Effect of Limb Position on U Plan Shaped Tall Building Under Wind Load

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1 Introduction

Increasing the vertical orientation of a building to cope up with the rapid urban development and exponential growth of population facilitates the unavailability of the necessary space for horizontal development. The construction of buildings is often unconventional, resulting in a lack of land and architectonic esthetic. Depending on the building configuration, the wind forces behave differently. Within those unorthodox structures, wind structure interaction is quite different from regular plan shaped structures which creating additional complexity in structural design problem. The information about the wind effect on various alphabetical plan shape structures is beyond the scope of various codal provisions. The experimental and numerical approach is the available option to study the effect of wind on this type of structures. In the recent past, several researchers have explored the wind behaviour on alphabetic shapes. Gomes et al. [1] observed that the pressure variations in internal faces of the L and U shape buildings on various tested wind angels are mainly due to the influence of the extra wing on U shape building. The interference effect of the closely spaced T and L shaped pattern group buildings has been studied by Zhao and Lam [2]. Amin and Ahuja [3] presented the distribution of pressure on T and L shaped building models at an extended wind angle range. The wind effect has been evaluated by Raj and Ahuja [4] on the varying cross plan shaped structure having an equal plan area. The Shear Stress Transport (SST) and k-ε turbulence model have been used in Computational Fluid Dynamics (CFD) code by Mukherjee et al. [5] to find out the pressure on Y shape building on wind load. The wind effect on interfered and isolated case of T shape building has been studied by Ahlawat and Ahuja [6]. Cheng et al. [7] examined the variation in dynamic responses of H and square shape building

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by the wind tunnel and proper orthogonal decomposition technique. Mashalkar et al. [8] evaluated the design loads on C, I, L and T type building. Li and Li [9] provided a reliable and simple procedure to evaluate the effect of dynamic load on L shaped buildings across wind direction. Ranka and Shingade [10] compared the drag and pressure coefficients of T, rectangular, L and square shape buildings on 0°, 45° and 90° wind angle. Paul and Dalui [11] investigated the wind exerted pressure and force coefficients on Z shaped buildings. Ullas and P [12] inspect the wind responses on + , V and Y shape buildings. Bhattacharyya and Dalui [13] calculated the wind pressure on the E plan shaped tall buildings. Mallick et al. [14] experimentally investigate the surface pressure of C shape models for 0°–180° wind angle taking 30° intervals. The comparison of wind effect on chamfered, rounded and shape corner U shape building has been presented by Shanku et al. [15]. The study of Bhattacharyya and Dalui [16] using CFD and wind tunnel showed the pressure distribution on E shaped building.

The alphabetic E, T, I, C, U, Y and T shapes are widespread structural form in modern construction practices. The past research covers various fundamental wind effects on such structures. Among those shapes, U shaped building is a popular choice to build residential complex, shopping malls, academic buildings etc. The construction of a primary shape U building can often not be feasible due to the space availability and its forces to build a peculiar U shape building. In our present study, the change in aerodynamic behaviour has been investigated around the U shape buildings due to the shifting of limbs for 0° and 90° wind induced angle. The various sifting length cases have been considered in our present for numerical simulation using CFD. The comparison of force and pressure coefficients has been presented to understand the variation in wind responses.

2 Scope of the Work

The wind behaviour of the original U shape has been measured at the mentioned induced angle. This study further extended with the shifting of two limbs by 0.05L, 0.1L, 0.15L, 0.2L and 0.3L from each side (L is the length of the building taken as 250 mm) keeping the plan area same. The different cases of shifted models have been presented in Fig. 1.

The building models are marked as U1, U2, U3, U4, U5 and U6. The presence of two limbs at the extreme corners is the original shape (U1). The U2 model has sifted limbs by 12.5 mm from both ends. In the case of U3, U4, U5 and U6 model, the sifting length of 25, 37.5, 50 and 75 mm has been adopted. The height and width of the building are taken 500 and 150 mm. The limb width is 50 mm, and the 150 mm initial gap is considered in between two limbs.

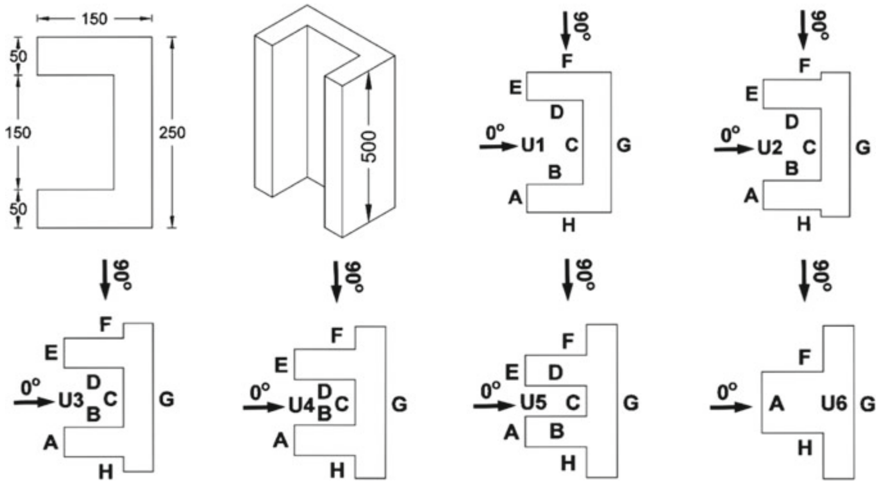


Fig. 1 The building models for this study (all dimensions are in mm)

3 Solution Methodology

The wind flow around the buildings has been simulated using computational fluid dynamics (CFD). The CFD technique in the recent past has become advance, and it is capable enough to predict the fluid–structure interaction (Löhner et al. [17]). However, CFD approaches need validation to gain credibility in the calculated results.

3.1 Computational Domain Setup

All the building (see Fig. 2) has been modelled at 1:300 scale and analyzed by considering the k-ε turbulence model using the Computational Fluid Dynamics (CFD) module of Ansys CFX. Where k represents the turbulence kinetic energy and the turbulence eddy dissipation is termed as ε. To avoid blockage correction,

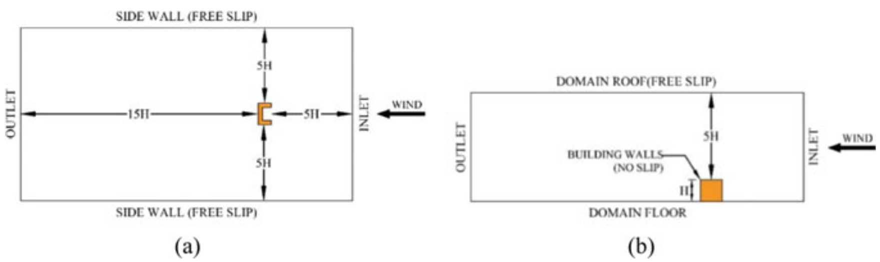


Fig. 2 The domain used for numerical simulation. **a** Plan View **b** Elevation View

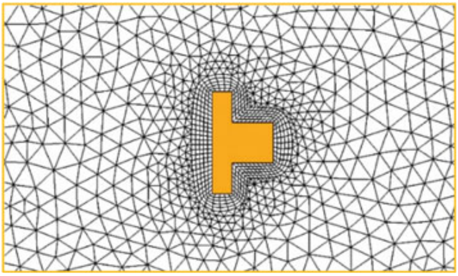


Fig. 3 The mesh details of the U6 building case

5H distance from the building has been maintained from the sidewalls, inlet and roof. The domain outlet has been considered at a distance of 15H (H = height of the building = 500 mm). Free slip condition has been taken on sidewalls and roof on the domain. This large size domain (Revuz et al. [18]) is suitable for unrestricted wind flow. No slip condition has been adopted on the faces of the building and floor of the domain. 10 m/s wind velocity has been provided at the inlet. The boundary layer velocity profile has been generated in the domain by the power-law equation (see Eq. 1). The length of the Atmospheric Boundary Layer (ABL) is taken 1 m.

$$\mathbf{U}_{\mathrm{x}}/\mathbf{U}_{\infty} = |\mathbf{x}/\mathbf{x}_0|^{\alpha}. \tag{1}$$

Here, any point height from the ground and the atmospheric boundary layer height are denoted as 'x' and 'x_0'. The wind velocity at any point at x-height and the velocity of free steam are noted as 'U_x' and 'U_∞' respectively. The power low exponent α has been taken as 0.133, which is dependent on the surroundings.

3.2 Generation of Mesh

The tetrahedral type meshing elements (Bhattacharyya and Dalui [16]) are infiltrated in the entire domain expect the building model. The delicate layers of meshing have been adopted around the building. This technique is helpful to simulate good wind flow around the building and effective in the calculation of better wind induced responses. In Fig. 3, the meshing patterns of a typical U6 model has been demonstrated in which it is visible that some delicate layers of mesh have been generated near the buildings.

3.3 Grid Sensitivity Study

The grid sensitivity study has been carried out to find out the suitable mesh size for the numerical study. The results' accuracy depends on the adopted meshing. This

Table 1 The variation in the drag coefficient of primary shape (U1) model for different mesh types

Mesh type	Total elements	Drag coefficient	% of Error
M1	2,884,984	0.8754	−20.264
M2	5,165,448	0.9476	−13.688
M3	12,546,748	1.0142	−7.625
M4	19,853,472	1.0453	−4.791
M5	26,709,214	1.0716	−2.396
M6	33,935,947	1.0959	−0.182
M7	41,093,375	1.0977	–

study initially started on the original U shape with coarser meshing (M1), which involves low computational time and step by step the fine meshing (M2–M7) has been implemented in each step until the calculated response of the current case matches with the previous one. The drag coefficient of the primary U shape model at a wind angle of 0° has been calculated for each case and corresponding errors in results have been estimated, as shown in Table 1.

The M6 meshing pattern has been adopted for the numerical study though the error is almost negligible and also it saves some computation time.

3.4 Validation

The validity of the software package has been checked with the horizontal pressure coefficient values along the horizontal centerline of Face C and D data of the previous research article. For the validation, the model and numerical details are adapted from the article published by Gomes et al. [1]. The wind pressure along the horizontal centreline of mentioned faces for 180° wind angle has been calculated. The comparison of the extracted values has been presented in Fig. 4. The obtained results of the current numerical simulation follow almost the same trend as given in the published article.

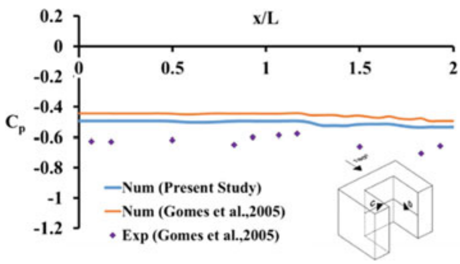


Fig. 4 The pressure variation along the horizontal line for Face C and D

4 Results and Discussion

The change in limb position has a significant impact on the nature of wind behaviour around the building shapes. The various important wind induced responses of different building cases has been extracted from the numerical analysis at 0° and 90° wind angle.

4.1 Wind Flow Streamline

The flow streamlines around the building shape for examined wind angles has been demonstrated in Fig. 5. The position of the limbs greatly affected the wind flow around the building model. However, the axisymmetry in each building case creates an asymmetric flow pattern on both sides. The symmetry in the wind flow has been disturbed by the change in wind angle because of the two limbs. The limbs of the U shape not only irregularize the plan shape but also creates unpredictable wind behaviours around the building. The vortex has been generated in the leeward side of the building and at the wake zone. Those pattern of the vortex reforms because of the shifts. With the change in angle, the vortices are also formed in between the two limbs and the variation in vortex formation is also visible when those limbs are gradually shifted to the centre.

The variation in flow pattern causes a variation in wind induced responses on those limbs shifted U shape buildings. The velocity has been increased at the flow separated corners.

4.2 Comparison of Force Coefficients

The force coefficient values have been extracted for two limbs shifted buildings at 0° and 90° wind angle and presented in Fig. 6 to understand across and along wind response of those buildings.

It is visible that the along wind response decreases with the shifting up to a specific limit and the axisymmetric position of limb manages the effect of across wind response at 0° angle. The drag coefficient of the building has minimized gradually due to the shifting of both limb from 0.05 to 0.2 L for 0° wind angle but some increment is observed with the further shifting. However, the change in wind angle causes some concern. The drag coefficient and lift coefficient has increased gradually up to the extreme sifting length of 0.3L for 90° wind angle. This indicates that the sifting of the limb is effective in drag coefficient reduction when the wind angle is 0°, but when the angle of wind changes, these benefits are no longer exists instead it creates huge variation in wind responses.

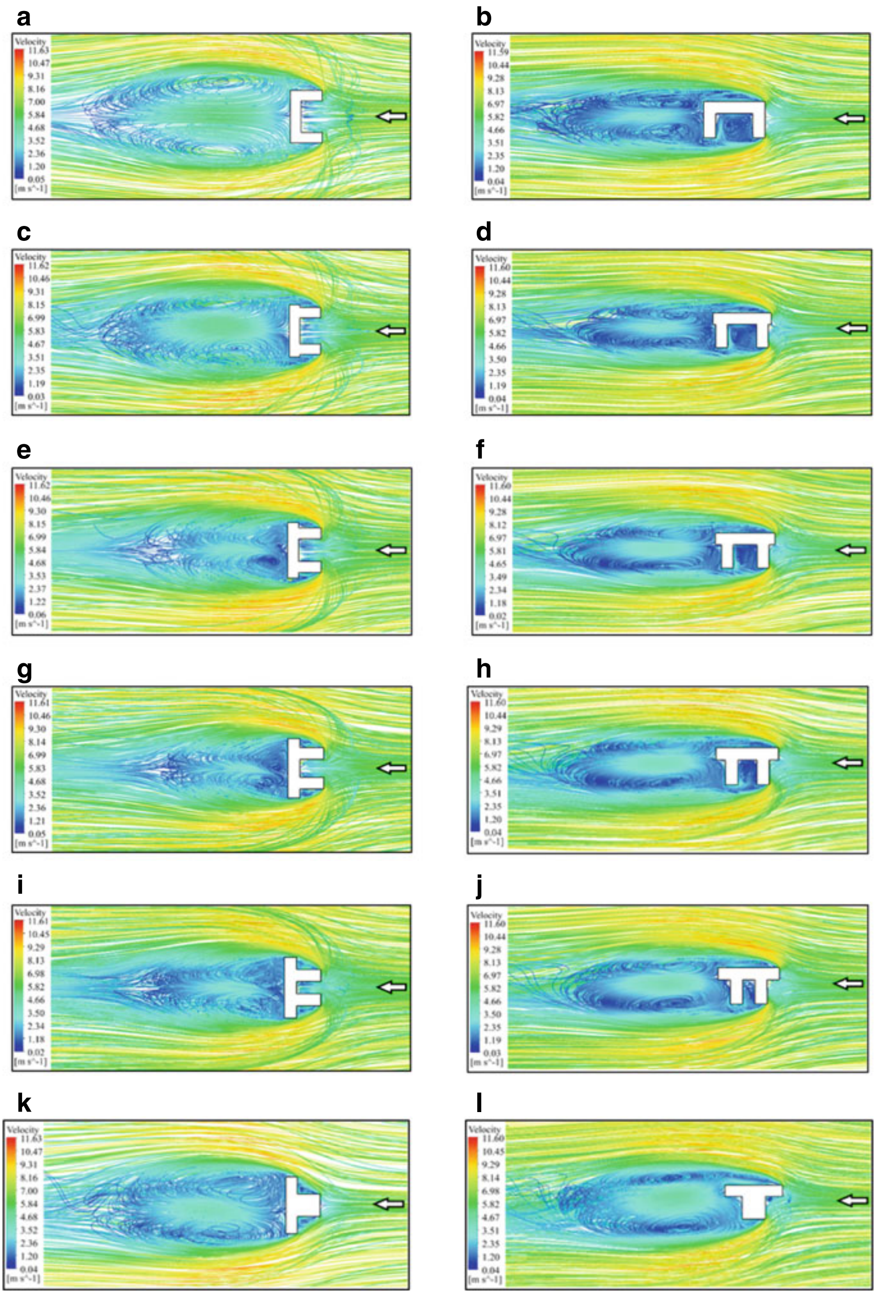


Fig. 5 The wind velocity streamlines around the various building for 0° and 90° wind angle **a** U1 Building at 0° wind angle, **b** U1 Building at 90° wind angle, **c** U2 Building at 0° wind angle, **d** U2 Building at 90° wind angle, **e** U3 Building at 0° wind angle, **f** U3 Building at 90° wind angle, **g** U4 Building at 0° wind angle, **h** U4 Building at 90° wind angle, **i** U5 Building at 0° wind angle, **j** U5 Building at 90° wind angle, **k** U6 Building at 0° wind angle, **l** U6 Building at 90° wind angle

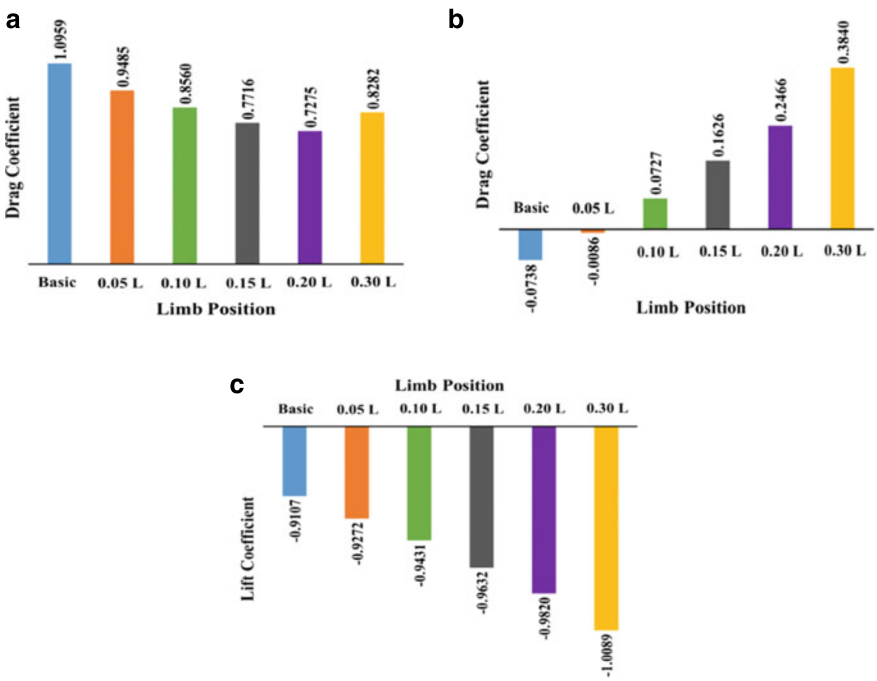


Fig. 6 The variation in force coefficients for limb shifting, **a** Drag Coefficient for 0° angle, **b** Drag Coefficient for 90° angle, **c** Lift Coefficient for 90° angle

4.3 Comparison of Pressure Coefficients

The mean pressure coefficient on the faces of different cases is presented in Tables 2, 3, 4 and 5. The flow pattern around the shape directly influences the pressure distribution on the building face.

For 0° wind angle, the mean positive pressure on face A increases with the shifting. However, on the interior faces (B, C and D) the mean pressure decreases because of

Table 2 The mean pressure coefficient on primary faces of the various shape for 0° angle

Limb Position (L)	Face A	Face B	Face C	Face D	Face E	Face F	Face G	Face H
0.00	0.4100	0.8275	0.8702	0.8275	0.4100	−0.5610	−0.3805	−0.5610
0.05	0.4385	0.8239	0.8636	0.8239	0.4357	−0.5714	−0.3554	−0.5714
0.10	0.4435	0.8224	0.8617	0.8224	0.4435	−0.6621	−0.4086	−0.6621
0.15	0.4726	0.8098	0.8470	0.8098	0.4726	−0.6159	−0.4152	−0.6159
0.20	0.5525	0.7912	0.8257	0.7912	0.5525	−0.4002	−0.3962	−0.4002
0.30	0.6995	–	–	–	–	0.0793	−0.3771	0.0793

Table 3 The mean pressure coefficient on the corner faces of the various shape for 0° angle

Limb Position (L)	Face F1	Face F2	Face H1	Face H2
0.00	–	–	–	–
0.05	−0.4576	−0.4521	−0.4576	−0.4521
0.10	−0.4277	−0.4890	−0.4277	−0.4890
0.15	−0.4013	−0.4941	−0.4013	−0.4941
0.20	−0.2332	−0.5454	−0.2332	−0.5454
0.30	0.2065	−0.5502	0.2065	−0.5502

Table 4 The mean pressure coefficient on primary faces of the various shape for 90° angle

Limb Position (L)	Face A	Face B	Face C	Face D	Face E	Face F	Face G	Face H
0.00	−0.4369	−0.5730	−0.5450	−0.5493	−0.6747	0.5671	−0.4764	−0.2803
0.05	−0.4711	−0.5990	−0.5739	−0.5796	−0.7344	0.6351	−0.4959	−0.2908
0.10	−0.4810	−0.5787	−0.5570	−0.5626	−0.7156	0.6288	−0.4881	−0.3066
0.15	−0.4928	−0.5637	−0.5460	−0.5496	−0.6912	0.6256	−0.4948	−0.3233
0.20	−0.4954	−0.5499	−0.5362	−0.5390	−0.6747	0.6198	−0.5040	−0.3401
0.30	−0.5124	–	–	–	–	0.6056	−0.4892	−0.3624

Table 5 The mean pressure coefficient on the corner faces of the various shape for 90° angle

Limb Position (L)	Face F1	Face F2	Face H1	Face H2
0.00	–	–	–	–
0.05	0.8585	0.5228	−0.2684	−0.2902
0.10	0.8480	0.5324	−0.2921	−0.2958
0.15	0.8224	0.5444	−0.3166	−0.3091
0.20	0.7874	0.5477	−0.3427	−0.3270
0.30	0.7046	0.5574	−0.3834	−0.3558

the increase in suction pressure due to the interference between shifted two limbs when the limbs are shifted. The suction on leeward faces increases with the sifting up to 0.15L after that the suction is decreased due to the presence of positive pressure on shifted position. The suction on face F1 and H1 decreases with the increase in sifting length but an increase in suction is observed in face F2 and H2. The axisymmetric faces exerted the same pressure variation at 0° wind angle (Fig. 7).

At 90° wind angle, all the faces exerted suction except face F, F1 and F2. The suction in face A, H, H1 and H2 increases with limb shifting. The increase in suction is noticed on face B, C, D and E up to the sifting of 0.05L, but after that, it decreases with further shifting. The increase in positive pressure is observed in face F2, but a

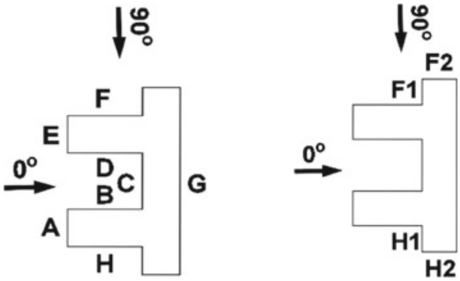


Fig. 7 The building faces of a typical shifted case

decrease in positive pressure occurs in face F1 with the sifting. At face F, the positive pressure increases up to 0.05L then decrement observed till 0.3L limb shifting.

Figure 8 is showing the various faces of the original U shape, a typical limb shifted case and 0.30L shifted case. These figures are also showing the direction of measured horizontal pressure. The pressure has been calculated at mid-height (250 mm) for each case. The pressure coefficient along the horizontal centerline for all the shapes has been presented in Fig. 9 to visualize the pressure variation along the perimeter of those shapes due to the shifting.

From Fig. 9 it is clear that the variation in pressure is visible mainly at the corner faces (A, E, F, F1, F2, H, H1 and H2) of shifted limbs. The shifting of 75 mm from each side has a significant variation compared to all other shifts for each wind angle. The inner faces (B, C and D) are experiencing almost similar wind pressure in all limb locations.

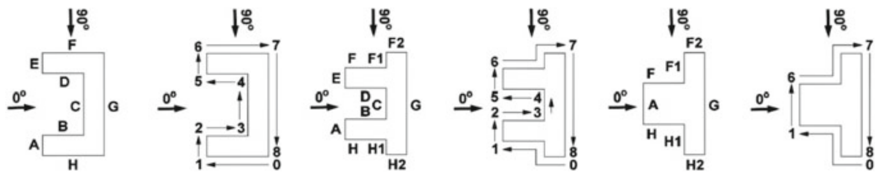
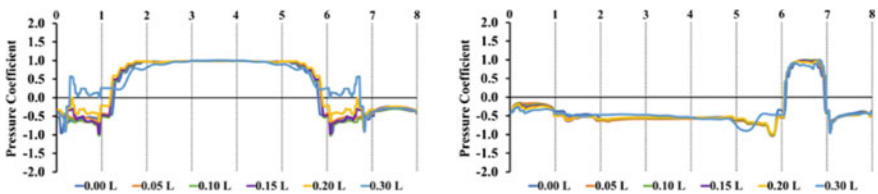


Fig. 8 The building faces of typical cases and the measured pressure coefficient direction



(a) 0° (b) 90°

Fig. 9 The pressure coefficient along the horizontal centerline for various cases **a** 0°, **b** 90°

5 Conclusions

In the present study, the variation in wind effect has been investigated because of both limbs shifting from extreme end to centre points at 0° and 90° wind angle. The shifting of both limbs has the advantage to have an axisymmetry shape in each shifting case. The wind induced pressure, lift and drag coefficient has been measured and compared. The comparison of those value indicates the impact of wind on those altered shape. The observations from this study can be summed up as follows.

- The drag coefficient of the building minimizes with the increase in shifting length from both sides of the end up to a distance of 50 mm for 0° wind angle, but further increase in sifting length attracts more drag force than the previous shifting length case. The axisymmetric shape does not draw significant lift force on that mentioned angle.
- The change in wind angle attracts more drag and lift force in shifted shape than the basic shape. The drag and lift coefficient both gradually increase with the increase in shifting length.
- The suction and pressure both are increased at the outer surfaces of those shifted shapes for 0 and 90° wind angle respectively. However, the inner surface of those shape exerted less suction and pressure in these cases. The significant pressure variations are observed on the outer faces of the entirely shifted (0.30L) shape. Those points should be considered for the cladding design of those buildings.

From the above discussion, it is quite clear that limb shifting has the benefit over basic shape when the wind flows at a normal angle, but the benefits no longer exist when the wind angle changes because of the increase in both lift and drag force. So, these factors have to be taken with special care. Therefore, this research indicates the benefits as well as the drawback of the limb shifting under wind loads which fulfils the objective of the study. The explored information from this study is significant and unique since no past literature has information about the effect of limb position on U plan shaped tall building. This study also indicates the requirements of a detailed study in different wind direction if the designer wants to construct a U shape building having shifted limbs from both sides. This study will guide the designer about the factors which should be considered for a safe design.

References

1. Gomes MG, Rodrigues AM, Mendes P (2005) Experimental and numerical study of wind pressures on irregular-plan shapes. J Wind Eng Ind Aerodyn 93(10):741–756
2. Zhao JG, Lam KM (2008) Interference effects in a group of tall buildings closely arranged in an L- or T-shaped pattern. Wind Struct An Int J 11(1):1–18
3. Amin J, Ahuja A (2011) Experimental study of wind-induced pressures on buildings of various geometries. Int J Eng Sci Technol 3(5):1–19
4. Raj R, Ahuja AK (2013) Wind loads on cross shape tall buildings. J Acad Ind Res 2(2):111–113

5. Mukherjee S, Chakraborty S, Dalui SK, Ahuja AK (2014) Wind induced pressure on 'Y' plan shape tall building. Wind Struct An Int J 19(5):523–540
6. Ahlawat R, Ahuja AK (2015) Wind loads on 'T' plan shape tall buildings. J Acad Ind Res 4(1):27–30
7. Cheng L, Lam KM, Wong SY (2015) POD analysis of crosswind forces on a tall building with square and H-shaped cross sections. Wind Struct An Int J 21(1):63–84
8. Mashalkar BS, Patil GR, Jadhav AS (2015) Effect of plan shapes on the response of buildings subjected to wind vibrations. IOSR J Mech Civ Eng 1:80–89
9. Li Y, Li QS (2016) Across-wind dynamic loads on L-shaped tall buildings. Wind Struct An Int J 23(5):385–403
10. Ranka S, Shingade PVS (2016) Analytical and numerical analysis of wind load on tall buildings. Int J Eng Sci Technol 5(11):3188–3197
11. Paul R, Dalui SK (2016) Wind effects on 'Z' plan-shaped tall building: a case study. Int J Adv Struct Eng 8(3):319–335
12. Ullas A, Nimisha P (2017) Response of buildings of different plan shapes subjected to wind vibrations. Int Res J Eng Technol **4(**5):1625–1628
13. Bhattacharyya B, Dalui SK (2018) Investigation of mean wind pressures on ' E ' plan shaped tall building. Wind Struct An Int J 26(2):99–114
14. Mallick M, Kumar A, Patra KC (2019) Experimental investigation on the wind-induced pressures on C-Shaped buildings. KSCE J Civ Eng 23(8):3535–3546
15. Mandal S, Dalui SK, Bhattacharjya S (2020) Effect of aerodynamic modifications on a tall building with horizontal irregularity. Adv In Struc Sys Mat 99–107
16. Bhattacharyya B, Dalui SK (2020) Experimental and numerical study of wind-pressure distribution on irregular-plan-shaped building. J Struct Eng (United States) 146(7):1–14
17. Löhner R et al (2015) Journal of wind engineering recent advances in computational wind engineering and fluid-structure interaction. J Wind Eng Ind Aerodyn 144:14–23
18. Revuz J, Hargreaves DM, Owen JS (2012) On the domain size for the steady-state CFD modelling of a tall building. Wind Struct An Int J 15(4):313–329