Proximity effects between two plus-plan shaped high-rise buildings on mean and RMS pressure coefficients

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Abstracts. Wind-induced interference effects may result in a substantial increase or reduction in the wind forces on the buildings constructed in groups due to modifying wind flow around, according to the shape and relative position of the buildings. Experimental study of wind-generated proximity effects on mean and root mean square (RMS) pressure coefficients between two tall buildings are investigated in detail for various interference conditions in this study. The interference effects on mean and RMS pressure coefficients are presented as interference factors, i.e., mean interference factor (MIF) and RMS interference factor (RIF). Results show that the interference effects on local wind pressure are significantly higher on the windward side's faces near the recessed corner. The full blockage condition generates suction on walls facing the gap. The half blockage and no blockage conditions create a more severe interference effect than the full blockage. The maximum value of MIF is 4, 9 and 13 in full, half, and no blockage condition, respectively. Interference effects result in reduced wind load on side faces and faces at the leeward side. Suction at side faces reduced approximately by 65\% in full blockage condition. RIF’s values less than unity are observed for all interference cases.

Keywords: Tall buildings, interference effect, wind load, wind tunnel, mean pressure coefficient, interference factor

1. Introduction

With the rapid urbanization and shortage of land in urban areas, modern high-rise buildings are often constructed in groups. When several high-rise structures are situated in the near vicinity, the wind flow patterns around the building are quite intricate than isolated buildings due to interaction effects. This may have a contrary wind effect in such areas depending on the shape of the building, as the external shape of tall buildings plays an influential role in the generation of wind load on high-rise buildings. This problem is likely to increase significantly in the future due to the increasingly dense arrangement of buildings in cities caused by the shortage of land. Guidelines for estimating the wind loads on tall buildings in current design codes and standards are only available for regular and symmetric shapes. Also, codes and standards offer little guidance regarding the proximity effect for
unconventional plan-shaped buildings. Since wind effects depend on the shape and size of buildings, their relative positions, wind direction, etc., are involved [1, 2], it is challenging to provide the compendious and generalized set of recommendations for modification in wind load due to the presence of adjacent buildings. Therefore, the proximity effect due to nearby structures should be appropriately investigated for the realistic design of buildings for wind [3].

Many researchers have studied proximity effects between tall buildings [4, 5, 6, 7, 8, 9, 10, 11, 12-19]. Behera et al. [20] studied the proximity effect between high-rise buildings with different plan ratios and interfering building positions. It was observed that interference effects were beneficial with respect to the maximum positive pressure, but minimum negative pressure significantly increased. Dongmei et al. [21] assessed the Interference factors of global aerodynamics & local wind pressure and lift spectra of a square building in the presence of a lower height building but of the same cross-section at different positions. It was observed that fluctuating aerodynamic forces on the principal building were increased significantly for the oblique upstream position of the interfering building. Kim et al. [22, 23] analyzed the effect of a structural link on the lateral wind response of two square-linked buildings. Results showed that at a small gap between buildings, channeling is strong, and the linked building system acts as a single bluff body. Kim et al. [24] studied the effect of gap distance on wind flow around linked buildings. The results showed that for a parallel arrangement of buildings, the single vortex street and biased flow is observed for a small gap between buildings at 0-degree wind incidence. Lam et al. [25] studied the proximity effects on closely spaced square buildings under different wind angles and gap distances between buildings. They concluded that strong channeling through the building gaps exists due to the close proximity. Xie and Gu [13] studied the mean proximity effects between a group of two and three tall buildings. It was concluded that shielding due to upstream building causes a reduction in mean wind forces on the principal building. Yan and Li [26] investigated the interference effects between a pair of aerodynamically modified super-tall buildings. Results showed that the dynamic response has substantially enlarged in a critical arrangement. Yu et al. [27] developed a relationship between interference factor and spacing through high precision regression equations for interference effects between two buildings with different arrangements. Results showed that the interference effect was beneficial for mean pressure, but the peak pressure at the lateral façade near the interfering building was amplified. Zhao and Lam [28] investigated the interference effects between five square tall buildings in the wind tunnel, arranging them in L- and T-shaped patterns. It was observed that a strong interference effect exists on all member buildings, which significantly modifies wind loads as compared to the isolated building. Zu and Lam [29] studied the shielding effect on building of square plan in presence of row of low rise or medium-rise building, and it was concluded that at normal incidence angle, the mean along-wind loads on the principal tall building is always reduced.

Hui et al. [30, 31] investigated the mutual interference effects on local peak pressure coefficients between two high-rise building models of different shapes. It was observed that proximity effects depend much on building shapes, configuration and wind angles. The smallest minimum peak pressure at the face increased up to 40%. Kim et al. [32] studied the interference effects on local peak pressures for different wind incidence angles and height ratios of interfering building. The results showed that the peak suction enlarged with higher height ratio. Oblique arrangement generates more severe peak suction compare to tandem configuration. Michel et al. [33] studied aerodynamic interference between three cylindrical buildings present in a row and surrounded by small buildings. A substantial increase in the local pressure was observed through experimental results. Mara et al. [10] performed wind tunnel tests to assess the proximity effects among two buildings having similar heights and geometries associated with square plan building of interest. Aerodynamic interference factors greater than unity were observed for RMS cross-wind forces for the direct upstream location of the interfering building.

Flaga et al. [34] studied the effect of interference between closely spaced irregular shaped tall buildings on mean pressure distribution, global forces and pedestrian comfort for wind. It was discovered that the close proximity between buildings generates high negative peak pressure on the surfaces facing the gap. Kar and Dalui [35] investigated the wind interference effects in mean pressure coefficients on an irregular shape building due to a group of three square plan buildings of the equal heights at different locations in along-wind and across-wind directions. Li and LI [36] investigated the interference effect on the irregular shaped twin-tall tapered buildings with recessed corners. It was observed that the proximity effects between tapered buildings were considerably different from that of the square building. Nagar et al. [37] examined the proximity effects between closely spaced square and H plan shape twin tall buildings. It was observed that the interfering building generates suction at windward of the principal building when the interfering building present upstream. Zhang et al. [38] analyzed the interference effects between two linked “H” type
twin-tower structures. It was concluded that the surrounding building’s channeling effect is the main source of the maximum crossbridge displacement.

Chen et al. [39] and Quan et al. [40] studied the proximity effects on an existing target tall building with existence of a proposed super tall building and a pair of adjacent buildings of similar height. The results showed that the aerodynamic response of the target building was considerably increased when the proposed super-tall building existed upstream. Farhadi and Rehnama [41] studied the flow about a surface-attached cube through numerical simulation. Jing et al. [42] analyzed the proximity effects between two oil storage tanks on wind fields and dynamic response due to the wind effects. Results revealed that the pressure acting on the tank under interference is notably higher compared to the single one. Liang et al. [43] examined the interference effects on the wind pressure at the windward facade of the principal building through wind tunnel tests. It was observed that by varying the relative position of the secondary building, the bimodal distribution could be altered to a unimodal form. Sun et al. [44] conducted pressure measurement tests to study the proximity effects between two chimneys with various distances and wind angles. It was concluded that the interference effects were significantly higher on across-wind load compare to those of along-wind load. The maximum interference factor of 1.9 was observed for the extreme across-wind response. Tavakol and Yaghoubi [45] investigated the flow around a surface-mounted hemisphere. The study was done experimentally and numerically, and flow patterns were studied for different flow velocities at various sections. Xing and Qian [16] numerically studied the flow around a group of three circular cylinders arranged in equilateral-triangle arrangements. It was observed that the wake in the back of two parallel cylinders downstream of the three was asymmetrical at small spacing, which disappeared with an increase in spacing ratios.

Although numerous research work has been done to investigate the interference effects between building with square, rectangular or circular sections [1, 8, 9, 12, 16, 18, 31-32, 43, 46-53], the interference effects between unconventional plan tall buildings had been rarely studied [26, 35-39, 54]. Also, studies on proximity effects between closely spaced tall buildings are rare [23-25, 28, 34, 38]. Therefore, these findings need further investigations for a pair of high-rise buildings with unconventional plans. Large-sized recessed corners are generally provided in the twin residential tall buildings to provide amenities and to allow ventilation to washrooms and kitchens and for maximum views to all apartments [55]. The study of interference effects between closely spaced plus-plan shaped tall buildings with large-sized recessed corners has not yet been conducted. This paper centered on the wind-induced proximity effects between two identical plus-plan shaped high-rise buildings on mean and RMS pressure coefficients.

Three different arrangements of the interfering building that provides a full blockage, half blockage, and no blockage conditions for the principal building have been examined. The interference effects on mean and RMS wind pressure coefficients are presented as MIF and RIF for the three interference conditions. The contours of the interference factors greater than one at critical faces are presented.

2. Experimental Setup

2.1. Approach wind Characteristics

The tests have been performed in an open circuit boundary layer wind tunnel (BLWT) at the Civil Department of the Indian Institute of Technology Roorkee, Roorkee, India. The tunnel had a single fan to generate uninterrupted flow, which was operated by 125 HP motor. The working section of the tunnel was 15m long with cross-section of 2m size, and the total length was 38 m long (Fig. 1). Wind flow characteristics were simulated similar to the conditions of IS 875: Part 3 (IS 875 Part 3, 2015) by placing vortex generators, cubical blocks, and barrier wall at the inlet region.

The mean velocity (V) and turbulence intensity(T.I.) profile inside the tunnel are simulated with a power law index (α) = 0.22 for the current study. Models were placed at the center of the turntable, which was located at 12.21m from elliptical effuse, and which can be rotated to set the angle of wind incidence. A dyno drive attached to the diffuser or fan at the outlet of the tunnel was used to vary the wind speed in the tunnel with a maximum speed of 20 m/s. The velocity profile measured at the downstream end of tunnel and the variation of the turbulence intensity of flow is reflected in Fig. 2. The T.I. near the floor of the wind tunnel was found to be about 12 %, and wind velocity at building height was 9.87 m/sec. The wind speed in the wind tunnel was evaluated with the help of “TESTO-480”. A probe was connected to this instrument to measure the wind velocity at a different height, which
had a length of 1 m. This instrument was connected to and operated through a computer. Wind pressure on the models was measured using a “Baratron Pressure Transducer”, which was capable of measuring extremely low differential heads.

2.2. Details of Model

Experimental building models considered in this study comprised two buildings, out of which one is the rigid pressure model for the principal building under consideration, and the second is the wooden model of interfering building. The principal building model was made of a transparent Perspex sheet of 4 mm thickness with stiff faces to ensure sufficient rigidity and strength of the model, whereas the interfering building model was a wooden model of the similar shape and size without pressure taping (Fig. 3). The length scale was set as 1:300 to study the model with Plan area 40,000 mm$^2$ and 600 mm in height in the wind tunnel. Pressure tapings were made of steel tubes with an internal diameter of 1 mm and 15-20 mm in length. The total number of 196 pressure taping were installed on the wall of the pressure model, which were located at seven different heights levels of 10, 60, 180, 320, 420, 540, and 590 mm (Level G-A) from the bottom as shown in Fig. 4(a) to get a proper distribution of wind pressure at all the surfaces. Total 28 measuring points were there at each level (Fig. 4 b). The plan showing different faces and detailed dimensions are shown in Fig. 4 (c).

2.3. Pressure measurement

Total four sets of test arrangements were made for measurement of the pressure and interference effect between building models. In set-1, the principal building was tested in an isolated condition with face A as a windward face, as shown in Fig. 4(c). Set-2 to set-4 are shown in Fig. 5, which indicate the different positions of the interfering buildings with respect to the principal building. In set-2, the interfering building was positioned in line with the principal building. Distance (x) between the principal building and the interfering building was kept equal to 60 mm (1/10$^{th}$ of the model height) for all cases. In set-3 and set-4, the interfering building was positioned in oblique arrangement, creating a half blockage and no blockage conditions for the principal building, respectively.

The value of the mean pressure coefficient ($C_{p,\text{mean}}$) at any pressure measuring point is calculated by normalizing the measuring pressure at the corresponding measuring point based on the following equation:

$$\bar{c}_p = \frac{\bar{p} - P_{\text{static}}}{P_{\text{dyn}}}$$  \hspace{1cm} (1)

Where $\bar{p}$ is mean pressure; $P_{\text{static}}$ is the static pressure at reference height; $P_{\text{dyn}}$ is pressure at reference point given by $\frac{1}{2} \rho a U^2$, where $U$ is the reference velocity at the reference height.

For the fluctuating pressure, root mean square (rms) pressure coefficient ( $C_{p,\text{rms}}$ ) has been calculated using the following expression [3]:

$$C_{p,\text{rms}} = \sqrt{\sum_{k=1}^{N} \left( C_{pk} - C_{p,\text{mean}} \right)^2 / (N - 1)}$$  \hspace{1cm} (2)

Where $C_{pk}$ is the time history of pressure measuring point; $N$ is the total number of samples, and $C_{p,\text{mean}}$ is mean pressure coefficient.

3. Results and Analysis

3.1 Data validation

Before proceeding to study the distribution of pressure on the plus-plan shaped building, it is necessary to verify the calculation method used for wind loading measurements. The experimental parameters of a base square building model with aspect ratio 1:5 at 0-degree wind incidence have been compared with the experimental parameter [56, 57, 58] of classical model of Commonwealth Advisory Aeronautical Research Council (CAARC) standard tall building model tested at several research institutions, including the University of Bristol (BU), Monash University (MU), National Aeronautical Establishment (NAE) and National Physical Laboratory. Fig. 6 presents the comparison of $C_{p,\text{mean}}$ at 0.7H height of the square building model with the $C_{p,\text{mean}}$ of the CAARC standard tall building model at 2/3H. The mean wind pressure coefficients obtained from this study for the reference square building model are consistent with those of the CAARC model.
3.2 Mean and rms wind pressure coefficients

Prediction of wind load is a difficult task with interfering buildings present in the near vicinity. The relative location of these interfering buildings is an essential parameter that affects the characteristics of wind load on the principal building. A detailed study in isolated as well as in interference condition is employed to investigate the distribution of $C_{p,\text{mean}}$ and $C_{p,\text{rms}}$ on the surfaces of the principal building. Results are presented as contours of $C_{p,\text{mean}}$ and $C_{p,\text{rms}}$ on all faces.

3.2.1 Isolated Building Condition

The contour of $C_{p,\text{mean}}$ and $C_{p,\text{rms}}$ on different faces corresponding to the isolated condition are shown in Fig. 7 and Fig. 8, respectively. Herein only half of the surfaces are presented because due to symmetry in plan and wind flow about the axis in the direction of wind flow, similar pressure distribution occurs on symmetric surfaces. The distribution of $C_{p,\text{mean}}$ is symmetric about the vertical centerline at the central windward and leeward faces, i.e., at face A2 and C2, respectively. Pressure on the whole face A2 is positive. The maximum $C_{p,\text{mean}}$ is 0.58 with 0.34 face average value. The high pressure region is located on the central upper surface, while the lower pressure region is located on the bottom of side edges. Face C2 experiences suction with a small variation of pressure on face ranging from -0.44 to -0.54. High value zone is located at the top, while low value zone is located at central surface at H/3 from bottom. All the surfaces at side and leeward are under suction as expected due to side wash and vortices generated in the wake. Front side faces A1 and A3 have a maximum negative and average value of $C_{p,\text{mean}}$ -0.39, and -0.20 respectively, whereas leeward side faces C1 and C3 have an almost similar distribution of pressure throughout the face ranging between -0.47 to -0.58 with average $C_{p,\text{mean}}$ -0.54. Side front face B1 and D3 have suction on inside edges, which may be due to the formation of eddies in reentrant corners. Suction tends to reduce on the side faces B2 and D2 from windward edge to leeward edge, with maximum and face average value of $C_{p,\text{mean}}$ -0.86, and -0.69, respectively. Distribution of $C_{p,\text{mean}}$ varies between -0.48 to -0.62 with face average -0.56 on leeward front face B3 and D1. The RMS pressure coefficients vary from .04 to 0.19 for isolated building condition. The largest value of $C_{p,\text{rms}}$ is observed at side surface B2. Large values of fluctuating component is observed for side faces and faces which are adjacent to re-entrant corners due to increased turbulence at corners and edges of building in windward side.

3.2.2 Full Blockage Condition

The distribution of $C_{p,\text{mean}}$ corresponding to full blockage interference condition, is shown in Fig. 9. The distribution of $C_{p,\text{mean}}$ on all surfaces of the principal building in the presence of the interfering building, creating full blockage condition for the principal building is quite dissimilar from that of the isolated building. Pressure tends to increase with respect to height, like isolated building on the front face and reduces near the top edge. Strong interference effect is created on front faces because it immersed in the wake of interfering building, which causes suction on front face A2, unlike for isolated building and distribution of suction coefficient varies between -0.32 to -0.63. The high suction zone is located at a height between .75H to 0.85H. The absolute value is approximately 29% higher than those for isolated building. The mean suction coefficient for the windward face (B1 and D3) at the side is significantly increased compared to an isolated building. The suction coefficient increased for windward side faces (A1 and A3) compared to the isolated building by 51% correspond to the average of the face; however suction decreases for leeward side faces (C1 and C3) with a small variation in suction coefficient between -0.21 to -0.24 on the surface. The considerable reduction (Approx. 65%) is noticed in suction on side faces (B2 and D2), and all leeward faces (B3, C1, C2, C3, and D1), and the percentage reduction is in the range of 55-65%. Suction coefficients on these side faces tend to decrease from windward to leeward edge, and maximum suction is at the middle height of the windward edge with $C_{p,\text{mean}}$. Distribution on windward face A2 and leeward face C2 is symmetric about the vertical centerline.

As shown in Fig. 10, RMS pressure coefficient on all faces of the principal building at full blockage condition is significantly decrease compared to isolated building and maximum decreased is for side faces from 0.13 to 0.04. Overall maximum face $C_{p,\text{rms}}$ is decreased compared to isolated building and is at faces attached with reentrant corners on the windward side.

3.2.3 Half Blockage Condition

Fig. 11 shows the distribution of $C_{p,\text{mean}}$ at all faces of the principal building at half blockage interference condition. Interference building creates unsymmetrical wind flow around the principal building due to half blockage and thus creates different pressure
distribution on the symmetric faces. The interference effect on all faces depends on the face position in the wake area and orientation concerning the flow of wind. Active shielding is created by interfering building. Unlike isolated and full blockage interference conditions, the distribution of pressure is not symmetrical about the vertical centerline on front face A2. Both sides are under the opposite nature of pressure. The surfaces towards the interfering building, which come under the wake region of the interfering building, are under suction, whereas the opposite side has positive pressure. High pressure zone is located near the right edge from bottom to top. Suction on the side face A1 at the center on the windward side increased, and the average $C_{p,\text{mean}}$ of the face is -0.47, which is 57% higher than isolated building. Front side face A3 has positive pressure, which was in suction for isolated as well as full blockage conditions. Windward face B1 at the side also experienced positive pressure, whereas face D3 is under increased suction compare to the isolated building and full blockage case. The effect of interference on all other faces is small, and the distribution of $C_{p,\text{mean}}$ is likely similar to that of isolated building case.

The fluctuating pressure component, as shown in Fig. 12, again decreased significantly at half blockage interference position compared to the isolated building for all faces. But maximum of $C_{p,\text{rms}}$ for face A1 is increased by 58% compared to isolated building and doubled with respect to full blockage building condition. For all other faces, the maximum of $C_{p,\text{rms}}$ is decreased compared to an isolated building.

#### 3.2.4 No Blockage Condition

Contour plot of $C_{p,\text{mean}}$ and $C_{p,\text{rms}}$ at all faces of principal building for the no blockage interference condition are shown in Fig. 13 and 14, respectively. Interference effects for this location of interfering building are critical for faces in the left side of the centerline along the windward direction due to the fact that faces on this side are also affected by the wake generated due to the existence of the nearby building. Suction at the front side face A1 significantly increased and was maximum among isolated and all three interference conditions. The distribution of $C_{p,\text{mean}}$ varies from -0.68 to -0.86 with an average at the face is -0.76, which is 60% higher than half blockage condition. Pressure distribution on front face A2 is similar to that for half blockage interference condition. Maximum and face average values of $C_{p,\text{mean}}$ for front face D3 at the side toward the interfering building are also increased crucially as compared to isolated, and all other interference conditions and are -0.89 and -0.65, respectively. The face average value for face D3 is increased by 45% from half blockage condition. The interference effect on all other faces is favorable i.e. reduced.

RMS pressure coefficient $C_{p,\text{rms}}$ is either similar for most of the surfaces or reduced to that of isolated building case. Maximum value increased by 40% to that of an isolated building for face A1 and for all other faces, it has reduced.

A detailed study of mean and rms pressure coefficients is employed along the surface at each level of the principal building in isolated as well as with an interfering building at all three interference conditions. Fig. 15 renders the distribution of $C_{p,\text{mean}}$ along measuring points at different levels for isolated building and three different blockage conditions of interference. The fluctuation in $C_{p,\text{mean}}$ is significantly large for measuring points which lie on faces at the front (i.e., at points 1 to 9, 27 and 28). The effect of re-entrant corners and edges can be seen from the figure clearly. Fluctuation in $C_{p,\text{mean}}$ at measuring points on faces at side and back, is significantly small and absolute $C_{p,\text{mean}}$ is maximum for isolated building. It seems that the largest absolute value of $C_{p,\text{mean}}$ occurs for no blockage condition at the bottom most level at 10 mm from the bottom.

The distribution of rms pressure coefficients is shown in Fig. 16 at different levels of the principal building. $C_{p,\text{rms}}$ is increased toward the central height of the building and significant at middle levels compare to the top and bottom levels except face A1. $C_{p,\text{rms}}$ is reduced for leeward building side i.e. between measuring points 11 and 25 at each level for all conditions. For half blockage, the fluctuating component of pressure coefficient is significant at the windward edge of face A1 at level A; however, at level B, it is significant for no blockage condition near the corner on face A1. At the center height of building $C_{p,\text{rms}}$ is greater and variation along the surface is also significant for isolated building. For bottom level G, distribution is similar to that of top level A except for face A1 for half blockage.

#### 3.3 Interference Factor

The interference effects corresponding to different interference conditions on pressure coefficients ($C_p$) related to all measurement points are of composite nature and challenging to present for all. To clarify the intricacy and to scrutinize the interference effects on $C_p$ in detail, interference factors (I.F.) for an average of $C_{p,\text{mean}}$ and $C_{p,\text{rms}}$ at each face are proposed as given by Khanduri et al.[1], to indicate the severity of interference effects on $C_{p,\text{mean}}$ and $C_{p,\text{rms}}$ as follows:
(MIF) = \frac{C_{p,\text{mean\ with\ interfering\ building}}}{C_{p,\text{mean\ isolated\ building}}} \\
(RIF) = \frac{C_{p,\text{rms\ with\ interfering\ building}}}{C_{p,\text{rms\ isolated\ building}}}

Where MIF and RIF are the interference factors for mean and RMS pressure coefficients, respectively. Fig. 17 renders the variation of MIF and RIF along the different faces of the principal building starting from the front side face A1 to side front face D3 anticlockwise for all three interference conditions. From Fig. 17(a), interference effects are significant for face A1, B1, and D3 only. Interference effects for full blockage interference condition are critical at Face B1 and D3 only, for which MIF greater than 4. For half blockage condition, MIF is greater than 2, whereas for face B1, absolute MIF is greater than 7 with a negative sign, the significance of which is that the nature of pressure is changed due to interference. MIF for face D3 is greater than 9, which is maximum among all faces and signifies that effects of interference for full blockage condition are maximum for face D3, which is a side front face toward the interfering building and falls in the wake zone of interfering building.

Interference effects for full blockage condition are more severe for D3 among three critical faces. MIF for face D3 is greater than 13, which shows a large interference-effect. Interference effect on this face is most severe among all faces and all interference conditions, which can be explained by the fact that this face immersed in the wake region of interfering building corresponding to no blockage condition and the velocity of flow increased after separating from the upwind interfering building due to which suction is increased by a significant amount and results in a high value of interference factor. Form Fig. 17(b), the maximum value of RIF for surface average $C_{p,\text{rms}}$ is 1.03, which shows that the fluctuating component of pressure coefficient is not much affected due to the existence of an interfering building at three positions. Average of surface $C_{p,\text{rms}}$ for all surfaces are reduced due to the presence of the interfering building, but peak values at the top level for some surfaces have increased, which may be due to vortex shedding for half blockage and no blockage conditions. From Fig. 17(a) it is clear that interference effects are significant for three critical faces, namely A1, B1 and D3 for which LFs are very high, hence the distribution of LFs herein only deals with the results for these three faces of the principal building. Fig. 18 render the contour of MIFs on these faces for three interference conditions, created due to different relative positions of the interfering building. In order to highlight the unfavorable positions of measuring points on the face, only those absolute I.F $\geq 1$ are retained. For full blockage interference condition, on face A1 I.Fs distributed evenly on the surface from 0.51 to 2.31. Distribution on face B1 and D3 are similar due to symmetry in position and wind flow around. Outer edges are significantly affected by interference, and from Fig. 18 (a) it is quite clear that positions above the middle of the inner edge are favorable, and regions of unfavorable locations concentrate on outer edges at 1/3 height from the bottom. MIF for half blockage condition on face A1 distributed on bottom 2/3 height with small variation, whereas variations at top 1/3 height are significant, and MIF varies from 1.67 to 4.27. For face B1 and D3 distribution is similar, but values are slightly different. MIF tends to increase near outer edges. The positions of favorable and unfavorable regions are similar as in the case of full blockage condition. For no blockage interference condition, the distribution of MIFs is quite different from previous conditions. A significantly large interference effect is noticed at face A1 and D3. MIF on face A1 is distributed evenly throughout the face, and varies from 2.0 to 5.33, whereas at face D3 MIF varies between a large range from 0.39 to 11.83, and regions of unfavorable positions concentrate on the bottom half. Unfavorable measuring points at face B1 concentrates on the outer edge between a quarter to the half-height.

The distribution of RIFs is shown in Fig. 19 for critical faces and unfavorable positions are highlighted by retaining IF $\geq 1$ only at surfaces. From the figure, it is evident that for full blockage regions of unfavorable are concentrate at the corner part of the building surfaces. The maximum value is 1.13. For half blockage distribution at central surface A2 is quite different than other because the boundary of the flow field at the back of interfering building lies at the center of this face. For no blockage interfering condition, windward faces A1 and A2 and leeward face D1 are the most critical surfaces for which larger area is covered by unfavorable positions.

4. Conclusions

Wind-induced proximity effects on $C_{p,\text{mean}}$ and $C_{p,\text{rms}}$ between two identical plus-plan models have been investigated in this study, using detailed wind tunnel experiments. Three different interference conditions as full blockage, half blockage, and no blockage were considered, which were created by arranging two buildings in tandem and oblique configurations. The distribution
of $C_{p,\text{mean}}$ at the surfaces of the principal building are presented as contour plots for isolated building and three interference conditions. Interference effects are presented by interference factors for $C_p$ at the face as $MIF$, and $RIF$ and contour of $MIF$ and $RIF$ were plotted for critical faces, where interference effects were significantly large. The following conclusion can be drawn from this study:

- Pressure distribution is symmetric for isolated building condition and full blockage interference condition but does not remain symmetrical for half blockage and no blockage interference conditions.
- For isolated building condition, side faces B2 and D2 have maximum pressure (suction), and the absolute value of average $C_{p,\text{mean}}$ at the face is 0.69. The maximum face average value of $C_{p,\text{mean}}$ equal for full blockage condition, is observed at front face A2. For half blockage and no blockage, maximum values are at face B2 and A1, respectively.
- Interference effects are significant at faces on the windward side only at which interference factors are greater than unity. Interference factors at other faces are less than unity, which shows that pressure coefficients are reduced compared to isolated building condition.
- The maximum mean interference factor (MIF) for full blockage condition is greater than 4 and observed at side faces B2 and D2. For half blockage condition, MIFs are significantly large at face B1 and D3. Values are higher than 7 and 9, respectively. Whereas for no blockage interference condition, the largest value of MIF greater than 13 is observed at face D3, which is the largest among all interference conditions. RIF is more significant for no blockage condition at face A1.
- Fluctuation in values of $C_{p,\text{mean}}$ at any level is large for measuring points at the windward side, which immersed in the wake region of upwind interfering building.
- Interference effects for individual measuring points on the face are more critical for face A1, B1, and D3, at which MIFs are greater than 2. For face A1 MIF are distributed evenly, whereas for face B1 and D3 regions of unfavorable locations concentrate on outer edges between ¼ to ½ height from bottom except for no blockage condition. Unfavorable regions corresponding to RIF have concentrated at corners parts of the building faces, except central windward face A2.
- The interference effect between closely spaced plus-plan twin tall buildings still needs more in-depth study and investigations. The study of the effect of wind direction is also required in the future, which is not presented here because of the large content of the paper.

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