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Fragility Analysis Of Australian Contemporary Housing Roof Sheeting Failure Due To Extreme Wind

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Abstract

The paper considers likelihood and extent of damage to metal roofing of a typical contemporary (new) Australian house subject to non-cyclonic extreme wind loading. A spatial and time-dependent reliability analysis enables fragility curves to be developed that relate likelihood and extent of roof cover loss to gust wind speed. It was found that mean extent of roof damage is less than 1% for a 100-year design wind event, and this estimate includes the effect of a dominant opening and construction defects.

Introduction

The paper focuses on the roof structure of a typical Australian house subject to extreme wind loading. The dominant failure modes considered 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 1,600 roof fasteners and 500 battens, load re-distribution and spatial variability 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 damage with wind speed.

Figure 1 shows the representative 1-storey Brisbane/Melbourne house obtained from field surveys [12]. Houses in these regions are classified by AS/NZS 1170.2 [1] as non-cyclonic and so are subject to synoptic winds (thunderstorms and east-coast lows). The house is timber framed brick-veneer construction with a 21.5° timber roof truss on a complex hip-end roof. Trusses are arranged with general trusses in the middle part of the roof and jack trusses connected to girder trusses at the hip-ends.

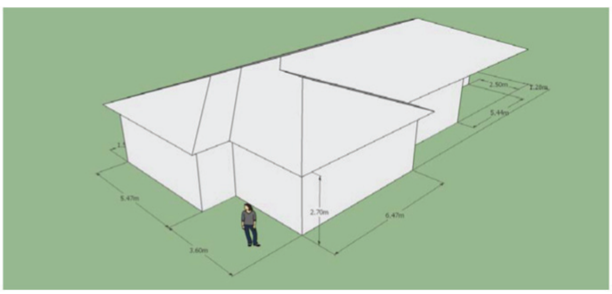


Figure 1. Representative 1-Storey House.

Risk, Fragility and Vulnerability

Decision criteria for climate, terrorist or other extreme events are typically based on (i) annual fatality risk, and (ii) cost-effectiveness of protective measures [11,16]. The annual risk from extreme wind events is

$$E(L) = \Pr(H)\Pr(DS|H)\Pr(L|DS)L \qquad (1)$$

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 state, and L is the loss or consequence if full damage occurs. A risk analysis allows costs and benefits of risk mitigating solutions to be compared, such as the wind-rating of garage doors in Australia, see Stewart [18].

The probability of component failure (p_f) is

$$p_f = \Pr\left[G(\mathbf{X}) \le 0\right] \qquad (2)$$

where $G(\mathbf{X})$ is the "limit state function" equal to resistance minus load, and the n-dimensional vector $\mathbf{X} = \{X_1,....,X_n\}$ are random variables each representing a resistance or a loading random variable acting on the system [15]. If $G(\mathbf{X}) \le 0$ then this denotes failure. The limit state function for failure of a roofing component is

$$G(\mathbf{X}) = R - (W - D_L) \qquad (3)$$

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 battens, is negligible when compared to wind loading and is considered to be deterministic. However, resistance and wind load are modelled probabilistically due to their high levels of variability and uncertainty. The fragility Pr(DS|H) is defined as damage likelihood at a specific wind speed v, where damage state DS is measured by proportion of roof sheeting loss which 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 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 the estimation of fragility Pr(DS|H).

Fragility Analysis

Wind Loading

The wind load is modelled probabilistically as [6]:

$$W=Bv^2 \quad \text{and} \quad B = \lambda\cdot M\cdot A\cdot\left(C\cdot T\cdot E^2\cdot D^2\cdot G\cdot\frac{\rho}{2}\right) \qquad (4)$$

where v is the maximum 0.2 second gust velocity at 10 m height in Terrain Category 2 (i.e. open terrain - AS/NZS1170.2 - 2011), C is the quasi-steady pressure coefficient, E is a terrain height multiplier that accounts for the exposure and height of the building considered, T is a shielding factor, D is a factor for wind directionality effects, G is a factor to incorporate the spatially and temporally varying pressures across the building envelope, ρ is the density of air, A is the tributary area, λ is the factor accounting for wind load modelling inaccuracies and uncertainties in analysis methods, and M is a factor for wind tunnel modelling inaccuracies. These parameters, with the exception of C, are assumed to have a lognormal probability distribution with statistical parameters given in Table 1.

Parameter	Nominal Value	Mean-to-Nominal	COV
λ/λ_N	1.0	1.0	0.10
M/M_N	1.0	1.0	0.10
A/A_N	Tributary area	1.0	0.10
E/E_N	1.0	0.95	0.10
T/T_N	1.0	1.0	0.10
D/D_N	1.0	1.0	0.00
G/G_N	1.0	1.0	0.05
ρ/ρ_N	1.2 kg/m^3	1.0	0.02

Table 1. Statistical Parameters for Wind Loading.

Wind tunnel tests were carried out on a model of the representative house at a length scale of 1/50 to obtain wind loads on the building envelope. A wind tunnel model of the 1-storey representative Brisbane/Melbourne house was constructed at a length scale of 1/50. Three hundred and twenty pressure taps were installed on the external roof surface to measure the spatial and temporal variation in external pressure. Statistical parameters for peak suction pressure values were obtained from the method of moments of the peaks observed for three sequential sets of 10 minute wind tunnel observation data for each tap location for each direction. The wind tunnel pressure coefficient data are assumed to have an Extreme Value Type 1 (Gumbel) probability distribution. The analysis assumes a correlation coefficient of 0.9 for all pressure tap data used in the spatially varying probabilistic wind loading model. Calculated fragilities are not sensitive to assumptions about the pressure tap correlation coefficient.

Progressive failure of the roof envelope (i.e. loss of roof sheeting) is likely to change internal pressures [9]. Figure 2 shows the mean change in internal pressure due to loss of roof sheeting with, and without, a large dominant opening (i.e. failed doors or windows in the house due to wind-borne debris) in the windward, side or leeward walls. When there is no loss of roof sheeting, Figure 2 is based on internal pressure coefficients obtained from AS/NZS 1170.2 [1], and is assumed that the dominant opening is located in the centre of a wall [17]. As roof sheets start to fail, Figure 2 is based on wind tunnel data and expert judgement, as there appears to be little information on quantitative models of variation of internal pressure with roofing loss. Variability of C_{pi} is likely to be low for an intact roof [3], and so is modelled as a normal distribution with an assumed standard deviation of 0.1. Internal pressures as a result of loss of roof sheeting are more variable and will depend on location of roofing loss, leading to a higher standard deviation of 0.2. Figure 2 provides a useful starting point for further research.

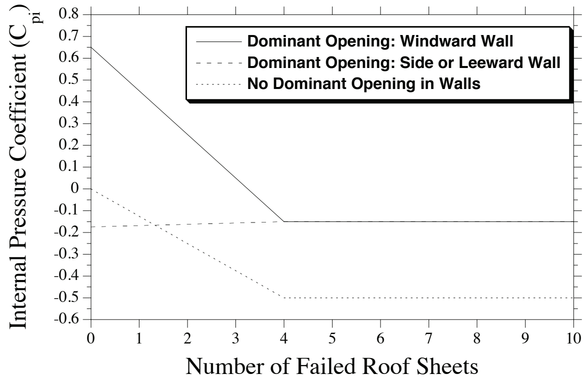


Figure 2. Effect of Failed Roof Sheeting on Internal Pressure Coefficient.

Resistance

The representative Brisbane/Melbourne house has 0.42 mm metal corrugated sheeting secured by screw fasteners at every 2nd corrugation (150 mm spacing) for edge battens, and every 3rd or 4th corrugation for other regions of the roof. Roof battens are 0.55 mm metal top-hat 40 battens at 900 mm centres secured to every truss with 6 mm diameter screw fasteners [10]. Soft wood prefabricated trusses are spaced at 600 mm.

Component Capacities

Probabilistic data for roof fastener pull-over and pull-out failures are inferred from existing literature and test data. Batten-to-truss connection capacities are obtained from pull-over and pull-out failure test data. Table 2 summarises the statistical parameters for component capacities. Component capacities are assumed statistically independent and taken as the lower of randomly generated pull-out and pull-over capacities. Component capacities are assumed lognormally distributed.

Component and Failure Mode	Mean	COV
(i) roof sheeting pulling over fastener	1.2 kN	0.3
(ii) roof fastener pulling out of roof batten	1.2 kN	0.2
(i) batten pulling over fastener	4.5 kN	0.15
(ii) batten fastener pulling out of roof truss	5.5 kN	0.2

Table 2. Statistical Parameters for Fastener and Batten Resistance.

Fastener and Batten Failure Progression

When a roof fastener fails, the load is distributed to adjacent fasteners, see Figure 3 [5]. A batten failure is modelled as if all roof fasteners connected to the batten have failed. This means, for example, that failure of a batten 'X' results in loads being distributed predominantly to battens 'Z' and 'Y'. The probabilistic representation of over 1,600 roof fasteners and 500 battens requires event-based modelling of fastener and batten failure progression for each increment of wind speed. As more connections fail the load is redistributed to other connections which in turn have a higher likelihood of failure leading to, in some cases, 'unzipping' of connections and rapid damage progression.

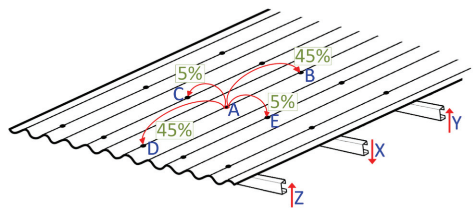


Figure 3. Load Redistribution of Failed Fasteners or Battens.

Sheet Failure Criterion

The number of failed fasteners to cause loss of an entire roof sheet is defined herein as the sheet failure criterion (SFC). When modelling roof sheathing for houses, HAZUS [4] assumed that 80% of roof panel fasteners had to fail before the sheet failed. On the other hand, Henderson et al. [5] found that the loss of 2 nails from a timber roof sheet (i.e. 6% of 33 nails) resulted in a 40% loss of sheet uplift capacity. Other studies assume that a panel is considered to have failed if any one of the fasteners fails [13]. Konthesingha et al. [9] based fragility modelling of metal clad industrial buildings on a 20% SFC. There appears to be more evidence that failure of a few fasteners will result in sheet failure than failure of many fasteners. Hence, a triangular probability distribution for sheet failure criterion is adopted, see Figure 4.

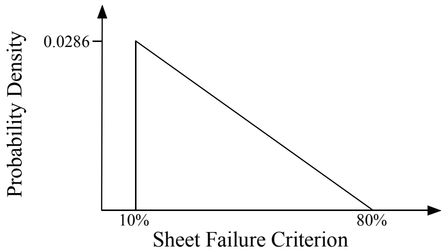


Figure 4. Triangular Probability Distribution of Sheet Failure Criterion.

Human Error and Construction Defects

The Human Reliability Analysis (HRA) approach is suitable for modelling construction errors in a risk analysis [15]. The statistical parameters for fastener capacities shown in Table 2 describe results of testing of connections constructed in the laboratory with good quality workmanship. In this case, a 'defect' may be defined as one that causes a loss of capacity in exceedance of acceptable variability. If we assume a lower bound of acceptable variability is the 1st to 5th percentile of the lognormal distribution of fastener capacities described in Table 2, then this relates to a minimum capacity reduction of 28-50% for roofing fasteners, and 22-37% for batten connections. Hence, minimum capacity reductions due to defects for roofing fasteners and batten connections are taken as 40% and 30%, respectively. The most likely capacity reduction for a roofing fastener is 100% as this relates to a screw fastener not attached to the batten or the fastener simply not installed. Two screws comprise a batten-to-truss connection, so a likely scenario may be the incorrect installation of both screws (installed at angle, or not centred), or one missing screw leading to a capacity reduction of 50%. Capacity reductions are modelled as triangular probability distributions as shown in Table 3.

Data on defect rates is more difficult to infer. Hong and He [7] conducted a statistical analysis of missing nails and improperly fastened nails in a timber sheath roof constructed in a laboratory. They found an error rate of 1.5%, but state that since their statistics are based on a laboratory setting the 1.5% error rate is perhaps closer to a lower bound. The task of installing metal roof cladding is different of course, for example, there may be higher accuracy of inspecting the location of roof fasteners as a fastener not connected to a batten will look out of line with other fasteners, but this data provides a useful benchmark for our analysis. Hence, the present analysis assumes a fastener defect rate of 1-3% assumed uniformly distributed. Batten-to-truss connections are more difficult to inspect visually, and involve the installation of two screws – defect rates are likely to be higher. Hence, we assume double the defect rate than that of fasteners (2-6%) and also assumed to be uniformly distributed, see Table 3.

There is much research to show that defects are correlated or dependent - i.e. one error or defect is more likely to lead to other errors or defects. Hence, some houses are likely to have many defects, others very few if any. Moderate dependence of defect rates is assumed [8], and roof fasteners and batten connection defect rates are fully correlated. There is a need for field data on construction defects, although collecting unbiased construction defect data can be problematic, see e.g., Stewart [14], but is necessary to better quantify defect rates and their magnitude.

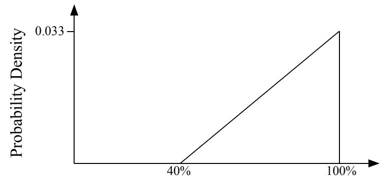
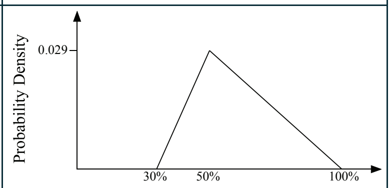
Component	**Defect Rate Per Component**	**Probability Distribution of Capacity Reduction**
Roof Fastener	1 - 3%	
Batten-to-Truss Connection	2 - 6%	

Table 3. Defect Rates and Capacity Reduction.

Results - Fragility Curves

The terrain multiplier specified in AS4055-2012 [2] is equal to $M_{z,cat}$=0.87 for suburban housing [1]. It is assumed there is no shielding of the roof from nearby houses and so shielding multiplier is M_s=1.0 [1]. The variability of real shielding and terrain are given in Table 1. The variation of the fragility due to presence and absence of openings in the building envelope (e.g., door failure, window breakage, openings not closed) is also analysed. Unless noted otherwise, wind direction is uniformly distributed in 10° increments between 0° and 360° to allow for variability of building orientation and wind direction - this allows for fragilities to be assessed for an entire housing stock. If a dominant opening is to occur, it is assumed herein to occur on the windward wall. The analyses to follow are based on 5,000 Monte-Carlo simulation runs, and gust wind speed v is the maximum 0.2 second gust velocity at 10 m height in Terrain Category 2.

Note that the loss of many roof sheets will significantly alter aerodynamic behaviour of the roof, and change internal and external pressures from that assumed in Figures 2 and 3. Hence, there is lower confidence in fragilities in excess of 10-20%. This is of little consequence for loss modelling, however, as roof sheeting is entirely replaced when roof cover damage exceeds 5%, and building interior and contents losses reach 100% when roof cover damage exceeds 25% [4].

Figure 5 shows the multi-directional wind fragility for the roof cladding and batten system for the representative house with and without construction defects. Construction defects increase fragility by up to 10% for high wind speeds, and reduce the damage threshold by 15 m/s. The effect of construction defects is significant, and should be included in fragility modelling. The roof damage threshold wind speed is reduced by about 25% when the house experiences a dominant opening compared with a house without an opening. The main reason for this is the increase in internal pressure.

The design wind speed for Brisbane is v=57 m/s considering an average recurrence interval of 500 years. In this case, the average extent of roof damage for a defect free roof is 0.02% and 1.46% for a building without and with a dominant opening, respectively.

Hence, a properly designed house with no construction defects or dominant openings should suffer negligible loss of roofing when subject to its design wind event. A house with defects increases roof damage more than three-fold when compared to the defect-free house. A more likely wind event is a 1 in a hundred year wind speed (v=48 m/s). In this case, roof damages reduces to 0.2% and 1.2% for a house with construction defects without and with a dominant opening, respectively.

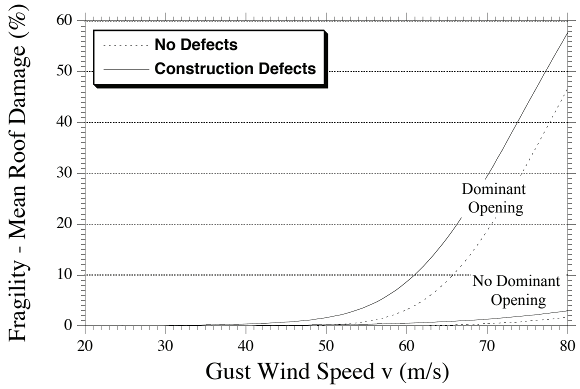


Figure 5. Fragility Curves with and without Construction Defects.

The design wind speeds in Melbourne are lower than Brisbane, and mean roof damage reduces to less than 0.7% for all scenarios. This would seem to represent a relatively low potential loss. However, a risk analysis based on Eqn. (1) is needed to assess if damage risks are at an acceptable level - this is a topic for future research. Sensitivity analyses showed the fragilities are relatively insensitive to SFC. For more details of the modelling see Konthesingha et al. [9] and Stewart et al. [17].

A worst-case climate change scenario is projected to increase Brisbane wind speeds by 6.5% by 2070 [19]. Under this climate scenario, for a house with construction defects roof sheeting damage risks will increase in relative terms, for the 1 in 500 year design wind speed, by 75% and 25% with and without a dominant opening, respectively.

Future work will incorporate the fragility of roof truss-to-wall connections. Truss-to-wall connections in non-cyclonic regions in Australia have been found to suffer from inadequate design and construction, leading to higher probability of failure and significant loss of roof covering.

Conclusions

It was found that mean extent of roof damage is less than 1% for a 100-year design wind event, and this estimate includes the effect of a dominant windward opening and construction defects. This would seem to represent a relatively low level of damage, however, a risk analysis based on Eqn. (1) is needed to fully assess if damage risks in contemporary houses in Brisbane and Melbourne are at an acceptable level.

Acknowledgements

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