Wind Effect on Closely Spaced Rectangular Tall Buildings of U Shape Geometrical Pattern

Shanku Mandal, Sujit Kumar Dalui, and Soumya Bhattacharjya

Abstract The modern cities of the developing world are facing challenges of extreme population and land availability. These challenges can easily overcome by utilizing the available areas properly with the development of closely spaced tall buildings. But most often, this solution attracts wind force that leads to severe wind interference. This study focuses on typical cases, where the three rectangular shapes with 75 m height, 45 m length and 15 m width each are closely spaced and formed a U shape geometrical pattern. Eight different cases have been considered in which one shape has been fixed at the same place and the other two shapes are moved both sideways and frontwards by 7.5 m, 15 m, 22.5 m and 30 m. Further, the two isolate U shape cases in which the three shapes are attached and a single isolated rectangular shape are also adopted. The wind flow at 0°, 45° and 90° has been generated by Computational Fluid Dynamics (CFD). The validation and mess sensitive study is attached to satisfy the requirements of a CFD method. The interference factor (IF) is calculated to demonstrate the impact of the interference. The wind pressure and force discrepancy have been observed due to the interference and flow angle. In most cases, the rise in mean pressure coefficients has been observed when the interference buildings are present at the sidewards. The pressure contour plots reveal that the location of the buildings and the flow angle has a significant impact on the face pressure distribution.

Keywords Closely spaced · Tall building · Wind interference · Wind effect · Computational fluid dynamics · Interference factor · Mess sensitive study · Flow angle

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1 Introduction

In modern cities, open land availability is a preliminary issue. So, those land must be used completely is always the answer in modern construction practices. Thus most often, closely placed tall buildings are constructed. The nature of the wind flow is quite complex in closely spaced structures than a stand-alone structure since wind interference is the critical factor. Although the assessment of interference effect is the important factor for wind-resistant design, a very limited section is available in various guidelines, which are not sufficient. A few manuscripts had highlighted some typical cases of wind interference. The numerical study of Sohankar [1] on twin square shapes, illustrated the effect of gap spacing and Reynolds numbers in wind force and pressure variations. Yu et al. [2] measured the effect of interference on pressure distribution in the various arrangement of the two buildings having different height and breadth ratios. Kar and Dalui [3] investigated the response of an octagonal shaped building in the presence of three square shapes. Zu and Lam [4] arranged two tall buildings at an arbitrary position and identified the across wind responses. Ma et al. [5] studied the differences in moment and force coefficients of twin rectangular shapes due to wind vibration. Korobkov et al. [6] investigate wind pressure and thermal effect between two interfered square shapes. Quan et al. [7] studied the interference effect on the surrounded building due to the presence of a tall building. Wu et al. [8] presented the wind induced effects of two circular shapes using Large eddy simulation. Behera et al. [9] concluded that the increment in plan ratio of the building extends the interference zone. Du et al. [10] presented the wind coefficients of two square shapes on diagonal and horizontal arrangement placed in close proximity.

The residential and academic buildings layout plan in modern cities are mostly following the U shape geometrical pattern where three rectangular buildings are placed in close proximity or a single isolated U shape where three rectangular buildings are attached to each other. The benefits of this geometrical pattern are that the open space in between two limbs can be utilized as a parking area, commercial requirements or a playground. Sometimes in the case where the buildings are not attached to each other, a street can be placed in between the open space of the buildings. Despite numerous studies, none of the research has considered this typical scenario. The uniqueness of this research is that in this study this typical case has been considered and the wind effect has been presented. Different cases have been adopted and the wind effect has been measured in the 0°, 45° and 90° wind angle using CFD. The variation in wind force, flow characteristics, mean pressure coefficients and pressure contour has been illustrated.

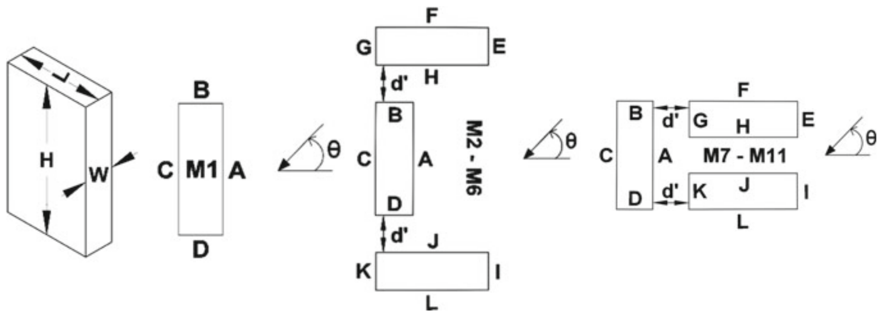


Fig. 1 The details of building models

2 Details of Building Models

The wind responses of an isolated rectangular building (M1) and the different interference cases (M2–M11) has been calculated at 0°, 45° and 90° wind angle. For the simulation, the dimensions of the buildings are reduced by following the 1:300 scale. The building models are shown in Fig. 1.

The height (H), length (L) and width (W) of the rectangular buildings are considered 250 mm, 150 mm and 50 mm respectively. ‘d′’ is the distance between an isolated rectangular building and the interference rectangular buildings. ‘d′’ is varying from 0 to 100 mm at an interval of 25 mm. At the M1 model, only the rectangular building is considered where no interference building is present. In the case of M2 model, the three similar rectangular building is considered in which the buildings are attached in such a way that it forms a U shape geometrical pattern. At M3, M4, M5 and M6 model cases the two rectangular buildings are shifted sidewards by 25 mm, 50 mm, 75 mm and 100 mm respectively. In the case of M7 model the U shape pattern is formed where two rectangular buildings are attached at the front side of the isolated rectangular building. The frontward shift of two rectangular buildings by 25 mm, 50 mm, 75 mm and 100 mm has been considered for M8, M9, M10 and M11 models respectively. The M2–M11 model cases are formed a closely spaced U shape geometrical patterns.

3 Solution Methodology

The numerical simulation utilized the Ansys CFX module [3], where the wind flow has been produced through computational fluid dynamics (CFD). The solution methodology involves a few steps which started with the modelling of the building, then selection of suitable domain and meshing. After that, the boundary conditions have been implemented for the building and the domain and the turbulence model and the equations have been selected. Finally, the wind responses have been calculated after the successful completion of the numerical analysis.

3.1 Computational Domain Setup

The extreme boundary of the domain is placed at a distance of 15H, 5H and 5H from the model's back face, two side faces and the front faces respectively [11]. The sidewalls and roof of the boundary are governed by the free slip boundary conditions, whereas no slip is adopted for the model faces (Fig. 2). The simulation has been executed on k-ε turbulence model. 10 m/s wind velocity is produced at the domain inlet. 1 m height is considered for the Atmospheric Boundary Layer (ABL), which is generated by the power-law equation (Eq. 1).

$$\frac{V}{V_0} = \left(\frac{h}{h_0}\right)^{\alpha} \tag{1}$$

In the equation, 'h' and 'h_0' signify the reference height and the building depth above the ground respectively. 'V' and 'V_0' indicates the wind velocity at the 'h' and 'h_0' respectively. In this study, the exponent 'α' is taken as 0.133.

3.2 Generation of Mesh

The entire domain has meshed with tetrahedral elements but the fine layers of square elements are provided at the nearby locations of the building models (see Fig. 3) to measure the accurate wind responses of the building. This meshing technique is capable of generating reliable results without involving extensive computational resources.

3.3 Mesh Sensitivity Study

The suitable meshing technique has been determined by the mesh sensitivity study on the M2 type model at a normal wind angle. Seven mesh elements size has been adopted for this study. The total element sizes are 1,457,621 (MS1), 4,865,743 (MS2), 8,498,327 (MS3), 13,874,521 (MS4), 19,845,372 (MS5), 24,657,894

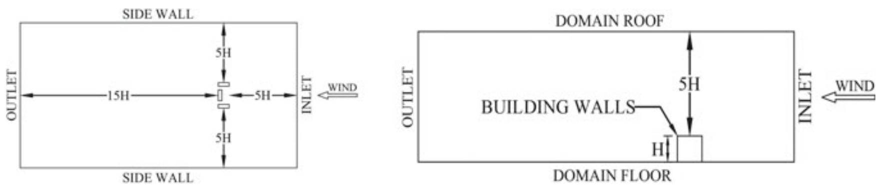


Fig. 2 Plan and elevation view of the domain

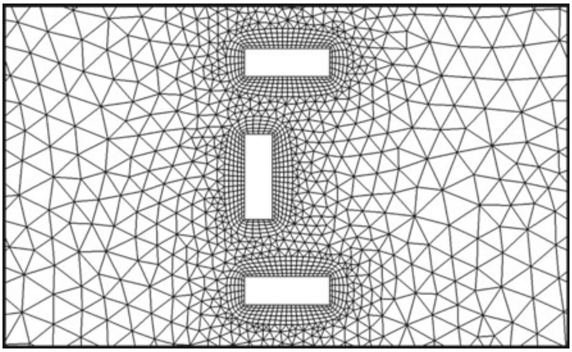


Fig. 3 The typical mesh pattern for the M5 model

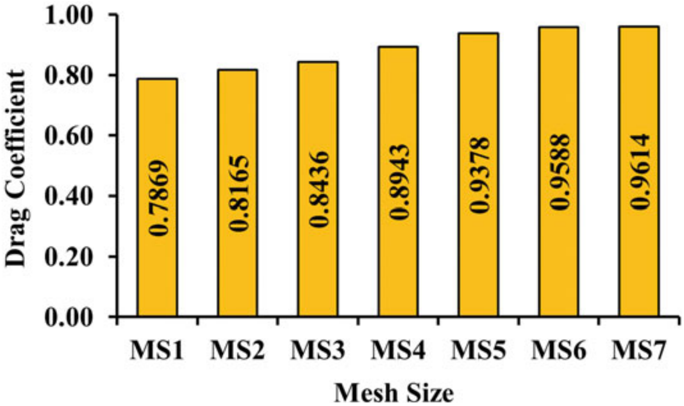


Fig. 4 The mesh sensitivity study of the M2 model

(MS6) and 31,287,459 (MS7), which represents course to fine meshing. From the drag coefficient comparison (see Fig. 4), the MS6 type mesh has been selected for this study since the computational error in the MS6 type is approx. 0.27% as compare to MS7 mesh type.

3.4 Validation

The validity of the measured responses of the current study has been investigated by comparing the pressure coefficient graphs from the literature [12] (see Fig. 5). Exactly the same model dimensions and the other analysis techniques have been

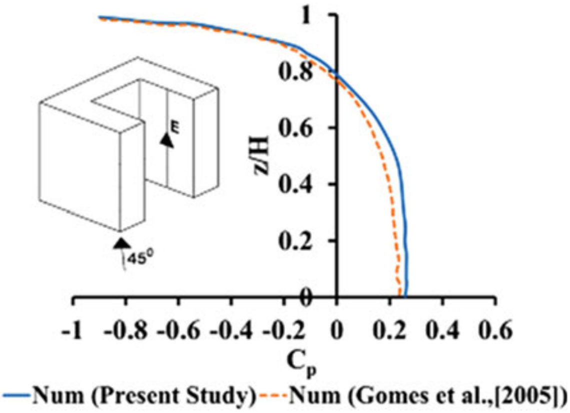


Fig. 5 The comparison of the vertical pressure profile

considered. The comparison of pressure plot shows almost similar trends and that validates the current study.

4 Results and Discussion

The wind responses of the isolated and closely spaced model cases have been demonstrated in 0°, 45° and 90° wind angle. The comparison of the responses on different model cases indicates the influence of the closely spaced interference buildings.

4.1 Variation in Wind Flow Streamline

Some typical wind flow patterns have been demonstrated in Fig. 6. The free flow of the wind largely affected by the presence of closely spaced buildings. The formation of vortices at the leeward and side faces of the interference building causes remarkable variation in wind responses compared to the isolated rectangular case. The prolonged vortices have been formed at the backside of the rectangular shape in the presence of interference buildings. It is also observed that the streamlines dependent on the location of the interfering buildings and the angle of the wind.

4.2 Variation in Force Coefficients

The force coefficients have been calculated at different wind angle for the isolated rectangular building (M1). When interferences cases have been considered the

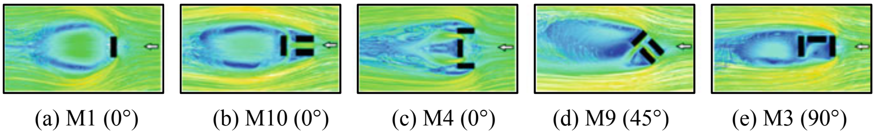


Fig. 6 The flow patterns around the typical building models

Table 1 The comparison of force coefficients at the various wind angle

	Wind angle (0°)		Wind angle (45°)		Wind angle (90°)	
Model	C_{fx}	C_{fy}	C_{fx}	C_{fy}	C_{fx}	C_{fy}
M1	1.036	0.011	0.786	−0.878	−0.052	−0.871
M2	0.959	0.011	0.817	−1.187	−0.092	−0.932
M3	1.125	0.005	0.741	−0.144	−0.002	0.074
M4	1.124	0.001	0.940	−0.186	−0.020	0.141
M5	1.024	0.007	1.062	−0.164	−0.047	0.165
M6	1.003	0.003	1.146	−0.036	−0.040	0.185
M7	0.932	0.004	0.689	−1.564	−0.030	−1.286
M8	0.393	0.048	0.209	−0.686	0.277	−1.169
M9	0.512	0.005	0.344	−0.568	0.306	−1.210
M10	0.519	0.021	0.469	−0.563	0.309	−1.221
M11	0.507	0.032	0.509	−0.589	0.342	−1.219

changes in the drag (C_{fx}) and lift (C_{fy}) coefficient of that building is tabulated in Table 1. At 0° the reduction in drag coefficient is measured when the three rectangular shapes are attached with each other to form a U shape (M2 and M7). The sidewards shifting of the two buildings (M3 and M4) attracts more drag force. However, when the distance of interference building is increased (M5 and M6) the darg force reduces. When the interference buildings are located at the front side of the rectangular building (M7–M11) the drag coefficient decreases. The lift coefficient at 0° is almost insignificant in all the model cases. In the case of 45° wind angle, when the interference buildings are located at sidewards the C_{fx} increases and C_{fy} decreases but both the coefficients increases in the attached U shape (M2). In the M7 case the C_{fy} is maximum but the frontward shifting of the interference buildings attracts less C_{fx} and C_{fy}. Almost negligible lift and drag force are noted in the M3, M4, M5 and M6 models but at M8, M9, M10 and M11 model cases the rectangular building experiences more drag and lift force as compared to the isolated rectangular model (M1) case. When the interference buildings are attached to the rectangular building (M7), it is observed that the lift force is critical at 45° and 90° angle. The maximum C_{fx} is noted at the rectangular building when the interference building is located sidewards at a distance of 7.5 m. In most cases, the interference caused a huge increment in drag and lift responses of the rectangular building.

Table 2 The Interference factor of the different faces of the isolated rectangular building

	Wind angle (0°)				Wind angle (45°)			
Model	A	B	C	D	A	B	C	D
M1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
M2	1.338	–	0.739	–	2.001	–	0.337	–
M3	1.058	1.326	1.160	1.332	0.827	−2.537	0.984	0.999
M4	0.946	1.457	1.369	1.454	1.231	−2.475	1.070	1.053
M5	0.949	1.238	1.055	1.245	1.392	−2.422	1.229	1.058
M6	0.966	1.117	1.569	0.687	1.486	−2.381	1.299	1.067
M7	0.923	1.027	0.950	1.027	1.110	2.348	0.884	0.873
M8	0.212	0.607	0.651	0.709	0.256	0.775	0.754	0.802
M9	0.376	0.716	0.675	0.704	0.024	0.657	0.835	0.647
M10	0.403	0.725	0.647	0.693	0.226	0.516	0.943	0.687
M11	0.398	0.708	0.625	0.659	0.378	0.437	0.920	0.736

4.3 Variation in Interference Factor of Pressure Coefficients

The mean pressure coefficients have been calculated on the different faces of the rectangular building in both isolated and interference conditions. The mean local pressure at the faces greatly influenced by the interference building since the presence of the building changes the wind flow pattern. The wind angle shifts also contribute to the pressure variation. The Interference Factor (IF) is the ratio of mean pressure of the particular face on interference condition to that of the mean pressure of this face at isolate condition. The interference factor and the mean pressure coefficient of isolated rectangular shape have been tabulated in Tables 2 and 3. On interfering conditions, the mean pressure coefficient (C_p) on the faces of the rectangular model can be calculated by the following formula.

$$C_{p,\text{Interfering}} = \text{Interference Factor (I.F)} * C_{p,\text{Isolate}} \tag{2}$$

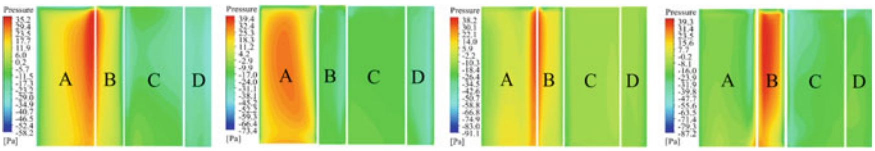
Almost all the faces have the positive IF but in some of the cases (M3, M4, M5 and M6) at face B, the negative IF is noted in 45° and 90° angle. The negative IF indicates the generation of high turbulence on that face because of interference building.

4.4 Variation in Pressure Contour

The pressure variation at different locations of the building faces has been illustrated through contour plots. The pressure contour on all the faces of the isolated

Table 3 The Interference factor of the different faces of the isolated rectangular building at a 90° angle and the mean pressure coefficient on the different faces of the isolated rectangular building

	Interference factor (90°)				Mean pressure coefficient			
Model	A	B	C	D	Face	0°	45°	90°
M1	1.000	1.000	1.000	1.000	Face A	0.641	0.349	−0.440
M2	1.209	–	1.058	–				
M3	1.140	−1.086	1.128	1.944	Face B	−0.447	0.209	0.487
M4	1.213	−1.118	1.159	1.795				
M5	1.222	−1.051	1.118	1.590	Face C	−0.319	−0.404	−0.440
M6	1.167	−1.082	1.092	1.573				
M7	1.734	0.978	1.819	1.903	Face D	−0.447	−0.629	−0.236
M8	0.968	0.926	1.623	2.491				
M9	0.954	0.917	1.633	2.658				
M10	0.932	0.929	1.613	2.661				
M11	0.883	0.943	1.625	2.620				



(a) M1 (45°) (b) M4 (45°) (c) M9 (45°) (d) M8 (90°)

Fig. 7 The comparison of pressure contour plot on the faces of the rectangular building

rectangular shape (M1) at 45° has been presented. To visualize the pressure variation due to interference buildings the M4 and M9 model has been adopted with the same wind angle. The pressure contour profile of the M8 model at a 90° angle has been attached to show the pressure variation when the wind angle shifts. The comparison of pressure contour has been given in Fig. 7. The comparison clearly shows that the pressure on the faces of rectangular building altered in the presence of interference buildings. The location of the interference building and the wind angle also contributes to pressure differences on the building faces. In isolated condition the corners of face A and B exerted positive pressure and face C and D has negative pressure but when interference building is present in sidewards (M4), most of the location of face A experiencing the positive pressure and all other faces have negative pressure. When interfering buildings are present at frontwards the corners of face A and B have positive pressure but the locations of these pressure are very limited compare to isolated condition. When the angle shifts, the positive pressure is observed in most of the locations at face B of the M8 model and the other faces are experiencing the negative pressure.

5 Conclusions

The influence of closely spaced interference buildings on wind responses in the existing structure has been demonstrated at 0°, 45° and 90° wind angle using CFD. The comparison of pressure contour, lift, drag and interference factor of pressure has been illustrated. The findings point out some important factors.

- The nonhomogeneous flow pattern yields since the location of interference buildings and wind angle changes. Thus, a significant variation in responses has been recorded. It indicates that the location, wind angle and distance between buildings should be considered for understanding the interference effect.
- The structural elements of the buildings should be designed by taking the effect of the presence of interference buildings because if the distance between the buildings is less, it causes a significant variation in drag and lift coefficient.
- The pressure on the building faces shows the critical variable in the presence of interference buildings. Hence the strong clad elements are required for the safety of the structure.
- Among all the building configurations, the M8 type is best suitable since this model type attracts less force and pressure most of the times compared to other model types. However, it is also observed that the sidewards building configurations draw lesser force when the flow angle charges.

As the wind effect on a rectangular building in the presence of closely spaced tall buildings in U shape geometrical pattern is not stated in earlier studies, this study provides a piece of information and a reasonable idea about the interference effect of the wind.

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