Engineering Structures 128 (2016) 333–343

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Fragility analysis of roof damage to industrial buildings subject to extreme wind loading in non-cyclonic regions

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ARTICLE INFO

Article history:
Received 19 January 2016
Revised 22 September 2016
Accepted 24 September 2016

Keywords:
Structural reliability
Fragility
Wind
Buildings
Roof damage

ABSTRACT

A fragility analysis is conducted for loss of roof cladding for low rise metal-clad industrial buildings located in non-cyclonic regions of Australia. The stochastic analysis includes possible component and connection failures, load redistribution based on progressive failure, spatial distribution of wind load, and internal pressure variation caused by roof sheeting failure. This spatial and time-dependent reliability analysis will enable fragility curves to be developed that relate likelihood and extent of roof cover damage with wind speed. Industrial buildings representative of new construction in the Australian cities of Brisbane, Sydney and Melbourne are considered. Fragility functions are proposed for industrial buildings designed and constructed to existing codes, and also for improperly designed or constructed buildings where a roller door or other dominant opening prematurely fails during a storm for a building designed as nominally sealed. It was found that damage risks double if a roller door or other dominant opening prematurely fails during a storm.

1. Introduction

Severe storms, cyclones, and other extreme wind events account for 50% of all losses from natural disasters in Australia [4]. Most damage occurs to housing (e.g. [20,27]), although damage surveys have found increasing incidence of damage to industrial buildings, particularly in non-cyclonic regions of Australia [43]. Climate change projections show that many regions in Australia may experience more intense and/or frequent storms, which can significantly affect the vulnerability and damage to infrastructure (e.g., [45,46,37]). An improved understanding of the vulnerability of buildings to wind damage is key to assessing the current and future impacts of climate change, and then deciding if it is cost-effective to implement design or construction changes to reduce the vulnerability of infrastructure [47].

A wind fragility function expresses building damage as a function of wind speed. Fragility models can be developed either by fitting curves to data from historical wind damage or loss records (i.e. empirical models and insurance data) or by using engineering and structural reliability methods by modelling the behaviour of a building and its components. The latter approach is our preference, as a key limitation of empirical modelling is that it is based on what has happened in the past and cannot predict changes in vulnerability due to future changes in design standards, materials or construction practices.

There is much research on developing engineering fragility or vulnerability models which use reliability-based methods (e.g., [39,36,29,49,15,32,7,55]). Few publicly available engineering fragility models are found in the literature for Australian buildings, and those that exist have been developed for housing [15,53,42]. However, Konthesingha et al. [24] have developed a fragility analysis of low rise metal-clad industrial buildings located in cyclonic regions of Australia. The stochastic analysis included possible component and connections failures and also considered load redistribution based on progressive failure, spatial distribution of wind load, and internal pressure variation. However, only two wind directions were considered, and the windward wall always contained a dominant opening. The present analysis extends this work by considering the random location of doors or openings on all walls, the stochastic nature of multi-directional wind directions and building orientation, and consideration of contemporary metal-clad industrial buildings located in non-cyclonic regions of Australia, specifically Brisbane, Sydney and Melbourne. These are the three largest cities in Australia with a combined population of more than 11 million (about 50% of the total population of Australia). These cities are located in southeast Australia where wind hazard is dominated by synoptic winds (thunderstorms and east-coast lows).

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http://dx.doi.org/10.1016/j.engstruct.2016.09.053
0141-0296/

In extreme wind events most losses accrue due to damage of the roof envelope [16,5]. Most of these losses arise from water damage to interior and contents arising from roof cladding failure. Consequently, the paper herein focuses on the roof structure. Monte-Carlo simulation and structural reliability methods are used to stochastically model spatially varying pressure coefficients, roof component failure for 9000 roof fasteners and 300 cold-formed purlins, load re-distribution across the roof as connections progressively fail, loss of roof sheeting as a critical number of connections fail, and changes in internal pressure coefficient with increasing roof sheeting loss. This spatial and time-dependent reliability analysis enables fragility curves to be developed that relate likelihood and extent of roof cover loss with wind speed for multi-directional winds from 0° to 360°. Damage surveys of industrial buildings show that "modern engineered construction failed at wind speeds estimated to be less than design speeds", and "the assumption that buildings would remain nominally sealed is a risky one with high incidence of window and roller door failures observed" [43]. Hence, the present paper will assess building fragility when a building designed to be nominally sealed experiences a dominant opening due to window or door failure. The structural configuration of metal industrial buildings in North America and Europe are similar to those in Australia, hence, the stochastic modelling proposed herein has broad applicability.

2. Framework for fragility modelling

Fragility is defined herein as the likelihood and extent of roof cover damage, as this can be directly related to losses due to water ingress from roof envelope damage. The percentage roof damage is based on the number of roof sheets which have failed at a given wind speed. A roof sheet is defined to have failed (i.e. loss of entire roof sheet) herein, when a predetermined number of fasteners fail in each roof sheet.

The probability of component failure (p_f) is:

$$p_f = Pr[G(\mathbf{X}) \leqslant 0] \quad (1)$$

where $G(\mathbf{X})$ is termed the "limit state function" equal to resistance minus load, and the n-dimensional vector $\mathbf{X} = \{X_1,\ldots,X_n\}$ are random variables each representing a resistance or a loading random variable acting on the system (e.g., [44]). If $G(\mathbf{X}) \leqslant 0$ then this denotes failure. The limit state function for failure of a roofing component (fastener or purlin) is

$$G(\mathbf{X}) = R - (W - D_L) \quad (2)$$

where R represents resistance of the element considered, W is the uplift wind load, and D_L is the roof dead load. The dead load, which arises from roof sheets and purlins, is considered to be deterministic. However, resistance and wind load are modelled probabilistically due to their high levels of variability and uncertainty. The fragility is defined as damage likelihood at a specific hazard H (in this case, wind speed v), where damage state DS is measured by proportion of roof sheeting loss (R_{loss}), giving

$$Pr(DS|H) = Pr[DS = R_{loss}|H = v] \quad (3)$$

Vulnerability is the integration of fragility with loss functions to provide a measure of economic loss for each wind speed. A vulnerability assessment is beyond the scope of the present paper, but is an area for ongoing research.

A probabilistic event-based Monte-Carlo simulation approach is used to calculate the probability of failure of components facilitating the detailed incorporation of load re-distribution and spatial variability of resistance and loads across the roof. For instance, when a fastener fails at a given wind speed, its load is re-distributed to adjacent fasteners. If sufficient fasteners fail then this causes loss of a roof sheet, which in turn may change the internal wind pressure, and so on for the next increment in wind speed.

3. Stochastic model development

3.1. Structural configuration

The details of a typical Australian industrial building utilised herein are presented in Fig. 1. The layout is based on industrial buildings surveys carried out by the Cyclone Testing Station (CTS) at James Cook University [26]. The structural frame consists of hot rolled structural steel members, while the cladding consists of 0.42 mm metal sheeting attached to purlins and wall girts using screw fasteners. Cross-bracing between the end frames resist longitudinal wind loads. The industrial building is designed according to Australian Standards [1,2].

The building consists of eleven portal frames with triple span purlins spaced at 1.3 m with one row of bridging [30]. The width of the roof cladding is 762 mm and a single sheet is laid from eave to ridge of the roof. The total number of fasteners along one purlin line (between the two ends of the building) is 301. 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. Over 9000 fasteners and 300 purlins are used in the roof. The total number of roof sheets used in the industrial building is 150.

3.2. Resistance models

3.2.1. Fastener failure

The resistance of the roof cladding fastener connection is considered to be the minimum resistance of the three failure mechanisms; (i) roof cladding pulling over fastener (pull-over failure), (ii) fastener failure by tension, or (iii) fastener pulling out of purlin (pull-out failure). The probabilistic parameters for cladding fastener connection resistance were obtained from experimental component testing and expert judgement [31,24]. Mean fastener capacity is taken as 1.0 kN with a COV (coefficient of variation) of 30%. Component capacities are assumed lognormally distributed [14] and statistically independent. There may well be some correlation between fastener capacities due to similar fastener installation practices by a builder, but mean damages increase by less than 0.3–0.8% at 100-year design wind speeds even if fastener capacities are assumed to be fully correlated. The values used for the probabilistic model do not reflect performance of any one cladding profile or fixing but rather provide a level of wind load resistance of an average of the typical cladding/fixing combinations.

3.2.2. Purlin failure

The probabilistic parameters for purlin resistance are obtained from experimental testing carried out by Pham and Hancock [35] that incorporate both buckling failure and failure of the connection to the supporting rafter. The actual to nominal capacity (R/R_n) is a function of variability of model error, yield stress variability, and member thickness variability, resulting in a mean R/R_n value of 1.36 and a COV of 0.11 for a triple span purlin with one row of bridging [6,35]. In the context of load re-distribution, it is noted that the model assumes that when a purlin fails all roof fasteners attached to that purlin have failed.

3.2.3. Roof sheet failure criterion

A roof sheet is deemed to have failed (i.e. loss of entire roof sheet) when a predetermined number of fasteners fail in each roof sheet. This number of failed fasteners is a difficult parameter to assess as the sheet failure criteria can differ depending on wind