Nineteenth Australasian Wind Engineering
Society Workshop, April 4-6, 2018,
Torquay, Victoria

Climate Impact and Cost-Effectiveness of Window Shutters to Reduce Roof Sheeting Wind Damage to Contemporary Australian Housing

Mark G Stewart[1]
[1] Centre for Infrastructure Performance and Reliability, The University of Newcastle, Australia
email: mark.stewart@newcastle.edu.au

ABSTRACT

A risk assessment is conducted to assess the risks and economic impact of roof cladding wind damage to contemporary (new) Australian houses in Brisbane and Melbourne. The failure modes considered are roof cladding and batten-to-truss connection failures, with the effect of defective construction also considered. Roof cover loss includes structural, interior, contents, and loss of use losses. The economic risks expressed in Australian dollars 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. A changing climate may increase expected losses for Brisbane by $2,000. A possible climate adaptation measure to enhance housing resilience is the installation of window shutters to reduce the likelihood of window damage and full internal pressurisation of the house. In this case, risk reduction is approximately 80%. A cost-benefit assessment is made for this climate adaptation measure, finding it to be cost-effective if the discount rate is less than 4%.

1. Introduction

In extreme wind events most housing losses accrue due to damage of the roof envelope. Consequently, the paper herein focuses on the roof structure of a typical Australian house subject to extreme wind loading. 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 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 reliability analysis enables fragility curves to be developed. 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 standards as non-cyclonic.

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 losses, and loss of use. The economic risks expressed in Australian dollars 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. A possible climate adaptation measure to enhance housing resilience is the installation of window shutters to reduce the likelihood of window damage and full internal pressurisation of the house. In this case, the benefit to cost ratio can be estimated.

2. Risk and Cost-Effectiveness

The risk from extreme wind events is:

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

where Pr(C) is the annual probability that a specific climate scenario will occur, Pr(H|C) is the annual probability of a climate hazard (wind speed) conditional on the climate, 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 (economic loss, loss of life, etc.) given occurrence of the damage (sometimes referred to as resiliency), and L is the loss or consequence if full damage occurs. The summation sign in Eqn. (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.

If the probability that a specific climate scenario will occur Pr(C) is too unreliable, then a decision analysis based on scenario analysis where climate scenario probability is decoupled from Eqn. (1) provides an alternative decision-making criterion - this is the approach adopted herein. 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

$$\Pr(DS \mid H) = \Pr\left[DS = R_{damage} \middle| H = v\right] \tag{2}$$

Damage to the roof envelope results in two forms of loss: (i) building and contents loss (roof, interiors and contents) expressed as proportion of building replacement cost, and (ii) loss of use.

3. Wind Hazard

Non-cyclonic gust speeds (winds not associated with tropical cyclones) dominate in South-East Queensland, and further south in Melbourne. For more details see Stewart *et al.* (2014) and Wang *et al.* (2013). The latest Commonwealth Scientific and Industrial Research Organisation (CSIRO) projections for changes in annual peak gust wind speeds for Brisbane are provided by Dowdy *et al.* (2015) 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). 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” (Dowdy *et al.* 2015). On the other hand, extreme wind projections for Melbourne are less clear, and “extreme winds could increase or decrease” (Grose *et al.* 2015). For this reason, projections for annual peak gust wind speeds in Melbourne are provided by CSIRO only for RCP8.5 (see Table 1). The cumulative distribution function for annual maximum non-cyclonic peak gust speed (Wang *et al.* 2013) is modified as

$$F_V(v,t) = e^{-e^{-A}} \quad \text{where } A = \frac{\left(\dfrac{v}{1+\dfrac{\gamma_{mean}(t)}{100}}\right) - v_g}{\sigma_g} \tag{3}$$

where v_g and σ_g are the location and scale parameters, respectively (v_g=26.0326, σ_g=4.0488 for Brisbane and v_g=27.7777, σ_g=1.664 for Melbourne), gust wind speed v is the maximum 0.2 second gust velocity at 10 m height in Terrain Category 2 (open terrain defined in AS1170.2 2011), and γ (t) represents the time-dependent percentage change in gust wind speed given in Table 1.

Table 1. Changes in wind speed γ(2090) for Three Emission Scenarios.

	RCP2.6			RCP4.5			RCP8.5		
Location	10^{th}	Median	90^{th}	10^{th}	Median	90^{th}	10^{th}	Median	90^{th}
Brisbane	-2.5%	0.0%	+2.5%	-8%	-1.5%	+1.0%	-5.0%	-2.0%	+2.0%
Melbourne	NA	NA	NA	NA	NA	NA	-4.0%	-1.0%	+5.0%

4. Wind Fragility and Loss Modelling

Fragility models have been developed for representative single storey houses in Brisbane and Melbourne subject to extreme wind loading (Stewart *et al*. 2017). 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 arranged with general trusses in the middle part of the roof and jack trusses connected to girder trusses at the hip-ends. See Parackal *et al*. (2016) for details of wind loads on this representative building.

The Australian Standard “Wind Loads for Houses” AS4055-2012 assesses design wind speeds for housing and is used herein to determine terrain and shielding effects for houses in an urban environment. It is assumed there is no shielding of the roof from nearby buildings. Building design practice in non-cyclonic regions assumes that the building will remain effectively sealed for all wind speeds. Construction defects are typically observed in most houses, so the fragility analysis will include the effect of construction defects where roof fasteners and batten connection defect rates range from 1% to 6%. For more details see Stewart *et al*. (2017).

Monte-Carlo simulation and structural reliability methods were used to stochastically model spatially varying wind pressure coefficients, roof component failure for 1,600 roof fasteners and 500 cold-formed 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 enabled fragility curves to be developed that relate likelihood and extent of roof cover loss with wind speed for any building orientation and multi-directional winds from 0° to 360°. The fragility curve use a Weibull curve:

$$\Pr(\mathrm{DS}|\mathrm{H}) = \gamma\left\{1-\exp\left[-\left(\frac{v}{e^{\beta}}\right)^{\frac{1}{\alpha}}\right]\right\} \qquad v \le 80\ \mathrm{m/s},\ \Pr(\mathrm{DS}|\mathrm{H}) \le 100\% \tag{4}$$

where γ, α and β are parameters that describe the shape and position of the vulnerability curve. Table 2 shows the parameters for the best fit mean fragility functions.

Table 2. Best-Fit Parameters for Mean Fragility Functions.

Dominant Opening	γ	α	β
No	4.38	0.148	4.398
Yes	80.67	0.118	4.349

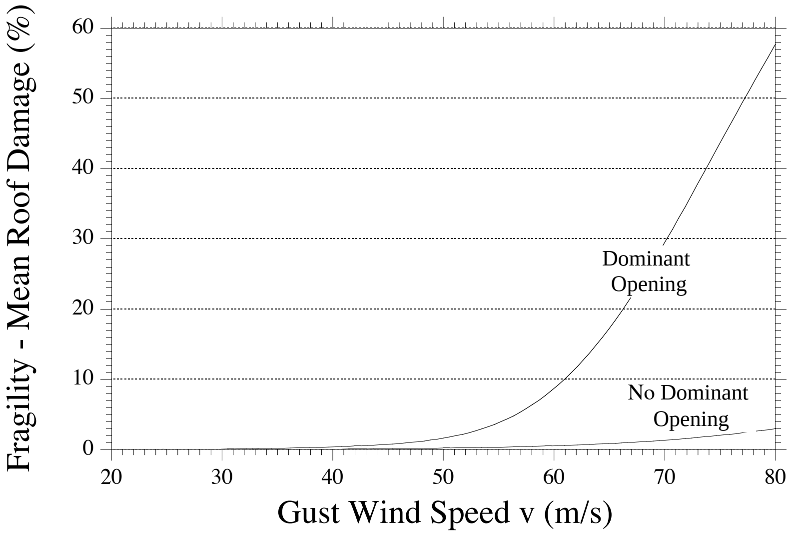

Figure 1. Fragility Curves with Construction Defects.

Note that the fragility functions shown in Figure 1 assume that a building either remains effectively sealed for all wind speeds, or has a dominant opening for all wind speeds. This is not realistic, for example, as premature window failure is expected to occur for extreme wind speeds, and not in usual service. Hence, two more realistic design and construction scenarios are considered:

(i) Wind-rated cyclone roller shutters – shutters are ‘wind-rated’ not to fail at wind pressures below a design wind speed of v_{TH} =60 m/s.

(ii) No shutters (current practice) -there is high likelihood that windows in non-cyclonic regions without shutters will prematurely fail during an extreme wind event. The wind speed necessary to cause window failure is variable, however, a conservative assumption is that most windows will survive typical wind events, but not extreme wind events. It is assumed herein that the threshold wind speed for window failure is an extreme wind with ARI of 50 years, then threshold damage wind speed for a typical window $v_{TH\text{-}no} = v_{50}$ which according to Eqn. (3) is equal to 41.8 m/s and 34.2 m/s for Brisbane and Melbourne, respectively.

The modified fragility functions are:

$$\Pr\left(\mathrm{DS}\middle|\mathrm{H}\middle|\text{cyclone shutters}\right)=\begin{cases}\Pr\left(\mathrm{DS}\middle|\mathrm{H}\middle|\text{no dominant opening}\right) & v\le v_{TH}\\ \Pr\left(\mathrm{DS}\middle|\mathrm{H}\middle|\text{dominant opening}\right) & v>v_{TH}\end{cases} \tag{5}$$

$$\Pr\left(\mathrm{DS}\middle|\mathrm{H}\middle|\text{no cyclone shutter}\right)=\begin{cases}\Pr\left(\mathrm{DS}\middle|\mathrm{H}\middle|\text{no dominant opening}\right) & v\le v_{TH-no}\\ \Pr\left(\mathrm{DS}\middle|\mathrm{H}\middle|\text{dominant opening}\right) & v>v_{TH-no}\end{cases} \tag{6}$$

where Pr(DS|H|dominant opening) and Pr(DS|H|no dominant opening) are derived from parameters given in Table 2 for a building designed as effectively sealed with and without dominant openings, respectively.

Damage to the roof envelope results in the following losses: L_1: roof covering, L_2: roof framing, L_3: building interior, L_4: contents losses, and L_5: Loss of use. House replacement value is clearly variable and depends on the location, type, size, age and condition of the house. The average cost per new house in southeast Australia is approximately $300,000 in 2016 Australian dollars. The probabilities of loss (Pr(L|DS) are obtained from HAZUS (2014), and where L_1=5.6%, L_2=19.5%, L_3=72%, L_4=50% of building replacement value, and L_5=\$21,000 per year.

5. Climate Impact Risks and Cost-Benefit Assessment

The climate adaptation or risk mitigation measure is for cyclone roller shutters to be installed on all new housing in non-cyclonic regions. The benefit of this risk mitigating measure is the expected damage (risk) of a building without shutters minus the reduced damage risk if cyclone shutters are installed.

Results are calculated using Monte Carlo event-based simulation methods. Costs and benefits are calculated for the 50-year period 2016 to 2066. The stochastic variability of wind speed means that risks are variable. The distribution of NPV is highly non-Gaussian which suggests that Monte Carlo methods are well suited to this type of analysis. Note that in this scenario-based approach Pr(C)=100%. Unless noted otherwise, all economic risks are presented as 2016 Australian dollars, and discount rate is r=4%.

The cumulative economic risks over the 50-year design life of the building are shown in Table 3 for a 4% discount rate. A house without cyclone shutters will increase damage losses by up to $15,000 by 2066. These are significant losses. A changing climate will slightly reduce median losses for Brisbane. Note also that economic losses due to loss of use are negligible when compared to the cost of repairing building damage and replacing contents. Cyclone shutters reduce risk by approximately 80%.

Table 3. Cumulative 50-year Economic Risks and Discount Rate of 4%.

	Cyclone Shutters			No Cyclone Shutters		
	10th	Median	90th	10th	Median	90th
Brisbane						
No Change	-	$3,012	-	-	$17,930	-
RCP2.6	$2,856	$3,029	$3,210	$16,195	$17,927	$19,833
RCP4.5	$2,468	$2,929	$3,106	$12,923	$16,880	$18,701
RCP8.5	$2,644	$2,856	$3,139	$14,603	$16,521	$19,452
Melbourne						
No Change	-	$182	-	-	$327	-
RCP2.6	NA	$184	NA	NA	$329	NA
RCP4.5	NA	$182	NA	NA	$293	NA
RCP8.5	$158	$175	$222	$283	$314	$394

A suitable decision metric is the Benefit-to-Cost Ratio (BCR) defined as benefit divided by the additional cost of cyclone window shutters per house. Table 4 shows the median Benefit-to-Cost Ratios (BCR) for assumed wind-rated door additional costs ranging from $2,500 per building to $25,000 per building, where the Benefit is $14,198 and $145 for Brisbane and Melbourne, respectively, for the RCP2.6 emission scenario. For more details of BCR see Stewart (2016).

The additional cost of cyclone shutters in non-cyclonic region will depend on the size, location, and type of house. Recent cost modelling suggests that installing cyclone shutters can cost up to $15,000 per house. In this case, Table 4 shows that the median BCR is 0.99 for Brisbane - i.e. $1 of cost buys 99 cents in benefits, so the measure is very close to being cost-effective. However, there is a 90% chance that the BCR will exceed 0.88, and a 10% chance that the BCR is higher than 1.1 for the same mitigation cost.

Table 4. Benefit-to-Cost Ratios (BCR), for RCP2.6 and a 4% Discount Rate.

Location	Cost of Cyclone Shutters Per House						
	\$2,500	\$5,000	\$10,000	\$15,000	17,500	\$20,000	\$25,000
Brisbane	6.0	3.0	1.5	0.99	0.85	0.75	0.59
Melbourne	0.06	0.03	0.01	0.01	0.09	0.007	0.006

As expected, BCR is very sensitive to replacement value of the house. The BCR will reduce as the discount rate increases. For example, if the discount rate is 7% the BCR reduces from 0.99 to 0.65.

6. Conclusions

A risk analysis was conducted to assess risks and economic impact of roof cladding damage for a representative house located in a non-cyclonic regions of Australia. The economic risks were calculated as the product of hazard likelihood, fragility, and loss over the 50-year design life of the house. The analysis included time-dependent changes in wind patterns due to a changing climate. The climate adaptation (or risk mitigation) strategy adopted was to install cyclone window shutters in non-cyclonic regions of Australia. The analysis assumed a building designed to be nominally sealed may experience a premature dominant opening due to failure of window. The probabilistic risk assessment found that a cyclone shutters reduces damage risk by approximately 80%. Specifying cyclone shutters for all new construction in non-cyclonic regions enhances resilience and is cost-effective if the additional cost per house is less than \$10,000 to \$15,000. Climate change has a minor effect on the cost-effectiveness of cyclone shutters.

References

AS/NZS1170.2, *Structural Design Actions, Part 2: Wind Actions*, Standards Australia, Sydney, 2011.

Dowdy, A. *et al*. (2015), *East Coast Cluster Report*, Climate Change in Australia Projections for Australia's Natural Resource Management Regions: Cluster Reports, eds. Ekström, M. *et al.,* CSIRO and Bureau of Meteorology, Australia, 2015.

Grose, M. *et al*. (2015), *Southern Slopes Cluster Report*, Climate Change in Australia Projections for Australia's Natural Resource Management Regions: Cluster Reports, eds. Ekström, M. *et al.*, CSIRO and Bureau of Meteorology, Australia, 2015.

HAZUS (2014), *Multi-hazard Loss Estimation Methodology - Hurricane Model*, Hazus–MH 2.1 Technical Manual, Federal Emergency Management Agency, Mitigation Division, Washington, D.C.

Parackal, K.I., Humphreys, M.T., Ginger, J. D., Henderson, D.J. (2016), Wind Loads on Contemporary Australian Housing, *Australian Journal of Structural Engineering*, 17(2): 136-150.

Stewart, M. G., Wang, X., Willgoose, G.R. (2014), Direct and Indirect Cost and Benefit Assessment of Climate Adaptation Strategies for Housing for Extreme Wind Events in Queensland*, Natural Hazards Review,* 15(4): 04014008(12).

Stewart, M.G. (2016), Climate Change Impact Assessment of Metal-Clad Buildings Subject to Extreme Wind Loading in Non-Cyclonic Regions, *Sustainable and Resilient Infrastructure*, 1(1-2): 32-45.

Stewart, M.G., Ginger, J.D., Henderson, D.J., Ryan, P.C. (2017), Fragility Analysis Of Australian Contemporary Housing Roof Sheeting Failure Due To Extreme Wind, *Proceedings of 9th Asia-Pacific Conference on Wind Engineering*, Auckland, New Zealand, 3-7 December 2017.

Wang, C-H., Wang, X., Khoo, Y.B. (2013), Extreme wind gust hazard in Australia and its sensitivity to climate change. *Natural Hazards*, 67(2): 549-567.