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Reliability based vulnerability modelling of metal-clad industrial buildings to extreme wind loading for cyclonic regions

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ABSTRACT

This paper presents an approach for developing a vulnerability model to predict the probability and extent of damage to metal-clad industrial buildings due to extreme wind loading. Structural reliability-based methods that describe the spatially distributed wind load and component/connection strengths probabilistically are used in the model. Two failure mechanisms are considered for the roof envelop, namely; failure of roof cladding, and purlin failure. Interdependency between the failure mechanisms, load sharing effects due to connection/component failure, and internal pressure variation due to roof cladding failure are also considered. The industrial building examined in the study is a hot rolled structural steel, metal-clad, gable-end building designed for cyclonic regions in Australia. The likelihood and extent of roof damage for this buildings is presented using wind vulnerability curves obtained from the probabilistic model. It is found that internal pressure (e.g. an open door) and the use of cyclone washers has a significant effect on wind vulnerability. The utilisation of cyclone washers is found to reduce damage risks by over 70%.

1. Introduction

Extreme wind events (e.g. wind storms, cyclones, hurricanes) are one of the main natural hazards which cause damage to buildings and result in large economic losses in Australia and elsewhere (Middelmann, 2007; Holmes, 2007). The prediction of damage to buildings from extreme wind events is essential to developing policies to effectively reduce economic losses. Wind vulnerability models are used to predict the probability of damage to buildings and their contents due to wind loading. Vulnerability models play a key role in cost-benefit analysis which contributes to developing design procedures and other mitigation strategies to reduce economic losses due to severe wind events (e.g., Li and Stewart, 2011, Stewart, 2003, Stewart et al., 2014, Stewart, 2014, Vickery et al., 2006a). The models can be developed either by fitting curves to the actual damage data from historical wind damage records (i.e. empirical models and insurance data) or by using engineering knowledge to obtain the damage due to wind loading by investigating the behaviour of a building and its components (i.e. engineering models). Empirical models have drawbacks such as, lack of wind damage data (Ham et al., 2009), lack of capability to examine the changes in building design and construction methods, lack of ability to examine the effectiveness of building adaptation measures for climate change (Zhang et al., 2014). There are also a number of issues associated with utilising claim data such as; access to the insurance claim data, insurance valuation cost and the actual damage cost, and insurance claim databases that do not disaggregate losses between building exterior and interior (Pita et al., 2013). Moreover, empirical vulnerability curves are based on what has happened in the past. They cannot assess changes in vulnerability due to future changes in design standards, materials or construction practices. This highlights the need of developing vulnerability models based on engineering and structural reliability methods. It is noted however that, as with all models, engineering vulnerability models should be validated or benchmarked with empirical models based on past events where possible to give more confidence in modelling assumptions and realism.

There are several engineering vulnerability models developed for different types of structures which use reliability-based methods (Vickery et al., 2006a, b; Pinelli et al., 2004, 2008; Ham et al., 2009; Henderson and Ginger, 2007; Rosowsky and Ellingwood, 2002; Ellingwood et al., 2004; Unanwa et al., 2000; Lee and Rosowsky, 2005; Li and Ellingwood, 2006; Zhang et al., 2014; Ham et al, 2009; Lindt and Dao, 2009). Most of these models are developed for U.S. structure types and have mainly considered residential buildings such as single-family houses. Few publicly

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available engineering vulnerability models are found in the literature for Australian buildings. A suite of vulnerability curves were developed for different Australian building types by Geoscience Australia and James Cook University (Wehner et al., 2010) through the expert opinion of the Australian wind engineering community. The curves were developed based on the expert's experience in post-event survey activity. Many of these curves are proprietary, however, some details are described by Wehner et al. (2010) and Ginger et al. (2010). Henderson and Ginger (2007) developed a reliability-based engineering vulnerability model for Australian high-set houses against wind loading. This study examined possible component and connections failures such as, roof cladding pulling over fixing, cladding fastener failure, batten joint failing at rafter and rafter joint failing at ridge. However, the features such as load redistribution based on progressive failure load paths, spatial distribution of wind load and internal pressure variation caused by the roof sheeting failure, were not considered in the Henderson and Ginger model. Consequently, it was not possible to determine the extent of roof damage at a given wind speed. Given that industrial buildings are vulnerable to extreme wind loading, particularly in the presence of a dominant openings in Australia, it is necessary to identify the extent of wind vulnerability of such buildings, and take actions to protect them against damage where appropriate. In Australia, gable roof metal clad industrial buildings are the most commonly used for manufacturing, storage and processing industries.

An engineering vulnerability model is developed in this paper for metal clad industrial buildings subject to wind loading, based on structural reliability, spatial variability, and probabilistic analysis. Roof sheeting failure is considered in this model which includes two main failure mechanisms (i) roof cladding failure at fastener (i.e. roof cladding pulling over fixing, fastener failure by tension or fastener pulling out of purlin) and (ii) purlin failure (i.e. purlin to rafter connection failure or purlin buckling failure). The external pressure coefficients are obtained from wind tunnel model testing. The vulnerability curves developed are for representative industrial buildings (i.e. hot rolled structural steel, metal-clad, gable-end industrial building) designed to current Australian building standards in cyclonic regions in Australia (North Queensland). Results are presented herein considering the effect of roof cyclone assemblage (washers) and large or dominant openings in the building envelope. Experience in recent cyclones in Australia suggests that some roller doors fail at their connections to the building, thus causing a dominant opening, leading to increased building damage (Henderson and Ginger, 2008). In this model, load redistribution after connection/component failure is incorporated based on the progressive failure load paths. This allows the model to track the timing and extent of fastener and purlin failure, which lead to loss of roof sheeting. Damage is defined as proportional loss of roof sheeting. Internal pressure is treated as a function of openings created by failed roof sheets due to wind load. The interdependency of the component failure is also considered in this model.

2. Stochastic model development

As discussed in the Introduction, a vulnerability model is developed herein for industrial buildings in cyclonic regions in Australia subject to extreme wind loading. Industrial buildings with spans of 20–40 m, lengths of 50 m or more, heights of 5–10 m, and gable-end low pitch (less than 10°) roofs are used in industrial applications in Australia. The structural systems of these buildings generally consist of portal or pin-jointed structural steel frames, spaced at 4 m to 8 m along the length of the building. Metal sheet cladding is attached to roof purlins and wall girts

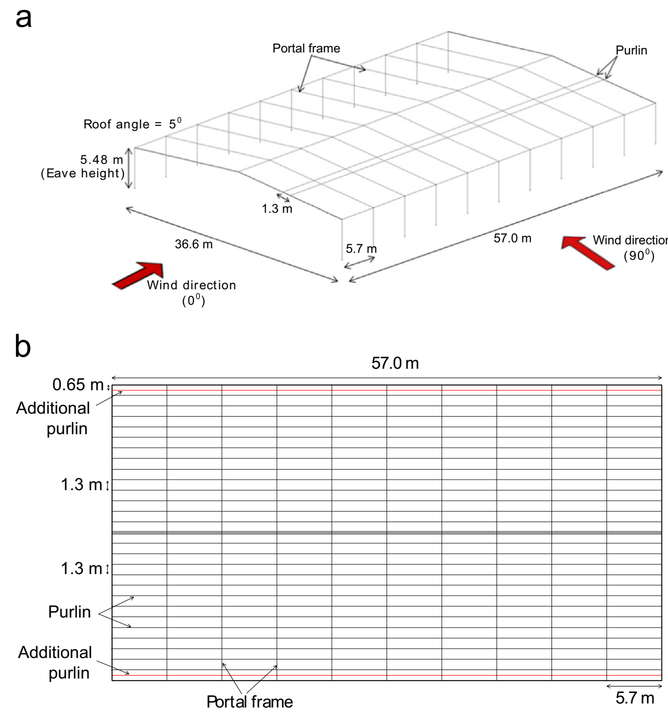

Fig. 1. Industrial building details (a) Overall dimensions (b) Plan view of the roof with purlin arrangement.

using screw fasteners. Cross-bracing between the end frames resist longitudinal (i.e. in direction of ridge-line) wind loads.

Details of a representative hot rolled structural steel, low-pitch roof, metal-clad, metal-framed industrial building for cyclonic regions of Australia are shown in Fig. 1. This building layout is used to investigate the wind vulnerability in this study. These details were obtained from a survey carried out by the Cyclone Testing Station (CTS) at James Cook University, Australia (Leitch et al., 2006). The industrial building is designed according to Australian Standards (AS 4100, 1998; AS/NZS 1170.2, 2011) with consideration of a dominant opening on windward and side walls. The building consists of eleven portal frames. Triple span cold formed purlins (Z25019) with one row of bridging (Lysaght, 2008) are used. The metal cladding thickness is 0.48 mm, while cladding sheet width is 762 mm, with a single sheet laid from eave to ridge of the roof (length = 18.6 m). There are a total of 301 fasteners along one purlin line (between the two gable ends of the building). These fasteners are equally spaced, with five fasteners per cladding sheet for the first roof sheet on each side of the roof, and four fasteners per cladding sheet thereafter. Purlins are equally spaced at 1300 mm (Fig. 1b), except for the first span on each side of the roof. Typical designs in Australia utilise an additional purlin near each eave, in between the first two purlins as shown in Fig. 1b. The total number of roof sheets used in the industrial building is 150.

The possible failure modes in this type of buildings can be identified as cladding pulling over fixing, cladding fastener failure, purlin to truss failure, purlin failure, girt to column failure, girt buckling, support failure (foundation), collapse of the end wall (connections from gable end wall columns to portal frame), failure of roller doors, bracing failure of portal frames (diagonal cross bracing and/or compression in girts and purlins), and buckling/collapse of portal frame (failure at knee joint) (Boughton et al., 2011).

Most building losses accrue from damage to roofing, so two dominant roof failure mechanisms: (i) roof cladding failure at fastener (i.e. roof sheet pulling over fixing, fastener failure by tension or fastener pulling out of purlin) and (ii) purlin failure (i.e.