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Fragility analysis of steel roofing cladding using wind tunnel data

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Abstract

Based on an illustrative low-rise building model whose wind pressure data were from a wind tunnel, a wind–induced damage estimation method for steel roofing is addressed in this paper. First, the proper orthogonal decomposition (POD) is adopted to interpolate the wind pressure for locations where the pressure tap is not assigned. Second, the internal wind pressure is calculated using a simulation method. Third, the internal force on the fastener is computed using the influence surface and the corresponding peak internal force is then estimated by a Gumbel conversion method. Fourth, the failure probability of a single panel and the fragility of whole roof are determined based on the Monte Carlo simulation (MCS), where the correlation among internal forces of fasteners is incorporated via the Nataf model.

1. INTRODUCTION

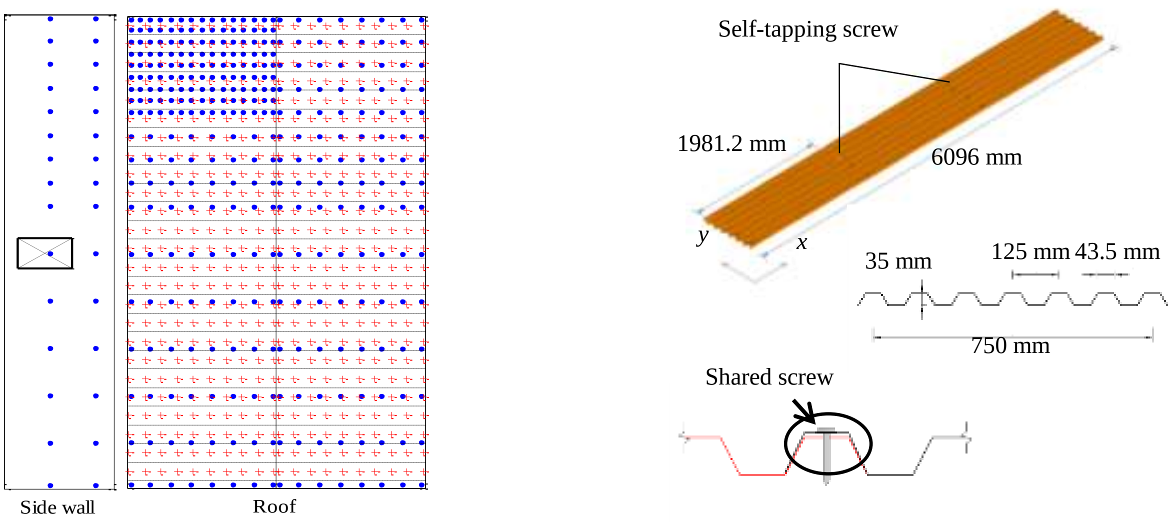
Metal structures are widely used in low-rise buildings, especially in non-residential buildings. Based on the statistics from Metal Building Manufacturers Association, approximately 65% of non-residential low-rise buildings are built with metal structures in USA (e.g., Dabral and Ewing 2009). Among these metal structures, the lightweight steel structure takes a major portion and is more popular for industrial buildings. However, much of these wind-vulnerable structures are located in wind-devastating coastal areas (e.g. China, USA and Australia). Every year the strong winds will cause significant economic loss on the lightweight steel structure. Hence, it is necessary to make a prediction of wind-induced damage to steel claddings for loss mitigation.

1.1. Description of steel roofing

The illustrative prototype industrial building with the size of 19.05 m × 12.2 m × 3.66 m and the roof slope of 1:12 is located on the suburban terrain. High-strength trapezoidal steel cladding, widely used as roofing cladding on low-rise industrial buildings for its larger spanning capacity and low price, is selected in this study. The layout of the cladding on the roof is shown in Fig. 1 (a). Dimensions and connection type for a cladding are illustrated in Fig. 1 (b).

1.2. Wind pressures data

The wind pressure data were obtained from the wind tunnel at the University of Western Ontario (UWO). The test model scale is 1:100. 335 taps were distributed on the roof top, as shown in Fig. 1(a) (see blue dots). The sampling frequency is 500 Hz while sampling time is 100 s. Details can be found in Ho et al. (2010) and Huang et al. (2015)



(a) Tap locations and panel arrangement (b) Cladding configurations

Figure 1 Illustrations for roof surface and steel cladding

2. EXTERNAL AND INTERNAL PRESSURES

2.1. External pressure

External pressures are based on data from wind tunnel. However, many panels even have no pressure tap. In order to evaluate the internal force on the screw more conveniently, the 10 proxy taps are evenly distributed on the central line of the each panel (see the red + in Fig. 1 (a)). With the help of POD technology, measured wind pressures at non-uniformly distributed taps can be used to interpolate those for proxy taps.

2.2. Internal pressure

Internal pressures have a significant influence on the structural and cladding-system loads and often arise due to leakage or openings. A rectangle dominant opening on the windward wall is assumed in the study (see Fig. 1 (a), side wall). A widely used method for simulating internal pressures (e.g. Oh et al. 2007) is adopted here.

3. INTERNAL FORCES AND THEIR PEAKS ON SCREWS

Strong winds often cause large uplift/suction loads on roof claddings, and these loads will be transferred to screw fasteners. According to Mahaarachchi and Mahendran (2009), the trapezoidal steel cladding is typically destroyed at the screw connection. Hence, the determination of the pulling force on the screw and its peak value is an important task. To circumvent the time-consuming finite element analysis, the influence surface-based approach is used to calculate the internal forces on screws as depicted in Eq. (1).

$$F_p(t) = \iint q(x,y,t) I_c(x,y)\,dxdy \tag{1}$$

where $I_c(x,y)$ is the internal force influence coefficient; $q(x,y,t)$ is the corresponding total pressure. Then their peak value distributions are estimated via Gumbel conversion method due to its straightforwardness, accuracy and efficiency.

4. CONSIDERATION OF CORRELATION FOR INTERNAL FORCES

Correlation among the internal forces exists due to the high correlation of the surface pressures. Hence, it should be considered to better estimate the wind-induced damage on steel claddings. Typically, the correlation for the processes is larger than that for peak values. The former will be used in this study for convenience and conservativeness. To incorporate the correlation in the cladding damage estimation, Nataf transformation is adopted (e.g. Liu and Der Kiureghian 1986).

$$f_{\mathbf{W}}(\boldsymbol{w}) = f_{W_1}(w_1) f_{W_2}(w_2) \cdots f_{W_n}(w_n) \frac{\varphi_n(\mathbf{z}, \mathbf{R_Z})}{\varphi(z_1)\varphi(z_2)\ldots\varphi(z_n)} \tag{2}$$

where $f_{\mathbf{W}}(\boldsymbol{w})$ is the joint PDF of peak forces; $\varphi_n(\mathbf{z}, \mathbf{R_Z})$ is the standard Gaussian n-variate joint PDF with the correlation matrix $\mathbf{R_Z}$.

5. DAMAGE ANALYSES ON ROOF SYSTEM

5.1. Failure probability of a roof cladding

Mahaarachchi and Mahendran (2009) showed that the trapezoidal steel cladding is vulnerable at the screw connection due to the pull-through failure by the strong wind uplift force. Based on a comprehensive parametric study, they developed strength formulae for the faster failure load for trapezoidal steed claddings with closed space ribs.

An appropriate assumption that one screw failure leads to the failure of whole cladding was made considering the redistribution of internal force. The failure probability for a cladding can then be expressed as

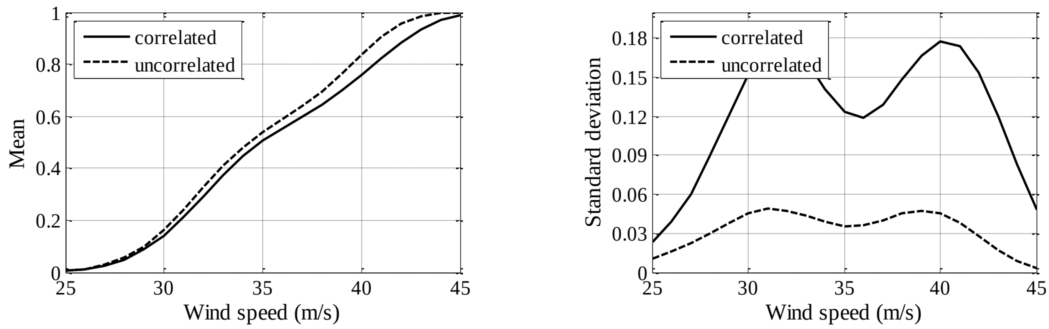
$$p = 1 - \iint\limits_{w_1<\phi r_1} \iint\limits_{w_2<\phi r_2} \cdots \iint\limits_{w_n<\phi r_n} f_{\mathbf{R}}(\boldsymbol{r}) f_{\mathbf{W}}(\boldsymbol{w})\,d\boldsymbol{r}d\boldsymbol{w} \tag{3}$$

where $f_{\mathbf{R}}(\boldsymbol{r})$ is the joint Gaussian PDF of strengths; ϕ is a capacity reduction factor.

5.2. Damage ratio of the entire roof

Damage ratio (*DR*) is used to estimate the overall damage over the roof. It describes the damage degree on the roof cladding and is defined as the percentage of total failed claddings, i.e., *DR* = *M* / *N*, assuming the number of failed and total claddings is *M* and *N*. When the number of involved variables (or screws) is large and the correlation is incorporated, MCS can be an efficient way in damage analysis.

Assume the MCS is repeated for n_t rounds. In *j* th simulation, $f_{i,j}$ denotes whether the *i* th cladding is failed ($f_{i,j}$ = 1 means damaged.). The failure probability of the *i* th cladding can be replaced to be $p_i = \frac{1}{n_t}\sum_{j=1}^{n_t} f_{i,j}$. And $\sum_{j=1}^{n_t} f_{i,j}$ is known to be the number of failed claddings in *j* th simulation. So the damage ratio for *j* th simulation will be $dr_j = \frac{1}{N}\sum_{i=1}^{N} f_{i,j}$. Every round in simulation is independent of the others. According to central limit theorem, the random variable *DR* will approach the Gaussian distribution approximately. The mean and standard deviation of damage ratio are determined accordingly. Results of mean and standard deviation for two cases (correlation is considered or not) are plotted in Fig. 2 (a) and (b) for various wind speeds under AOA of 315˚.



(a) Mean (b) STD

Figure 2 Damage ratios for various wind speeds under AOA of 315˚

6. CONCLUSIONS

Nataf transformation is well-performed in maintaining correlation among the simulated sample series for multivariable problem; and it is effective and convenient for damage estimation using MCS through which some damage analysis can be made. For every single cladding, the correlation among internal forces has little influence on failure probability. However, it will cause differences in both the mean and, especially, the standard deviation of damage ratio.

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