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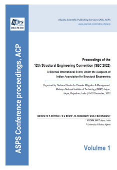

Wind Induced Responses of Corner Modified Irregular Plan Shaped Tall Building

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Abstract

The effectiveness of aerodynamic modification on a U plan shaped irregular tall building is depicted in this paper. The introduction of chamfer corner (25%) replaces the sharp corners of the building. Various wind direction ranging from 0° to 360° at an interval of 15° is considered to study the effect of wind direction by using Computational fluid dynamics (CFD) which simulate the wind environment around the building. Suitable grid size for simulation is obtained by using a grid independence study. The calculated structural response from the numerical analysis due to wind attack has been validated with the experimental values of a published article. The force coefficients and pressure coefficient has been extracted and compared considering the static effect of wind. The power spectral density of pressure on various points on the faces of the building has been plotted to indicate the dynamic behaviour of those building. The implementation of minor aerodynamic modification by chamfered corners lead to a better reduction in force coefficient. However, most of the cases more pressure has been attracted by the faces of those modified corners compared to unmodified sharp corner buildings. That indicated that the cladding design should be done with special care.

Keywords: Irregular Plan Shape, Aerodynamic Modification, Computational Fluid Dynamics, Grid Independence Study, Power Spectral Density

1. Introduction

Rapid urban development due to the globalization increases the requirements for high rise building day by day to cope up with the exponential growth of the population. The building of irregular plan shape is eye-catching, but it creates additional complexity in the design problem. The reduction of wind force is the primary concern of the designer though wind force becomes critical with the height. The designer can build a more safe and economic structure by incorporating corner modifications which not only enhance the aerodynamic behaviour of building by changing the wind flow around the building at greater extend but also it required minor changes to the existing design.

The measurement of drag and lift on square rigid cylinders [1] having modifications for cutdown vortex-induced vibrations is presented. The stability of rectangular cross-sections can be increased by a tiny modification in corners [2]. The wind effects on across and along direction can be mitigated on the rectangular building by chamfered, slotted and combination of both [3]. The oscillation of square shape has been calculated [4] for a variety range of wind angle, Reynolds number and velocity. The aerodynamic forces of square shape, corner recessed, corner rounded, triangular shape, corner cut triangular shape, Y shape, corner recessed Y shape and circular shape buildings have been studied [5]. The openings in a square tall building can reduce wind induced motion [6]. The varying length of a splitter plate can produce galloping in square shaped structures [7]. The wind characteristics on chamfered corner and opening of square building have been observed [8]. The outcome of recession, rounded and chamfer cut in rectangle and square shapes on excitation and oscillation due to vortex and galloping formation has been assessed [9] using wind tunnel experiment. The urban and suburban wind flow has been generated in a wind tunnel to understand the effect of cross-sectional change in square prisms along with height [10]. The advancements in wind tunnel and data acquisition systems can be capable of generating comprehensive data about wind-load for the design of structures, problems related to the environmental issue of wind in pedestrian-level and estimation of air quality [11]. The crosswind loads on the rectangular, bevel and concave corner cut square and primary square section buildings of different aspect ratios has been demonstrated [12]. The nine rectangular sections of different height, side ratio and aspect ratio have been considered to analyse the spectra, local wind force and spanwise cross-correlation [13]. The wind tunnel experiment illustrates the pressure distribution in the different faces for varying wind direction on 1:100 scale irregular shape model [14]. The various factors for designing a wind-resistant tall building are discussed and the importance of use CFD code

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is discussed [15]. The distribution of pressure on the faces of T and L shape buildings at different wind flow angle has been measured by experimental set up [16]. The discussion has been noted about the overall economics and benefit of type and size of edge alteration [17]. The helical cross-section has less attraction to wind force over other basic shape and major, minor altered, tapered, tilted, composite and opening square models [18]. The shear stress transport and *k-ε* turbulence model for numerical analyses along with experimental approaches have been executed [19] to study the pressure development on the faces of Y plan shape. The extensive study on base moment coefficients, mean wind pressure, local wind force, vertical correlation coefficients and power spectral densities on 10% cut-rate square shape models gives a conclusion that chamfering and recessing is useful than rounded corner [20]. The artificial neural network, optimization algorithm and large eddy simulation have been utilized to explore the wind force dependency of aerodynamically optimized CAARC standard buildings [21]. The comparison of numerical experiment results between the tall building of CAARC standard and two types of altered edges buildings indicated the influence of the edge modifications [22]. The wake zone length of triangular and square forms can be reduced by rounded, recessed and chamfered corners and the maximum reduction is possible for straight cut [23]. The prediction of mean wind pressures on the building having balconies is given using large eddy simulation and RANS turbulence model in CFD [24].

The past study on regular shape buildings having minor changes at corners and major changes through the change in cross sectional shapes showing the modifications is a suitable technique which can be considered for wind resistance design. The applicability of this technique on plan irregularity shapes should be explored in detail though such information is not available in recent past. The shapes of the alphabet like L, C, T, E and U etc. is generally utilized for public and commercial construction. The research on such shapes has been done by a few researchers but the exact prediction of the wind effect on those abstract shape is not possible from these. In this present study, the merits and demerits of chamfered edges have been observed on horizontally irregular U-shaped building. The factor of the unpredictable direction of the wind has been considered. The assessment of dynamic response on the basic shape and altered edges shape building has been demonstrated through the curves of power spectral density (PSD) of pressure.

2. Analytical Model Details

The corners of the basic building having sharp edges have been altered by chamfered cutting of 25% of limb length. The 0° to 360° range of wind directions at 15° interval has been incorporated in our study. The dynamic and static wind flow has been taken into account. The details of analytical models (see Fig. 1) showing that the buildings are taken of 150 mm depth, 375 mm height, 250 mm length, 50 mm limb length and 100 mm limb width. The building dimensions are taken 1:300 reduced geometric scale. The corresponding faces of the buildings as Face A-H and the direction of the wind flow are marked clearly.

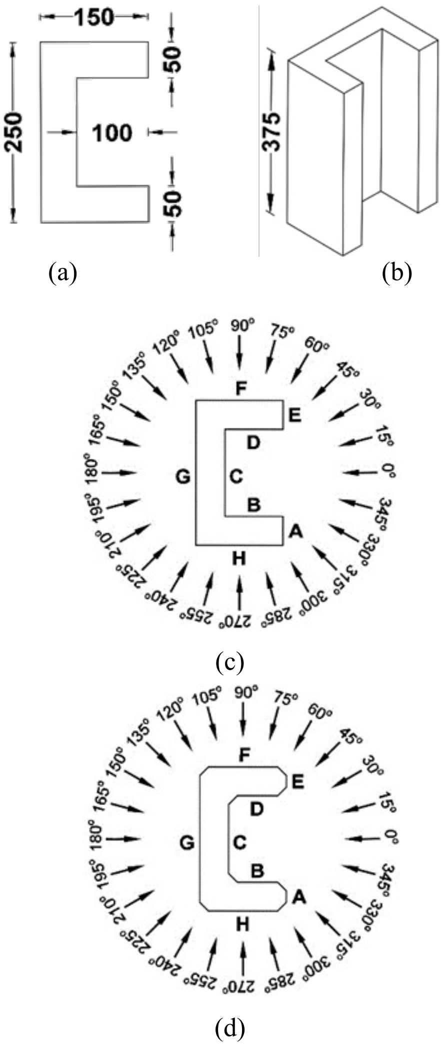


Fig. 1: Analytical Building models (a) Plan view of Basic U shape Building (b) Elevation view of Basic U shape Building (c) Basic Building with wind angle and different face name (d) Corner chamfered building with wind angle and different face name (all dimensions are in mm)

3. Methods of Solution

The uses of computational fluid dynamics (CFD) code for generation of wind responses have gained popularity day by day. The unavailability of experimental set up can be compromised by the application of CFD. The Ansys CFX package is taken for CFD simulation. The *k-ε* model generates the turbulence in CFD. The atmospheric boundary layer (ABL) flow has been generated in the simulation by the powers-law equation.

$$\frac{U_x}{U_\infty} = \left(\frac{x}{x_0}\right)^{\alpha} \quad (1)$$

Where,
The free steam and any height (x) velocity are marked as 'U_∞' and 'U_x' respectively, the height of atmospheric boundary layer and the height of any point from the ground is noted as 'x_0' and 'x'.
The dominator 'α' represent the exponent of power-law and the value (0.133) of this is depends on the terrain category. The boundary layer height for present study is taken 1 m.

The computational domain for CFD application is as per guidelines from past literature [25]. The colossal size domain having 5H side clearance, inlet clearance, roof clearance and 15H outlet clearance from the model set up. This domain has no blockage effect and no restriction in wake generations is backside. The responses have been measured by adopting wall condition as no slip for domain floor and faces of the model. No responses have been calculated on free slip walls of the domain sides and roof. Fig. 2 and Fig. 3 shows the pictorial representation of the domain. All the dimensions are depending on the height of the building (H), which is taken as 375 mm in the study. The 10 m/s wind flow has been generated at the inlet side.

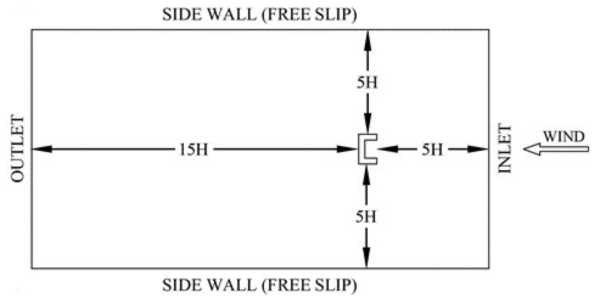


Fig. 2. The plan view of CFD domain

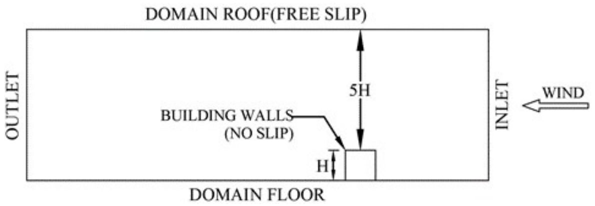


Fig. 3. The elevation view of CFD domain

The whole domain has meshed with tetrahedral element [26], but the regions near the model have meshed with the fine element for the accurate flow generation in the responsive zones. Fig. 4 is showing the meshing patters around the building and rest of the region.

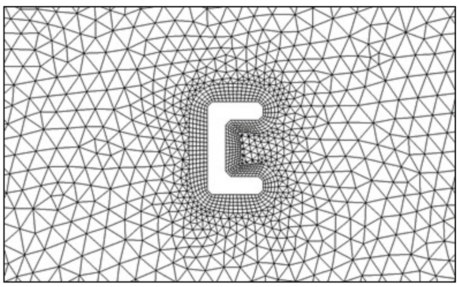


Fig. 4. The meshing patterns around a typical corner chamfered building

4. Grid Independence Study

The findings of suitable grid size through grid independence study for accuracy of analysis result showing in Table. 1. The unstructured grid is not suitable for the simulation because the generated results are questionable. The series of experiment in search of the structured grid has been done on primary U building at normal wind angle. The along wind force for each case has been extracted and the experiment is continuing until the negligible change in the values has been observed. The M1 to M7 case has been presented in table 1 in which M6 and M7 have the same force value and this indicates that the grid converges in this size. The further study has been done using M6 size case because it saves time for each computation.

5. Validation of Present Study

The experimental result of wind pressure on wall C along centreline through vertical direction from the published article [15] and the results from the current numerical study has been compared to see the variation. For this comparative study, the dimensions of the model and other required information have been adopted from the article. All the coefficient values are obtained for the 0° wind flow. The comparison of data indicates little variation and that is in an acceptable range.

6. Results and Discussion

The important wind responses for structural design such as velocity streamline, wind force coefficients and pressure coefficients has been illustrated in this section. The comparison of those responses between edge modified and basic building showing the wind effect on both buildings in various wind angle condition. The dynamic and static wind behavior on irregular shapes has been discussed elaborately.

Table-1. Grid independent study for basic U building

Mesh Case	Total no. of Elements	Along Wind Coefficient	% of Error
M1	2957615	0.946	-18.536
M2	8834753	0.993	-14.489
M3	12974301	1.042	-10.269
M4	24608476	1.097	-5.533
M5	32769804	1.139	-1.916
M6	41934768	1.161	-----
M7	48472137	1.161	-----

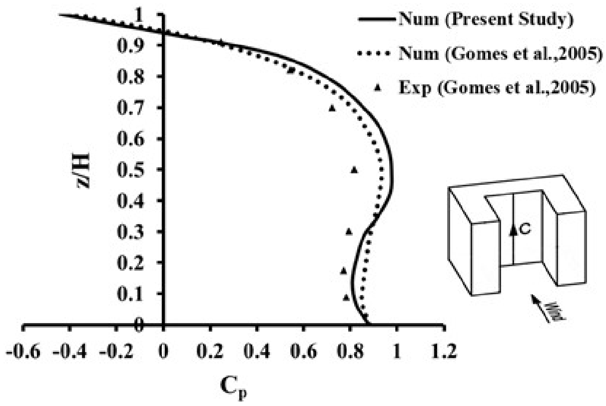
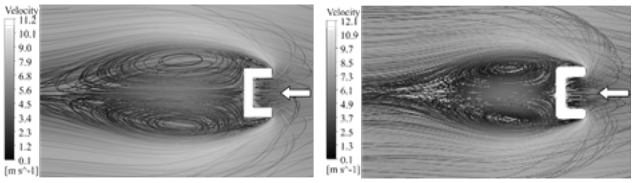
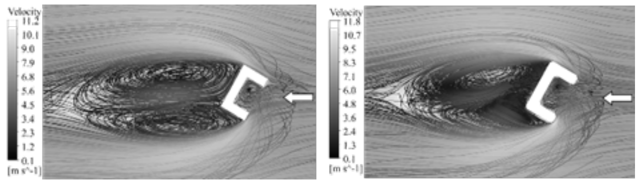


Fig. 5. The pressure coefficient comparison between the published article and current study for 0° wind flow

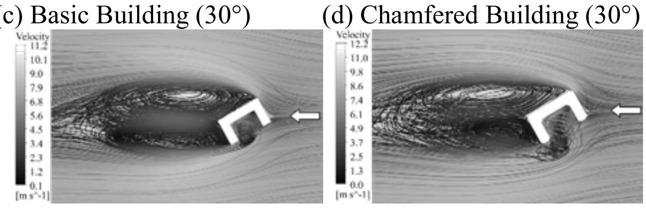
2.1 Wind Velocity Streamline



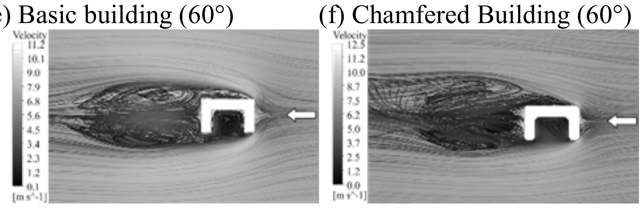
(a) Basic building (0°) (b) Chamfered Building (0°)



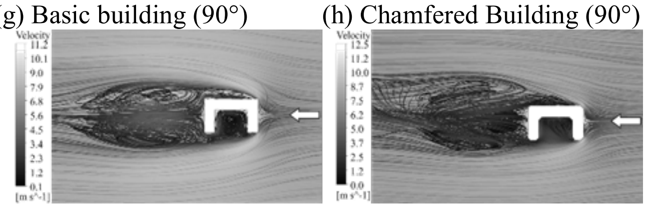
(c) Basic Building (30°) (d) Chamfered Building (30°)



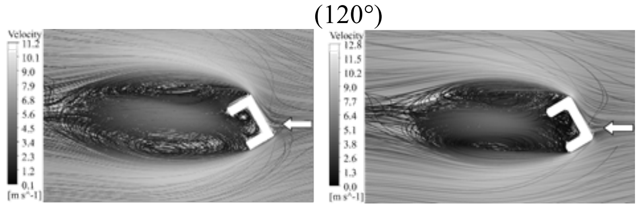
e) Basic building (60°) (f) Chamfered Building (60°)



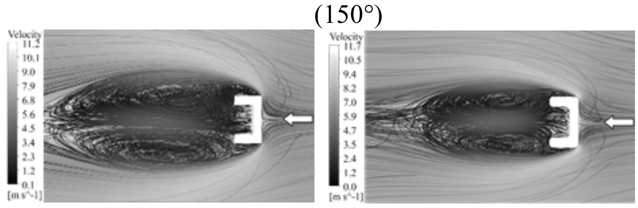
(g) Basic building (90°) (h) Chamfered Building (90°)



(i) Basic building (120°) (j) Chamfered Building (120°)



(k) Basic building (150°) (l) Chamfered Building (150°)



(k) Basic building (180°) (l) Chamfered Building (180°)

Fig. 6. Wind flow velocity streamline around the chamfered and basic building for various wind direction

The characteristics of wind flow velocity streamline around the chamfered and basic building shows that the variation in flow and corresponding velocity. The modified edged building not only creates the smaller wake zone than the unmodified edged building but also promotes the creation of weak irregular vortices. The presence of limbs also irregularize the wind flow when the position of wind changes from its natural position. The quite different shape of vortices is produced in the presence of chamfered edges. Most disturbed and long vortices have been formed for 120° wind angle. It is also visible that the abrupt increase in flow velocity is present at the modified edges mainly where the separation of flow occurs.

2.2 Wind Force Coefficients

The graphical comparison of across and along wind force coefficients of the buildings for various angels indicate that most of the cases the altered edges have less attraction to wind force. However, the negligible increase in drag force has been observed in corner modified models for 75°, 90°, 105°, 255°, 270° and 285° wind angle. The Fig. 7 and 8 demonstrate the comparison, which reveals that corner alteration has the benefits over sharp corners buildings.

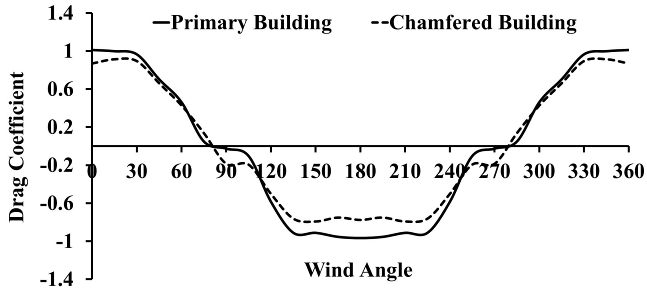


Fig. 7. The comparison of drag force coefficients for various wind angle

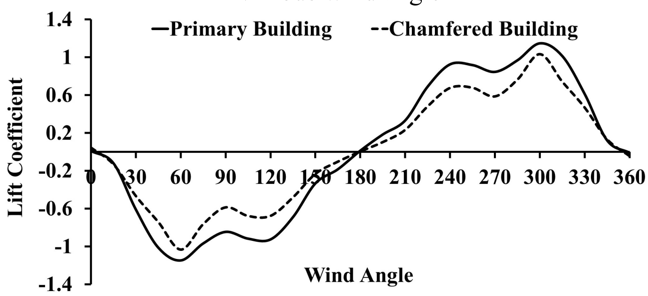
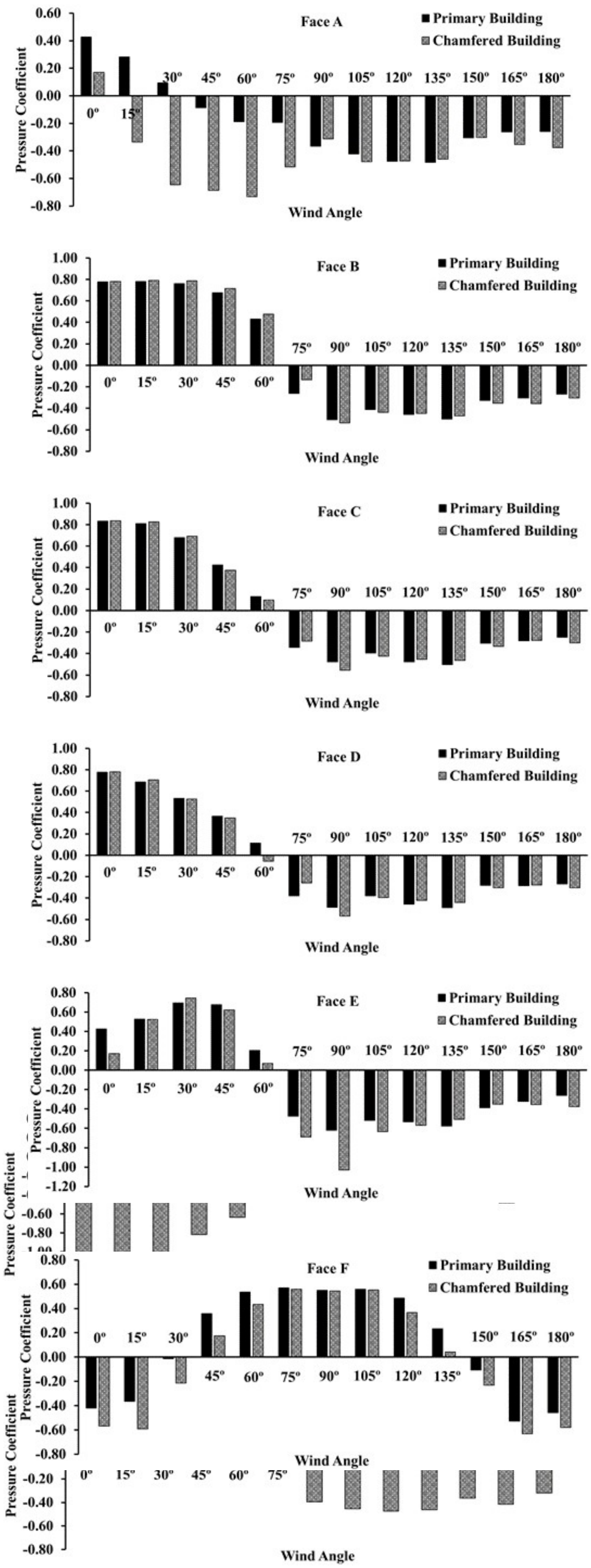


Fig. 8. The comparison of lift force coefficients for various wind angle

2.3 Wind Pressure Coefficients

The variation in wind pressure exerted on the different faces of those buildings. The mean pressure coefficients of the building faces have been noted because of the change in flow patterns with the change in wind angle. The suction and positive pressure on a specific face have been changed with flow direction. Most of the times, the faces of altered building have more wind pressure than unaltered building.



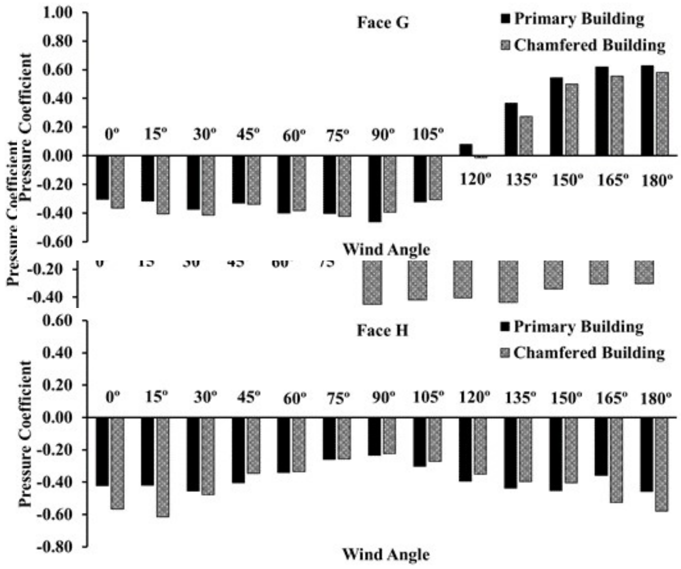


Fig. 9. Comparison of mean pressure coefficient on all faces of the altered corner and basic buildings

The comparison of mean pressure coefficient between the studied buildings is represented in Fig. 9. The wind angle 15°, 30°, 45°, 60° and 75° generates enormous suction on face A. The internal faces (B, C and D) of the basic and altered building has experienced very fewer pressure fluctuations in a variety of wind flow. At 90° wind angle sudden increment in pressure in face C indicates that the flow separation has a significant influence. The face H of all building encountered suction for each angle because it is in the wake zone region. The same phenomenon will occur in face F when the direction of the wind changes from 180° to 360°. In the present picture, the variation is shown only for 0° to 180° because the axisymmetric plan of U shape produces similar responses on symmetrical faces that means the responses on various faces for the angle range will just become opposite on their symmetrical faces when the angle range changes from 180° to 360°. The mean pressure coefficients on the edges of altered corners for various wind angle has been presented in Fig. 1. It is noted that those faces attract tremendous wind pressure. This effect indicates that the alteration can cause an issue in cladding element design on these regions.

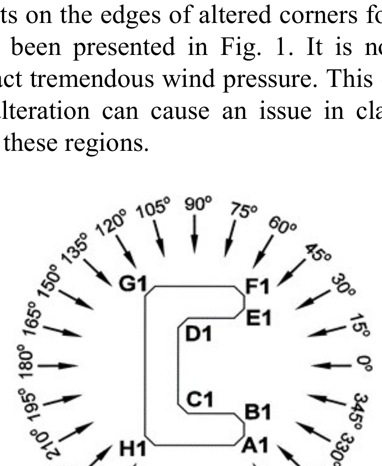
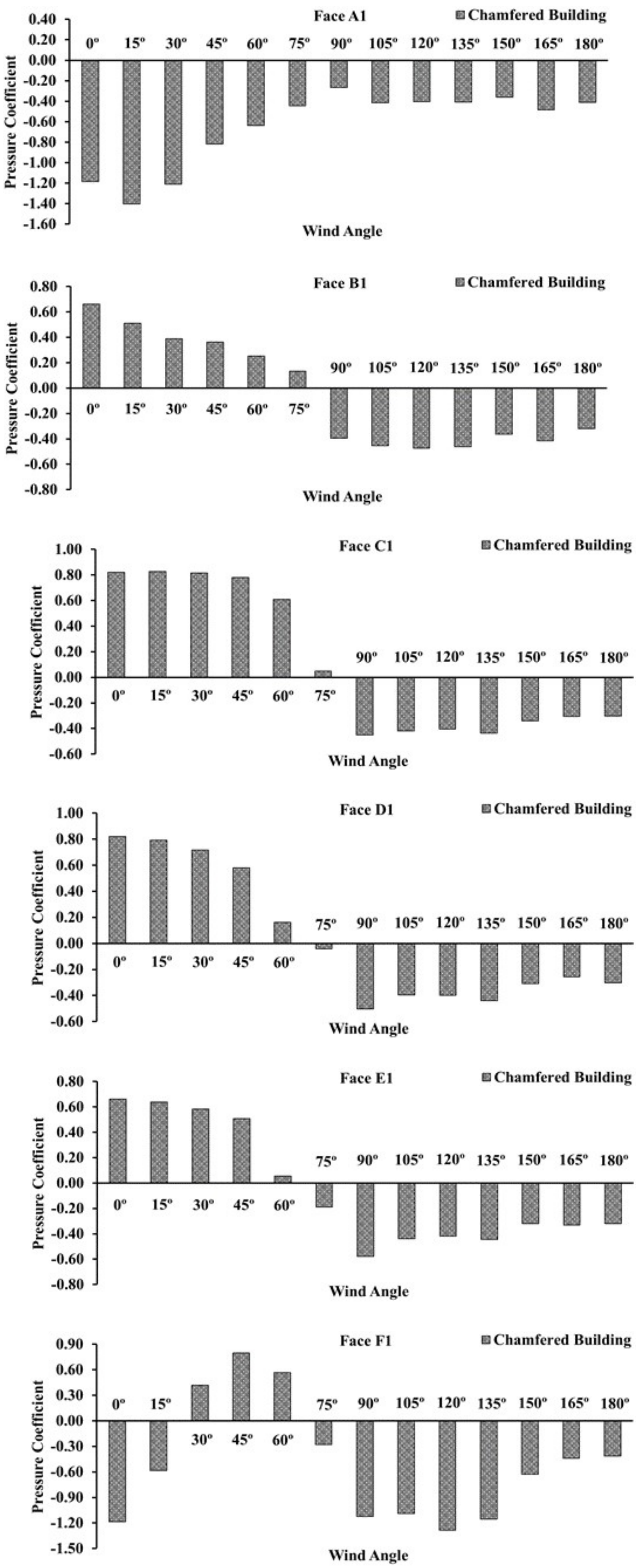


Fig. 10. The corner faces of the altered corner building



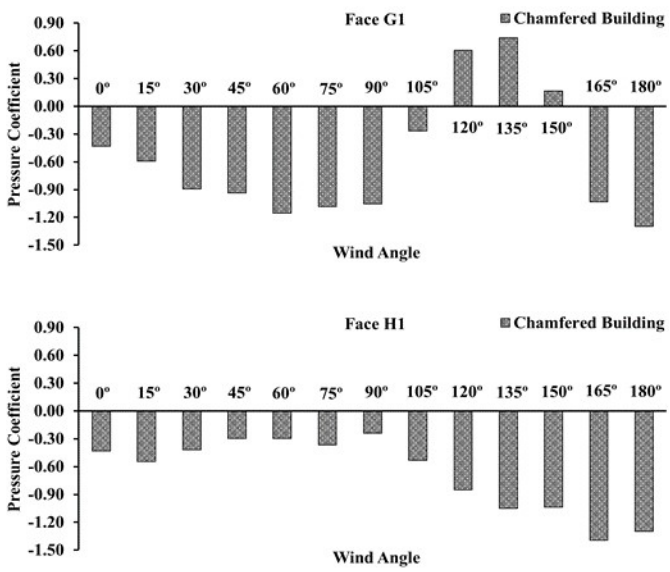


Fig. 11. The mean pressure coefficient on all corner faces of the altered corner buildings

The wind pressure and suction are very critical on altered corner face, as shown in Fig. 11. The significant increment in pressure is mainly due to the fact that the velocity of the flow abruptly increases at those corner zones. So special attention is required at the time of the construction.

2.4 Dynamic Effect of Wind

The influence of the time-varying wind load is also taken into consideration in current study. The dynamic wind effect on altered and basic building has been studied taking the wind gust of 3 sec along with various wind direction. of Some critical faces has been identified and the pressure plot of Power Spectral Density (PSD) is shown at certain points on those faces. The frequency variation function of energy due to the effect of wind as lift, pressure, drag and moment at a particular point is defined as power spectral density (PSD). The PSD curves have been plotted for a point located at the height of 365 mm from the ground surface and 10 mm from the edges of face A for 15°, 30°, 60° and face E for 90° wind angle. Fig. 12 shows the various points and the wind angels in which the PSD curves are plotted. Pressure spectra have been modified [$nSp(n)/\sigma p^2$] and plotted against the reduced frequency (nD/U_H) at different points for the above-mentioned faces. Here, *n* represents the frequency, PSD of pressure and the standard deviation of pressure variation with respect to the time at that point is noted as *Sp(n)* and σ_p respectively. The static velocity of wind at height H and the depth of the building is marked respectively as U_H and *D*.

The dynamic response of unmodified and modified building has been compared using those plotted curves shown in Fig 13. All the cases the higher peak is observed at the same frequency range for each building. At point H1 and H2 for 90° wind flow another major peak is visible at high-frequency range. The PSD curve area is more for each case in the basic building. That indicates that the dynamic effect of wind is significant on unmodified buildings.

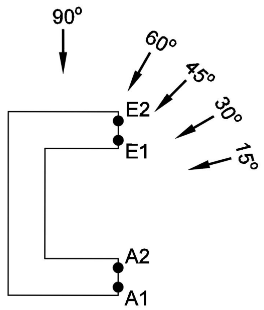
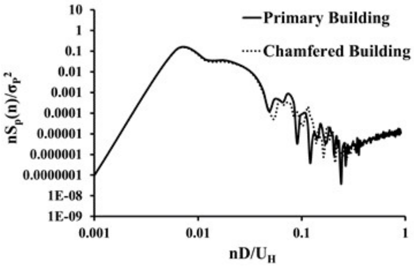
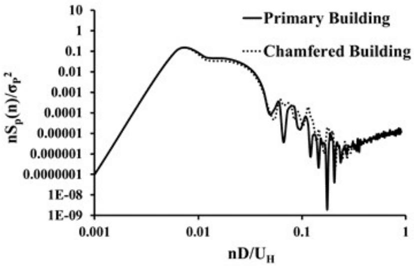


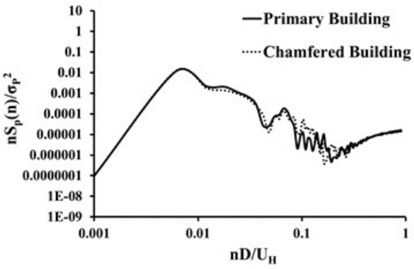
Fig. 12. Position of the curve point



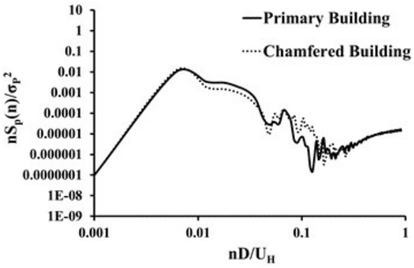
(a) Point A1 at 15º wind angle



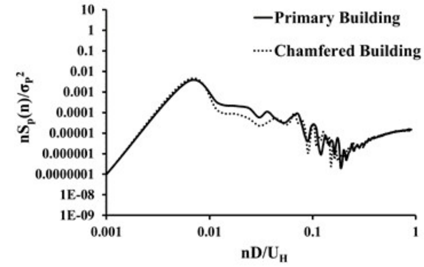
(b) Point A2 at 15º wind angle



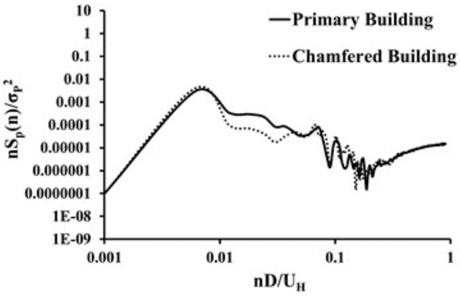
(c) Point A1 at 30º wind angle



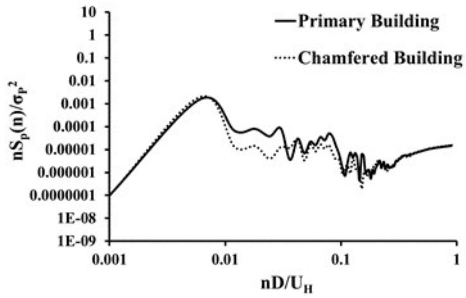
(d) Point A2 at 30º wind angle



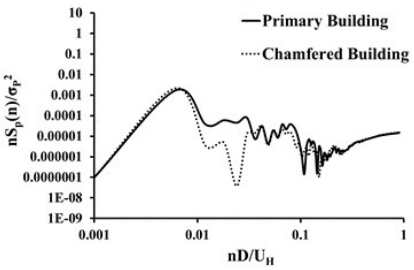
(e) Point A1 at 45º wind angle



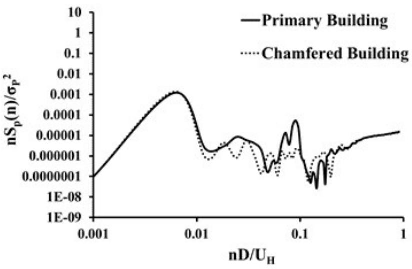
(f) Point A2 at 45º wind angle



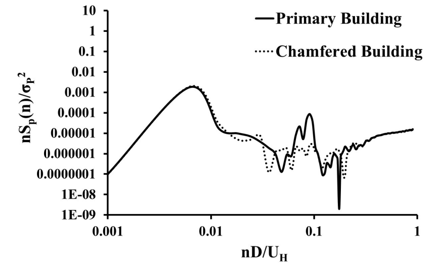
(g) Point A1 at 60º wind angle



(h) Point A2 at 60º wind angle



(i) Point E1 at 90º wind angle



(j) Point E2 at 90º wind angle

Fig. 13. The comparison plot of the power spectral density

7. Conclusions

The current numerical study demonstrated that the application of chamfered edges is beneficial for the design of the structural elements though the overall force on along and crosswind direction reduces significantly. All most in all wind direction, the lift and drag force is quite less in the altered building. However, the comparison of mean pressure for different building faces shows a different phenomenon. The severe pressure increment in corner zones has left some issue regarding the clad element design. This study also shows that wind behaviour is very unpredictable when it interacts with an irregular shape structure. The free flow patterns of wind substantially change around the building for the irregularity in plan shape because of the two limbs. The uncertain wind direction and the dynamic and static effect of wind should be considered on the structural design phase. This study gives some important design inputs for the construction of U plan shape building with or without altered edges. The overall cost of the construction will cut down because of the requirements of less size structural elements for safe design in altered building than the basic building. So, the adaptation of the chamfered corner on the sharp corners with proper design considerations for cladding will be advantageous.

Disclosures

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