August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering

Numerical Evaluation of Spatial Variability of Pressure Coefficient on Tall Buildings against Wind Forces

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SUMMARY:
The current design standards consider a constant pressure coefficient which does not represent the actual behaviour which is spatially varying in nature. A comprehensive study to numerically evaluate the spatial variability of pressure coefficients on tall buildings due to wind forces is performed. The spatial variability is captured in the horizontal plane at reference height which is selected such that it can be used to scale the pressure coefficients at others levels. CFD simulations are performed for various plan aspect ratios of building with constant building height using steady-state RANS modelling. The results indicate that the pressure coefficient is independent of plan aspect ratio for the front face, whereas it can be represented as a constant value across the back face. In case of the side face, the pressure coefficient variation can be decomposed into two parts, a constant linear curve independent of plan aspect ratio and curve which is a function of plan aspect ratio for the latter portion. The model will help in capturing actual distribution which the design standards ignore and may lead to under- and over-estimation of design wind forces at various location of building.

Keywords: CWE, Turbulence Modelling, Spatial Variability

1. INTRODUCTION

Tall-building infrastructure is increasing at a tremendous pace around the world over the last few decades. Wind hazard usually governs the behaviour of tall buildings as the frequency content is in the same range. The behaviour against wind loads mainly depends on the shape and orientation of the building, which is usually captured through either Computational Fluid Dynamics (CFD) simulations (Huang et al., 2007; Kareem, 2020) or Boundary Layer Wind Tunnel (BLWT) experiments (Venanzi et al., 2018; Zhou et al., 2003).

Pressure (and pressure coefficient) at the building surface is a major response which governs the behaviour under wind loads and is specified by the design standards to determine the design forces. The mean pressure coefficient is a spatially varying response i.e., the value will be a function of space. The current design standards (ASCE 7, 2016; IS: 875 (Part 3), 2015) specify a constant pressure coefficient over each face which does not represent the actual behaviour which is a major drawback. The current study attempts for numerical evaluation of spatial variability of the pressure coefficient in the horizontal plane through CFD simulation using steady-state realizable k-ε RANS (Reynolds Averaged Navier-Stokes) model. The CFD simulations are performed for different plan aspect ratios with constant height and spatial variability captured as a function of plan aspect ratio.

2. NUMERICAL MODEL DESCRIPTION

The current study considers a numerical model of rigid rectangular tall building with 1:300 length scale and 1:3 velocity scale. Turbulent flow is ensured in the simulation by keeping the Reynolds number greater than 105. Steady-state analysis using realizable k-ε Reynolds Averaged Navier Stokes (RANS) turbulence model has been performed for different plan aspect ratios on commercially available ANSYS Fluent using Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm for solving discretized equations along with second-order upwind discretization for all variables.

A constant building height (150m) and width of the building perpendicular to the wind flow (45 m) is considered with reference velocity at building height as 30 m/s. The simulation is performed for 13 plan aspect ratio $(r_p = B/D)$ varying from 0.5 to 2.0 (D = *90m* to *22.5m*). The inlet velocity and turbulence intensity profile is obtained from the wind tunnel studies conducted by the NatHaz database (Zhou et al., 2003) as shown in Fig. 1 along with the computational domain of the simulation. A mesh convergence study is performed along with an optimum domain size study following the process in line with Abu-Zidan et al., (2021) to determine the minimum domain size which does not affect the results on the building.

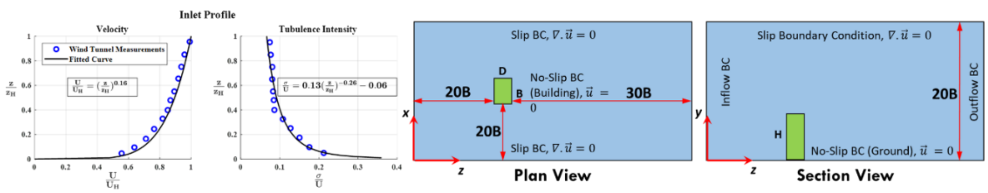

Figure 1. Inlet Boundary Conditions and Computational Domain

The calibrated model is validated with the CFD and wind tunnel experiment described in Huang et al., (2007) is performed by comparing the drag coefficient. The drag coefficient reported in the literature is 1.83 and the calibrated CFD model gives 1.82. This indicates that the calibrated CFD model can be used to assess the wind effects on buildings.

3. RESULTS AND DISCUSSION

The pressure coefficient, $C_P = (p - p_o)/(0.5\rho U_H^2)$ on the building surface obtained from the CFD analysis performed on 13 building with various aspect ratio is decomposed into each face of the building (front, sides, and back face). The schematic of the building section and associated length used for spatial variability formulation is shown in Fig. 2.

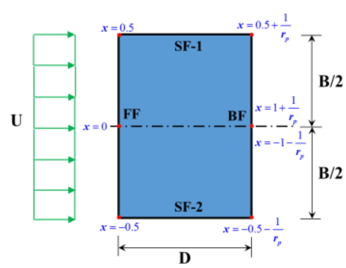

Figure 2. Schematic of Building Section

3.1. Selection of Reference Height

The reference height (z_s) for the spatial variability is selected such that the pressure coefficient at that height can be used to scale the pressure coefficients at other levels with minimum total variance at each face. The coefficient of variance (standard deviation to mean) results at each level for different faces are in same range and hence equally contribute to the variance. The total variance is in the same range when the reference height is between *0.2H to 0.8H*. Based on this, *2H/3* is considered as the reference height in this study as a stagnation point is also formed in the region (Holmes, 2018; Huang et al., 2007).

3.2. Spatial Variability of Pressure Coefficient

The mean pressure coefficient at the building surface at the reference height ($z_s = 2H/3$) for various plan aspect ratios is shown in Fig. 3. The main observations about the mean pressure coefficient that can be drawn are listed below.

1. It is symmetric around the cross-sectional and hence the model will be symmetric function.
2. It is independent of the plan aspect ratio at the front face which can be represented using single equation.
3. It is nearly constant at back face and represented as constant mean value across the back face.
4. It can be decomposed into two parts at side faces: linear variation up to |x| = 0.63 (independent of the aspect ratio) and function of plan aspect ratio after that.

Based on the above observations, the regressions are performed and the final set of equations for the spatial variability is given in below equation.

$$C_P = \begin{cases} -62.97|x|^{5.71} + 0.93 & ; \quad 0 < |x| < 0.5 \\ -5.5(|x| - 0.63) - 0.95 & ; \quad 0.5 < |x| < 0.63 \\ a_{SF}(|x| - 0.63)^{b_{SF}} & ; \quad 0.63 < |x| < 0.5 + 1/r_P \\ a_{BF} & ; \quad 0.5 + 1/r_P < |x| < 1 + 1/r_P \end{cases} \qquad (1)$$

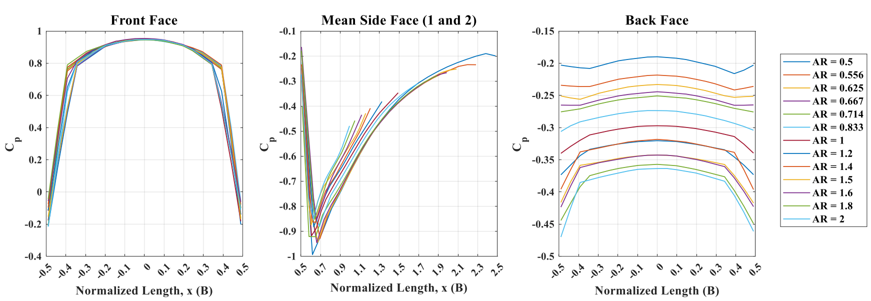

Figure 3. Pressure Coefficient at Reference Height (z_s = *2H/3*)

The Eq. (1) is fitted for all plan aspect ratios using least square minimization and the coefficients are determined. The coefficients are then fitted as a function of plan aspect ratio and the resulting equation is given below. The plot of the fitted equations with the simulation results for 3 plan aspect ratio is shown in Fig. 4 for ready reference which indicates a good fitting.

$$a_{SF} = 0.81 - 0.13/r_P \quad ; \quad b_{SF} = 0.72 - 0.09r_P \quad ; \quad a_{BF} = 0.4e^{-1.37r_P} - 0.41 \qquad (2)$$

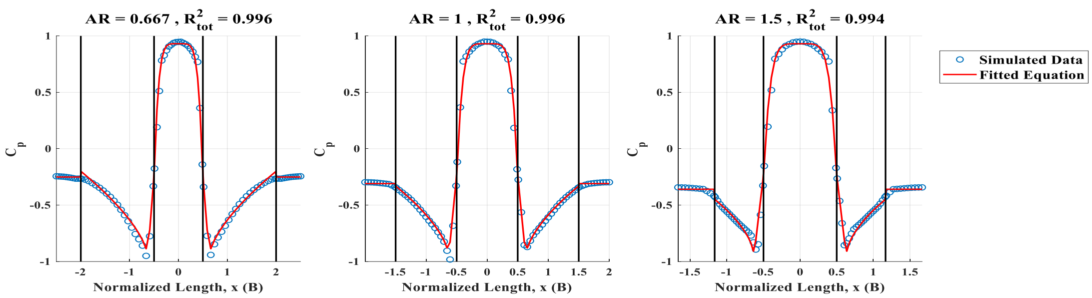

Figure 4. Pressure coefficient at reference height for 3 plan aspect ratios

This concludes the spatial variability of pressure coefficient in horizontal plane. The developed model will indeed increase the complexity in calculation of the forces on the building when compared with the codal provisions, however they may lead to under-estimation and over-estimation of design forces at various location in the building.

4. CONCLUSIONS

Following conclusions can be drawn from the CFD simulation performed for wind flow around tall buildings.

1. The current design standards consider a constant pressure coefficient on the building surface which does not represent the actual behaviour which is spatially varying in nature.
2. The 2H/3 is selected as the reference height to characterize the spatial variability of pressure coefficient such that the pressure coefficient at that height can be used to scale the pressure coefficients at other levels with minimum variation at each face.
3. The results indicate that pressure coefficient is independent of the plan aspect ratio at the front face, can be represented by mean value across the back face, and can be decomposed into two curves which can be represented as a function of the plan aspect ratio across the side face.
4. The spatial variability equations fitted to the simulated data show a good overall fitting.

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