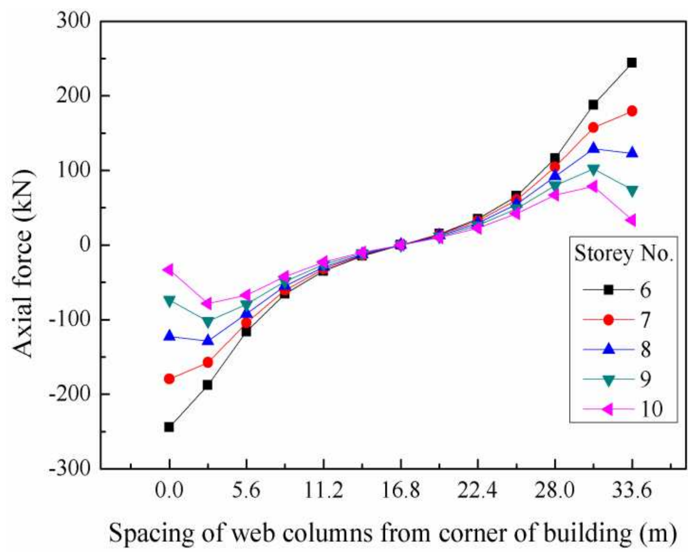


Fig. 6.25. Axial force in web panel (6-10 Storeys)

The distribution of axial forces is almost linear for middle half portion column of the web for first five storeys. The quarter portion of the web panel from either end reveals the nonlinear and rapid change. The maximum nonlinearity in axial force distribution is for the 1^{st} storey and reduces along with the height of the building. In the web panel, half of the columns are in tension and other in compression. The distribution of axial force along with the height of the building get flatten pattern and for the 5th storey, it is very close to simple bending theory.

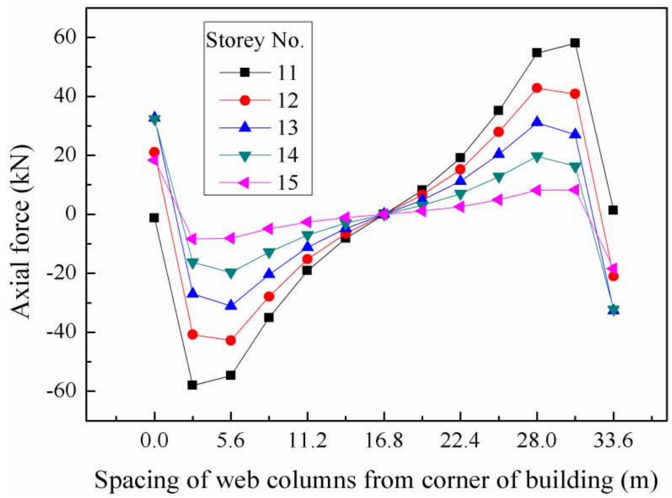


Fig. 6.26. Axial force in web panel (11-15 Storey)

Afterward, axial forces in corner columns of web panel decrease and axial force in column adjacent to corner column increases as increasing floor level. Corner columns which are under compression for 1st to the 10th storey are in tension for top five storeys and maximum axial forces are shifting to columns towards the center from either end of the web panel.

6.4.2 Additional Bending Moment and Location of Inflection Point

For comparison between box beam and framed-tube structure, a plot of additional axial force for columns C1 to C6 of flange panel to study the inflection point have been plotted in Fig. 6.27. It can be said that inflection point varies between 18 m to 44 m from the fixed end which is 0.375 to 0.92 from the support whereas in box girder inflection point generally occurs approximately at 1/4th span from the support [Chang and Zheng 1987]. In the Table 6.1, one can see that. For the corner column the inflection point is at 0.61th of the height of the building from support (Table 6.2). This is far apart from the range of Chang and Zheng (1987).

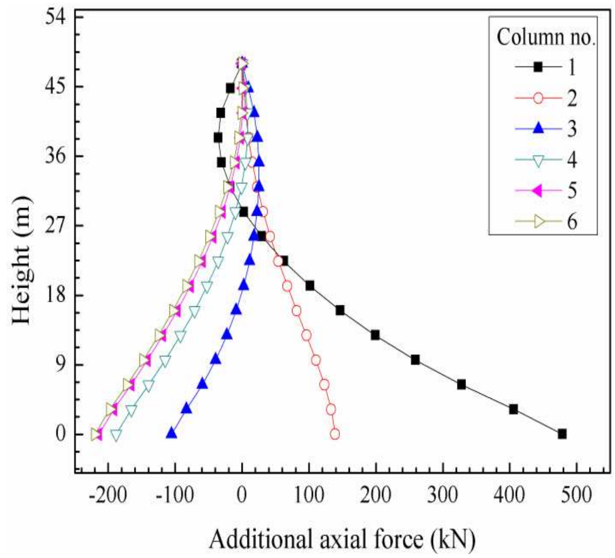


Fig. 6.27. Additional axial force vs. height of the building

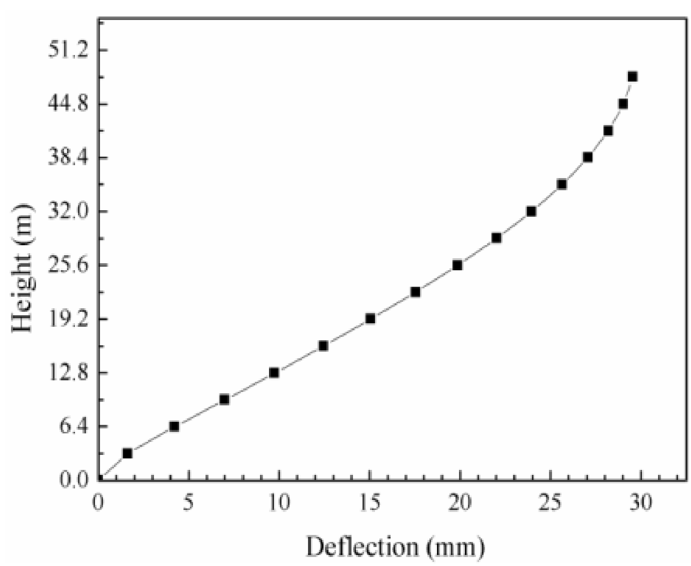
Table 6.2. Location of inflection point for different columns in the flange

Column No.	Level of inflection point	Height from base (m)
C1	10th storey	29.5 m
C2	-	-
C3	6th storey	18 m
C4	11th storey	32.7 m
C5	13th storey	41.1 m
C6	14th storey	44 m

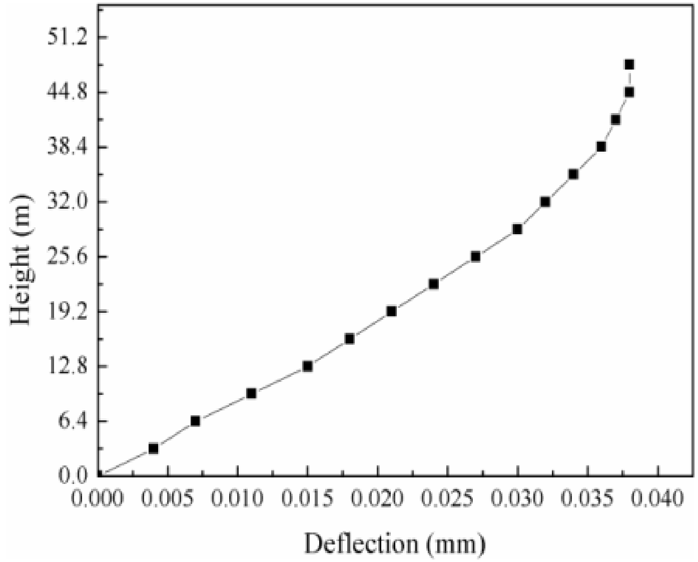
6.4.3 Lateral and Vertical Displacements of Framed-Tube

Fig. 6.28 shows the lateral as well as the vertical displacement of the framed-tube due to lateral load for particular columns mention. The lateral displacements of the node at same elevation are same. As the height increasing, lateral displacement is also increasing. Displacement of the tube is almost linear with the height of the building. Maximum lateral displacement of the building is 29.6 mm, same as reported by Kwan (1994).

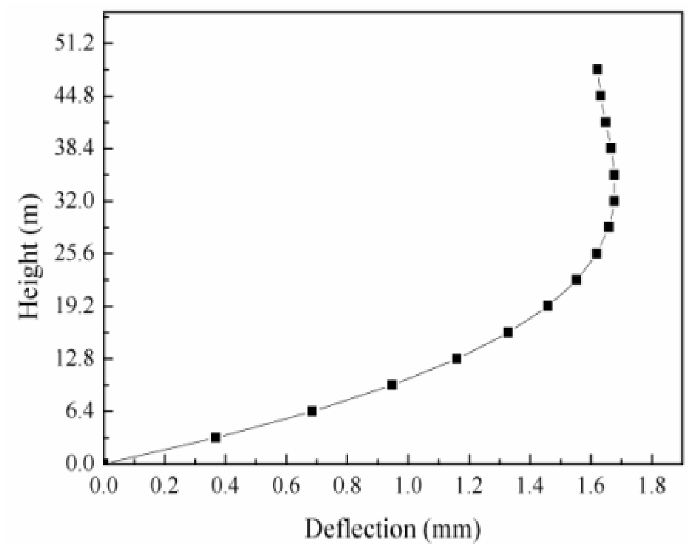
Vertical displacements of the structure at two locations (i) C_f, i.e., the column which is loaded by the lateral load and (ii) C_1, i.e., a corner column at the junction of web and flange, have been plotted to see their relative variation. It is clear that vertical displacement is increasing with the height of the building. The relative storey-wise vertical displacement reduces at the higher level and practically reducing to zero and thereafter it become negative in column C_1 due to significant axial tension developed at the top storeys.



(a) Lateral deflection



(b) Vertical deflection of column C_f



(c) Vertical deflection of column C_1

Fig. 6.28. Deflections of the building

These variations of the vertical displacement correspond to the negative shear lag phenomenon. The maximum vertical displacement is in the 11th storey. Also, higher stress at the corner column causes vertical displacement of about 10 times the column C_f. This can also be appreciated from Fig. 6.21-6.23 where, it is clearly indicated that the central column experiences almost zero axial force.

6.5 SUMMARY AND CONCLUDING REMARKS

The analysis carried out in the present chapter summarized as bellow:

1. The positive shear lag occurs at the support and changes to negative at the top of the structure. Axial force distribution, which is concave upward at the support, becomes convex upward at the top of the building. Near the top, the effect of negative shear lag may be so pronounced that column near the corners may develop axial forces opposite to those in the other column.

2. Corner columns are subjected to more axial forces than other columns at the bottom of the building. As the height increases, the axial force in the column immediately adjacent to corner column increase and with further increase in height it shifts towards central column. Loading pattern on structure does not affect much shear lag phenomenon. The inflection point for framed tube structure does not fall within 1/4th of the span from the support as applicable for box girders.

3. Variation of axial forces in columns is altered by the variation of the stiffness of beam as well as column. The positive shear lag occurs at base level & at 30 m level. Whereas negative shear lag effect occurs at 60 m height level. In the flange columns, axial force increases with increasing stiffness of beams as well as columns.

4. Base bending moment reduces consistently as the beam stiffness increases from I to 3I. The increase in column stiffness has increased base bending moment in both flange & web columns. Lateral deflection of the tubular building decreases with increasing stiffness of both beam and columns. However, compared to beams, increased stiffness of column has more effectiveness in reducing lateral deflection.

5. Positive and negative shear lag occur in the bottom and top portion of the building, respectively. As the height increases, the axial force in the column immediately adjacent to corner column increase and with further increase in height it shifts towards central column.

6. Some column of compression flange may also develop tension right from the support depending upon the height of the structure and loadings. Columns in upper storeys are critical columns for the designer as they may develop tension.