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Fragility and climate impact assessment of contemporary housing roof sheeting failure due to extreme wind

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ABSTRACT

The paper describes a risk analysis of the economic impact of damage to metal roofing of a typical contemporary (new) Australian house subject to extreme wind loading. The failure modes considered are roof cladding and batten-to-truss connection failures, with the effect of defective construction also considered. Monte-Carlo simulation and structural reliability methods are used to stochastically model spatially varying pressure coefficients, roof component failure, and load re-distribution across the roof. This spatial reliability analysis enables fragility curves to be developed that relate likelihood and extent of roof cover loss to gust wind speed. The annual economic risk is up to 0.3% of house replacement value. A typical house with construction defects increases economic risk more than sixfold when compared to the defect-free house. There is a 10% chance that a changing climate will increase expected losses for houses in Brisbane and Melbourne by 6–18% over the next 50 years.

1. Introduction

Severe storms (excluding tropical cyclones) cause insured losses of nearly $400 million annually in the Australian states of Queensland, New South Wales and Victoria [5]. These losses account for nearly 25% of all losses from natural disasters in Australia. Most damage occurs to housing (e.g. [25,32]). Climate change-induced increases in wind speed may occur in some regions of Australia [58]. An improved understanding of the vulnerability of housing to wind damage is key to assessing the current and future impacts of climate change, as well as deciding if it is cost-effective to implement design or construction changes to reduce climate change impacts (e.g., [48,49,50]).

Wind fragility expresses building damage as a function of wind speed. Engineering fragility, vulnerability, and risk assessment models have been developed for different types of structures which use reliability-based methods (e.g., [55,20,29,33,53,34,38,12,59,6,43,9]). Many of these models are developed for timber roof sheathing which is representative of housing in hurricane prone regions of North America, and some of these studies include the effect of climate change. In Australia, many houses have metal roof cladding. Much research has focused on roofing vulnerability as this is an important indicator of loss, for example, HAZUS [18] estimates total loss of building interiors and contents with 25% loss of roof covering. Few engineering fragility models are publicly available for Australian buildings. Henderson and Ginger [20] developed a reliability-based engineering fragility model for the older, more vulnerable Australian high-set houses against cyclonic wind loading. This study examined metal roof cladding pulling over fixing, cladding fastener failure, batten joint failing at rafter and rafter joint failing at ridge, and assumed a relatively simple series system based on the weakest-link hypothesis. However, load redistribution based on progressive failure load paths, spatial distribution of wind load, internal pressure variation caused by the roof sheeting failure, sheet failure criterion, and construction defects were not considered. Konthesingha et al. [28] has implemented some of these features into the fragility analysis of low rise metal-clad industrial buildings, however, the analysis ignored construction defects.

Housing losses due to extreme wind events often accrue to damage to the roof envelope [21,7]. Consequently, the paper herein focuses on the roof structure of a typical Australian house. The dominant failure modes considered in this study are (i) roof cladding failure, and (ii) batten-to-truss connection failure. The effect of defective construction at connections on wind fragility is also considered. Monte-Carlo simulation and structural reliability methods are used to stochastically model spatially varying pressure coefficients, roof component failure for 1600 roof fasteners and 500 battens, load re-distribution across the roof as connections progressively fail, loss of roof sheeting as a critical

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number of connections fail, and changes in internal pressure coefficient with increasing roof sheeting loss. Fragility curves can then be developed that relate likelihood and extent of roof cover damage with wind speed. Housing representative of contemporary (new) houses in the Australian cities of Brisbane and Melbourne are considered, and houses in these regions are classified by the Australian wind loading standard AS/NZS1170.2 [3] as non-cyclonic. As noted above, most wind fragility analyses in the literature focus on extreme winds caused by hurricanes or cyclones. Houses in these regions in the United States and Australia tend to be constructed to higher standards. However, in Australia more than 95% of the population live in non-cyclonic regions, and wind damage to these houses can also be significant (e.g., [32]).

Finally, a risk assessment is conducted to assess the risks and economic impact of roof cladding wind damage. Roof cover loss includes structural, interior, contents, and loss of use losses. The economic risks are calculated as the product of hazard likelihood, fragility, and loss, over the 50-year design life of residential houses designed to be nominally sealed. The effect of climate change on wind speed and damage risks is also considered.

2. Risk, fragility and vulnerability

The risk from extreme wind events is:

$$E(L) = \sum \Pr(H)\Pr(DS\,|H)\Pr(L|DS)L \tag{1}$$

where Pr(H) is the annual probability of a hazard (wind speed), Pr(DS|H) is the damage state probability conditional on the hazard (also known as fragility), Pr(L|DS) is the conditional probability of a loss given occurrence of the damage, and L is the loss or consequence if full damage occurs. The summation sign in Eq. (1) refers to the number of possible hazards, damage states and losses. If the loss refers to a monetary loss, then E(L) represents an economic risk.

The probability of component failure (p_f) is:

$$p_f = \Pr[R-(W-D_L) \leqslant 0] \tag{2}$$

where R-(W-D_L) is the "limit state function" equal to resistance minus load, R represents resistance of the element considered, W is the uplift wind load, and D_L is the roof dead load. The dead load 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 wind speed v, where damage state DS is measured by proportion of roof sheeting loss (R_{damage}) which is based on the number of roof sheets which have failed at a given wind speed, giving

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

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 probabilistic model examines roof failure down to the cladding and batten fastener element level, facilitating the detailed incorporation of load re-distribution and spatial variability across the roof as fasteners progressively fail. Event-based Monte-Carlo simulation methods are used to model damage progression and hence the estimation of fragility Pr(DS|H) for gust wind speeds of up to 80 m/s. The simulation analysis allows for the spatial distribution of wind loads across the roof. This event-based methodology then allows the consequences of a given failure event to be incorporated into the model as wind speed increases. For instance, when a fastener fails at a given wind speed, its load is re-distributed to adjacent fasteners for subsequent wind speeds. The event-based approach also allows for changes in internal wind pressure with roof sheet failure to be incorporated into the model. The event-based simulation flowchart of the fragility model is described in Fig. 1.

3. Wind hazard and climate change

Non-cyclonic gust speeds (winds not associated with tropical cyclones) dominate in South-East Queensland, and further south in Melbourne. The latest Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) projections for changes in annual peak gust wind speeds for Brisbane and South-East Queensland (this region accounts for nearly 20% of the population of Australia) are provided by Dowdy et al. [11] and summarised in Table 1 for low, medium and high CO_2 emission scenarios RCP2.6, RCP4.5 and RCP8.5, respectively, to 2090. Note that climate projects are relative to 1995 levels (1986–2005 average), and the Australian Government uses CSIRO projections for their climate impact modelling. It is clear from Table 1 that "projections of extreme winds indicate that reductions are more likely than increases based on the model ensemble median" [11]. On the other hand, extreme wind projections for Melbourne are less clear, and "extreme winds could increase or decrease" [17]. For this reason, projections for annual peak gust wind speeds in Melbourne are provided by CSIRO only for RCP8.5 (see Table 1). It is important to note that the wind projections for much of the coastal region of Victoria and New South Wales are very similar to those for Melbourne (this region accounts for over 40% of the population of Australia). It is also noted that "The projections of extreme winds are less certain than for other variables since there is a limited number of GCMs (general circulation models) that provide wind data, and maximum wind speed needs to be estimated using indirect means" [17]. The cumulative distribution function for annual maximum non-cyclonic peak gust speed [57,49] is modified as:

$$F_V(v,\,t) = e^{-e^{-A}} \text{where } A = \frac{\left(\dfrac{v}{1+\frac{\gamma_{mean}(t)}{100}}\right) - v_g}{\sigma_g} \tag{4}$$

where v_g and σ_g are the location and scale parameters, respectively ($v_g = 26.0326$, $\sigma_g = 4.0488$ for Brisbane and $v_g = 27.7777$, $\sigma_g = 1.664$ for Melbourne), $\gamma_{mean}(t)$ is the time-dependent percentage change in gust wind speed, and gust wind speed v is the maximum 0.2 s gust velocity at 10 m height in Terrain Category 2 (open terrain defined in [3]). Fig. 2 shows the relationship between gust wind speed and return period calculated from Eq. (4) when $\gamma_{mean}(t) = 0$. Information is scarce to non-existent on time-dependent changes in wind speed for Australia. A time-dependent linear change in wind speed is assumed as it has been shown that the effect of a non-linear time-dependent change in wind speed has a minor influence on damage risks even when investigated for a wind speed change scenario of +20% (e.g., [47]). In the present case, the projected changes in wind speed over the next 50 years are less than 4%, hence, results will be insensitive to assumptions about the nature of the time-dependent increase in wind speed.

4. Fragility analysis

4.1. Representative house

Field surveys of contemporary houses being built in the suburbs of Brisbane and Melbourne were completed in 2014 by the Cyclone Testing Station (CTS) at James Cook University (JCU) as part of a CSIRO Climate Adaptation Engineering for Extreme Events (CAEx) project [39]. It was found that houses in Melbourne are of similar size, shape and construction type to houses in Brisbane. The data from this detailed survey was used to define a representative house. Median values of variables such as footprint dimensions, roof pitch, and wall heights were selected to determine the dimensions of the representative houses. These houses are, in general, designed to be nominally sealed.

Fig. 3 shows the representative 1-storey Brisbane/Melbourne house. It is timber framed brick-veneer construction with a 21.5° timber roof truss (at 600 mm spacings) on a complex hip-end roof. Trusses are