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Vulnerability analysis of steel roofing cladding: Influence of wind directionality

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ABSTRACT

Steel roofing is widely used for non-residential facilities. However, it is vulnerable to high winds. This paper addresses a damage estimation framework that incorporates wind loading correlation and wind directionality effects for steel roofing. In this framework, external pressures were measured from wind tunnel testing. At positions where pressure measurements are not available, a proper orthogonal decomposition (POD) method is introduced to interpolate external wind pressures. Internal pressures due to openings in the building envelope are taken into account by simulation. Then, the internal forces on fasteners distributed on the steel roof are evaluated by the influence-surface-based method, with corresponding peak values estimated by a Gumbel conversion approach. Furthermore, the failure probability of a single cladding element and the damage ratio for the whole roof are determined based on Monte Carlo simulation (MCS), where the correlation among internal forces of fasteners is incorporated by a Nataf transformation. Finally, wind directionality effects are integrated in order to provide a comprehensive damage assessment for the roofing. Although the proposed framework works for existing buildings, it may potentially benefit the performance-based design for new low-rise buildings.

1. Introduction

Metal structures are widely used for low-rise buildings, especially for non-residential buildings. Based on the statistics from Metal Building Manufacturers Association (MBMA), approximately 65% of non-residential low-rise buildings are built with metal structures in USA (e.g., [8]). Among these metal structures, lightweight steel structures represent a significant proportion and are popular for warehouses, sheds, airplane hangars and industrial buildings, which are vulnerable during hurricanes (or typhoons or tropical cyclones), thunderstorms and tornadoes (e.g., [35,10]). For example, typhoon "Rananim" in 2004 devastated industrial buildings in Zhejiang Province, China, including collapsed area of 2.72 million m^2 and damaged area of 7.56 million m^2 [37].

Post-event damage surveys have indicated that the majority of damage to steel structures is related to the breach of the envelope instead of the collapse of the main frame [31]. The breach of the roofing not only introduces losses to the building itself, but also triggers further damage to interior contents due to secondary perils, e.g., rain penetration. Additionally, business interruption increases indirect losses of income, which is a common concern for the insurance sector. Therefore, it is important to analyze and predict wind-induced damage for steel roofing in order to conduct damage mitigation and risk management assessment.

Damage analysis of low-rise buildings, especially wood-frame structures, under high winds has received significant attentions from the engineering community. Lee and Rosowsky [26] assessed the wind-induced fragility of roof sheathing for light wood-frame structures. Li and Ellingwood [27] proposed probabilistic risk assessment methods to evaluate performance and reliability of low-rise light-frame wood residential constructions in hurricane-prone region of the United States, where the importance of uncertainties is highlighted. Recently, aerodynamic databases have been applied to wind damage assessments. Zhao and Gu [44] presented a database-assisted wind vulnerability assessment model for metal buildings. Huang et al. [19] introduced a database-assisted probabilistic damage estimation approach for asphalt shingle roofing. Konthesingha et al. [22] developed a vulnerability model for metal-clad industrial building in a tropical cyclone region. Huang et al. [20] developed a damage estimation method for roof panels where the wind loading correlation was taken into account. In addition to structural component damage analyses, the wind-induced economic loss for metal roofing was discussed by Dabral and Ewing [8].

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Despite these achievements, there is a need to develop an integrated database-assisted approach to incorporate important factors such as wind loading correlation and wind directionality effect into the wind-induced damage analysis of low-rise building roof components. Cope et al. [7] showed that the correlation of the surface pressures varies with direction and become strong under quartering winds and winds perpendicular to the roof gable. Huang et al. [20] had found that the wind loading correlation may significantly influence the standard deviation (STD) of the damage ratio for roof panels. Although the directionality effect has been widely recognized and incorporated in structural and cladding design, it has not yet been well addressed in vulnerability studies. Obviously, the wind damage of roof components depends on the wind direction. To develop a comprehensive understanding of structural vulnerability, and for the sake of wind-induced damage mitigation and risk management, one needs to integrate the vulnerabilities of all directions with the local wind climate data within a framework that also considers wind load correlation and other influential factors.

Based on an illustrative low-rise building model whose wind pressure data were measured in a wind tunnel, a wind damage estimation method incorporating the wind loading correlation and wind directionality for steel roofing is addressed in this paper. The paper is organized as follows. First, descriptions of the steel roofing and wind pressure data are introduced. Second, POD is adopted to interpolate the external wind pressure for roof locations where there are no pressure data. Third, the internal pressure is determined by simulation. Fourth, the internal forces on fasteners distributed on the steel roof are computed with the aid of the influence-surface approach, with the corresponding peak internal forces estimated by a Gumbel conversion method. Fifth, the failure probability of a single panel and the damage ratio of whole roof are determined based on MCS, where the correlation among internal forces on fasteners is considered by a Nataf transformation. Sixth, the influence of wind directionality is incorporated in the damage estimation. In the end, concluding remarks are given.

2. Descriptions of wind pressures and steel roofing

The illustrative prototype industrial building used in this study has a full-scale size of 62.5 ft × 40 ft × 12 ft (19.05 m × 12.2 m × 3.66 m), a roof slope of 1:12, and is assumed to be located in suburban terrain. The wind pressure data were obtained from wind tunnel tests conducted at the University of Western Ontario (UWO), as reported by Ho et al. [14], with significant comparisons to existing data provided by St. Pierre et al. [38]. The model scale was 1:100, with 335 taps distributed on the roof top and marked by blue dots in Fig. 1. The sampling frequency was 500 Hz with a sampling time of 100 s. The tests were conducted in suburban terrain with roughness length of about 0.3 m, under a reference mean wind speed of 13.7 m/s at the equivalent of 10 m above the ground, which corresponds to a mean wind speed of 6.1 m/s at the roof height (3.66 m). The tests were carried out at various wind angles of attack (AOAs) with intervals of 5° from 0° to 90° and from 270° to 360°. In the rest of paper, if without any specification, wind speeds are referred to 10-min mean wind speeds at the roof height.

There are some types of steel cladding profiles that are commonly used in construction, such as pierced-fixed and standing-seam steel cladding systems. Due to the requirements of large spans, low price, and simplicity of construction and also being well-researched (e.g., [30], the high-strength trapezoidal steel cladding with closely spaced ribs is selected as the roof panel for this study. In the current study, the size of a single cladding panel is assumed to be 750 mm × 6096 mm with a thickness of 0.6 mm. The height of crest is 35 mm and ribs are closely spaced with an interval of 125 mm between two neighboring crests. The layout of the cladding on the roof is shown in Fig. 1 (denoted by dash lines) where 50 (2 × 25) steel cladding panels are distributed on the roof. The cladding is made of high-strength steel G550 (yielding stress = 690 MPa). Self-tapping screws with head diameters of 11 mm are used as the connection fasteners. Further details on this type of cladding can be found in Mahaarachchi and Mahendran [30].

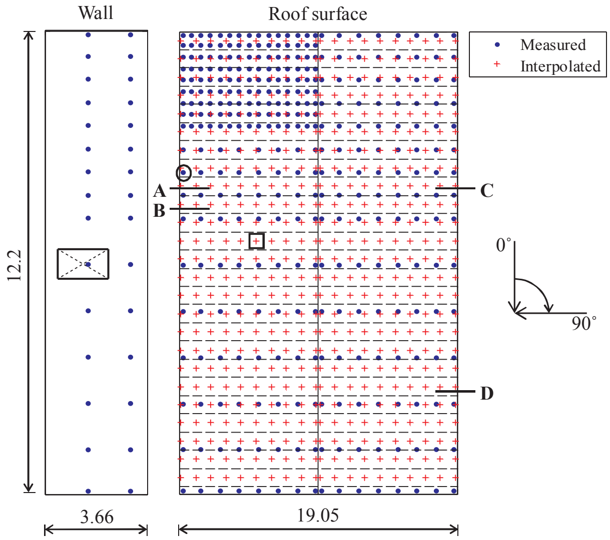
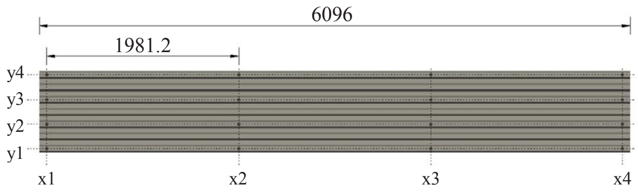
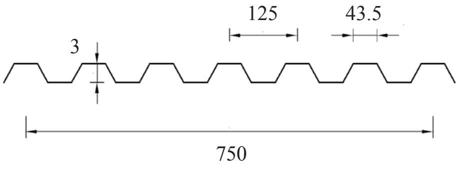


Fig. 1. Tap locations and panel layout (Unit: m).

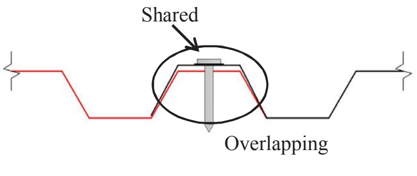
For the cladding cross section, four screws are used to connect the roof cladding to the purlins at alternate crests. Along the rib, four screws are uniformly distributed. A schematic description can be found in Fig. 2(a) and (b). The locations of screws on a cladding panel are represented by the coordinate system shown in Fig. 2(a). For example, x2y3 denotes the screw at the intersection of line x2 and line y3 on the panel. Two adjacent cladding panels overlap at marginal crests and share common screws, as shown in Fig. 2(c). It should be mentioned the purlin spacing of the prototype building in Mahaarachchi and



(a) Cladding configuration and screw distribution



(b) Cross section



(c) Overlap

Fig. 2. Configuration, dimension and joint type of cladding (Unit: mm).