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Benefit-Cost Analysis of Retrofitting a High-Set House for Wind Hazard

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ABSTRACT

Benefit-cost analyses for retrofitting houses for severe wind hazard requires an accurate measure of the vulnerability of the structures being assessed. In this study, the Vulnerability and Wind Simulation (VAWS) Software was used to determine the vulnerability of a high-set Australian house to wind loads for several retrofitting scenarios. Benefit-cost analyses were then performed, using the difference between the Average Annual Loss (AAL) of the unretrofitted house and each retrofitting scenario to determine the net benefit of retrofitting. The analyses showed that considering the reduction in physical damage alone, there is generally no economic benefit for retrofitting older houses for wind hazard, especially in Australia's non-cyclonic regions where the probabilities of damaging wind speeds are lower than in the cyclonic regions.

1. Introduction

The development of the Vulnerability and Adaptation to Wind Simulation (VAWS) software was undertaken as part of the Bushfire and Natural Hazards CRC (BNHCRC) Project Titled 'Reducing the Vulnerability of Existing Housing to Severe Wind Events' by The Cyclone Testing Station and Geoscience Australia. The Case study presented in this paper on the benefit-cost analyses of retrofitting a high-set Australian house is presented in detail in the final report of this BNHCRC project. Results of the additional nine house types analysed as part of this project are also presented therein.

Vulnerability and Adaptation to Wind Simulation (VAWS) is a software package that has been developed to model the vulnerability of small buildings such as domestic houses and light industrial sheds to wind loading (Geoscience Australia 2020). Previous work documenting the development of the VAWS software have been presented in Smith, Edwards et al. (2020)

VAWS uses probability-based reliability analysis and structural analysis for the loading and response coupled with an extensive test database and field damage assessments of component properties to calculate the damage experienced by houses. VAWS is also used to estimate the change in vulnerability afforded by retrofit measures that improve a building's resilience to windstorms.

The VAWS model applies a component-based approach to modelling vulnerability, based on the premise that overall building damage is related to the failure of key connections. The program requires a user-specified building model for the house type and assigns values to parameters from probability distributions. These parameters include structural component spacings, component and connection strengths, external pressure coefficients, shielding factors, wind speed profile with height, building orientation, debris damage parameters, and component masses. Then, for progressive wind speed increments, it calculates the forces in all critical connections using influence coefficients, assesses which connections have failed and translates these into a damage scenario and costs the repair and calculates a damage index at each wind speed.

Figure 1 describes the logic of VAWS including the main modules: the house type and structural system, external and internal pressure distribution, structural response, initiation and progression of damage, and other effects such as wind-borne debris impact, water ingress and cost of repair. A case study for a high-set legacy Australian house is presented to show the outputs from VAWS, retrofit scenarios and the follow-on calculations for the benefit-cost of retrofitting.

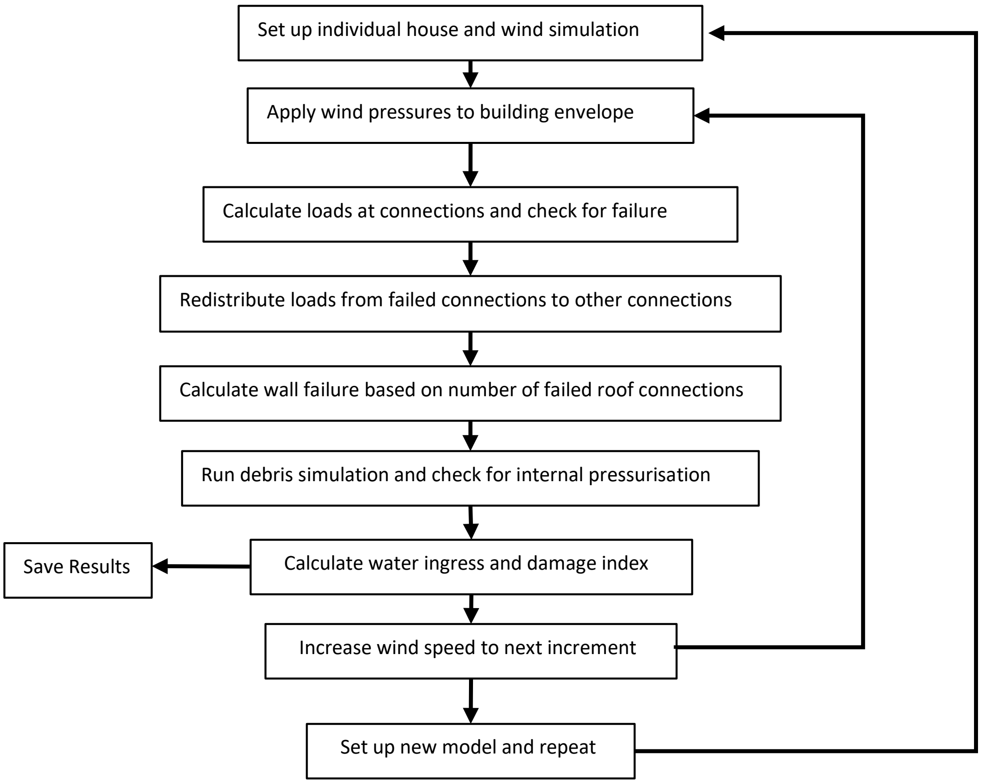

Figure 1. Vulnerability and Adaption to Wind Simulation (VAWS) model logic

1.1 Roof Damage and Load Redistribution

The VAWS program accounts for load redistribution and progressive failures of the roof structure by using structural analysis methods with several simplifying assumptions. Connections considered in the analysis are cladding fasteners, batten to rafter connections and rafter to top plate connections. The program relates pressures applied on envelope zones to the loads on cladding connections and the supporting structure using influence coefficients. Once connections have failed, the effects of redistribution are preserved for subsequent wind speed increments, thus ensuring that increasing wind loads act on the damaged structure. Following connection failures, redistribution of loads is modelled by changing the values of influence coefficients depending on the position of the failed connection in the load path.

1.2 Wind-borne debris and water ingress

Wind-borne debris impact on the envelope and the resulting damage is simulated by modelling the generation, trajectories and impact of debris in VAWS by a dedicated module (Holmes, Wehner et al. 2010, Wehner, Sandland et al. 2010). The level of water ingress is estimated in order to account for the repair costs associated with water damage to internal linings, using user-defined empirical relationships, as a function of wind speed based and the extent of damage to the house envelope.

1.3 Damage Costing

The program determines a repair cost for a damaged house by modelling the damage state(s) that a house is in at each wind speed and then costing the required repair work. The modelled house may have experienced one or more damage states (for example, loss of roof sheeting and debris damage to walls). The repair cost for any particular damage state is made up of three components: repair damage to the external envelope, repair of consequential damage to the interior, and repair to internal linings and fittings caused by water ingress calculated separately.

The project then expresses repair costs as a damage index calculated in Equation 1:

$$\text{Damage Index} = \frac{\text{Total building repair cost}}{\text{Building replacement cost}} \tag{1}$$

2. Case Study: High-Set Australian House

The VAWS software was used to model the vulnerability of a high-set Northern Australian house. The house is a high-set timber-framed structure with metal roof cladding and fibre cement wall cladding; an example is shown in Figure 2. The dimensions and structural system were determined from survey data, and the resulting representative house was originally described in Henderson and Harper (2003) as the Group 4 House. Further study on the vulnerability of this house type was also performed by Henderson and Ginger (2007). The house is 12.6 m long, 7.3 m wide and 4.4 m tall, constructed on 2.0 m high stumps. The roof structure consists of rafters at 10° pitch spaced at nominally 900 mm centres supporting battens also at 900 mm centres, which support corrugated metal cladding.

Figure 2. Example of the high-set house, Henderson and Ginger (2007)

2.1 Wind pressures

Wind pressures on the high-set house were determined by carrying out wind tunnel model studies. The tests were carried out in the 2.0 m high × 2.5 m wide × 22 m long Boundary Layer Wind Tunnel at the Cyclone Testing Station, James Cook University. The approach atmospheric boundary layer profile (suburban terrain, category 2.5 as per AS/NZS 1170.2) was simulated at a length scale of 1/50 using a 250 mm high trip board at the upstream end followed by an array of blocks on the tunnel floor.

2.2 Retrofit scenarios

For each of the house types, several retrofit scenarios were modelled to explore the benefit-cost of a variety of retrofit measures. Table 1 sets out the practical retrofit scenarios considered for the high-set house.

Table 1. Retrofit Scenario Descriptions for the high-set house

Retrofit Scenario	Retrofit Scenario Description
-	Nil (existing house)
1.1	Window protection and door upgrade
1.2	Roof sheeting upgrade
1.3	Roof sheeting and batten connection upgrades
1.4	Roof sheeting, batten connection and roof structure upgrade
1.5	All upgrades 1.1 to 1.4

3. VAWS outputs

The output from VAWS is a series of coordinates defining a graph of damage index versus gust wind speed at the house, as shown for the high-set house in Figure 3. These are the mean curves obtained from multiple realisations (typically n = 100). The high-set house is initially modelled in its baseline or unretrofitted condition. Following this, each retrofit scenario is modelled separately by changing the strength properties of the connections appropriate to the retrofit scenario under consideration, as defined in Table 1.

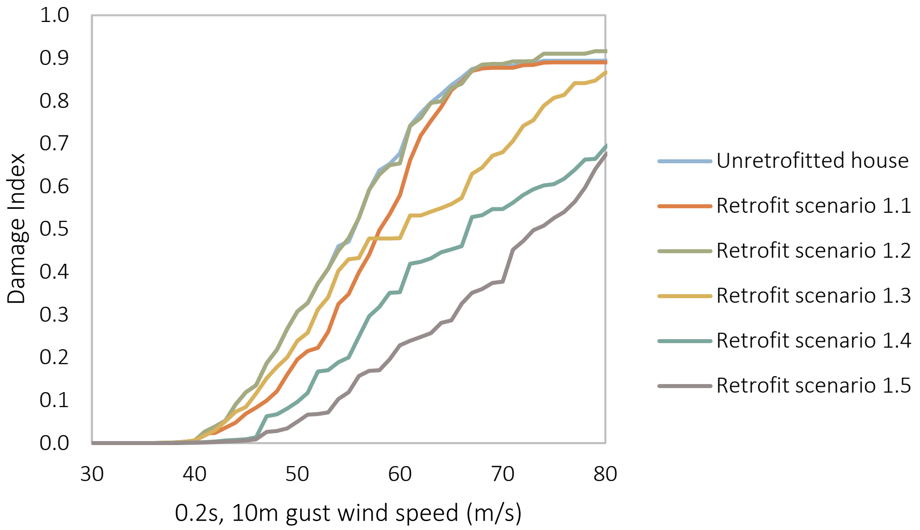

Figure 3 Damage index vs wind speed for the high-set house: unretrofitted house and with a range of retrofit scenarios

As shown in Figure 3, there are small reductions in vulnerabilities when strengthening windows (scenario 1.1) and strengthening batten to rafter connections (scenario 1.3). However, there is no significant change in vulnerability when upgrading roof cladding alone (scenario 1.2) as initial failures are most often associated with batten to rafter connections. The onset of damage for these retrofitting scenarios and the unretrofitted case begins at approximately 40m/s and complete damage at approximately 65m/s. Wind speeds of onset and complete failure of houses compare satisfactorily with observations from damage investigations.

4. Calculation of benefit-Cost

The economic advantage of retrofitting is often expressed as a benefit-cost ratio. Where the cost is that of installing the retrofit, and the benefit is the reduction in average annual loss over the remaining life of the building plus any reduction in indirect costs such as temporary housing required whilst repairs are carried out following wind damage. A ratio greater than one indicates a positive economic advantage of undertaking retrofit cost.

4.1 Costs of Retrofitting

Estimates of the cost of retrofit were determined through a contract with a professional quantity surveyor (Turner & Townsend 2019). The estimates included sufficient data to establish a full cost estimate for each retrofit scenario. Apart from the work of installing the actual retrofit, costs were also provided that cover access, removal and replacement of linings and fittings for access to install retrofit, builders' preliminaries and profit.

4.2 Calculation of benefit

The method used by the project to calculate benefit-cost is described in Wehner, Ryu et al. (2019). The calculation of benefit represents the largest task when calculating a benefit-cost ratio; the present value of benefit is shown in Equation 2:

$$PVB = \sum_{i} \left((AAL_{bi} - AAL_{ri}) \times \left(\frac{1}{(1+r)^{i}} \right) \right) \tag{2}$$

Where:

AAL_{bi} is the average annual loss of the unretrofitted house at year *i,*

AAL_{ri} is the average annual loss of the retrofitted house at year *i*,

i is the year number from current year varying from 1 to the remaining number of years in the house's lifespan and is taken as 30 years in this analysis.

r is the interest rate.

The benefit-cost ratios for the Type 1 house are given in Table 2.

Table 2 Estimated benefit-cost ratios for retrofit to high-set house

Retrofit scenario	**Benefit-cost in a non-cyclonic wind region**	**Benefit-cost in a cyclonic wind region**
1. Window and door protection	0.00	0.48
2. Roof sheeting upgrade	0.00	0.00
3. Roof sheeting and batten upgrade	0.00	0.15
4. Full roof upgrade	0.00	0.43
5. Full roof upgrade and door and window protection	0.00	0.36

5. Conclusions

Benefit-cost analyses showed that there is generally no economic benefit for retrofitting older houses for wind hazard, especially in the non-cyclonic regions of Australia where the probabilities of damaging wind speeds are lower than in the cyclonic regions. The present value of benefit for retrofitting in non-cyclonic regions is very low, and therefore, further reductions in retrofitting costs would still not be able to justify retrofitting.

The most obvious way to improve the economic benefit of retrofitting is to reduce the cost of retrofit. Typically the cost to undertake the actual retrofit (i.e. upgrading connection strengths or fitting window protection) is quite small. Often the largest components of the total retrofit cost are for access (scaffolding and fall-restraints) and removal of the existing envelope to expose the structure. For example, for House Type1 whose benefit-cost ratios are shown in Table 2, the contribution of access cost to the total retrofit cost ranges from 48% for retrofit scenario 2 to 26% for retrofit scenario 5. Thus if the retrofit work could be undertaken when the house is scaffolded for another reason, such as the replacement of corroded roof sheeting or painting, the economic benefit of retrofit becomes more attractive.

Further reductions in costs can occur when there is increased demand in the market for retrofitting. For example, the average retrofitting costs for a full roof upgrade (scenario .4) during the Queensland Household Resilience Program was approximately $18,000 which would produce a benefit-cost ratio of approximately 0.9 for the high-set house. Additional benefits that are not accounted for in this study are potential reductions in insurance premiums that may be offered to customers for implementing retrofitting measures.

Finally, structural damage, contents damage and costs of temporary accommodation are only a part of the costs to a town or community due to damaged houses during a tropical cyclone or thunderstorm. Costs related to the disruption of economic activity in the community and mental health impacts of the event on citizens and other intangible costs also add to the overall cost to the community. Accounting for these community-level costs would improve the benefit to cost of retrofitting older houses. This community level of analysis is a topic for further research. Additionally, a better understanding of the water ingress into houses by conducting a series of focused tests and research will enable these costs to be estimated more reliably and correlated with insurance payouts.

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