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Correlation and combination of wind force components and responses

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ABSTRACT

This paper summarizes the findings from extensive wind tunnel tests carried out by the authors' group for the evaluation of wind load combination effects for various types of building models. Characteristics of correlations of wind force components are examined using the absolute ratio of wind forces, phase–plane trajectories and (absolute) cross-correlation, and then wind load combinations are examined. The necessity to consider wind load combinations is inferred from the instantaneous pressure distributions, and the cross-correlation coefficients of the absolute values of wind force components are found to be more important when examining wind force combinations. Wind load combination effects are directly examined using frame models. Based on the peak normal stresses in columns under various loading conditions, combination factors for low-, middle- and high-rise buildings are proposed. Lastly, effects of wind direction on wind load combinations are discussed.

1. Introduction

Fluctuating pressures on building surfaces are due to approach-flow turbulence, flow separation and re-attachment, vortex shedding and so on. The necessity to capture maximum wind forces was first identified by Davenport (1961), and introduced as a gust loading factor. Based on the concept of maximum wind load effects, Davenport (1983) discussed the reliability of methods for obtaining wind loadings on low-rise buildings, and suggested some important factors for their more accurate assessment. According to observations of fluctuating pressure fields on building models, instantaneous pressure distributions are mostly non-symmetric even when the mean wind direction is normal to a wall of a rectangular plan model. Holmes (1988) studied the distributions of instantaneous wind pressures along a gabled roof frame producing peak loads and load effects, and found considerable variations in the instantaneous pressure distribution.

A phenomenon relating to concomitancy has also been studied in the context of equivalent static wind loads (ESWLs), which were established by Kasperski (1992) using the load–response correlation method. ESWLs defined the most probable load profiles corresponding to specific structural responses, but they were limited to background response. For the intermediate responses between background and resonant, Chen and Kareem (2001) formalized ESWLs by using a weighted combination of modal inertia load components, or background and resonant load components. Those studies produced huge mathematical expressions, which were not widely applicable.

The maximum and minimum values that may reach any structural responses define the envelope, and equivalent static wind loads allow recovery of extreme responses in the envelope. The design of a structure by means of static wind loads is nothing but an envelope reconstruction problem (Blaise and Denoel, 2013), and the envelope reconstruction problem has been criticized by Katsumura et al. (2007), Fiore and Monaco (2009) and Zhou et al. (2011). Blaise and Denoel (2013) proposed the principal static wind loads to solve the envelope reconstruction problem.

Huge numbers of samples were analyzed for low-rise building models, and it is in Tamura et al. (2000, 2001) that instantaneous wind pressure distributions are never symmetric even when the along-wind force reaches a maximum. Therefore, in order to reflect actual maximum load effects in structural design of buildings, combination of these wind force components should be considered. It is commonly known that along-wind force fluctuations are mainly generated by approaching flow turbulence, but the dominant cause of across-wind force and torsional moment fluctuations is vortex shedding. Thus, it had been believed that across-wind force and torsional moment were well correlated, but along-wind force was not correlated with the other two components. However, Tamura et al. (2003) explained that in design of low- and medium-rise buildings, along-wind response was generally predominant, but that their combinations tended to be

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Table 1
Experimental building models and flow conditions (Unit: mm).

Model	Plane	Name	B	D	H	Scale	Case
Low	Square	LS	200	200	50	1/250	2
Low	Rectangular	LR	170	120	50	1/250	
Medium	Square	MS1	200	200	200	1/250	21
Medium	Square	MSa1–5	100	100	100–500	1/400	
Medium	Rectangular	MRa1–5	200	100	100–500	1/400	
Medium	Rectangular	MRb1–5	250	100	100–500	1/400	
Medium	Rectangular	MRc1–5	300	100	100–500	1/400	
High	Square	HS2, 3, 4, 5	100	100	200, 300, 400, 500	1/400	16
High	Rectangular	HRa2, 3, 4, 5	200	100	200, 300, 400, 500	1/400	
High	Rectangular	HRb2, 3, 4, 5	250	100	200, 300, 400, 500	1/400	
High	Rectangular	HRc2, 3, 4, 5	300	100	200, 300, 400, 500	1/400	
Flow condition			Power-law exponent α=1/4, 1/6				$39\times 2=78$

ignored. Tamura et al. (2008) shows the directional influence of wind force combinations and its load effect on middle-rise buildings. They also introduced the concept of a combination factor for estimating the equivalent across-wind load applied simultaneously with along-wind load.

Currently, different procedures for obtaining wind load combinations were found in some codes and standards. Architectural Institution of Japan (2004) provides a procedure for obtaining wind load combinations that depends on the aspect ratio of the building. For buildings with an aspect ratio less than 3, it is not necessary to estimate across-wind and torsional wind loads, but equivalent across-wind load expressed in terms of a combination factor should be applied in the across-wind direction in combination with along-wind load. For buildings with an aspect ratio larger than 3, three equations were provided for wind load combinations, including gust effect factor and correlation coefficients between across-wind load and torsional moment. AS1170.2 (Australian/New Zealand Standard, 2009) gives a formula for peak resultant vector moment, where it is assumed that the peak resultant base moment is equal to the peak along-wind moment when the mean across-wind response is equal to zero and the across-wind dynamic response is less than or equal to the along-wind response. ASCE7-10 (2010) gives simple load combinations for buildings, where 75% of along-wind load and the same values are simultaneously applied in the across-wind direction, and the torsional load is also taken into account when there are any eccentricities in the X- and Y-principal axes.

This paper summarizes the findings from extensive wind tunnel tests carried out by the authors' group for the evaluation of wind load combination effects. The main purpose of the present paper is to comprehensively compare separately published results of low-, medium- and high-rise buildings to extract some common features and inherent natures, which cannot be seen from separate discussions. These include characteristics of correlations of wind force components such as the absolute ratio of wind forces, phase–plane trajectories and (absolute) cross-correlation. The second-order properties of cross-correlations were used to examine the interdependency between wind force components, although the along-wind force is a non-Gaussian process. Based on the peak normal stresses in columns under various loading conditions, the combination factors for low-, middle- and high-rise buildings are proposed. Lastly, effects of wind direction on wind load combinations are discussed.

2. Wind tunnel tests

Wind tunnel studies were carried out on rigid building models (78 cases in total) as shown in Table 1 under two different turbulent boundary layer flows. Fluctuating pressures were measured using a simultaneous multi-channel pressure measuring system. Pressure taps were uniformly distributed over the model surfaces and examples of low- (LS) and high-rise (HS3) building models and corresponding frame models for the analysis of peak normal stresses are shown in Fig. 1. Low-rise buildings are one- or two-story buildings, middle-rise buildings are three- to five-story buildings and high-rise buildings are buildings with more than 6 stories. Aspect ratio is defined as H/B.

The wind directions were varied from 0° to 90° at intervals of 5°. The power-law exponents α of mean wind speed profile were set at 1/6 for open flat terrains and 1/4 for urban areas (Fig. 2), and the wind speeds at the top of the model varied from case to case, ranging from 11 to 14 m/s. The geometrical scale was set at 1/250 and 1/400, and the time scales ranged from 1/109 to 1/178. The sampling frequency was set to 781 Hz, and tubing effects were numerically compensated by gain and phase-shift characteristics of the pressure measuring system. The fluctuating pressures were integrated to obtain along-wind force F_D, across-wind force F_L, vertical wind force F_T, two base overturning moments M_D and M_L, and base torsional moment M_T. They are expressed in non-dimensional forms based on the mean velocity pressure q_H at roof height: e.g., along-wind force coefficient $C_D=F_D/q_HBH$, across-wind force coefficient $C_L=F_L/q_HBH$, vertical lift force coefficient $C_T=F_T/q_HBD$, along-wind overturning moment coefficient $C_{MD}=M_D/q_HBH^2$, across-wind overturning moment coefficient $C_{ML}=M_L/q_HBH^2$, and torsional moment coefficient $C_{MT}=M_T/q_HBHR$, where $R=(B^2+D^2)^{0.5}/2$.

3. Results and discussions

3.1. Maximum wind force and other instantaneously observed wind forces (absolute ratio of wind force)

The combinations of the maximum value of one of the wind force components and the two other simultaneously recorded components have already been reported in Tamura et al. (2000, 2001, 2003, 2008) for low- and middle-rise buildings. The main findings can be summarized as follows: when the maximum along-wind force C_{Dmax} was recorded, the accompanying absolute ratio of torsional moment coefficient $|C_{MT}(C_{Dmax})/C_{MTmax}|$ is distributed almost uniformly from 0% to 100%. When the maximum across-wind force C_{Lmax} was recorded, relatively small torsional moments were recorded. When the maximum torsional moment C_{MTmax} was recorded, around 80% of the maximum along-wind force C_{Dmax} was simultaneously recorded, while a relatively small across-wind force $C_L(C_{MTmax})$, i.e., around 20% of its maximum value C_{Lmax}, was recorded. For high-rise building models, similar