Chapter 6

EFFECT OF TORSIONAL WIND LOADING ON FRAMED-TUBE BUILDING

6.1 Introduction

High-rise tubular buildings experience torsional wind load due to windy environment. This chapter attempts to study the effect of torsional wind loading on framed-tube building. Six load cases are taken from American and Canadian codes to analyse the torsional wind load effects on a 40-storeyed tubular building. The results indicate that axial force distribution changes significantly with change in the loading patterns of the building. A difference in axial force distribution is observed between torsional and non-torsional load cases. Axial force in columns in the case of uniform loading is more significant as compared to partial loading cases. Due to loading on half of the face, axial force distribution becomes unsymmetrical, and a minimum axial force in corner columns is observed. Also, notable differences can be seen in the axial force distribution of load cases having both direction loadings compared to single direction loadings. Axial force distributions in cases of both face loading are unsymmetrical for the central column.

6.2 Codal provisions

A limited amount of information is provided in codes and standards regarding the estimation of wind-induced torsional loads. ASCE 7-22, NBCC 2020, and EN 1991-1-4 (2005) are the only codes with provisions for wind loading incorporating torsion load. Two approaches are used in the codes to assess wind-induced torsional loads on buildings. In the first approach, reduced wind load is applied with some eccentricity from the centre of the building. However, in the second approach, non-uniform load is applied by introducing partial loading on part of the face or triangular loading. ASCE 7-22 recommended the directional method for main wind force resisting systems (MWFRS) of building. Figure 6.1 shows the wind load cases that must be considered when designing MWFRS for buildings of all heights. P_{WX} and P_{LX} are considered equal here and it is equal to design wind pressure (p_d). Since this research is conducted in India, we have taken into account the wind forces specific to the Indian region. To calculate the design wind pressure (referred to as "p_d"), we have followed the guidelines outlined in the Indian standard [IS 875 (Part 3): 2015]. Subsequently, this calculated design wind pressure (p_d) is applied to the building in the form of "P_{WX}" and "P_{LX}" aligning with the prescribed load cases.

6.2.1 ASCE 7-22: 2022

For estimating wind loads on MWFRS, ASCE/SEI 7-22 provides two analytical methods: (i) the simplified (envelope) method is applicable to buildings under 18.288 meter in height, and (ii) the detailed (directional) method applies to buildings of any height. The torsional moment (M_T) in Case 2 is calculated as Equation (6.1) and Case 4 as Equation (6.2).

$$M_T = 0.75\,(P_{WX} + P_{LX})B_X e_X \tag{6.1}$$

$$M_T = 0.563\,(P_{WX} + P_{LX})B_X e_X + 0.563\,(P_{WZ} + P_{LZ})B_Z e_Z \tag{6.2}$$

Where, $e_x = \pm\, 0.15B_X$ and $e_z = \pm\, 0.15B_Z$ and the building plan dimensions considered are B_X = 30 m, and B_Z = 35 m.

6.2.2 NBCC 2020

There are two analytical procedures provided in NBCC 2020 for predicting wind loads on buildings. The first is a static method used for low rise (H < 20m) and medium rise (H = 20-60m) buildings while the second method, namely, dynamic method, is used for high rise buildings (H > 60m). However, for medium rise and high-rise buildings four load cases are shown in Figure 6.1 (full and partial wind loads). In Cases A and C, structure is subjected to uniform wind load for calculating maximum base shear while in Cases B and D, structure is subjected to partial loading to produce torsion.

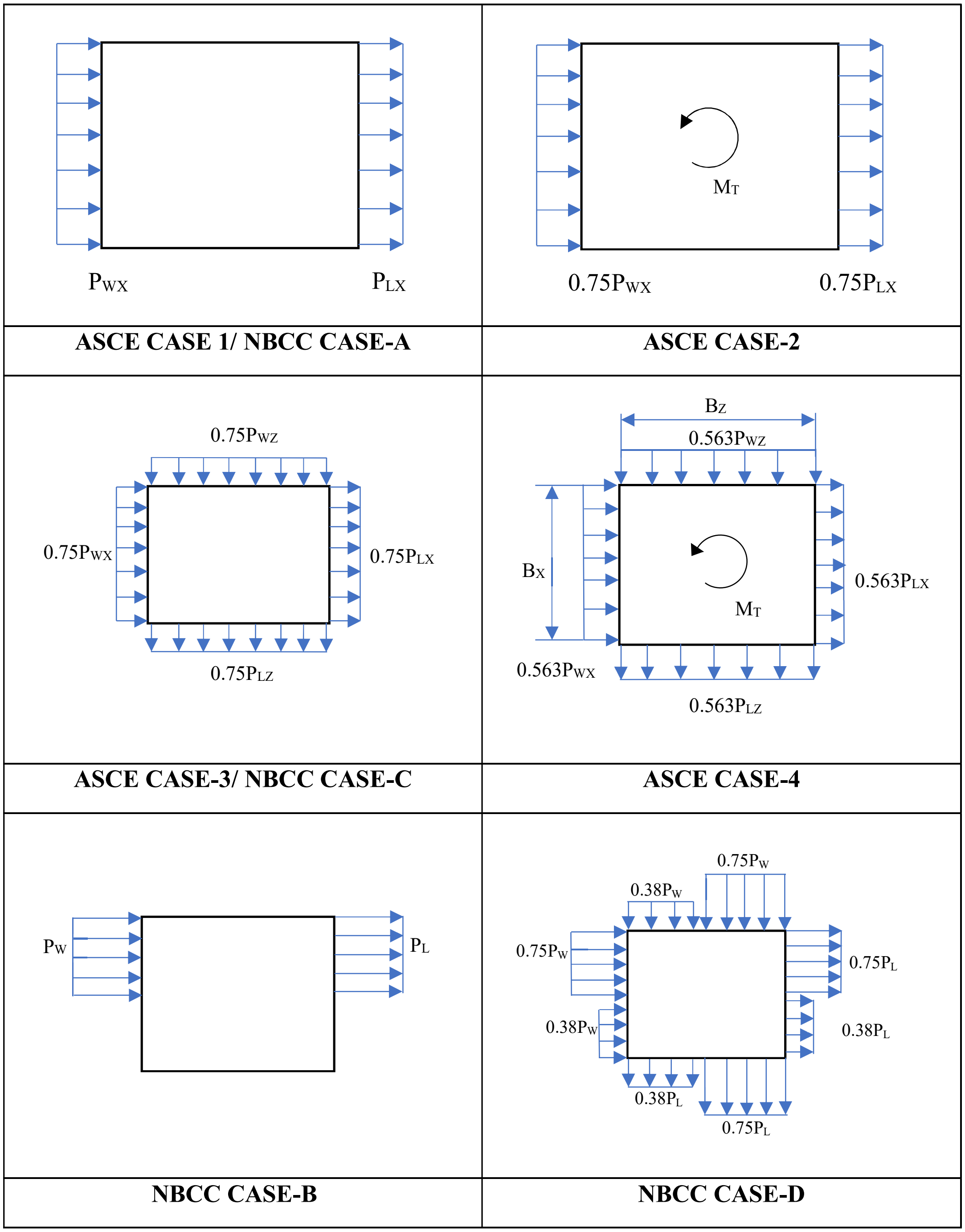

Figure 6.1 Six wind load Cases taken from ASCE 7-22 and NBCC 2020

6.3 Modelling and analysis

6.3.1 Building

A building model of 40 storey reinforced cement concrete (RCC) framed tube building is analysed using STAAD-pro software. Dimensions and structural properties of the building are taken from Singh *et al*. (2015). The height of the building is 120 meters and each floor has a height of 3 meters. The plan dimensions of the framed tube are 35 meters along X-axis and 30 meters along Z-axis as shown in Figure 6.2. The beam and column sizes are 0.8m × 0.8 m; the centre-to-centre spacing of the columns is 2.5 meters in each direction, and the modulus of elasticity (E) is 20 GPa and Poisson's ratio (v) is 0.15. Also, a uniform dead load of 3.43 kN/m^2 has been considered for all the cases and self-weight of the building is also considered.

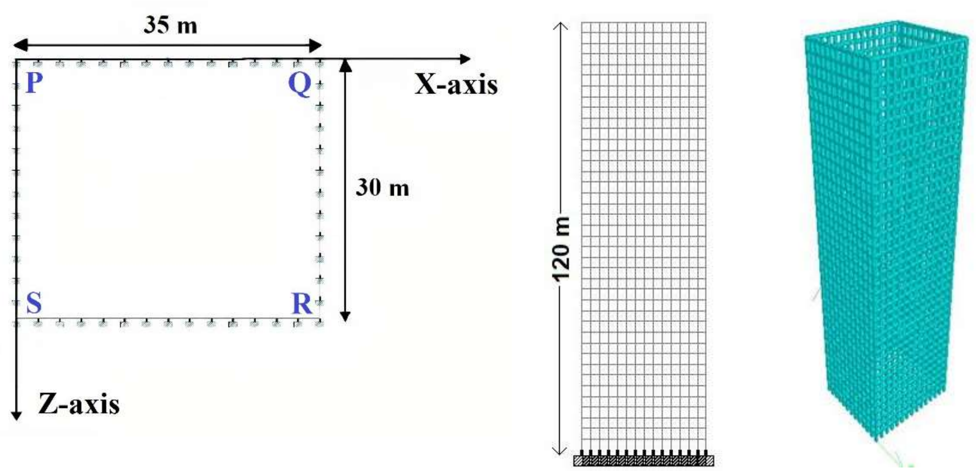

Figure 6.2 Plan, Elevation and Isometric view of STAAD-pro building model

6.3.2 Calculation of wind pressures

Wind pressure calculations have been done as per clause 6.3 (Design Wind Speed) and clause 7.2 (Design Wind Pressure) of code IS 875 (Part 3): 2015. All the parameters used in calculating wind load and their respective values are listed in Table 6.1. Design wind speed (V_z) is calculated for terrain category 1 using Equation (6.3). Velocity (V_z) varies with height as coefficient k_2 changes with height.

$$V_z = V_b k_1 k_2 k_3 k_4 \tag{6.3}$$

Description and values of all the parameters are given in Table 6.1 except the k_2 which is terrain roughness and height factor, values of k_2 are given in Table 6.2. Design wind pressure is calculated using Equation (6.4).

$$p_d = p_z K_a K_c K_d \tag{6.4}$$

Where, $p_z = 0.6. (V_z)^2$, K_a, K_c and K_d are given in Table 6.1.

Table 6.1 Specification of the wind load

Parameters and Descriptions	Values
Basic wind speed (V_b)	55(m/s)
Terrain Category	1
Probability factor (k_1)	1.08
Topography factor (k_3)	1
Importance factor for cyclonic region (k_4)	1
Area averaging factor (K_a)	0.8
Wind directionality factor (K_d)	0.9
Combination factor (K_c)	0.9

6.3.3 Wind load cases applied on the building

Each of the codes, ASCE 7-22 and NBCC 2020, recommends four cases. However, two of the loading cases are exactly the same in both the codes, thus making for a total of six cases. Therefore, in this study, a total of six load cases are analysed based on the recommendations of the ASCE 7-22 and NBCC 2020 codes, which encompass most of the load cases.

6.4 Results and Discussion

This section discusses the results obtained from the analyses based on the six load cases. Variations in the axial force of columns are studied due to six different loading cases on a 40-storeyed tubular building. Axial force in columns of short edge (QR & PS - face) and long edge (SR & PQ -face) is plotted for 1st storey, 10th, 20th, 30th and 40th storey in Figures 6.3 to 6.8. Moreover, the comparison has been made between different load cases separately for single direction loadings (ASCE Case-1 or NBCC Case-A, ASCE Case-2 and NBCC Case-B loadings) and two direction loadings (ASCE Case-3 or NBCC Case-C, ASCE Case-4 and NBCC Case-D loadings). Throughout the discussion, it is to be noted that the short edge panel refers to QR & PS - face and the long edge panel refers to SR& PQ - face (Figure 6.2).

Table 6.2 Wind velocity and pressure with height

Height (m)	***V_b (m/s)***	***k_1***	***k_2***	***k_3***	***k_4***	***V_z (m/s)***	***p_z (N/m²)***	***p_d (kN/m²)***	***$0.75p_d$ (kN/m²)***	***$0.563p_d$ (kN/m²)***	***$0.38p_d$ (kN/m²)***
10	55	1.08	1.05	1	1	62.37	2334.01	1.51	1.13	0.85	0.57
20	55	1.08	1.12	1	1	66.53	2655.58	1.72	1.29	0.97	0.65
30	55	1.08	1.15	1	1	68.31	2799.75	1.81	1.36	1.02	0.69
40	55	1.08	1.18	1	1	69.80	2922.81	1.89	1.42	1.07	0.72
50	55	1.08	1.20	1	1	71.28	3048.50	1.98	1.48	1.11	0.75
60	55	1.08	1.21	1	1	71.99	3109.78	2.02	1.51	1.13	0.77
70	55	1.08	1.22	1	1	72.71	3171.66	2.06	1.54	1.16	0.78
80	55	1.08	1.24	1	1	73.42	3234.16	2.10	1.57	1.18	0.80
90	55	1.08	1.25	1	1	74.13	3297.26	2.14	1.60	1.20	0.81
100	55	1.08	1.26	1	1	74.84	3360.97	2.18	1.63	1.23	0.83
110	55	1.08	1.27	1	1	75.32	3403.79	2.21	1.65	1.24	0.84
120	55	1.08	1.28	1	1	75.79	3446.87	2.23	1.68	1.26	0.85

6.4.1 ASCE Case-1/NBCC Case-A loading

In Figure 6.3, axial force distribution in all the four edges of columns at the 1st storey, 10th, 20th, 30th and 40th storey for ASCE Case-1/NBCC Case-A loading are shown. From Figure 6.3(a) and 6.3 (c), it is observed that axial force in 1st storey of short edge panel is maximum in corner columns positive in QR edge and negative in PS edge here positive indicates compression and negative indicates tension. The axial force decreases as one moves toward the centre of the short edge panel and it becomes minimum at middle column. This distribution is called as positive shear lag, *i.e.*, corner columns have more axial force than middle columns. As storey height increases, axial force in corner column decreases when compared to central column. At 30th storey, axial force in corner columns of edge-QR is tensile in nature. With a further increase in height, axial force in corner columns of edge-QR increases and continues to be tensile. At storeys near the top of the building, the axial force decreases but remains in tension which needs to be considered by the designer appropriately. In Figures 6 (b) and 6 (d), axial force distribution for the long edge panel (SR & PQ), axial force in corner column S and P is tensile and column R and Q is compressive. As height increases, axial force in the corner column decreases as compared to adjacent columns. From storeys near to 30th storey, axial force in corner column again increases but in opposite nature. At 40th storey, axial force again decreases to some extent but remains in the same pattern as 30th storey.

6.4.2 ASCE Case-2 loading (including torsion)

In Case of ASCE Case-2 loading (which includes torsional moment), axial force distribution in short edge and long edge columns at the 1st storey, 10th, 20th, 30th and 40th storey are shown in Figure 6.4. From the Figure 6.3 and 6.4, it can be seen that the distribution of axial force along both the panel is similar to that ASCE Case-1 which have no torsion. However, in this case, the magnitude of axial force gets reduced due to the application of partial (75% of ASCE case -1) loading. Axial force in columns on either side of middle column has a small difference in magnitude, *i.e.*, not symmetrical about central column as in the ASCE Case-1 loading. At base storey, axial force in corner

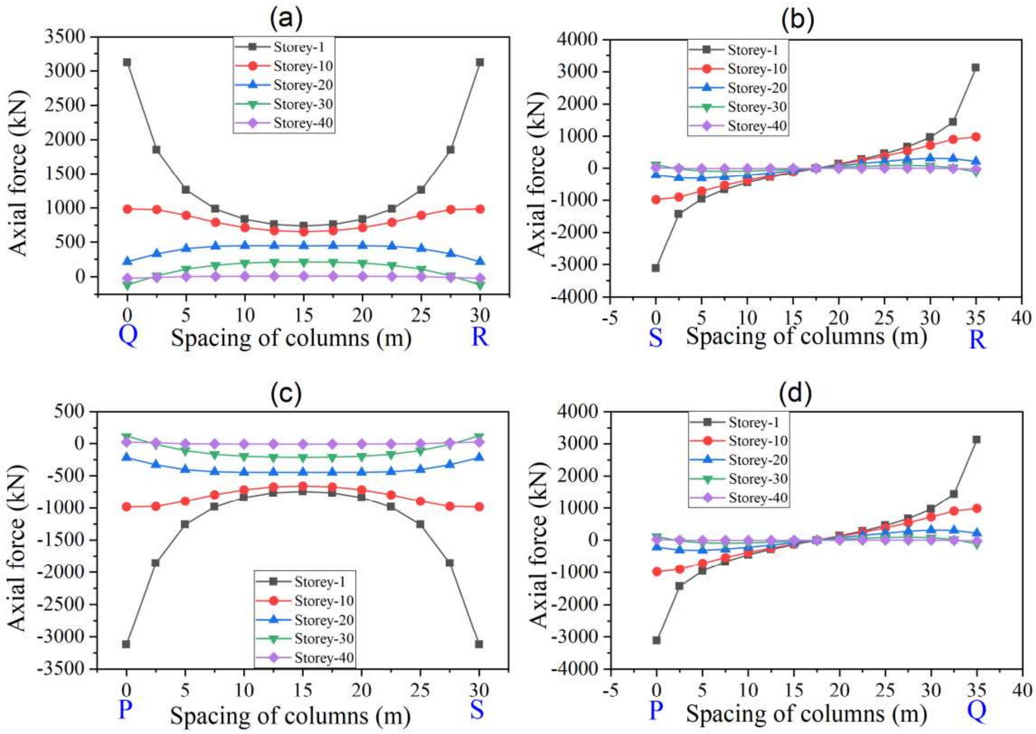

Figure 6.3 Axial force in edge of (a) QR (b) SR (c) PS & (d) PQ edge panels columns for ASCE Case-1/ NBCC Case-A

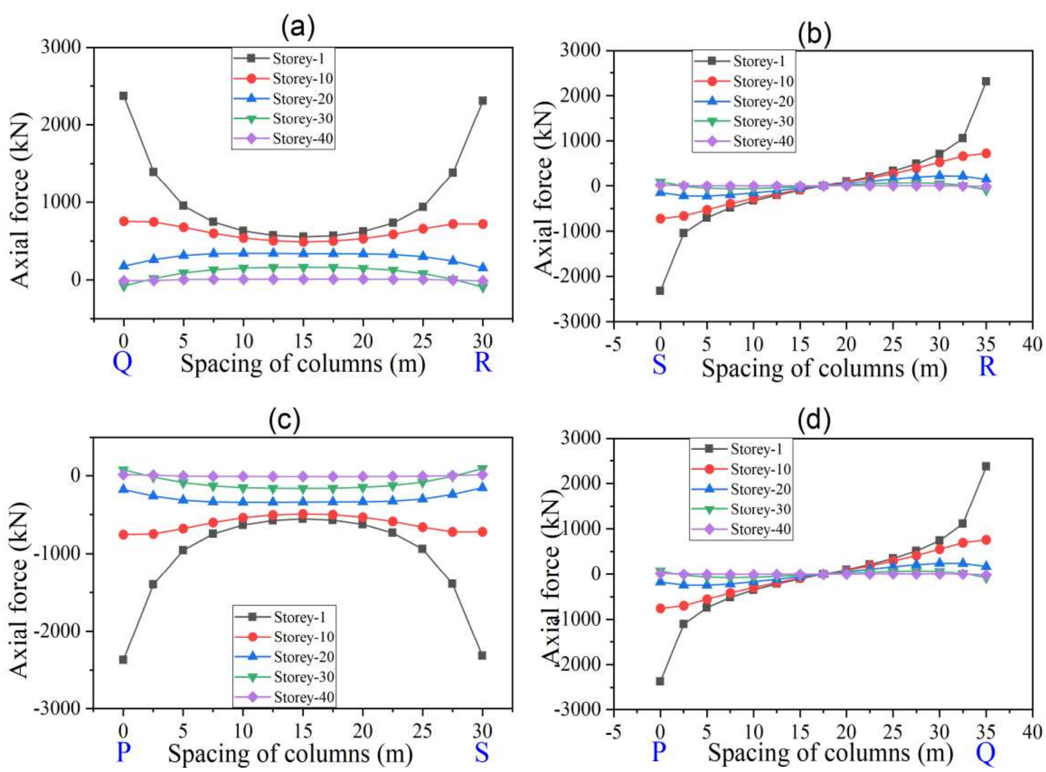

Figure 6.4 Axial force in edge of (a) QR (b) SR (c) PS & (d) PQ edge panels columns for ASCE Case-2 loading (including torsion)

columns and central column is reduced by 24% and 24.9% respectively than that of corresponding columns in ASCE Case-1, which conforms to the reduction of 25% in the load values. Here, also negative shear lag occurs below 20^{th} storey as in previous case but after that with the increase in height axial force in corner columns again increases in opposite direction. At top storey axial force in corner columns and middle column get reduced by 24.64% and 24.9% respectively than that of ASCE Case-1. In long edge panel, axial force in columns is less than that evaluated in non-torsional loading Case (*i.e.*, ASCE Case-1). Axial force in corner columns of 1^{st} storey is approximately 25.64% lesser than corresponding column of previous case whereas in middle column axial force get reduced by 25%.

6.4.3 NBCC Case-B loading

Axial force distribution due to NBCC Case-B loading in short edge and long edge panel columns are shown in Figure 6.5. It can be seen from Figure 6.5 that the distribution of axial force is significantly different from ASCE Case-1/NBCC Case-A (refer Figure 6.3). The distribution of axial force in short edge panels is not symmetrical around the central column. Since the loading is acting on half of the building, close to corners Q, the axial force is greater in column Q. Positive shear lag is observed in some storeys near the base and at the 10^{th} storey. From the 20^{th} storey, negative shear lag occurs where the corner columns on both sides have less axial force than the central column. As height increases, the axial force in the corner column changes its nature and increases in the opposite direction. Near the 30^{th} floor, axial forces on corner columns become tensile and near the top stories, they decrease again but remain in tension. Whereas in long edge panel the axial force distribution is similar to ASCE Case-1 loading but smaller than in ASCE Case-1 and 2 loading due to lesser loading in this case.

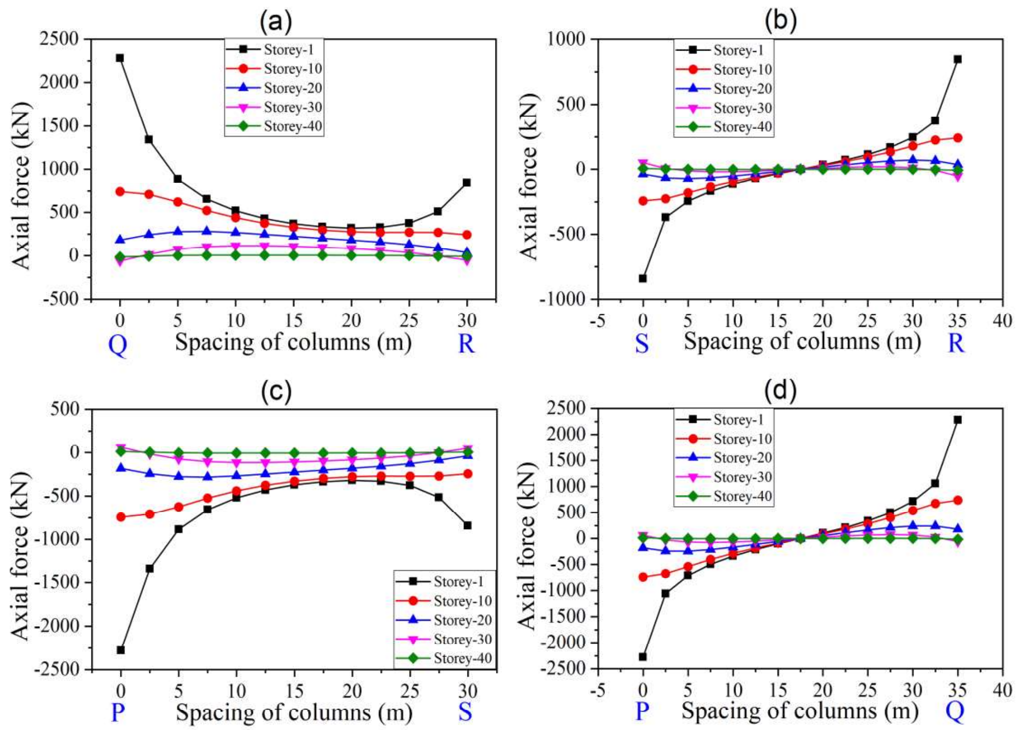

Figure 6.5 Axial force in edge of (a) QR (b) SR (c) PS & (d) PQ edge panels columns for NBCC Case-B loading

6.4.4 ASCE Case-3/NBCC Case-C loading

This section discusses the results obtained for the loading ASCE case 3/ NBCC Case - C, as shown in Figure 6.6. The results obtained from this loading pattern become more prominent than the loading pattern of ASCE Case-1/ NBCC case-A. This case gives the axial force of 5510 kN in column R (story-1) compared to 3120 kN in case 1. This increase is approximately 1.77 times that of loading case 1. As shown in Figure 6.6 (a) and 6.6 (b), axial force distribution is similar in short edge and long edge. In this case, the axial force in column Q (story-1) is much less than in column R (story-1). The long edge corner column S (story-1)has much lesser axial force than corner column R (story-1).

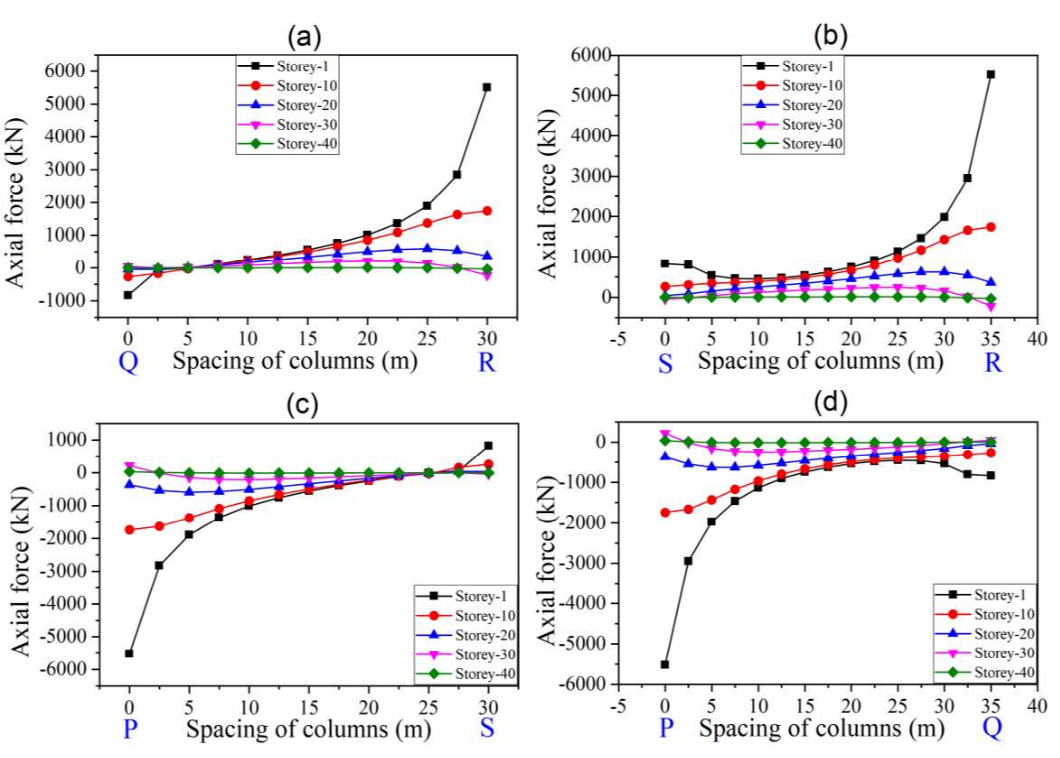

Figure 6.6 Axial force in edge of (a) QR (b) SR (c) PS & (d) PQ edge panels columns for ASCE Case-3/NBCC Case-C loading

6.4.5 ASCE Case-4 loading

The axial force distribution shown in Figure 6.7 is similar to that of ASCE Case-3 loading, but the magnitude of the force is reduced due to applied partial (56.3% of PW) loading. Similar to the ASCE Case-3 loading, the axial force in corner column Q is negative and is positive in corner column R. As the height increases, axial force in corner columns decreases and nearly at the 20th storey, axial force in columns adjacent to corner column is more significant than corner column. In the long edge panel, axial force distribution is not symmetrical about the middle column because loads act on both faces. Axial force in corner column R of 1st storey is higher than other columns of the same level. From Figure 6.7 (b), it can be observed that storeys near the base show positive shear lag similar to Fig.6.6 (b) of ASCE Case-3 loading. As height increases axial force in corner columns decreases, and negative shear lag has occurred from storeys near to 20th storey. With further increase in height, axial force in corner column increases in tensile. At corners, the axial force is 26% lesser than the ASCE Case-3 loading.

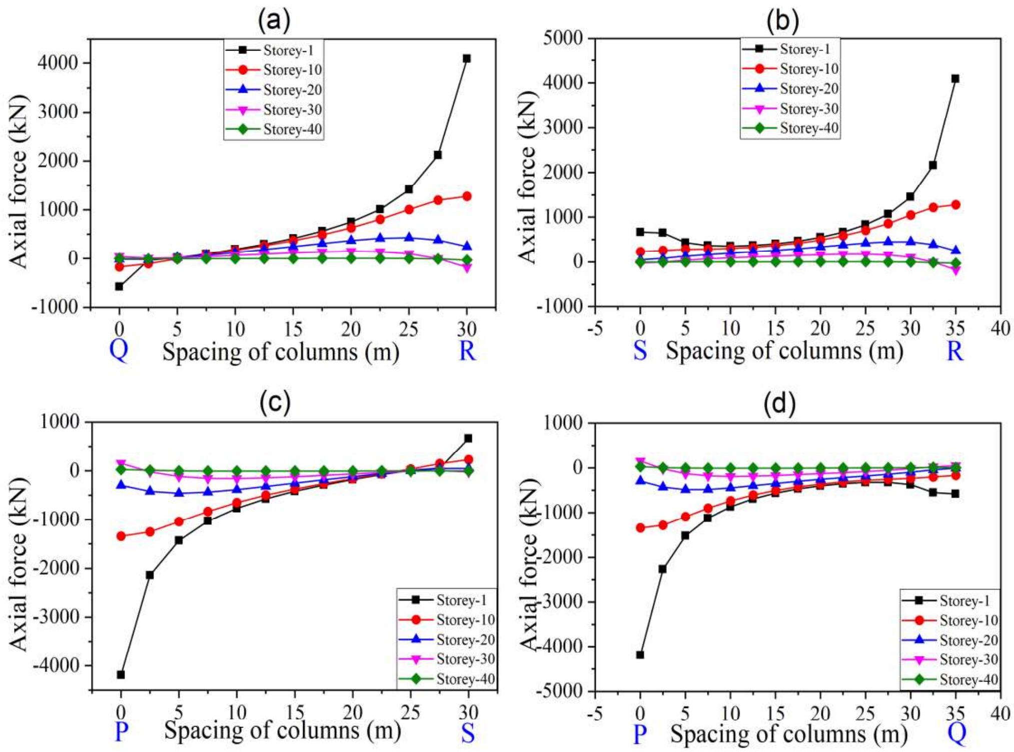

Figure 6.7 Axial force in edge of (a) QR (b) SR (c) PS & (d) PQ edge panels columns for ASCE Case-4 loading

6.4.6 NBCC Case-D loading

Axial force distribution of NBCC Case-D loading is shown in Figure 6.8. The Axial force distribution is found similar to that of ASCE Case-3/NBCC Case-C and ASCE Case-4 loadings, and the magnitude of the axial force is in between both types of loadings. In this case, due to varying partial loadings (Figure 6.1), which cause torsion in the building, the axial force in columns is lesser than ASCE Case-3/NBCC Case-C loading. However, it is more than ASCE Case-4 loading. Axial force is very high in corner column R at the base as compared to other columns of the same storey due to variable loading at the edges. In corner columns, axial force decreases with height, and in adjacent columns, it increases as compared to corner columns up to a certain storey. With further increase in height, axial force in corner columns changes its behaviour, and becomes tensile in nature. Axial force in corner column R of base storey is higher than other columns of base storey.

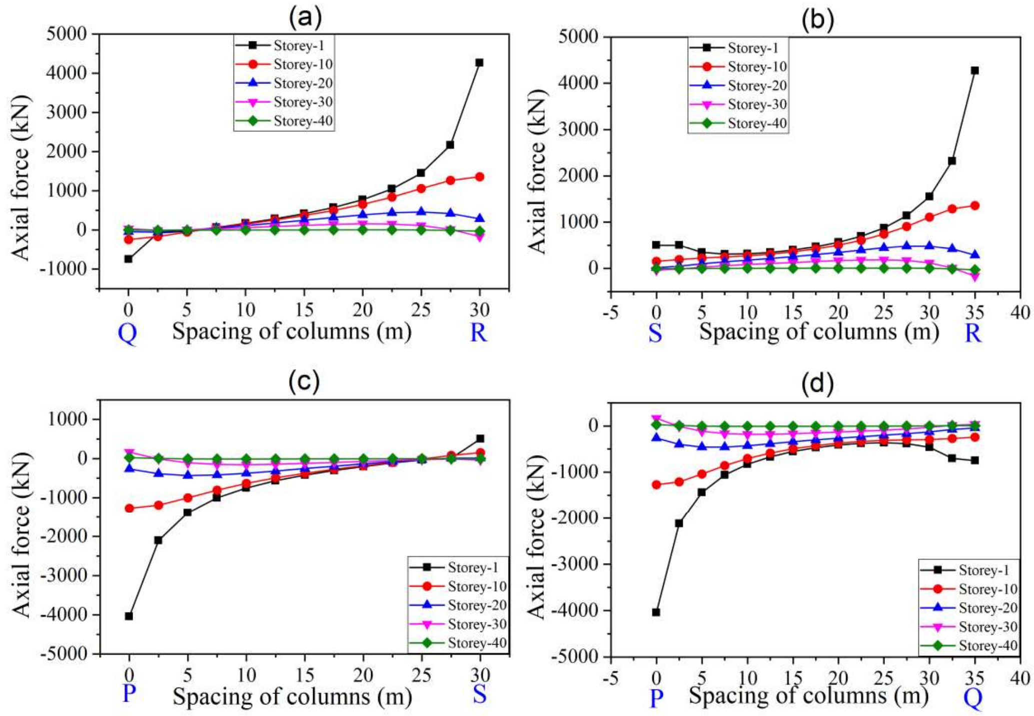

Figure 6.8 Axial force in edge of (a) QR (b) SR (c) PS & (d) PQ edge panels columns for NBCC Case-D loading

Comparative remark

The axial force distribution in columns, as obtained for the given load cases (Section 6.4.1 to Section 6.4.6), reveals distinctive patterns that warrant a comparative discussion for comprehensive insights into the structural behaviour. In ASCE Case-1/NBCC Case-A loading (Section 6.4.1), positive shear lag is evident at the base, with axial force decreasing towards the centre of short edge panels. As height increases, axial force in corner columns shifts from compressive to tensile. ASCE Case-2 loading introduces torsional moments, reducing axial force magnitude and causing asymmetry in short edge columns. NBCC Case-B loading (Section 6.4.3) exhibits a significantly different axial force distribution, especially in short edge panels, where positive shear lag transitions to negative shear lag with height. ASCE Case-3/NBCC Case-C loading (Section 6.4.4) results in increased axial force, particularly in corner column R, emphasizing the influence of loading pattern on force magnitudes. ASCE Case-4 loading (Section 6.4.5) shows similarities with Case-3 but with reduced force magnitudes due to partial loading. Finally, NBCC Case-D loading (Section 6.4.6) combines characteristics of Cases 3 and 4, displaying varying axial force patterns with height. Scientifically, these studies provide insights into the complex interplay between loading conditions, axial force distribution, and building response, offering valuable information for optimizing structural design and understanding load-sharing mechanisms.

6.4.7 Comparison of axial forces due to loading in one direction

This section conducts a comparative analysis of the results obtained from three loading scenarios: ASCE Case-1/NBCC Case-A, ASCE Case-2, and NBCC Case-B, applied to a tubular tall building. These particular loading patterns have been selected for comparison as they represent single-direction loading. The comparison focuses on the axial forces within the building's columns at three distinct levels: 1st storey, 20th, and 40th storey. Figure 6.9 illustrates the variation of axial forces in the columns corresponding to three levels (1st storey, 20th, and 40th storey) and single-direction loading conditions. As anticipated, the columns at the top storey experience axial forces in tension. Notably, when examining the axial force distribution for NBCC Case-B loading, it becomes evident that it differs from the patterns observed in the other two loading cases. This discrepancy is attributed to the partial loading characteristics inherent to NBCC Case-B.

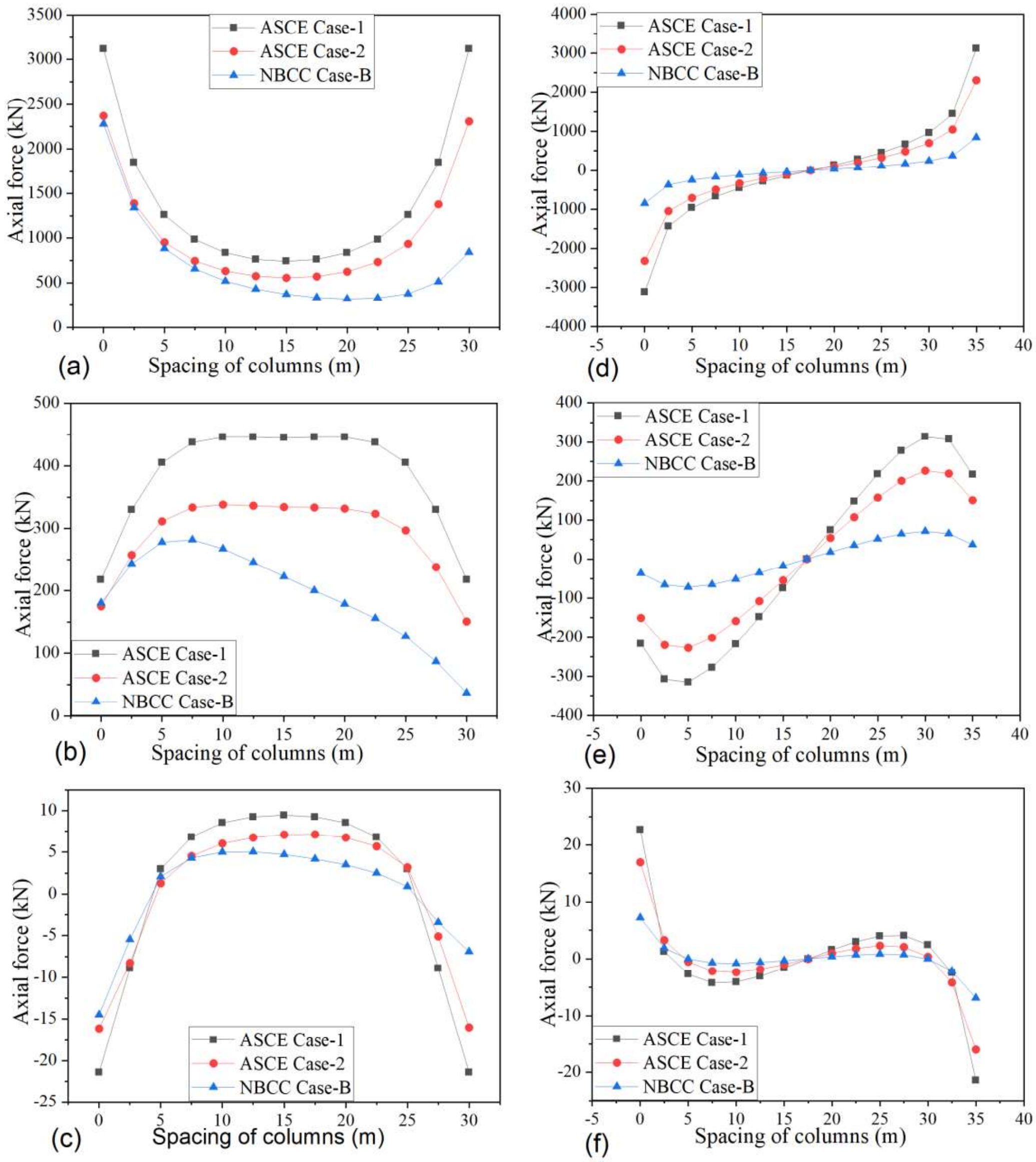

Figure 6.9 Comparison of axial forces of single direction loading cases (ASCE Case-1, ASCE Case-2 and NBCC Case-B), Axial force in short edge panel's columns of (a) 1st, (b) 20th, and (c) 40th storey; Axial force in long edge panel's columns of (d) 1st, (e) 20th, and (f) 40th storey.

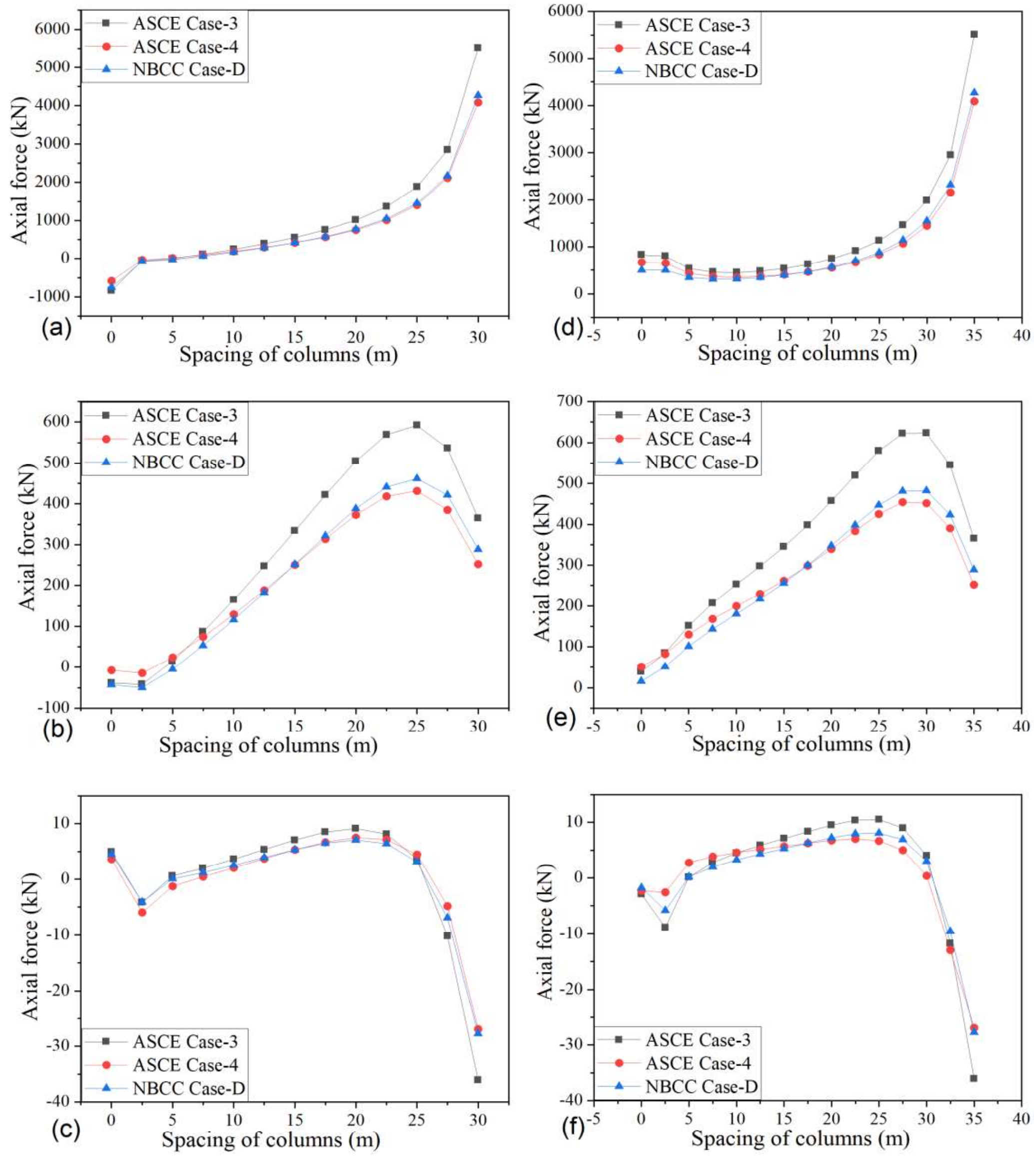

Figure 6.10 Comparison of axial forces of two direction loading cases (ASCE Case-3, ASCE Case-4 and NBCC Case-D), Axial force in short edge panel's columns of (a) 1st, (b) 20th, and (c) 40th storey; Axial force in long edge panel's columns of (d) 1st, (e) 20th, and (f) 40th storey.

6.4.8 Comparison of axial forces due to loading in two direction

This section compares the axial force distribution obtained from ASCE Case-3/NBCC Case-C, ASCE Case-4, and NBCC Case-D loadings on a tubular tall building. It is chosen to compare these three loading patterns because loads are acting in both directions. The 1st storey, 20th storey, and 40th storey are considered when comparing axial forces in column. Figure 6.10 depicts the variation of axial forces for the three different levels of the buildings corresponding to two direction loading. The top storey columns experience the tensile nature of axial forces. Here, it is essential to emphasize that the variation of axial forces is unsymmetrical about the central axes of the building. Also, it is interesting to note that the magnitude of axial force in corner Q is negative at the first storey itself. The reason for it is a multi-directional wind loading pattern. None of the previous studies on shear lag effect of tall tubular building subjected to lateral load reported this uncertainty. While designing such buildings, these recommended loading patterns should be carefully considered. Axial forces in the 1st story of corner columns for all the loading case are shown in Table 6.

Table 6.3 Axial forces in the 1st storey of corner columns for all the loading case

Loading Cases	Axial force in Column P (kN)	Axial force in Column Q (kN)	Axial force in Column R (kN)	Axial force in Column S (kN)
ASCE Case-1/NBCC case-A	-3120	3120.00	3120.00	-3120.00
ASCE Case-2	-2370	2370.00	2310.00	-2320.00
ASCE Case-3/NBCC case-C	-5520	-833.14	5510.00	827.09
ASCE Case-4	-4190	-578.68	4090.00	667.60
NBCC Case-B	-2280	2280.00	843.09	-842.66
NBCC Case-D	-4040	-749.20	4270.00	503.33

6.5 Conclusion

This study investigates the variation in the axial force in columns for a 40-storey RCC framed tube building using STAAD-pro software. Six different wind load patterns have been considered, as given in ASCE 7-22 and NBCC-2020 codes for the tall building. These patterns include uniform loading on all faces and non-uniform loading combined torsional moments. Also, two loading cases consist of partial loading applied to the faces of the building. The results from this study help in understanding the effect of torsional wind loading on the axial force in columns of tubular tall structures. Based on the results, the following conclusions can be drawn regarding variations in shear lag:

- Axial force distribution also changes with changing load patterns. For NBCC Case-B, where loading is only on half of the face, axial force distribution becomes unsymmetric. In addition, there is a significant difference between axial force distributions of load cases with both directions of loading and those with only one direction of loading.
- ASCE Case-3/NBCC case-C gives an axial load in corner columns P and R, having magnitudes 1.76 times that of ASCE Case -1/NBCC case-A.
- Comparing the axial force distribution at corner columns, in the case of single face loading at 1st storey indicates that axial force in case of uniform one direction loading case (ASCE Case-1/NBCC Case-A) is more than the loading cases including torsional moment (ASCE Case-2 and NBCC Case -B). Axial force in case of NBCC Case-B loading is lower than ASCE Case-1/NBCC Case-A and ASCE Case-2 loadings. In the case of ASCE Case-2 loading, it is in between these two loadings.
- In the case of both face loadings, a comparison of the axial force distribution at 1st storey indicates that axial force in the uniform loading case (ASCE Case-

3/NBCC Case-C) is also more than the loading cases, including torsional moment (ASCE Case-4 and NBCC Case-D). However, the difference in axial force distribution in the case of ASCE Case-4 and NBCC Case-D loadings is insignificant.

- The results from ASCE Case-4 and NBCC Case-D are close to each other in magnitude and their nature of variation.