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# A Study on Causes of Variability in Peak Wind Pressure Coefficients on Low-Rise Building Evaluated by Large-Eddy Simulation

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## SUMMARY

This study investigates the causes of variability in peak wind pressure coefficients on a low-rise building evaluated using Large-Eddy Simulation (LES). While ensemble averaging is standard practice, the specific flow mechanisms causing scatters among ensembles in CFD results remain unclear. By analyzing five ensemble samples, we identified that samples yielding atypically large negative peak pressures were subjected to spatially coherent high-speed flow structures acting on the building. Detailed analysis of the inflow revealed that these specific samples possessed autocorrelation coefficients exceeding theoretical one based on the Von Karman spectrum at specific time lags. These unexpected "high-correlation" fluctuation components facilitate the formation of large-scale gust structures, which in turn generate extreme negative pressures. The findings suggest that incidental deviations in the autocorrelation of generated inflow turbulence in CFD are one of the significant contributing factors to the variability in peak wind pressure evaluation.

***Keywords:*** *Large-Eddy Simulation (LES), Peak wind pressure coefficient, Low-rise building, Bluff body, Autocorrelation*

## 1. INTRODUCTION

When evaluating design wind loads (specifically peak wind pressure coefficients) on buildings using wind tunnel tests, it is common practice to employ ensemble averaging over multiple evaluation times (samples). This approach accounts for the fact that the occurrence of extreme values is a stochastic phenomenon. It is generally recognized that the variability of peak wind pressure coefficients evaluated by means of wind tunnel tests - arising from the randomness of the phenomenon itself and experimental uncertainties - typically exhibits a coefficient of variation (COV) of approximately 20% (Fritz et al., 2008). Similarly, ensemble averaging using multiple samples is applied in cases peak wind pressure coefficients evaluated using Computational Fluid Dynamics (CFD). However, in CFD simulations where boundary conditions are strictly controlled, the precise causes of this variability have not been fully investigated. Therefore, this study conducts Large Eddy Simulations (LES) of flow around a low-rise building to analyze the factors contributing to the variability in peak wind pressure coefficients, specifically investigating how the fluctuating components of the approach flow generate this variability.

## 2. COMPUTATIONAL CONDITIONS

The subject of analysis was a low-rise gable roof building as shown in Figure 1. The experimental data in the TPU aerodynamic database (TPU, 2012) is employed as reference. The wind direction was set normal to the long wall, and the computational domain was configured as shown in Figure

2. The scales adopted were 1/100 for geometry, 1/3 for velocity, and 3/100 for time. The numerical simulations were carried out using OpenFOAM v2306. The standard Smagorinsky model ($Cs$ = 0.12) was used for the LES subgrid-scale model. The mesh was primarily hexahedral, refined such that the grid resolution on the building surface was less than $B/100$. Additionally, three prism layers were arranged near wall boundaries for both building surface and ground. A second-order central difference scheme was used for spatial discretization, and a standard wall function based on Spalding's law of the wall was applied to wall boundary conditions. The inflow turbulence was generated using the digital filter method (Xie and Castro, 2008) targeting the flow characteristics of AIJ terrain category III (AIJ, 2015). A total duration of 100 seconds was simulated. Excluding the initial transient period, five samples of 18 seconds each (equivalent to 10 minutes in full scale) were extracted from the 10 to 100-second interval. The reference wind speed ($U_{ref}$) was defined as the wind speed at the mean roof height located 0.5 m upstream of the building center. The wind pressures acting on the building surface were sampled at 1000 Hz at 256 points identical to the TPU experimental locations. A time averaging equivalent to 0.2 seconds in full scale was applied, followed by normalization using the mean velocity pressure of each sample. Mean, maximum, minimum as well as fluctuating wind pressure coefficients ($C_p$) were calculated for each sample.

## 3. ANALYSIS RESULTS

The vertical profiles of the mean wind speed and turbulence intensity at the reference position, along with the Power Spectral Density (PSD), are shown in Figure 3. Here, $n$, $S_u$, $\sigma_u$, and $L_u$ denote frequency, power spectral density, RMS fluctuating

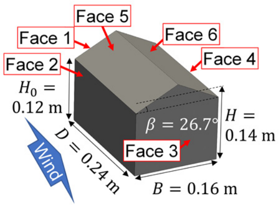


Figure 1: Specimen.

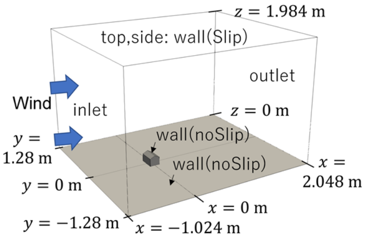
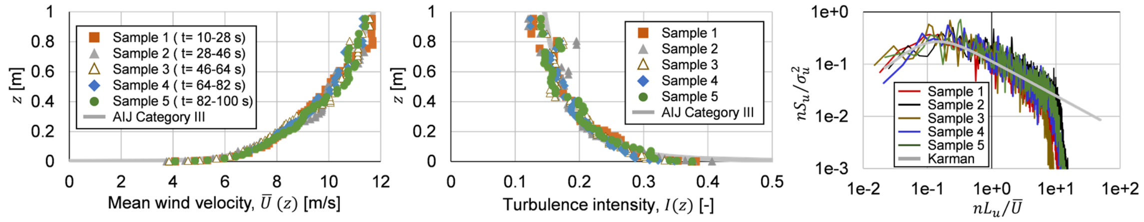
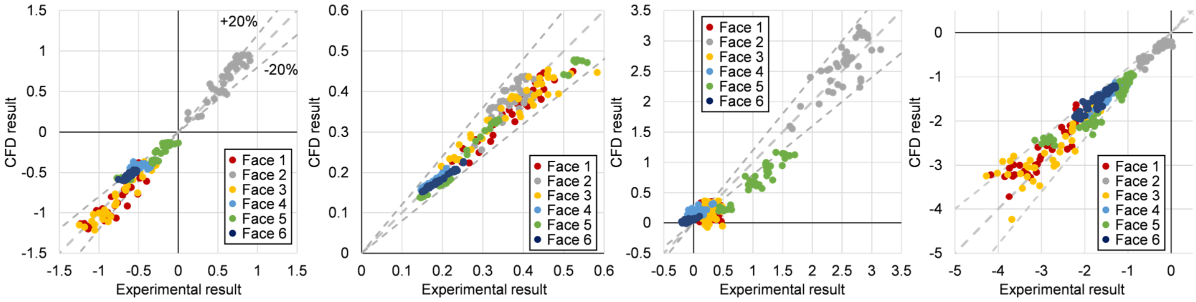


Figure 2: Computational domain.



(a) Mean wind speed. (b) Turbulence intensity. (c) Non-dimensional PSD.

Figure 3: Vertical profiles of mean wind speed and turbulence intensity at the reference position, along with the PSD.



(a) Mean $C_p$. (b) RMS $C_p$. (c) Maximum $C_p$. (d) Minimum $C_p$.

Figure 4: Comparisons of the statistical values of $C_p$ between experimental and CFD results.

wind speed, and turbulence scale, respectively. The generated inflow shows good agreement with the targeted AIJ terrain category III profiles and the Karman spectrum, confirming the reproduction of an appropriate boundary layer flow. A comparison of the statistical values of various coefficients $C_p$ between experimental and CFD results is presented in Figure 4. The experimental values represent the ensemble average of 10 samples, whereas the CFD values are the average of 5 samples. The CFD results generally agree with the experimental results within a range of approximately $\pm 20\%$, indicating reasonable predictive accuracy. The variability of the minimum peak wind pressure coefficients among the five samples is shown in Figure 5. The values fluctuate among the samples; notably, Sample 5 (simulation time 82-100 s) recorded significantly larger negative peaks compared to other samples. To investigate the cause, the time history of the reference wind speed for each sample was plotted against the occurrence times of the minimum peak wind pressure coefficients for all 256 measurement points (Figure 6). In Sample 5 specifically, it is evident that many measurement points simultaneously experienced negative peaks around $t = 85$ s. Confirming the instantaneous velocity contours at the mean roof height section around this time (Figure 7), a spatially large-scale high-speed region (gust) is observed. This is inferred to be the cause of the widespread generation of large negative pressures. Furthermore, to analyze the characteristics of the inflow in detail, the autocorrelation coefficient $R(\tau)$ of the reference wind speed for each sample is shown

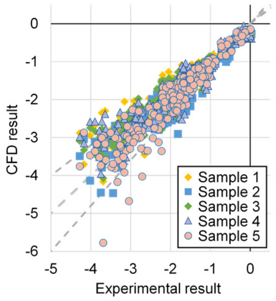
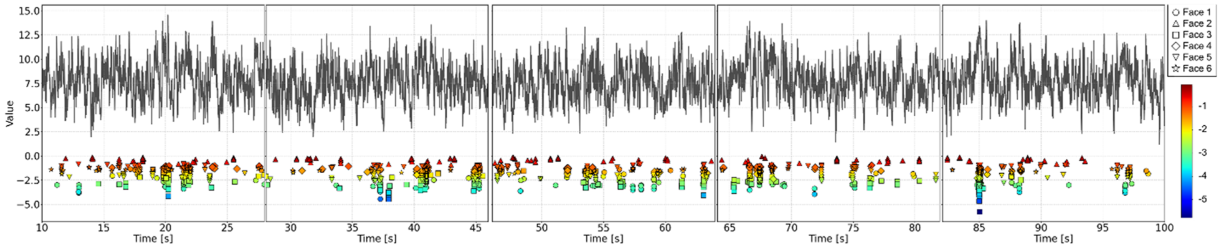


Figure 5: Variability of the minimum $C_p$ among the five samples.



(a) Sample 1. (b) Sample 2. (c) Sample 3. (d) Sample 4. (e) Sample 5.

Figure 6: Time history of $U_{ref}$ against the occurrence times of the minimum $C_p$.

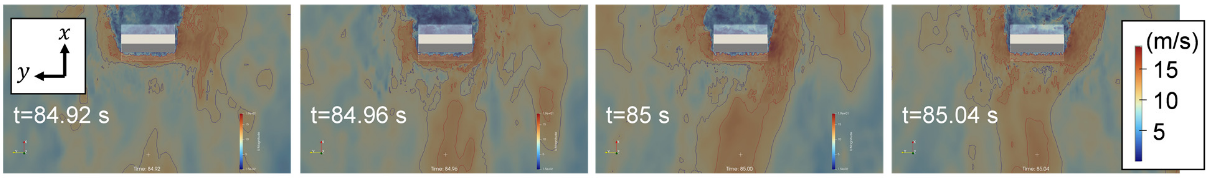
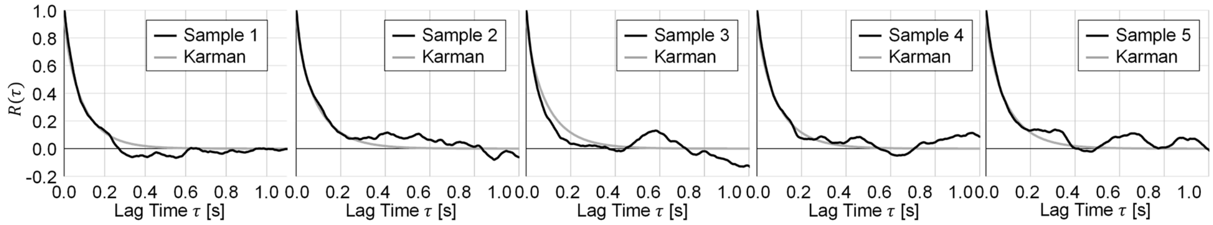


Figure 7: Instantaneous velocity contours at the average roof height section around $t = 85$ s.



(a) Sample 1. (b) Sample 2. (c) Sample 3. (d) Sample 4. (e) Sample 5.

Figure 8: Autocorrelation coefficient $R(\tau)$ of the reference wind speed for each sample.

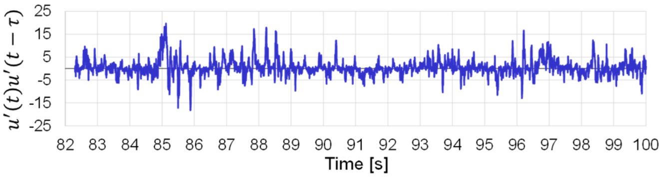


Figure 9: Time series of the covariance contribution component $u'(t)u'(t-\tau)$ at $\tau = 0.3$ s for Sample 5.

in Figure 8, along with the theoretical curve based on the Von Karman spectrum. In Sample 5, the correlation value is notably higher than this theoretical prediction (and other samples) in the lag range of $\tau = 0.2 \sim 0.4$ s. To clarify the relationship between this high autocorrelation region and wind speed fluctuations, the time series of the covariance contribution component $u'(t)u'(t-\tau)$ at $\tau =$ 0.3 s is shown in Figure 9 (where $u'$ is the fluctuating wind speed). Since the autocorrelation coefficient corresponds to the average value of this time series, intervals with large positive deviations are the main factors increasing autocorrelation. The figure indicates that these intervals of large positive contribution correspond to the time zones where negative peaks occurred at many measurement points, e.g. 85s, 88s and 97s. Based on the above, it is considered that when regions with unexpectedly high autocorrelation (large temporal and spatial scale fluctuation components) occur in the approaching fluctuating wind, they form spatially coherent high-speed flow structures. The impact of these structures on the building generates statistically extreme negative peak pressures, becoming a contributing factor to increased variability between ensemble members.

## 4. CONCLUSIONS

This study conducted LES analysis of flow around a low-rise building to elucidate the factors causing variability in the evaluation of peak wind pressure coefficients using CFD, analyzing the fluctuation characteristics of each sample in detail. The results confirmed that in samples recording atypically large negative peak wind pressure coefficients, spatially coherent high-speed flow structures were observed acting on the building. Furthermore, autocorrelation analysis of the wind speed revealed that these specific samples exhibited autocorrelation values exceeding the theoretical predictions at particular time lags ($\tau = 0.2 \sim 0.4$ s). It was clarified that the presence of these "fluctuation components with stronger-than-expected correlation" is a primary factor leading to the formation of spatially large-scale gust structures, consequent increases in peak wind pressure, and ultimately, variability in evaluated values.

### ACKNOWLEDGEMENTS

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