IMPROVING THE RESILIENCE OF EXISTING HOUSING TO SEVERE WIND EVENTS

Final project report

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Cover: Wind induced damage to a legacy house, TC Yasi.

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EXECUTIVE SUMMARY

This BNHCRC project titled: *Improving the resilience of existing housing to severe wind events* prescribes practical structural retrofits that will make improvements to the performance of Pre-80s (Legacy) houses in windstorms as well as measures to reduce damage and loss to contemporary houses.

Damage investigations carried out by the Cyclone Testing Station (CTS) following severe windstorms have typically shown that houses built prior to the mid-1980s in Australia perform worse than houses constructed to contemporary building standards, during windstorms. Given that these older houses are a significant proportion of the housing stock, practical structural upgrading based on the latest research may improve performance of housing and the economic and social wellbeing of a community.

Some details for structural retrofitting currently exist, but their uptake is limited, and there is also evidence that these are not carried out when houses require repairs following severe storms. Therefore, the issues of retrofitting legacy housing, including feasibility and benefit-cost are analysed in this project.

The primary objective of this study was to identify vulnerable legacy house types across Australia and develop cost-effective retrofits for mitigating damage during windstorms. These evidence-based strategies will (a) aid policy formulation and decision making by Government and industry, and (b) provide guidelines detailing various options and benefits to homeowners and the industry for retrofitting typical at-risk houses in Australia. The main aims were to:

- Categorise houses into types based on building features that influence windstorm vulnerability using Geoscience Australia and CTS survey data. Following this, define a suite of ten (10) typical, representative house types across cyclonic and non-cyclonic regions of Australia.
- Develop the software VAWS (available at https://github.com/GeoscienceAustralia/vaws) to quantify the vulnerability of the houses before and after retrofits. Define a series of practical retrofit options for each house type and quantify the benefit-cost ratio of each option. Validate these outputs from available data and empirical/expert opinion.
- Produce Internet-based guidelines (www.weatherthestorm.com.au) and enable utilisation by involving end-users and stakeholders (i.e. homeowners, builders, regulators, insurers).

This report presents an overview of the research approach used for this project including the selection of house types, the development of the VAWS software and the Internet-based guidelines. A case study is presented of the vulnerability and benefit cost assessment of one of the selected house types, with the complete set of results presented in the Appendices. These results show that tile roofed houses in cyclonic regions of Australia benefit the most from retrofitting for severe wind events. The benefit-cost ratios for these tile roof houses and other house types are expected to improve when accounting for intangible costs, which are currently not included in the analyses presented in this report. In addition, examples of the impacts and utilisation of this project including the Queensland Government Housing Resilience Program are also presented.

END-USER PROJECT IMPACT STATEMENT

Leesa Carson, *Community Safety Branch, Geoscience Australia, ACT*

Year after year Australia has witnessed the damage that severe wind, in particular cyclones, can do to houses and consequently people's wellbeing and livelihoods. Post-event surveys undertaken by James Cook University and Geoscience Australia and analysis of insurance losses have established the significant contribution that wind-induced damage to pre-modern code legacy housing makes to the total losses.

This project has sought to provide an evidence base to inform future mitigation work to reduce the contribution that legacy housing makes to the nation's natural disaster repair bill and improve the lives of their inhabitants. This aligns with the aims of the National Disaster Risk Reduction Framework. The project has developed guidance information, contained in a publicly available website, to inform people of the steps required to retrofit a house together with typical details of the kind of work required. Furthermore, the project has examined the benefit-cost of undertaking such work and identified that the return on investment is sensitive to the cost of undertaking the retrofit work. The cost can be reduced by such factors as:

- Incentive schemes which subsidise the cost of retrofit;
- Undertaking the work simultaneously with other work such as roof maintenance so that access costs are amortised across two or more projects;
- Undertaking retrofit work as part of a wider retrofit campaign so that economies of scale are realised.

The modelled benefit can be increased by incorporating the reduction in indirect costs, arising from retrofit, such as mental and physical health, absenteeism, etc. when such costs can be quantitatively estimated.

The project's outputs have been tested with stakeholders either through workshops or online focus groups. This strong stakeholder engagement has ensured the project outputs will be of practical use.

It is pleasing to note that the project's outputs will be utilised by a project, led by Queensland Fire and Emergency Services, to examine the benefit of mitigation in reducing potential severe wind impact and risk in south-east Queensland.

PRODUCT USER TESTIMONIALS

Lindsay Walker, *Director Building and Legislation Policy Division, Queensland Department of Energy and Public Works, QLD*

The groundbreaking work undertaken by JCU – CTS through the BNHCRC project 'Improving the resilience of existing housing to severe wind events' continues to improve our understanding of the dangers posed by cyclones to the built environment and the practical steps that can be taken to improve the resilience of new and existing buildings.

The report findings, recommendations and web tools developed through this project have the potential to provide valuable information to assist government, industry and the community to understand the options and benefits associated with improving the resilience of housing.

The user-friendly website builds on the truth that a house "is only as strong as its weakest point" and identifies critical points in an easy-to-understand way across a variety of different house designs and provides a range of practical measures to minimise potential risks.

The fact that these measures are supported by extensive research and on-the-ground real-life evidence gathered after a number of severe wind events, lends to the credibility of the project.

Additionally, the development of VAWS to assess the risk of wind-related damage, including water penetration, to a broader range of building types, has the potential to identify those buildings most at risk of failure and the most cost-effective strategies to improve the resilience of these buildings.

Based on feedback from the stakeholder workshops conducted during the project, the outcomes from the project are expected to be used by many in the regulatory, engineering/building, education and insurance industries.

There would be a need for the outputs (software, websites etc.) to be updated and maintained. Additionally, further research and development will enable more reliable vulnerability and losses to be calculated.

The Household Resilience Program demonstrates the power of combining a clear pathway for action with the pre-existing awareness of the dangers posed by cyclone season. Under this program 1,749 Queensland households from Bundaberg to the Cape were able to negotiate reduced insurance premiums by an average of $310.

Additional funding for continued research into how to improve the resilience of the built environment would be of benefit to government regulators, emergency services and the wider community.

INTRODUCTION

Post windstorm damage investigations carried out by the Cyclone Testing Station (CTS) have shown that Pre-80s legacy houses across Australia are vulnerable to wind damage. This damage is mostly due to design and construction deficiencies such as poor connection details. These studies also show that wind-driven rainwater ingress related damage at low to moderate wind speeds is common across all (including Post-80s) house types.

This project titled, "*Improving the resilience of existing housing to severe wind events*" prescribes practical structural retrofit measures that will reduce damage to houses in windstorms. This project defines a range of broadly classified common house types across cyclone and non-cyclone regions of Australia, and their roof and wall components and fixings.

Wind loads acting on these houses and the structural response to these loads are specified in probabilistic terms to determine their vulnerability. A series of practical, structural retrofit measures for each of these house types are given, and their enhanced performance quantified. A Software Package, developed during this project, called VAWS is used for this analysis. The viability of carrying out these retrofits are measured by Benefit-Cost ratios.

Web-based guidelines are produced as part of this project's outcomes, allowing users to gain a basic understanding of the vulnerability of common Australian house types, and practical structural retrofit measures to improve their performance.

This report describes the research methods, outputs, impact and utilisation.

KEY MILESTONES

The following are the key milestones of the project.

SELECTION OF HOUSE TYPES

House types across Australia were compiled from survey data, other databases and insurance claims data analysis. The structural systems and construction methods of houses across Australia have been collated. This information and the NEXIS database were used to define the ten generic house types studied in this project. In addition, commonly encountered maintenance and construction shortcomings have been documented.

VAWS MODELLING

The Vulnerability and Adaptation to Wind Simulation (VAWS) software package for assessing the vulnerability of Australian houses to windstorms was developed through the duration of the project. This software package forms a significant part of the project and is used to determine the vulnerability and calculate the damage index for each house type in the unretrofitted sate and following each retrofit option.

SELECTION OF RETROFITTING OPTIONS

Practical and cost-effective retrofit options for each house type are developed to address components of the house structure and envelope that are points of failure commonly observed in post-windstorm surveys and hence significantly contribute to a house's vulnerability. These retrofit options are also provided in the web-based guidelines.

BENEFIT-COST ANALYSIS

The economic benefit of applying each of the specified retrofits to each generic house type is assessed via a benefit-cost analysis based on the output from the VAWS software.

WEB-BASED RETROFITTING GUIDELINES

A website that provides some basic information on wind loading and the structural system of common generic Australian houses has been produced. The website also presents the benefits of maintenance and retrofitting in reducing damage to a house during windstorms and describes the nature of possible connection retrofits.

BACKGROUND

This project examines the benefit-cost of retrofitting the legacy housing stock in cyclonic and non-cyclonic regions of Australia to improve their performance when exposed to severe winds.

Damage investigations carried out by the Cyclone Testing Station (CTS) following severe wind storms have typically shown that Australian houses built prior to the mid-1980s do not offer the same level of performance and protection during windstorms as houses constructed to contemporary building standards (Henderson, Ginger et al. 2006, Boughton, Henderson et al. 2011, Boughton, Falck et al. 2017).

Structural retrofitting details exist for some forms of legacy housing, but the uptake of these options is limited. There is also evidence that retrofitting is not carried out even when houses require major repairs following severe storm events, thus missing an opportunity to improve the resilience of the house and community.

Table 1 shows the proportion of legacy houses (here defined as those built before1982) and contemporary houses in Australia. In the non-cyclonic regions, legacy houses represent approximately 42% of the housing stock, whilst in cyclonic regions, legacy houses comprise approximately 45% of the housing stock. Hence, there is a significant proportion of the Australian housing stock built prior to the introduction of contemporary standards in the 1980s that may benefit from structural retrofitting against severe windstorms.

Wind regions	Pre 1982 (legacy)	1982+ (modern)
Non Cyclonic A and B	2,977,295	4,121,781
Cyclonic C and D	164,432	204,317

TABLE 1 NUMBERS OF HOUSES IN AUSTRALIA BY AGE AND WIND REGION EXTRACTED FROM NEXIS (NADIMPALLI, EDWARDS ET AL. 2007)

RESEARCH APPROACH

The research approach to answering the question "is it worthwhile to retrofit legacy houses exposed to severe wind" is a four-stage process.

1. Define a series of typical House Types and their structure that is representative of houses commonly found across Australia. Determine relevant data for the house types chosen:
    a. Structural systems and strengths of connections, both in the unretrofitted house and retrofitted house and,
    b. The magnitudes of wind loads acting on the house envelope.
2. Using the data developed in Stage 1, model the vulnerability of the chosen house types both in the unretrofitted state and with each retrofit scenario installed.
3. From the modelled vulnerability curves, compute the benefit-cost ratio for each retrofit scenario for each chosen house type.

Prepare guidelines on retrofitting legacy houses to improve their resilience to severe wind.

HOUSE TYPES

There is a large variety of house types across Australia. The project has selected ten generic house types of simple geometry based on surveys from different parts of Australia, interviews and extraction from databases. The selected house types are intended to broadly reflect the variety of houses found in the Australian building stock. Table 2 lists the ten (10) generic house types together with some descriptive attributes which are also provided in Appendix A, containing drawings of the overall form and dimensions for each of the generic house types.

Generic house type	Vintage	Wall construction	Roof material	Roof shape
1	Legacy	Fibro (high set)	Metal sheeting	Gable, low pitch
2	Modern	Reinforced block	Metal sheeting	Gable, medium pitch
3	Legacy	Double brick	Metal sheeting	Gable, medium pitch
4	Legacy	Double brick	Tile	Gable, medium pitch
5	Legacy	Double brick	Metal sheeting	Hip, medium pitch
6	Legacy	Double brick	Tile	Hip, medium pitch
7	Legacy	Brick veneer	Metal sheeting	Gable, medium pitch
8	Legacy	Brick veneer	Tile	Gable, medium pitch
9	Legacy	Brick veneer	Metal sheeting	Hip, medium pitch
10	Legacy	Brick veneer	Tile	Hip, medium pitch

TABLE 2 GENERIC HOUSE TYPES

ESTIMATION OF VULNERABILITY

In order to estimate the benefit of retrofit, it is necessary to quantitatively model the vulnerability of the subject house and how the vulnerability changes due to retrofit. To achieve this, the project developed a software package called Vulnerability and Adaptation to Wind Simulation (VAWS). The primary output of the software is a numerical definition (as a series of x, y points) of the modelled house's mean vulnerability curve.

The VAWS software and accompanying user manual are publically available on Github (Geoscience Australia 2020).

Vulnerability and Adaptation to Wind Simulation (VAWS) model

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. VAWS uses probability-based reliability analysis and structural engineering for the loading and response coupled with an extensive test database and field damage assessments of component properties to calculate the damage experienced by the ten Australian house types selected for this project. VAWS is used to estimate the change in vulnerability afforded by retrofit measures which improve a building's resilience to windstorms.

VAWS consists of modules for:

1. Wind hazard – external and internal pressures generated by the atmospheric wind.
2. Structural response – related to the structural system and load effects, and strengths of the components and connections.
3. Costing the repair of damage. The program is able to accommodate house types for which the structural system and their response, and the external pressure distribution for wind exposure from directions around the compass are given.

The critical structural components are probabilistically assigned their strengths, and the wind loads are applied for winds approaching from a specified direction. Failure is initiated when the load exceeds the capacity of a critical component or connection as the wind loads increase with wind speed. When components fail, loads are redistributed through the structural system. The cost of repair is calculated for the given level of damage, and the damage index is calculated at each wind speed increment.

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 (Type 1 as defined in Table 2) is presented to show the outputs from VAWS, retrofit scenarios and the follow-on calculations for the benefit-cost of retrofitting.

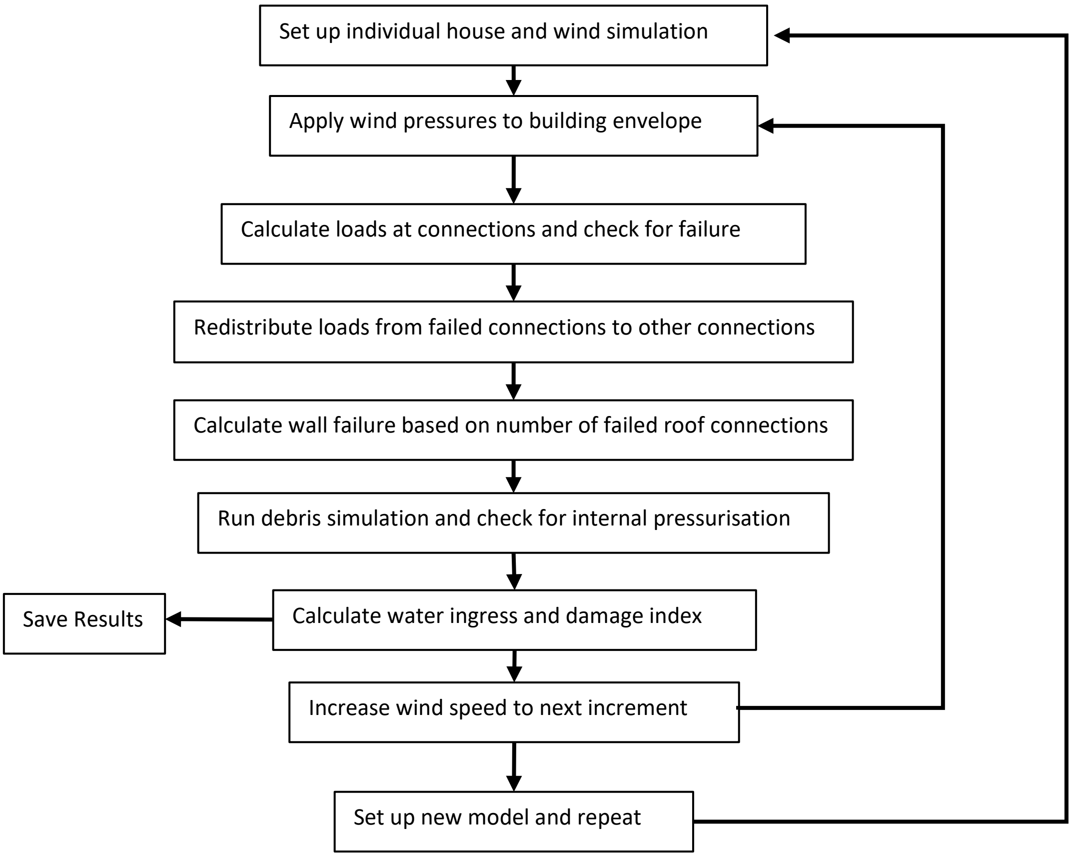


FIGURE 1 VULNERABILITY AND ADAPTION TO WIND SIMULATION (VAWS) MODEL LOGIC

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.

VAWS makes the following simplifications to solve the complex problem of modelling the structural vulnerability of houses:

- Damage is related to the failure of connections
- The contributions of components such as wall linings, cornices, etc. to the house's capacity to resist wind loads are accommodated by adjusting the strengths of modelled connections,
- The effects of fatigue are accounted for by adjusting connection strength rather than modelling time-varying loads
- Redistribution of loads in roof cladding and battens occurs independently without accounting for the interaction between components or their relative stiffnesses

- The loads in connections are analysed using influence coefficients. Redistribution of loads are modelled by overwriting influence coefficients with revised values assuming single failed connections, and
- The proportion of internal linings and fittings that require repair due to wetting from water ingress is related to the degree of envelope damage and wind speed.

Key parameters and variability simulation modules

The variabilities in wind loading and component parameters are captured by a Monte Carlo process. The parameter values are assigned for each realisation of the modelled house and kept the same, as the wind speed is increased incrementally up to a set maximum.

- For each house, its orientation with respect to the approach wind is either randomly chosen from the eight cardinal directions or assigned by the user.
- Variation in the gust wind speed profile with height is captured by random sampling from a suite of profiles related to the approach terrain category.
- External pressure coefficients for different zones of the house envelope are chosen from a Type III (Weibull) extreme value distribution based on wind tunnel model test data for different zones of the house envelope. The internal pressures are then derived from the external pressures and the openings in the envelope.
- 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).
- Connection strengths and dead loads for each realisation are sampled from log-normal probability distributions specified by the user.

Water ingress is estimated to account for the repair costs associated with water damage to internal linings. Predefined relationships for the extent of water damage as a function of the extent of damage to the house envelope and of wind speed are applied.

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 include: 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.

A database of influence coefficients is provided as input data for each intact house type. The influence coefficients are determined from structural analysis and full-scale tests on house systems. Another database of influence coefficients defines the changes in structural response and load paths that occur after the failure of connections in the roof structure, i.e. connections below the batten-to-rafter connections such as the rafter-to-top-plate or collar-tie-to-rafter, etc. Revised influence coefficients are provided for each connection on the rafter line of the failed connection and the adjacent rafter line.

Wall collapse

The extent of damage to walls in a house in a windstorm depends on many factors such as loss of support to the top plate occurring when the rafter to top plate connections fail; the location of internal cross-walls; wall types; and wind speed. Damage surveys have shown that the extent of wall collapse can vary markedly across similar house types. For example, after total roof loss, the house shown in Figure 2 has lost approximately 75% of its walls whilst, the house shown in Figure 3 experienced minimal wall collapse following total roof loss.

FIGURE 2 DAMAGE TO A HOUSE DURING TC LARRY

FIGURE 3 DAMAGE TOA HOUSE IN TC YASI

The collapse of walls contributes to a large component to the cost of repairs and hence should be taken into account.

VAWS models the collapse of walls, based on the extent of roof-to-wall connection failures that may typically occur during a windstorm. Figure 4 shows the empirical relationships between wall collapse and the failure of roof-to-wall connections determined in this project through engineering judgement and observations from damage surveys.

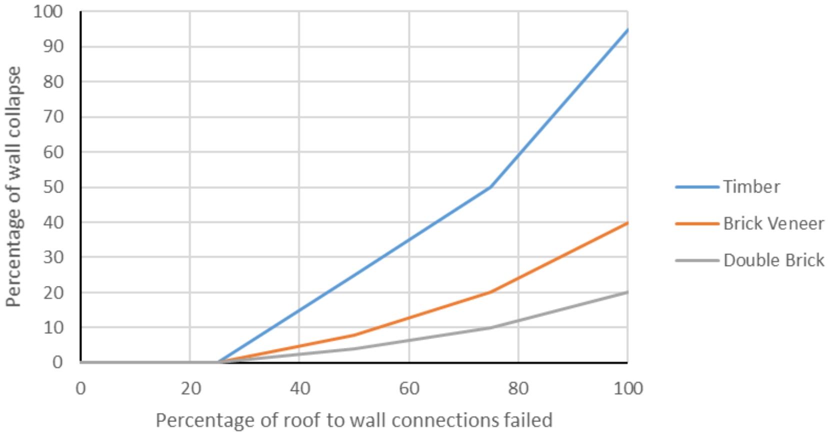


FIGURE 4 RELATIONSHIP BETWEEN WALL COLLAPSE AND FAILURE OF ROOF TO WALL CONNECTIONS BY PRIMARY WALL STRUCTURE.

Water ingress

Water ingress is estimated in order to account for the costs associated with water damage to internal linings, using user-defined empirical relationships, as a function of wind speed based on the extent of damage to the house envelope, as shown in Figure 5.

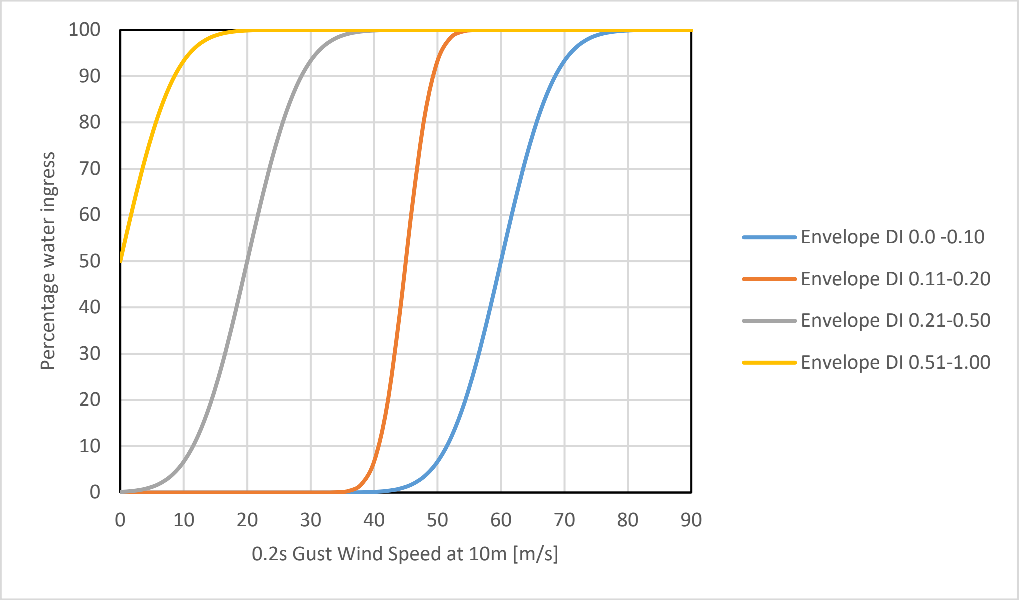


FIGURE 5 EMPIRICAL WATER INGRESS CURVES FOR A HOUSES WITH METAIL ROOF CLADDING IN THE UNRETROFITTED STATE.

Wind-borne debris induced damage

The effects of wind-borne debris are simulated in VAWS. The method requires the user to define the following parameters:

- The urban environment within which the modelled house is sited. This, in turn, defines the mix of debris (type and mass) that may become airborne.

- The number and distribution of upwind debris sources (usually houses) together with the population of debris pieces that may become airborne from each source house.
- The relationship between wind speed and the number of entrained debris items from each source house.

At each wind speed, the debris module samples the number of entrained debris items, assigns their properties probabilistically, computes their flight distance and determines their landing location. From this, the number of debris items that impact the modelled house together with their momenta is computed.

Debris items that impact the modelled house contribute to damage in two ways: firstly if they have sufficient momentum to pierce the envelope (doors and windows only) they cause direct envelope damage which requires repair; and secondly, if they pierce a window or door internal pressure is increased which affects the wind load on the house's envelope and structure.

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. Thus, the total repair cost for a house type at a wind speed is:

$$\begin{aligned}&\text{Total repair cost}\\&=\left(\sum_{\text{All damage states i}}\text{External envelope repair cost}_{\text{i}}+\text{Consequential internal repair cost}_{\text{i}}\right)\\&+\text{Water ingress repair cost}\end{aligned}$$

The two components of the repair cost for each damage state, *i*, are calculated as below. The calculation allows for each damage state to only affect part of the total susceptible area (for example, only a corner of the roof may have lost its roof sheeting).

$$\begin{aligned}&\text{External envelope repair cost}_{\text{i}}\\&=\text{Total quantity}_{\text{i}}\times\text{Percent damage}_{\text{i}}\times\text{Repair rate}_{\text{i}}\times\text{f}_{\text{i}}(\text{Percent damage})\end{aligned}$$

$$\begin{aligned}&\text{Consequential internal repair cost}_{\text{i}}\\&=\text{Internal repair cost}_{\text{i}}\times\text{Percent damage}_{\text{i}}\times\text{f}_{\text{i}}(\text{Percent damage})\end{aligned}$$

Where f_i(Percent damage) are functions adjusting the repair rate to allow for higher repair rates for extents of repair less than full repair. It is in the form of a quadratic equation ($a_1x^2+a_2x+a_3$) where x is the percent damage in a particular damage state, and a_1 to a_3 are user-supplied coefficients.

The repair cost due to water ingress is calculated from the modelled degree of water ingress, the dominant damage state and repair costs supplied in the costing data as follows.

$$\text{Water ingress repair cost}_{\text{i}} = \text{Water ingress repair cost}_{\text{i},\%} \times \text{f}_{\text{i}}(\text{Percent damage})$$

Here $\text{Water ingress repair cost}_{\text{i},\%}$ is repair cost data supplied as part of the costing module for the repair of damage caused by water ingress for a house. The costing algorithm contains logic to prevent double-counting of repair to building components where component repair is nominated in multiple damage states.

The project expresses repair costs as a damage index calculated as:

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

This permits the results to be applied to other houses of similar generic type but different floor areas. The repair cost is then calculated by multiplying the damage index by the floor area and the replacement rate for the house type.

CASE STUDY: HOUSE TYPE 1 – HIGH-SET AUSTRALIAN HOUSE

The VAWS software is used to model the vulnerability of the high-set Northern Australian house. The details of the model and an interpretation of the results are presented in the following sections. The house is a high-set timber-framed structure with metal roof cladding and fibre cement wall cladding, an example is shown in Figure 6. 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 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. The overall dimensions and locations of windows and doors are shown in Figure 7 and the structural system of the roof shown in Figure 8.

FIGURE 6 EXAMPLE OF A HOUSE TYPE 1 HENDERSON AND GINGER (2007)

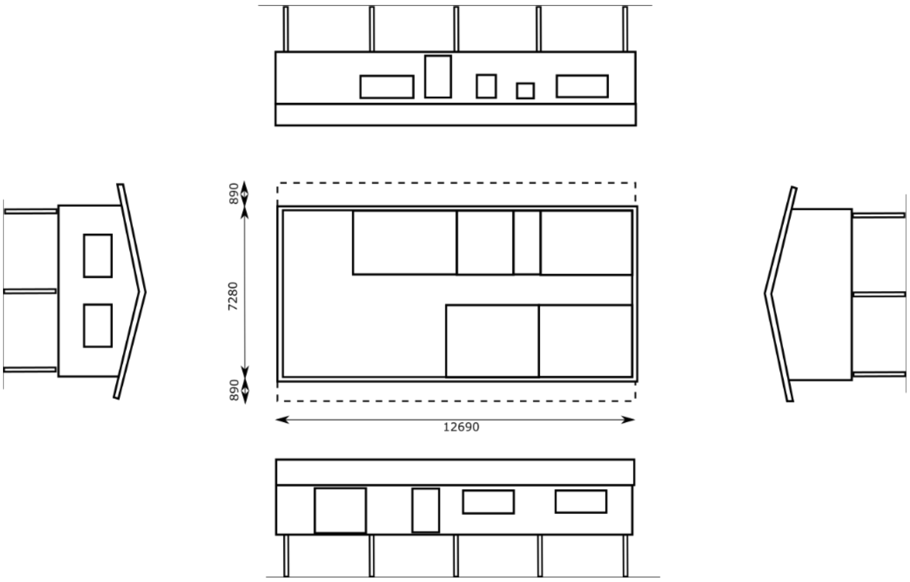


FIGURE 7 OVERALL DIMENSIONS OF HOUSE TYPE 1, DIMENSIONS IN mm

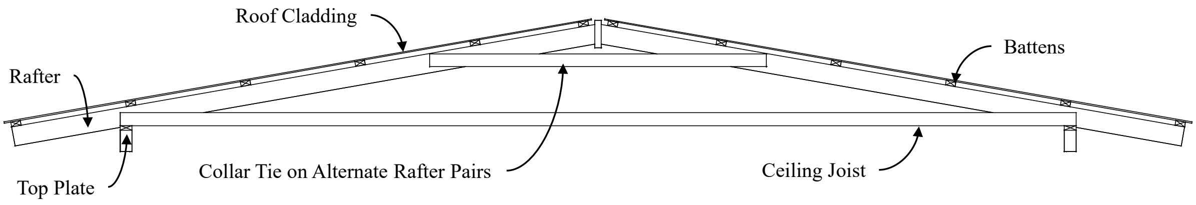


FIGURE 8 ROOF STRUCTURE OF HOUSE TYPE 1

Wind pressures

Wind loads on the generic house types analysed in this project 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.

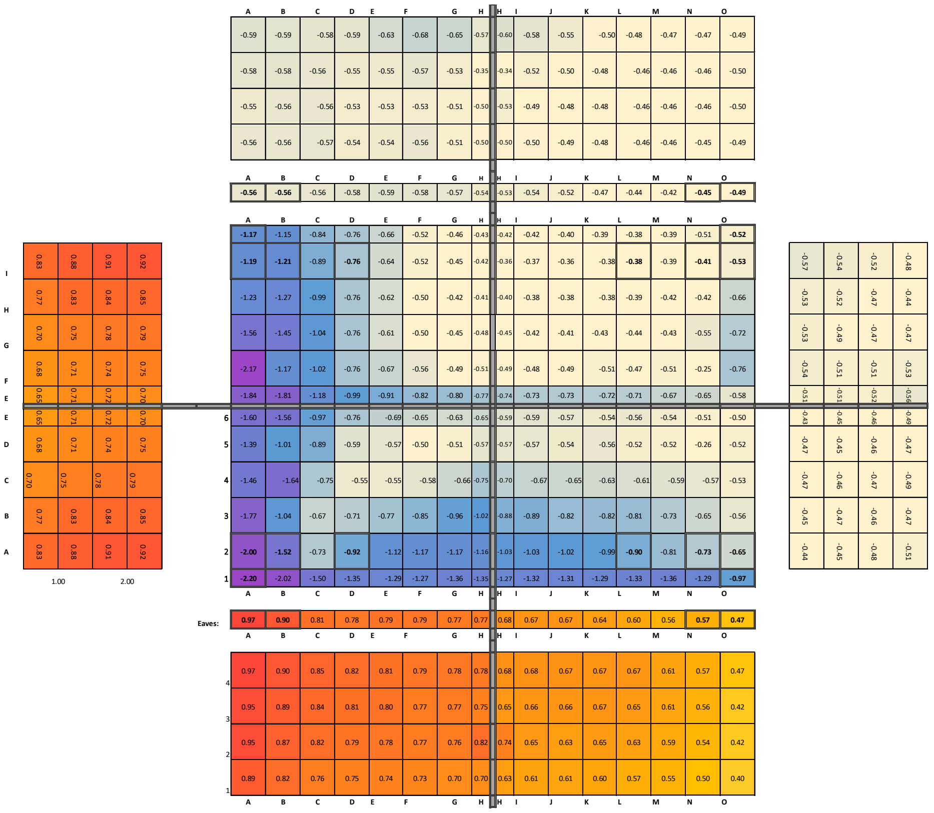
Pressure taps were installed on the external surfaces of the models to measure the external pressures. Each pressure tap was connected to transducers located below the wind tunnel floor/turntable via a length of tuned PVC tubing. External pressures on the roof, walls and floor were obtained for approach wind directions (θ) of 0° to 360° in steps of 10°. The fluctuating pressures were low-pass filtered at 500 Hz, sampled at 1000 Hz for 30 s (corresponding to ~ 10 min in full-scale) and and analysed to give the pressure coefficients referenced to the mean dynamic pressure at roof height:

$$C_p(t) = p(t) \Big/ \left(\tfrac{1}{2}\rho \overline{U}_h^{\,2}\right)$$

Where, $\overline{U}_h$ is the mean velocity at roof height and $p(t)$ is the recorded time varying pressure. The spatial pressure distributions were used to identify regions experiencing large wind loads, and for consistency with data given in AS/NZ 1170.2. The AS/NZS 1170.2 equivalent quasi-steady aerodynamic shape factor $C_{fig} = C_{peak}/G_u^2$, where C_{peak} are the maximum and minimum pressure coefficients within an observation time equivalent to 10 min in full scale and $G_U = (\hat{U}_h/\overline{U}_h)$ is the velocity gust factor. Here, $\hat{U}_h$ and $\overline{U}_h$ are the 0.2 s gust wind speed, and 10 min mean wind speed respectively at roof height.

Pressure distributions

The average of the peak pressure coefficients obtained for approach winds within a 45° sector was used to derive the pressure distributions used for eight cardinal directions. The wind pressure distributions for a cornering wind sector 225° ± 25° on House Type 1 is shown in Figure 9. These wind tunnel derived pressures account for local pressure effects in flow separation regions and are used for the application of load to cladding and immediate supporting members such as batten to rafter connections. The pressures are factored by 0.5 for loads applied to major structural elements to account for area averaging effects of pressure fluctuations on the tributary area of the element.



A	B	C	D	E	F	G	H	H	I	J	K	L	M	N	O
-0.59	-0.59	-0.58	-0.59	-0.63	-0.68	-0.65	-0.57	-0.60	-0.58	-0.55	-0.50	-0.48	-0.47	-0.47	-0.49
-0.58	-0.58	-0.56	-0.55	-0.55	-0.57	-0.53	-0.35	-0.34	-0.52	-0.50	-0.48	-0.46	-0.46	-0.46	-0.50
-0.55	-0.56	-0.56	-0.53	-0.53	-0.53	-0.51	-0.50	-0.53	-0.49	-0.48	-0.48	-0.46	-0.46	-0.46	-0.50
-0.56	-0.56	-0.57	-0.54	-0.54	-0.56	-0.51	-0.50	-0.50	-0.50	-0.49	-0.48	-0.46	-0.46	-0.45	-0.49

A	B	C	D	E	F	G	H	H	I	J	K	L	M	N	O
-0.56	**-0.56**	-0.56	-0.58	-0.59	-0.58	-0.57	-0.54	-0.53	-0.54	-0.52	-0.47	-0.44	-0.42	**-0.45**	**-0.49**

	A	B	C	D	E	F	G	H	H	I	J	K	L	M	N	O
	-1.17	-1.15	-0.84	-0.76	-0.66	-0.52	-0.46	-0.43	-0.42	-0.42	-0.40	-0.39	-0.38	-0.39	-0.51	**-0.52**
	-1.19	**-1.21**	-0.89	**-0.76**	-0.64	-0.52	-0.45	-0.42	-0.36	-0.37	-0.36	-0.38	**-0.38**	-0.39	**-0.41**	**-0.53**
	-1.23	-1.27	-0.99	-0.76	-0.62	-0.50	-0.42	-0.41	-0.40	-0.38	-0.38	-0.38	-0.39	-0.42	-0.42	-0.66
	-1.56	-1.45	-1.04	-0.76	-0.61	-0.50	-0.45	-0.48	-0.45	-0.42	-0.41	-0.43	-0.44	-0.43	-0.55	-0.72
	-2.17	-1.17	-1.02	-0.76	-0.67	-0.56	-0.49	-0.51	-0.49	-0.48	-0.49	-0.51	-0.47	-0.51	-0.25	-0.76
	-1.84	-1.81	-1.18	-0.99	-0.91	-0.82	-0.80	-0.77	-0.74	-0.73	-0.73	-0.72	-0.71	-0.67	-0.65	-0.58
6	-1.60	-1.56	-0.97	-0.76	-0.69	-0.65	-0.63	-0.65	-0.59	-0.59	-0.57	-0.54	-0.56	-0.54	-0.51	-0.50
5	-1.39	-1.01	-0.89	-0.59	-0.57	-0.50	-0.51	-0.57	-0.57	-0.57	-0.54	-0.56	-0.52	-0.52	-0.26	-0.52
4	-1.46	-1.64	-0.75	-0.55	-0.55	-0.58	-0.66	-0.75	-0.70	-0.67	-0.65	-0.63	-0.61	-0.59	-0.57	-0.53
3	-1.77	-1.04	-0.67	-0.71	-0.77	-0.85	-0.96	-1.02	-0.88	-0.89	-0.82	-0.82	-0.81	-0.73	-0.65	-0.56
2	**-2.00**	**-1.52**	-0.73	**-0.92**	-1.12	-1.17	-1.17	-1.16	-1.03	-1.03	-1.02	-0.99	**-0.90**	-0.81	**-0.73**	**-0.65**
1	**-2.20**	-2.02	-1.50	-1.35	-1.29	-1.27	-1.36	-1.35	-1.27	-1.32	-1.31	-1.29	-1.33	-1.36	-1.29	**-0.97**
	A	B	C	D	E	F	G	H	H	I	J	K	L	M	N	O

	A	B	C	D	E	F	G	H	H	I	J	K	L	M	N	O
Eaves:	**0.97**	**0.90**	0.81	0.78	0.79	0.79	0.77	0.77	0.68	0.67	0.67	0.64	0.60	0.56	**0.57**	**0.47**

	A	B	C	D	E	F	G	H	H	I	J	K	L	M	N	O
4	0.97	0.90	0.85	0.82	0.81	0.79	0.78	0.78	0.68	0.68	0.67	0.67	0.67	0.61	0.57	0.47
3	0.95	0.89	0.84	0.81	0.80	0.77	0.77	0.75	0.65	0.66	0.66	0.67	0.65	0.61	0.56	0.42
2	0.95	0.87	0.82	0.79	0.78	0.77	0.76	0.82	0.74	0.65	0.63	0.65	0.63	0.59	0.54	0.42
1	0.89	0.82	0.76	0.75	0.74	0.73	0.70	0.70	0.63	0.61	0.61	0.60	0.57	0.55	0.50	0.40
	A	B	C	D	E	F	G	H	H	I	J	K	L	M	N	O

		1.00		2.00
I	0.83	0.88	0.91	0.92
H	0.77	0.83	0.84	0.85
G	0.70	0.75	0.78	0.79
F	0.68	0.71	0.74	0.75
E	0.65	0.71	0.72	0.70
E	0.65	0.71	0.72	0.70
D	0.68	0.71	0.74	0.75
C	0.70	0.75	0.78	0.79
B	0.77	0.83	0.84	0.85
A	0.83	0.88	0.91	0.92

-0.57	-0.54	-0.52	-0.48
-0.53	-0.52	-0.47	-0.44
-0.53	-0.49	-0.47	-0.47
-0.54	-0.51	-0.51	-0.53
-0.51	-0.51	-0.52	-0.56
-0.43	-0.45	-0.46	-0.49
-0.47	-0.45	-0.46	-0.47
-0.47	-0.46	-0.47	-0.49
-0.45	-0.47	-0.46	-0.47
-0.44	-0.45	-0.48	-0.51

FIGURE 9 C_{fig} PRESSURE DISTRIBUTION FOR THE SECTOR 225 ± 25° ON THE ROOF, WALLS AND THE UNDERSIDE OF THE EAVES OF HOUSE TYPE 1

Analysis of pressure coefficients with wind direction, θ show that the windward edge of the roof experiences the largest peak suction pressures and the (windward) wall is subjected to high positive pressures. These pressures are generally close to values given in AS/NZS1170.2. The underside of the eaves is subjected to pressures similar to that on the adjacent wall surface. Roof cladding, battens and rafters near the windward gable-end experience the largest wind pressures.

Internal pressure coefficients are derived in accordance with AS/NZS 1170.2 depending on the distribution and sizes of openings in the walls. The presence of openings is ascertained by modelling debris impact during a storm and pressure-induced failures of windows and doors. The internal pressure in the nominally sealed house with the envelope intact is small, i.e. the internal pressure coefficient $C_{pi} = 0$. However, the failure of a door or window on the windward wall from wind pressure or debris impact with increasing wind speed can result in the internal pressure reaching the values of the external wall pressure at the dominant opening $C_{pi} = 0.6$ or more.

Component strengths

The assessment of vulnerability relies on many inputs and one of the most important is the assessment of connection strengths for both unretrofitted legacy houses and houses with retrofitted connections. VAWS does not model time-varying fluctuating loads; hence the connection strengths for those components susceptible to fatigue have to be reduced to account for the loss of strength due to fatigue. Table 3 presents the strengths and coefficients of variation adopted for the unretrofitted house type 1 considered in this study.

Connection type	Connection	Mean Strength	Strength CoV
Metal Roof Sheeting Connections - Legacy (Cyclonic)	3-4-3 fastener arrangement	2.6 kN per m Length	0.2
Metal Roof Sheeting Connections - Legacy (Non Cyclonic)	3-4-3 fastener arrangement	3.6 kN per m length	0.2
Metal Roof's Batten rafter connection - Legacy	2x plain shank nails	1.5kN	0.12
Roof to wall connection - Legacy High-set	Skew nails	2kN*	0.23
Ridge Connection - Legacy	Skew nails	4kN*	0.3
Collar tie connection - Legacy	Plain shank nails	2.4kN*	0.2
Racking of Piers		70kN/house	

TABLE 3 STRENGTHS OF CONNECTIONS IN UNRETROFITTED HOUSE TYPE 1

*Connections adjusted to 5kN in the modelling to account for load sharing effects.

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 4 sets out the practical retrofit scenarios considered by the project for House Type 1. Table 5 gives the revised strengths adopted for each upgraded connection type in house type 1.

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

TABLE 4 RETROFIT SCENARIO DESCRIPTIONS FOR HOUSE TYPE 1

Connection type	Connection	Mean Strength	Strength CoV
Metal Roof Sheeting Connections - Legacy (Cyclonic)	New roof cladding	4.1 kN per m length	0.2
Metal Roof Sheeting Connections - Legacy (Non-Cyclonic)	New roof cladding	4.1 kN per m length	0.2
Metal Roof's Batten rafter connection - Legacy	Addition of batten screw or strap	Additional 3.6kN	0.2
Roof to wall connection - Legacy High-set	Addition of a strap	12kN	0.1

Ridge Connection - Legacy	Addition of new collar tie - MGP10, with 2x 14 gauge Type 17 screws each end	Additional 4kN	0.2
Collar tie connection - Legacy	Addition of a type 17 screw through collar tie into rafter	Additional 4kN	0.2

TABLE 5 STRENGTHS OF RETROFITTED CONNECTIONS HOUSE TYPE 1

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 House Type 1 in Figure 10. These are the mean curves obtained from multiple realisations (typically n = 100). Each house is initially modelled in its baseline or unretrofitted condition. Following this, each retrofit scenario of each house is modelled separately by changing the strength properties for the selection of connections shown in Table 3 according to retrofitted details shown in Table 5 appropriate to the retrofit scenario under consideration as defined in Table 4.

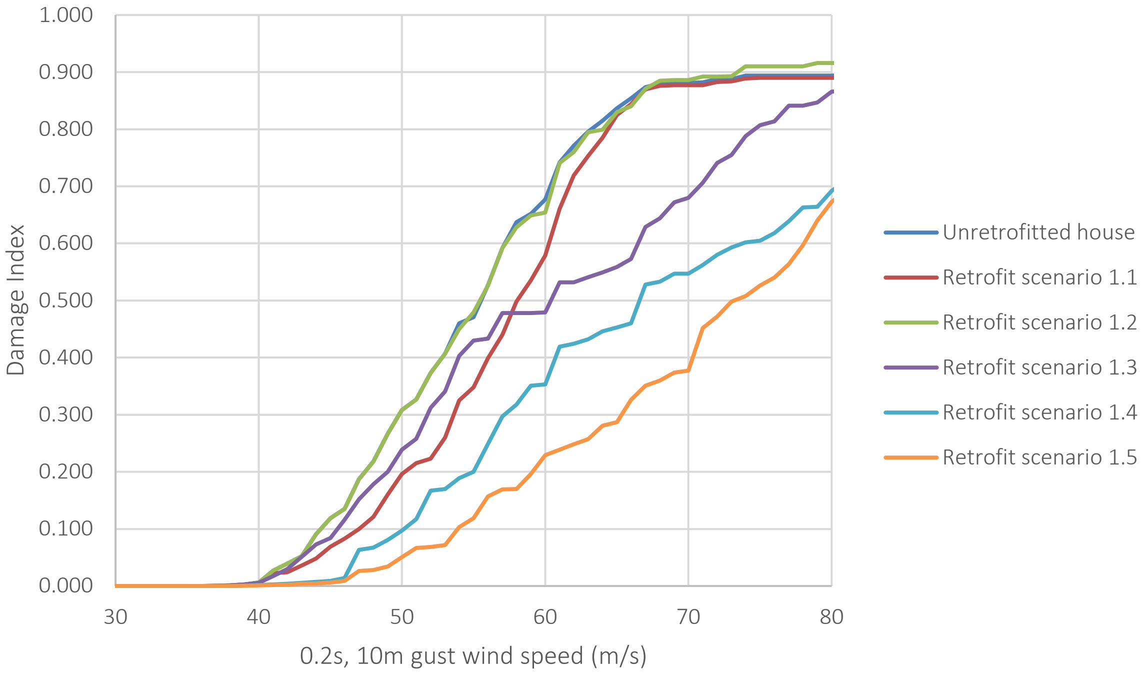


FIGURE 10 DAMAGE INDEX VS WIND SPEED FOR HOUSE TYPE 1: UNRETROFITTED HOUSE AND WITH A RANGE OF RETROFIT SCENARIOS

The vulnerability curves for the unretrofitted House Type 1, together with each retrofit scenario, are shown in Figure 10. It can be seen that there are small reductions in vulnerabilities when strengthening windows (scenario 1.1) and strengthening batten to rafter connections (scenario 1.3). There is no significant change in vulnerability when upgrading roof cladding alone (scenario 1.2) as initial failures are most often associated with the batten or rafter connections. The onset of damage for these retrofitting scenarios and the unretrofitted case begins at approximately 40m/s and complete damage occurs at approximately 65m/s.

The case study of a high-set Australian house (Type 1) shown, quantifies the vulnerability of a population of these house types. VAWS allows the reduction in vulnerability afforded by retrofit to be modelled by re-running a simulation with the connection strength parameters adjusted to suit the strengthening work. VAWS estimates similar extents of failure that would occur in a windstorm. The simulation of n = 100 realisations of House Type 1 allowed the fitting of vulnerability curves to the calculated damage index at each wind speed increment. Wind speeds of onset and complete failure of houses compare satisfactorily with observations from damage investigations.

The cost of repair of a house that has been damaged by severe wind is dependent on many factors. Of all the types of damage that contribute to the repair cost, damage caused by water ingress is the hardest to quantify yet can contribute a substantial proportion of the repair cost, particularly at low levels of structural damage. VAWS adopts the empirical approach outlined above, together with a simplified costing of water ingress damage.

CALCULATION OF BENEFIT-COST

The economic advantage of retrofitting is often expressed as a benefit-cost ratio where the cost is the cost 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.

The method used by the project to calculate benefit-cost is described in Wehner, Ryu et al. (2019)and summarised below.

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.

Appendix B provides out the computed costs to implement each retrofit scenario for each generic house type for the year 2019. The costs assume a builder is retrofitting a single house. A significant portion (from 15 to 47%) of each retrofit cost is the cost of scaffolding for roof access.

Table 6 is an extract from Appendix B that provides costs for retrofitting House Type1 in cyclonic and non-cyclonic regions of Australia. If retrofit can be undertaken when other work is being undertaken, such as roof sheeting replacement, the retrofit cost will be substantially cheaper as costs such as scaffolding will be removed from the retrofit cost. Additionally, experience from the Queensland Household Resilience Program has indicated that widespread retrofit programs can lead to significantly reduced retrofit costs (e.g. reducing the cost from $35000 to approximately $20000 in 2019).

Retrofit Scenario	Cost to retrofit in non-cyclonic region ($)	Cost to retrofit in cyclonic region ($)
1. Window and door protection	15865	15016
2. Roof sheeting upgrade	27784	26812
3. Roof sheeting and batten upgrade	29233	28210
4. Roof sheeting, batten connection and roof structure upgrade	35592	34346
5. Full roof upgrade and door and window protection	51457	49752

TABLE 6 ESTIMATED RETROFIT COSTS HOUSE TYPE 1

BENEFITS AND COSTS OTHER THAN BUILDING REPAIR

Whilst the repair of the building fabric is perhaps the most obvious cost incurred due to wind-induced damage; there are other costs which should be considered. This section discusses the non-building fabric costs that the project incorporated into the benefit-cost calculations. No allowance has been made for demand surge following a large storm such as a cyclone.

Casualties

In the modern Australian environment, casualties from the actions of severe wind on buildings are rare due to good education about the dangers posed by cyclones and storms, pre-cyclone season preparation and sensible behaviour by the population seeking shelter prior to storm arrivals. Thus, for this project, estimation of casualties arising from wind-induced building damage and reduction in casualty numbers afforded by retrofit was not considered.

Building contents

Wind-induced damage to the house envelope and structure together with water ingress may also damage contents within the house. The reduction in contents damage due to the retrofit of the house is a benefit that is accounted for in this analysis.

The replacement value of contents is taken as $893 per m^2 of floor area. This is an average figure derived from a small survey of Geoscience Australia staff's contents value and house floor areas.

The contents loss is taken as the damage index multiplied by the contents replacement value where the damage index is the damage index calculated using the VAWS software tool incorporating damage to the house envelope, structure and internal linings and fittings.

Temporary accomodation

If a house is substantially damaged during a storm, it is most likely that the occupants will require temporary accommodation while the damage is assessed, a builder found to undertake the repairs and the repair work executed. The project used the relationship shown in Figure 11 to establish the length of time for which temporary accommodation is required. The relationship is a heuristic relationship developed by the project team members based on damage survey experience and regional knowledge.

The rates for temporary accommodation were taken as, $1600 per month in cyclonic regions and $2000 per month in non-cyclonic regions. The values were sourced from a short survey of rental properties, of similar size to generic house types, advertised on the internet in Canberra, Townsville and Cairns, in 2019.

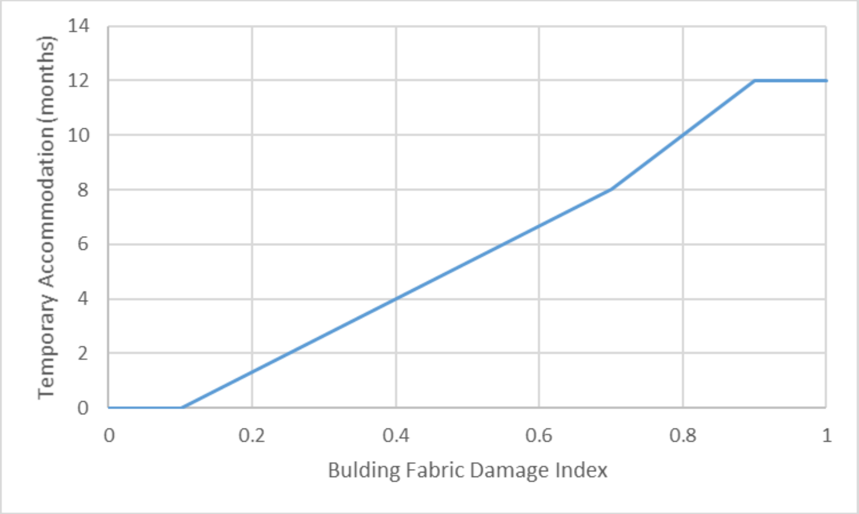


FIGURE 11 THE HEURISTIC RELATIONSHIP RELATING LENGTH OF TEMPORARY ACCOMMODATION REQUIRED TO DEGREE OF ENVELOPE DAMAGE IN A HOUSE

CALCULATION OF BENEFIT

The calculation of benefit represents the largest task when calculating a benefit-cost ratio.

The present value of benefit is taken as:

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

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 average annual loss is calculated as the area under the loss-probability curve for the particular house in a particular retrofit scenario.

The loss-probability curve is determined by transforming the vulnerability curve for the house whether mitigated or retrofitted. For this project, the mean vulnerability curve, a plot of damage index versus the 0.2s, 10m gust wind speed at the house of interest, is output from the project-developed VAWS software.

The vertical axis of the vulnerability curve is Damage index defined as repair cost divided by replacement cost. Hence, damage index is transformed to loss (the vertical axis of a loss-probability curve) by multiplying by the house's replacement cost. At this point, the loss can be included by adding any indirect losses, such as temporary accommodation losses, to the house's repair cost.

The horizontal axis of the vulnerability curve is the 0.2s gust wind speed at 10m at the house, which can be transformed into probability by relating the gust wind speed to an annual probability of exceedance. For this project, this relationship is modelled using the formulae provided in AS/NZS1170.2 Table 3.1 and modified for local wind speed effects. The relationship is shown in the equation:

$$R = \left(\frac{(C_1 C_3)}{\left(C_1 C_2 - \frac{V}{M_3} \right)} \right)^{10}$$

where:

R is the return period or inverse of the annual exceedance probability,

V is the local 0.2s gust wind speed at 10m at the house,

C1, C2 and C3 are constants provided in AS/NZS1170.2 and reproduced in Table 7, for each wind region.

M_3 is the product of the local wind multipliers accounting for upwind terrain category, shielding and topography.

The benefit-cost ratios calculated using the method outlined for all ten house types are presented in Appendix C. The benefit-cost ratios for the Type 1 house are given in Table 8.

Constant	**Wind Region A**	**Wind Region B**	**Wind Region C**	**Wind Region D**
C1	1	1	1.05	1.1
C2	67	106	122	156
C3	41	92	104	142

TABLE 7 CONSTANTS FROM AS/NZS 1170.2 TABLE 3.1 FOR COMPUTING RETURN PERIOD

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

TABLE 8 ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 1

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 component of the total retrofit cost is 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 8, 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, the economic benefit of retrofit becomes more attractive.

At some point in the life of a house, its roof cladding (metal sheet or tiles) will need to be replaced due to damage or deterioration. It is recommended that retrofitting of roof connections be done at a time when roof cladding is being replaced. In both cyclonic and non-cyclonic regions, retrofitting cladding and battens alone is not recommended as this causes connections to fail lower down in the tie-down chain.

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 House Type 1. 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.

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 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 provide additional information on the benefit to cost of retrofitting older houses. However, this level of analysis is outside the scope of the current project.

FINDINGS

This report presented a cost-benefit analysis of retrofitting several representative Australian house types for severe wind hazard. The VAWS vulnerability modelling software was used to quantify changes in vulnerability afforded by retrofitting structural components and protecting windows from debris impacts. The present value of benefit over a 30-year period was calculated based on the annual average loss of a sample of 100 houses in each house type.

VAWS was used to determine the potential reductions in vulnerability for several retrofitting scenarios for each representative house type, with effects of retrofitting modelled by increasing the strengths of relevant structural components in the software.

Costs of retrofitting were determined by a professional quantity surveyor for the selected representative house types. Costs due to windstorm-related damage include the replacement costs of the damaged structure, home contents, as well as the costs of alternative accommodation for the duration when the house is being repaired. However, costs such as insurance premiums, potential loss of income and intangible costs such as the mental health of homeowners are excluded from the analyses presented in this report.

The annual average loss, required for the calculation of the present value of benefit, was determined by transforming the vulnerability curves derived from the VAWS software into loss-probability functions. Finally, benefit-cost ratios were calculated based on the present value of benefit for a period of 30 years.

As shown in Appendix C, in non-cyclonic wind regions, none of the proposed retrofit scenarios shows a net benefit. This is because:

- The probability of exceedance of damaging wind speeds for non-cyclonic regions is low.
- Over the most likely wind speeds there is little difference in the vulnerability curves between the unretrofitted and the retrofitted houses.
- The high cost of installing the retrofit.

In cyclonic wind regions proposed retrofit scenarios to sheet-metal roofed houses come close to providing a net benefit and would provide a benefit if the cost of retrofit could be reduced. This reduction in retrofit cost can be achieved if the retrofit is undertaken when the roof sheeting is being replaced for maintenance reasons or retrofit can be undertaken as part of a campaign of retrofit where cheaper rates may be realised due to economies of scale.

The benefit-cost of retrofitting the house types analysed in this report is given in in Appendix C. Retrofitting becomes economically beneficial only when the benefit-cost exceeds 1.0, which is dependent on the cost of carrying out the retrofits and the combination of the likelihood of experiencing a windstorm in 30 years and shift in the vulnerability curve. The findings can be summarised as follows:

House type 1: high-set metal roof

The benefit-cost of retrofitting House Type 1 is given in Table C1 in Appendix C. Figure 10 shows that there are no significant changes in vulnerabilities for (scenario 1.1, 1.2 and 1.3) for wind speeds up to about 52 m/s. Retrofit scenarios 1.4 and 1.5 show a reduction in vulnerability. The benefit of carrying out these retrofits are only marginal even in cyclonic regions where there is a greater probability of windstorms with higher wind speeds than in non-cyclonic regions. However, a full roof upgrade (1.4) is recommended to be carried out, especially when the roof cladding is being replaced.

House type 3, 5, 7 and 9: metal roof houses

The benefit-costs of carrying out the specified retrofits on House Types 3, 5, 7 and 9 in cyclonic and non-cyclonic regions follow a similar pattern to House 1, as shown in Tables C3, C5, C7 and C9 in Appendix C. These houses have metal roof cladding with similar connection strengths and failure mechanism in windstorms and vulnerability curves. Therefore, the benefit of carrying out these retrofits in these houses are only marginal even in cyclonic regions.

House type 4, 6, 8 and 10: tile roof houses

The benefit-costs of carrying out the specified retrofits on House Types 4, 6, 8 and 10 in cyclonic and non-cyclonic regions are shown in Tables C4, C6, C8 and C10 in Appendix C. The economic benefit of carrying out retrofits for these house types follow the same pattern where window and door protection (scenario .1), installation of sarking (scenario .2) and full roof upgrade and sarking and door and window protection (scenario .5) provide significant benefits in cyclone region only. This is because:

- The substantial improvement in water tightness assumed in the analysis to be afforded by window protection and sarking.
- The increased likelihood of damaging winds occurring, and
- The reduction in tile dislodgement and consequential reduction in water ingress afforded by the installation of tile clips.

CONCLUSIONS

This report presents a summary of outcomes from the BNHCRC project titled: *Improving the resilience of existing housing to severe wind events*. The project focusses on practical structural retrofits that will make improvements to the performance of Pre-80s (Legacy) houses in windstorms as well as measures to reduce damage and loss to contemporary houses.

The analyses conducted in this project showed that with the costings applied, there is minimal economic benefit to retrofitting houses in non-cyclonic regions. However, retrofitting tiled houses in cyclonic regions can have a benefit-cost ratio exceeding 1.0 over a 30-year period.

The limited benefit-cost of retrofit is mainly due to the high costs of performing the works. However, these costs can be reduced by incentive schemes which subsidise the cost of retrofit. For example, the Queensland Department of Housing and Public Working Household Resilience Program. Such schemes have shown that costs can be further reduced when economies of scale are realised by such wider retrofitting programs

Performing retrofitting during routine roof maintenance such as the replacement of the roof cladding in houses in cyclone and non-cyclone will only accrue minimal additional costs, and provide significant benefit. The cost of the cladding and scaffolding etc. that are a significant portion of the overall cost will be borne irrespective of the level of retrofit. In these instances, it is recommended that a full roof upgrade (.4) is carried out.

Furthermore, 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 could extend the scope of the current BNHCRC Project. In addition, a better understanding of the water ingress into houses by conducting a series of focussed tests and research will enable these costs to be estimated more reliably and correlated with insurance payouts.

The web-based guidelines produced as part of this project's outcomes, enables users to gain a basic understanding of the vulnerability of common Australian house types, and the practical structural retrofit measures to improve their performance. Throughout the project, a range of stakeholders from the regulatory, building and insurance industries have shown interest in expanding and further developing the VAWS software package and the web-based guidelines.

UTILISATION AND IMPACT

SUMMARY

The project has had four important Utilisations and Impacts.

1. The Queensland Government Household Resilience Program (HRP)
2. Vulnerability and Adaption to Wind Simulation (VAWS)
3. Easy to use web-based guidelines
4. Queensland Reconstruction Authority Cyclone and Storm Tide Resilient Building Guidelines

THE QUEENSLAND GOVERNMENT HOUSEHOLD RESILIENCE PROGRAM

The Queensland Government Household Resilience Program (HRP) provides funding to help eligible homeowners improve the resilience of their homes against cyclones. This program developed with advice from the Cyclone Testing Station is managed by the Queensland Department of Housing & Public Works and commenced in late 2018 and was completed toward the end of 2019. The project was recently restarted on 1 July 2020.

Eligible homeowners can apply to receive a Queensland Government grant of 75% of the cost of improvements (up to a maximum of $11,250 including GST).

Eligibility criteria require that the homeowner:

- Live in a recognised cyclone risk area (in the area from Bundaberg to the Queensland/Northern Territory border within 50km of the coast);
- Own or be the mortgagor of a house built before 1984;
- Live in the home (primary place of residence);
- Meet certain income eligibility requirements.

Approved applicants are required to make a minimum 25% co-contribution towards the approved program works undertaken and may be able to arrange a loan to fund all or part of this co-contribution.

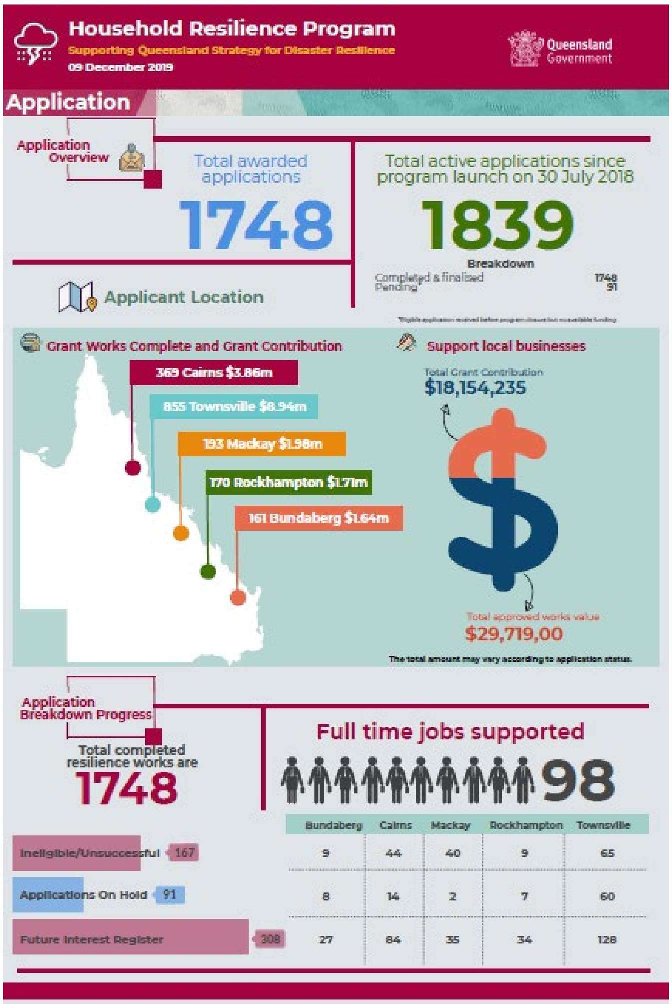
Improvements covered under the program, include:

- Roof replacement including an upgrade to roof tie-down.
- Roof structure tie-down upgrades using an external over-batten system.
- Replacement of garage doors and frames.
- Window protection, including cyclone shutters or screens.
- Tie-downs of external structures (e.g. sheds).
- Replacement of external hollow core doors with solid core external grade doors.

Extent of use, utilisation and impact

In December 2019 The Department of Housing and Public Works indicated that approximately 1800 applications had been received to date, of which about 1700 valued at $18.1M have been approved. The total works value of this is $29.7M. These works resulted in reductions in insurance premiums averaging about 8%. Summary statistics provided in reports from the Department of Housing and Public Works, an extract is shown in Figure 12.

Utilisation and impact evidence



Household Resilience Program

Supporting Queensland Strategy for Disaster Resilience

09 December 2019

Queensland Government

Application

Application Overview

Total awarded applications

1748

Total active applications since program launch on 30 July 2018

1839

Breakdown

Completed & finalised	1748
Pending*	91

Applicant Location

Grant Works Complete and Grant Contribution

369 Cairns $3.86m

855 Townsville $8.94m

193 Mackay $1.98m

170 Rockhampton $1.71m

161 Bundaberg $1.64m

Support local businesses

Total Grant Contribution

$18,154,235

Total approved works value

$29,719,00

The total amount may vary according to application status.

Application Breakdown Progress

Total completed resilience works are

1748

Full time jobs supported

98

		Bundaberg	Cairns	Mackay	Rockhampton	Townsville
Ineligible/Unsuccessful	167	9	44	40	9	65
Applications On Hold	91	8	14	2	7	60
Future Interest Register	308	27	84	35	34	128

FIGURE 12 SUMMARY STATISTICS OF THE QLD HOUSING RESILIENCE PROGRAM IN MARCH 2019. SOURCE: QLD GOVERNMENT DEPT OF HOUSING AND PUBLIC WORKS

VULNERABILITY AND ADAPTION TO WIND SIMULATION (VAWS)

Modelling the vulnerability of houses in windstorms is important for insurance pricing, policy-making, and emergency management. Models for Australian house types have been developed since the 1970s, and have ranged from empirical insurance to reliability-based structural engineering models, which provide estimates of damage for a range of wind speeds of interest. However, outputs from these models are frequently misinterpreted, and the basis of these models, including underlying assumptions, are often not adequately understood by the user. This project has developed and calibrated VAWS which uses probability-based reliability analysis and structural engineering for the loading and response coupled with an extensive test database and field damage assessments to calculate the damage experienced by selected Australian house types.

VAWS is able to accommodate a range of defined house types for which the structural system and their strengths and the external pressure distribution for wind exposure from directions around the compass are known.

For each house type, the cost of a specific retrofit option is calculated and the effect of this retrofit on the performance is ascertained via the vulnerability (i.e. damage index vs wind speed). The benefit of this retrofit is calculated by calculating the expected reduction in damage over a 30-year period, from which the benefit-cost for that retrofit is calculated. This process is applied to progressive retrofit options.

The VAWS program available as open source software for download via https://github.com/GeoscienceAustralia/vaws under an Apache 2.0 Licence. Extensive documentation is provided however, its intended users are engineers or actuarial scientists who are experienced in vulnerability modelling. The preparation of input data for a single house type can be time consuming depending on the complexity of the modelled structure.

Extent of use, utilisation and impact

The VAWS package was demonstrated during a stakeholder workshop held during the Cyclone Testing Station's Advisory Board meeting in October 2019. Attendees from a range of organisations from Government, the insurance industry, the building industry, product manufacturers and local Government, indicated an interest in the product and its outcomes. Further discussions with stakeholder groups (especially the insurance industry) in 2020 have elicited further interest Utilisation of such technical product requires stakeholder engagement during the development process. The extent of its use will be assessed following its launch at the end of 2020 at the completion of the project.

Additionally, it is anticipated that VAWS will be used during a new project examining the benefit of retrofit in six local government jurisdiction in south-east Queensland undertaken in conjunction with Queensland Fire and Emergency Services and other project partners.

Utilisation and impact evidence

The workshop aimed to raise awareness of the project to these organisations and gain feedback on the proposed development of VAWS and the guidelines to follow. Attendees were presented with an overview of the project details, including the vulnerability modelling and the cost-benefit analyses of retrofitting houses.

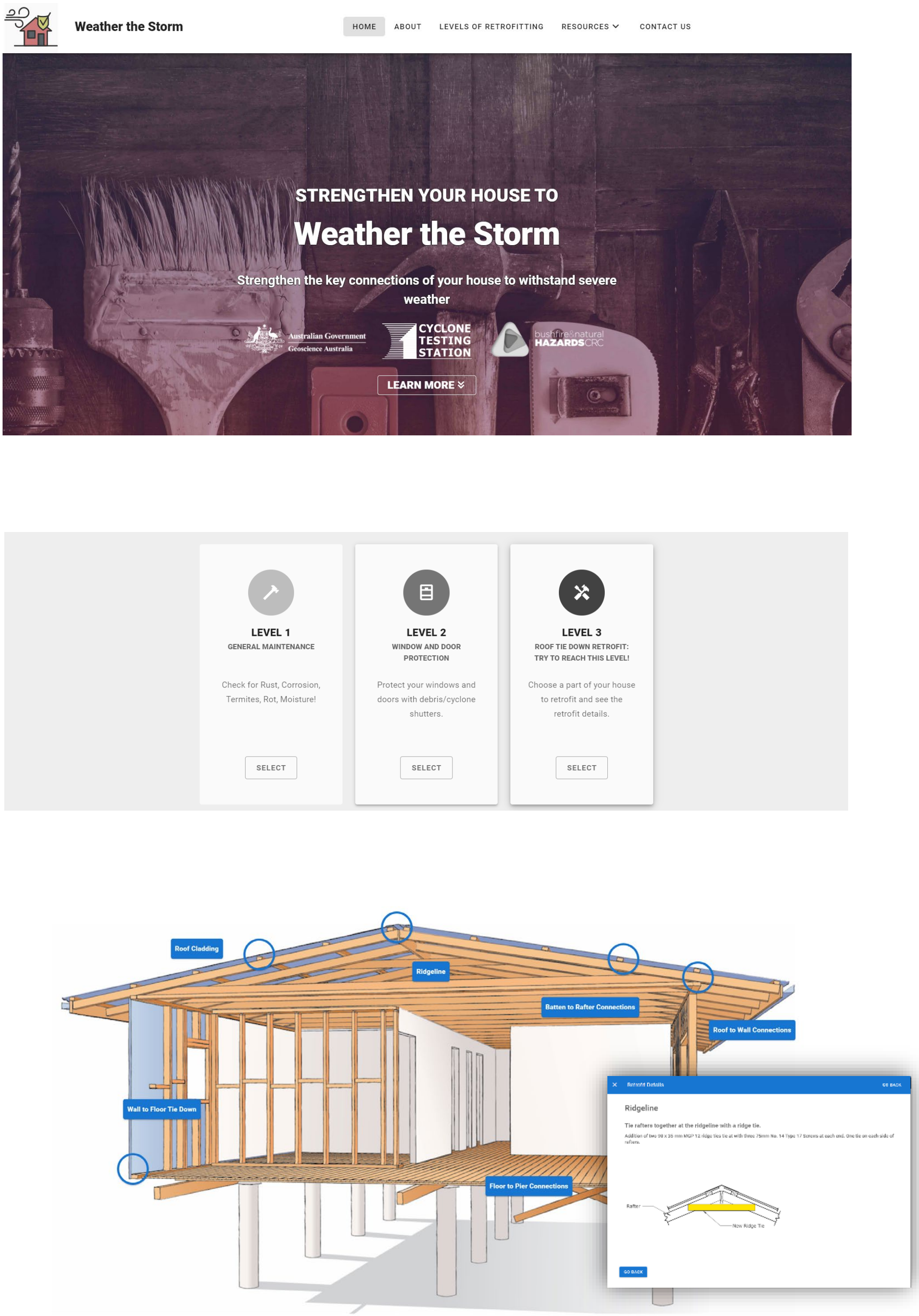
WEB-BASED GUIDELINES

Communicating the importance and the process of retrofitting houses is a crucial part of improving the resilience of older housing stock. Currently, retrofitting guidelines that are easy to use, and openly accessible to building professionals and homeowners for Australian houses is lacking. Several documents and websites are available regarding retrofitting of houses in other countries, mainly the United States. However, technical details of the retrofits and graphical explanations of key parts of the structures are usually not available. As such, the development of a set of online guidelines is a key this outcome of this project.

The guidelines provide information on general principles and technical details of retrofitting older houses for windstorms. Content is aimed at anyone with an interest in home-improvement/ renovations / DIY projects, not necessarily with formal engineering or construction qualifications. The guidelines contain a range of retrofitting measures for selected common Australian house types as well as basic background information on wind loading and house construction. Additionally, the importance of maintenance of houses as well as the benefits of window and door protection is highlighted

Retrofitting options for typical scenarios that apply to most houses are presented in the form of illustrations and drawings where descriptions are provided in both general and technical terms. For other scenarios of retrofitting that may require additional technical requirements, reference is made to existing codes and standards and handbooks for use by building professionals and engineers. A unique feature of these guidelines is that the effectiveness of retrofits is quantified using the VAWS vulnerability modelling software developed through the BNHCRC project.

The guidelines are presented in a modern website format that is compatible with desktop and mobile devices and can be viewed at weatherthestorm.com.au. The user experience has been designed to guide users of the website through a process of selecting an appropriate level of retrofitting for their particular house type. Different levels of mitigation are presented, such as maintenance requirements, window and door protection, and roof retrofitting. Retrofitting details are then presented in the form of interactive infographics with additional information on the science of wind loading, as shown in Figure 13.



Strengthen the key connections of your house to withstand severe weather

LEVEL 1
GENERAL MAINTENANCE

Check for Rust, Corrosion, Termites, Rot, Moisture!

LEVEL 2
WINDOW AND DOOR PROTECTION

Protect your windows and doors with debris/cyclone shutters.

LEVEL 3
ROOF TIE DOWN RETROFIT: TRY TO REACH THIS LEVEL!

Choose a part of your house to retrofit and see the retrofit details.

Ridgeline

Tie rafters together at the ridgeline with a ridge tie.

Addition of two 90 x 35 mm MGP 12 ridge ties tie at with three 75mm No. 14 Type 17 Screws at each end. One tie on each side of rafters.

FIGURE 13 NAVIGATION AND INTERACTIVE INFOGRAPHICS OF THE ONLINE RETROFITTING GUIDELINES

Extent of use, utilisation and impact

Stakeholder feedback and engagement is important for the development of the set of guidelines and to assess the usability of the site. The alpha version of this site that has been developed in 2020 and tested and critiqued by a range of stakeholders including government regulators, insurance agencies, builders and engineers. Due to the current COVID-19 restrictions, these stakeholder workshops were held via online focus groups consisting of individuals and key members of organisations.

Overall, the stakeholders were supportive of the proposed guidelines and further work may include working with organisations to promote incentive schemes and sources of funding for retrofitting of programs. Discussion points raised during this stakeholder meeting will shape the questions and agenda included in future stakeholder engagement activities.

Utilisation and impact evidence

The following are some positive comments from stakeholders:

QBCC - Queensland

"The key messages I took from the website are that anyone with some basic knowhow can undertake some things to their home, ranging from quite simple to more involved, and really see measurable benefit in the resilience of their home.

This is a great initiative and I look forward to seeing the completed product…

…Lastly, I note the title of your research project is 'Improving the resilience of existing housing to severe wind events', which I consider you have easily achieved with this website. A great reference for homeowners and those wanting to improve their homes."

DMIRS – Western Australia

"A great and welcome initiative – well done to all involved."

QUEENSLAND RECONSTRUCTION AUTHORITY CYCLONE AND STORM TIDE RESILIENCE BUILDING GUIDELINES

The Queensland Reconstruction Authority has recently released two sets of guidelines for cyclone and storm tide resilient buildings Figure 14. These documents were developed in collaboration with the Cyclone Testing Station with support from the BNHCRC, with the storm tide guide also being created in collaboration with Systems Engineering Australia Pty. Ltd.

The cyclone resilient guide provides information on the risks of tropical cyclones, including general information on the science and meteorology of these weather systems. Additionally, the guidelines provide information on resilient design principles, constructing new cyclone resilient homes and strengthening existing homes, as well as information on rebuilding after a cyclone.

Following a similar structure, the storm tide guidelines outline the impacts and risks of storm tides and provide details on design principles for new houses, recommendations for existing houses and information on rebuilding after storm tide damage.

Cyclone Resilient
Building Guidance
for Queensland Homes

Get Ready Queensland
Preparing for a stronger, more Resilient Queensland

Storm Tide Resilient
Building Guidance
for Queensland Homes

Get Ready Queensland
Preparing for a stronger, more Resilient Queensland

FIGURE 14 COVER PAGES OF THE CYCLONE AND STORM TIDE RESILIENT BUILDING GUIDES

PUBLICATIONS LIST

2019 – 2020

Peer-reviewed journal articles

1 Navaratnam, S., Ginger, J., Humphreys, M., Henderson, D., Wang, C.H., Nguyen, K.T. and Mendis, P., 2020. Comparison of wind uplift load sharing for Australian truss-and pitch-framed roof structures. *Journal of Wind Engineering and Industrial Aerodynamics*, *204*, p.104246.
2 Parackal, K.I., Ginger, J.D. and Henderson, D.J., 2020. Progressive failures of batten to rafter connections under fluctuating wind loads. *Engineering Structures*, *215*, p.110684.
3 Smith, D.J., Edwards, M., Parackal, K., Ginger, J., Henderson, D., Ryu, H. and Wehner, M., 2020. Modelling vulnerability of Australian housing to severe wind events: past and present. *Australian Journal of Structural Engineering*, pp.1-18.
4 Scovell, M., McShane, C., Swinbourne, A. and Smith, D., 2020. How fringe cyclone experience affects predictions of damage severity. *Disaster Prevention and Management: An International Journal*.
5 Parackal, K., Wehner, M., Ryu, H., Ginger, J., Smith, D., Henderson, D. and Edwards, M., 2019. Modelling the vulnerability of a high-set house roof structure to windstorms using VAWS. *Australian Journal of Emergency Management*, *4*, pp.51-63.

Conference papers

1 Henderson, D., Buckley, B., Dyer, A., Stone, G., Leplastrier, M., 2020, Wind and Rain – systemic failures resulting in loss of functionality of residences and commercial properties during severe weather, AMOS Conference, Australian Meteorological and Oceanographic Society, Perth.
2 Henderson, D., Smith, D., Boughton, G., Ginger, J. 2019. Damage and Loss from Wind-driven Rain Ingress to Australian Buildings. In the Proceedings of the 15th International Conference on Wind Engineering (ICWE15), 2019 Beijing, China.
3 Humphreys, M., Ginger, J., Henderson, D. 2019. Effect of Opening Area on Full-scale Internal Pressure Measurements. In the Proceedings of the 15th International Conference on Wind Engineering (ICWE15), 2019 Beijing, China.
4 Parackal, K., Ginger, J., Henderson, D., 2019. Progressive Failures of Light Framed Timber Roofs. In the Proceedings of the 15th International Conference on Wind Engineering (ICWE15), 2019 Beijing, China.
5 Smith, D., Morrison, M. 2019. Full-scale Wind Tunnel Testing of North American and Australian Roofing Tile Systems. In the Proceedings of the 15th International Conference on Wind Engineering (ICWE15), 2019 Beijing, China.

Posters

1 Parackal, K., Wehner, M., Ryu, H, Ginger, J., Henderson, D., Edwards, E., 2019. VAWS – Vulnerability and Adaptation to Wind Simulation. Poster presented at the 2019 BNHCRC and AFAC Conference, Melbourne.
2 Humphreys, M., Ginger, J., Henderson, H., 2019. Mitigating Wind Damage Caused by Internal Pressures. Poster presented at the 2019 BNHCRC and AFAC Conference, Melbourne.

Community presentations

1 Parackal, K. 2020, Engineering Houses to Resist Cyclones, Public Lecture at the Museum of Tropical Queensland, Townsville.
2 Parackal, K. 2019, Engineering Houses to Resist Cyclones, Public Lecture Townsville City Council's Disaster Ready Sunday.

Theses

1 Humphreys, M., 2020 Characteristics of wind-induced internal pressures in industrial buildings with wall openings, PhD Thesis Submitted to the Graduate Research School, James Cook University.

2018 – 2019

Peer-reviewed journal articles

1 Stewart, Mark G., Ginger, John D., Henderson, David J., Ryan, Paraic C. *Fragility and climate impact*

assessment of contemporary housing roof sheeting failure due to extreme wind. Engineering Structures, 171. pp. 464-475, 2018.

2 Parackal, Korah I., Ginger, John D. and Henderson, David J., *Wind Load Fluctuations on Roof Batten to Rafter/Truss Connections*, Journal of Wind Engineering & Industrial Aerodynamics, 175, pp. 193-201 2018.

3 Humphreys M.T., Ginger J.D., and Henderson D.J., *Internal Pressures in a Full-Scale Test Enclosure with windward wall opening,* Journal of Wind Engineering & Industrial Aerodynamics, 189, pp. 118-124 2019.

Conference papers

1 Henderson, D., Ginger J. and Smith D., *Large damage bills to buildings from cyclones can be reduced by small actions*, AFAC-BNHCRC, Perth, 2018.

2 Humphreys M.T., Ginger J.D., and Henderson D.J., (2018) *Effect of Opening Size And Wind Speed On Internal Pressures In Full-Scale Buildings.* 25th Australasian Conference on Mechanics of Structures and Materials Brisbane, Australia.

3 Bodhinayake G., Ginger J., and Henderson D., (2018) *Net cladding pressures on industrial building roofs.* 25th Australasian Conference on Mechanics of Structures and Materials Brisbane, Australia.

Posters/presentations

1 Henderson D. (2019) 12th Australasian Natural Hazards Management Conference in Canberra - David Henderson was an invited panellist for session on risk and resilience http://www.bnhcrc.com.au/events/2019-anhmc "The objective of this conference is to understand how we can reduce the impacts of catastrophic disasters by using an extreme, cascading weather scenario to see the contribution of current research, existing knowledge and future experiences of extreme weather and other emergencies".

2 Parackal, K. (2018), Progressive Failures of Roofs Under Wind Loads, Poster presented at the 2018 Bushfire and Natural Hazards CRC & AFAC conference, Perth.

3 Parackal, K. (2019), Engineering Houses to Resist Cyclones, Public Lecture at the Museum of Tropical Queensland, Townsville.

4 Parackal, K. (2019), Wind Loading and AS/NZS 1770.2, Presentation at the Australian Institute of Building Surveyors (AIBS) Regional Conference, Brisbane.

5 Humphreys, M, Engineering and Physical Sciences JCU Postgraduate Symposium, 15 minute presentation about PhD projects, 2 Nov 2018.

6 Humphreys, M, JCU 3MT, (3 minute presentation) about PhD projects, 16 August 2018.

7 Ginger J (2019), "Improving the Resilience of Existing Housing to Severe Wind Events" Seminar presented at USQ Toowoomba on 5 October 2018

8 Ginger J (2019) "VAWS modelling and outputs" Seminar presented at USQ Toowoomba on 6 June 2019

Theses

1 Parackal, K. (2018), The Structural Response and Progressive Failure of Batten to Rafter Connections under Wind Loads, PhD Thesis, College of Science and Engineering, James Cook University, Australia.

2017 – 2018

Conference papers

1 Humphreys M., Ginger J., and Henderson D., *Internal Pressure Fluctuations in Large Open Plan Buildings*, 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December, 2017.

2 Parackal, K., Ginger J., Smith D. and Henderson D, *Load sharing between batten to rafter connections under wind loading*. 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December 2017.

3 Bodhinayake G., Ginger J., and Henderson D., *External and Internal Pressure Fluctuations on Industrial-Type Buildings*, 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December 2017.

4 Humphreys M., Ginger J., and Henderson D., *Effect of Opening Geometry on Full-Scale Internal Pressure Measurements,* 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, 4-6 April, 2018.

5 Bodhinayake G., Ginger J., and Henderson D., *Correlation of internal and external pressures on building cladding elements*, 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

6 Wehner, M., H. Ryu, J. Ginger, M. Edwards, D. Henderson, K. Parackal, D.J. Smith, *Modelling residential mitigation effectiveness for severe wind*. 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

7 Smith, D.J., D.B. Roueche, R.J. Krupar, F.T. Lombardo, D.J. Henderson, *Parallels in tropical cyclone design strategies and building performance for Australia and U.S.*, 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

8 Nicoline Thomson, David Henderson, John Ginger, *Design of Potential Dominant Openings to Resist Cyclonic Winds*, 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.
9 Henderson, D., D.J. Smith, G. Boughton, J. Ginger, (2018) Damage and loss to Australian engineered buildings during recent cyclones. International Workshop on Wind-Related Disasters and Mitigation, Sendai, Japan.

2015 – 2016

Peer-reviewed journal articles

1 Smith, D., McShane, C., Swinbourne, A., Henderson , D. (2016) Toward Effective Mitigation Strategies for Severe Wind Events, Australian Journal of Emergency Management.
2 Satheeskumar, N., Henderson, D., Ginger, J., and Wang, C. (2016). Wind Uplift Strength Capacity Variation in Roof-to-Wall Connections of Timber-Framed Houses. J. Archit. Engineering. http://dx.doi.org/10.1061/(ASCE)AE.1943-5568.0000204.
3 Satheeskumar, N., Henderson, D. J., Ginger, J.D., Humphreys, M.T. and Wang, C.H., (2016) Load Sharing and structural response of roof-wall system in a timber-framed house, Engineering Structures.
4 Leitch C. J., Ginger J.D. and Holmes J.D., (2016) Wind loads on solar panels mounted parallel to pitched roofs, and acting on the underlying roof, Wind and Structures Journal, Vol. 22, No. 3, 2016, pp 307-328.
5 Smith, D.J., Masters, F. J., and Gurley, K. R., 2014 "An Historical Perspective on the Wind Resistance of Clay and Concrete Roofing Tiles" RCI Interface Vol. 32, No. 10.

Conference papers

1 Henderson D.J., and Ginger, J.D. 2014 "Improving the resilience of existing housing to severe wind events". Australasian Fire and Emergency Services Authorities Council Conference Proceedings, Wellington, New Zealand, 2-5 September, 2014.
2 Mason, M., Smith, D.J., Henderson, D.J., 2015. "Interference of surface wind speeds during Tropical Cyclone Marcia based on damage observations". Australian Meteorological and Oceanographic Society National Conference Proceedings, Brisbane, Australia, 15-17 July (to be presented).
3 Smith, D.J., Henderson, D., and Ginger, J. 2015. "Vulnerability models for Australian Housing Wind Resistance". Second International Conference on Performance-based and Life-cycle Structural Engineering Proceedings, Brisbane, Australia, 9-11 December, 2015.
4 Smith, D.J., Henderson, D., and Ginger, J. 2015. "Performance-based design considerations for roofing tile systems in Australia". Second International Conference on Performance-based and Life-cycle Structural Engineering Proceedings, Brisbane, Australia, 9-11 December, 2015.
5 Smith, D.J., Thompson, A.P., Prevatt, D.O., Roueche, D.B., 2015. "A vulnerability assessment tool for residential structures in extreme wind events". Second International Conference on Performance-based and Life-cycle Structural Engineering Proceedings, Brisbane, Australia, 9-11 December, 2015.
6 Smith, D.J., Henderson D.J., and Ginger, J.D. 2015 "Improving the Wind Resistance of Australian Legacy Housing". 17th Australasian Wind Engineering Society Workshop Proceedings, Wellington, New Zealand, 12-13 February, 2015
7 Smith, D.J., Henderson, D., and Ginger, J. 2015. "Insurance loss drivers and mitigation for Australian housing in severe wind events". 14th International Conference on Wind Engineering Proceedings, Porto Alegre, Brazil, June 21-26, 2015
8 Smith, D.J., Masters, F. J. 2015. "A study of wind load interaction for roofing field tiles". 14th International Conference on Wind Engineering Proceedings, Porto Alegre, Brazil, June 21-26, 2015

Technical reports

1 K. Parackal, M. Mason, D. Henderson, G. Stark, J. Ginger, L. Somerville, B. Harper, D. Smith, M. Humphreys 2015. "Investigation of Damage: Brisbane, 27 November 2014 Severe Storm Event". Cyclone Testing Station, Technical Report No. 60. ISBN 978-0-9941500-8-0.
2 Smith, D.J., Henderson, D., Humphreys, M., Parackal, K., Mason, M., Prevatt, D.O., Roueche, D.R. 2015. "Tropical Cyclone Marcia, Queensland Australia". Cyclone Testing Station, Rapid Damage Assessment Report, February 20th.
3 Smith, D.J., Henderson, D., Parackal, K., Mason, M., Prevatt, D.O., Roueche, D.R., Thompson, A. 2015. "Tropical Cyclone Nathan, Far North QLD, Australia". Cyclone Testing Station, Rapid Damage Assessment Report, March 20th.
4 Smith, D.J., Boughton, G., Falck, D., Henderson, Prevatt, D.O., Roueche, D.R., 2015. "Tropical Cyclone Olwyn, WA, Australia". Cyclone Testing Station, Rapid Damage Assessment Report, March 11-14th.

2014 – 2015

Peer-reviewed journal articles

1 Smith, D.J., Masters, F. J., and Gurley, K. R., 2014 "An Historical Perspective on the Wind Resistance of Clay and Concrete Roofing Tiles" RCI Interface Vol. 32, No. 10

2 Smith, D.J., Henderson D.J., and Ginger, J.D. 2015 "Improving the Wind Resistance of Australian Legacy Housing". 17th Australasian Wind Engineering Society Workshop Proceedings, Wellington, New Zealand, 12-13 February, 2015

3 Smith, D.J., Henderson, D., and Ginger, J. 2015. "Insurance loss drivers and mitigation for Australian housing in severe wind events". 14th International Conference on Wind Engineering Proceedings, Porto Alegre, Brazil, June 21-26, 2015

4 Smith, D.J., Masters, F. J. 2015. "A study of wind load interaction for roofing field tiles". 14th International Conference on Wind Engineering Proceedings, Porto Alegre, Brazil, June 21-26, 2015.

Conference papers

1 Henderson D.J., and Ginger, J.D. 2014 "Improving the resilience of existing housing to severe wind events". Australasian Fire and Emergency Services Authorities Council Conference Proceedings, Wellington, New Zealand, 2-5 September, 2014

2 Mason, M., Smith, D.J., Henderson, D.J., 2015. "Interference of surface wind speeds during Tropical Cyclone Marcia based on damage observations". Australian Meteorological and Oceanographic Society National Conference Proceedings, Brisbane, Australia, 15-17 July

3 Smith, D.J., Henderson, D., and Ginger, J. 2015. "Vulnerability models for Australian Housing Wind Resistance". Second International Conference on Performance-based and Life-cycle Structural Engineering Proceedings, Brisbane, Australia, 9-11 December, 2015

4 Smith, D.J., Henderson, D., and Ginger, J. 2015. "Performance-based design considerations for roofing tile systems in Australia". Second International Conference on Performance-based and Life-cycle Structural Engineering Proceedings, Brisbane, Australia, 9-11 December, 2015

5 Smith, D.J., Thompson, A.P., Prevatt, D.O., Roueche, D.B., 2015. "A vulnerability assessment tool for residential structures in extreme wind events". Second International Conference on Performance-based and Life-cycle Structural Engineering Proceedings, Brisbane, Australia, 9-11 December, 2015.

Technical reports

1 K. Parackal, M. Mason, D. Henderson, G. Stark, J. Ginger, L. Somerville, B. Harper, D. Smith, M. Humphreys 2015. "Investigation of Damage: Brisbane, 27 November 2014 Severe Storm Event". Cyclone Testing Station, Technical Report No. 60. ISBN 978-0-9941500-8-0

2 Smith, D.J., Henderson, D., Humphreys, M., Parackal, K., Mason, M., Prevatt, D.O., Roueche, D.R. 2015. "Tropical Cyclone Marcia, Queensland Australia". Cyclone Testing Station, Rapid Damage Assessment Report, February 20th

3 Smith, D.J., Henderson, D., Parackal, K., Mason, M., Prevatt, D.O., Roueche, D.R., Thompson, A. 2015. "Tropical Cyclone Nathan, Far North QLD, Australia". Cyclone Testing Station, Rapid Damage Assessment Report, March 20th

4 Smith, D.J., Boughton, G., Falck, D., Henderson, Prevatt, D.O., Roueche, D.R., 2015. "Tropical Cyclone Olwyn, WA, Australia". Cyclone Testing Station, Rapid Damage Assessment Report, March 11-14th.

TEAM MEMBERS

RESEARCH TEAM

John Ginger, CTS/JCU

David Henderson, CTS/JCU

Daniel Smith, CTS/JCU (2015 - 2018)

Korah Parackal, CTS/JCU (2019 - 2020)

Martin Wehner, GA

Hyeuk Ryu, GA

Mark Edwards, GA

Mitchell Humphreys, CTS/JCU (PhD Student, 2016 – 2019).

END-USERS AND STAKEHOLDERS

End-user organisation	End-user representative	Extent of engagement (Describe type of engagement)
Geoscience Australia	Leesa Carson	Quarterly review of project progress and deliverables

The following stakeholders were involved with the testing and development of the Internet based retrofitting guidelines and the VAWS software through a set of stakeholder workshops throughout this BNHCRC Project:

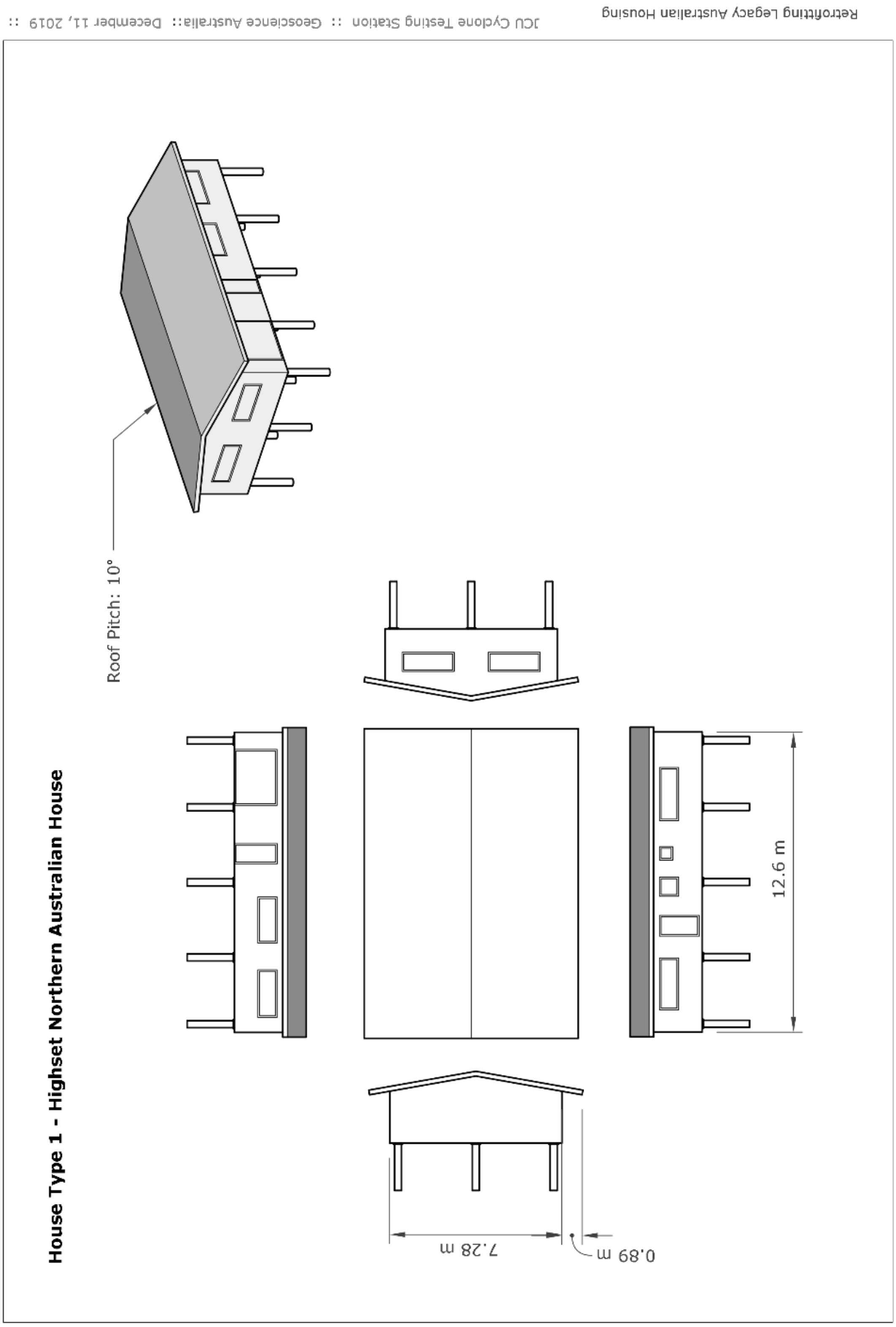
Government and Regulatory - Stakeholders
NT Department of Infrastructure, Planning and Logistics
QLD Department of Housing and Public Works
WA Department of Mines, Infrastructure and Safety
NSW Department of Planning, Industry and Environment
Townsville City Council
Queensland Reconstruction Authority
Queensland Building and Construction Commission (QBCC)
National Institute of Water and Atmospheric Research, New Zealand (NIWA)
Insurance and Risk Modelling – Stakeholders
IAG Insurance
Willis RE
Risk Management Solutions (RMS)
Munich RE
Suncorp Insurance

Risk Frontiers
Industry and Research - Stakeholders
Stramit Building Products
Australian Roof Tile Association
Master Builders Australia
MacCallum Planning and Architecture
Gabrielli Constructions
Northern Consulting Engineers
Arup Wind Engineering
Systems Engineering Australia
Imparta Engineers
JDH Consulting
Mel Consultants
University of Newcastle
Swinburne University of Technology

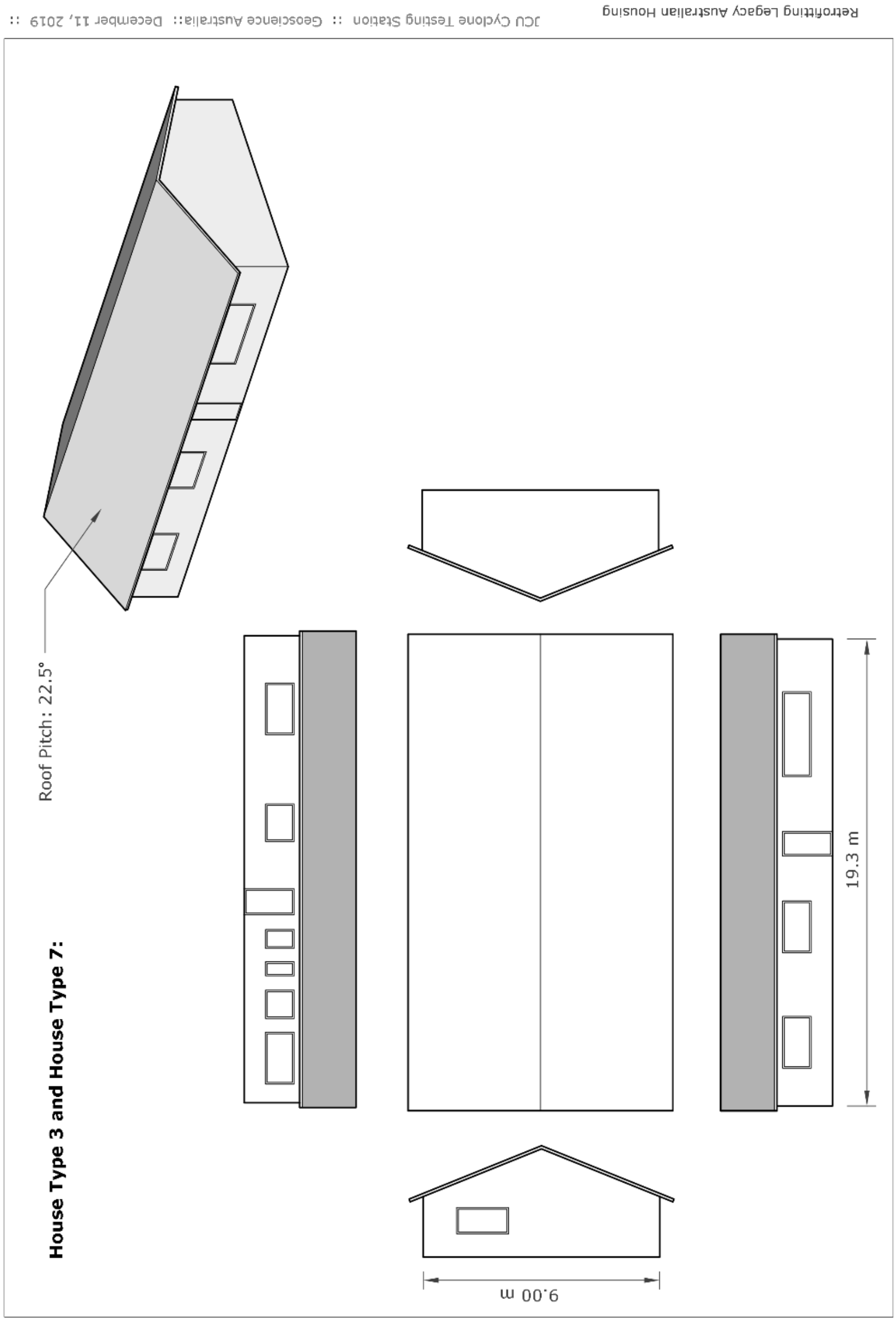
REFERENCES

1 Boughton, G., et al. (2017). Tropical Cyclone Debbie: Damage to buildings in the Whitsunday Region, Cyclone Testing Station, JCU, Report TR63.
2 Boughton, G., et al. (2011). Tropical Cyclone Yasi: Structural damage to buildings, Cyclone Testing Station, JCU, Report TR57.
3 Geoscience Australia (2020). Vulnerability and Adaptation to Wind Simulation (VAWS), Github Repository: https://github.com/GeoscienceAustralia/vaws.
4 Henderson, D. and J. Ginger (2007). "Vulnerability model of an Australian high-set house subjected to cyclonic wind loading." Wind & Structures 10: 269-285.
5 Henderson, D., et al. (2006). Tropical Cyclone Larry: Damage to buildings in the Innisfail area, Cyclone Testing Station, JCU, Report TR51.
6 Henderson, D. and B. Harper (2003). "Climate change and tropical cyclone impact on coastal communities' vulnerability." Queensland Government (Dept. of Natural Resources and Mines, and Dept. of Emergency Services), Brisbane, Australia.
7 Holmes, J., et al. (2010). Modelling damage to residential buildings from wind-borne debris - Part 1. Methodology. 14th Australasian Wind Engineering Society Workshop. Canberra, Australia: 54-57.
8 Nadimpalli, K., et al. (2007). National Exposure Information System (NEXIS) for Australia: Risk assessment opportunities. MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December.
9 Standards Australia (2011). AS/NZS1170.2 - Structural design actions Part 2: Wind actions. Sydney, Australia.
10 Turner & Townsend (2019). Repair and replacement costs for eight southern Australian house types. , Report to Geoscience Australia.
11 Wehner, M., et al. (2019). Evaluating the economic benefit of retrofit, Report to the Bushfire and Natural Hazards CRC.
12 Wehner, M., et al. (2010). Modelling damage to residential buildings from wind-borne debris - Part 2, implementation. 14th Australasian Wind Engineering Society Workshop, Canberra, Australia.

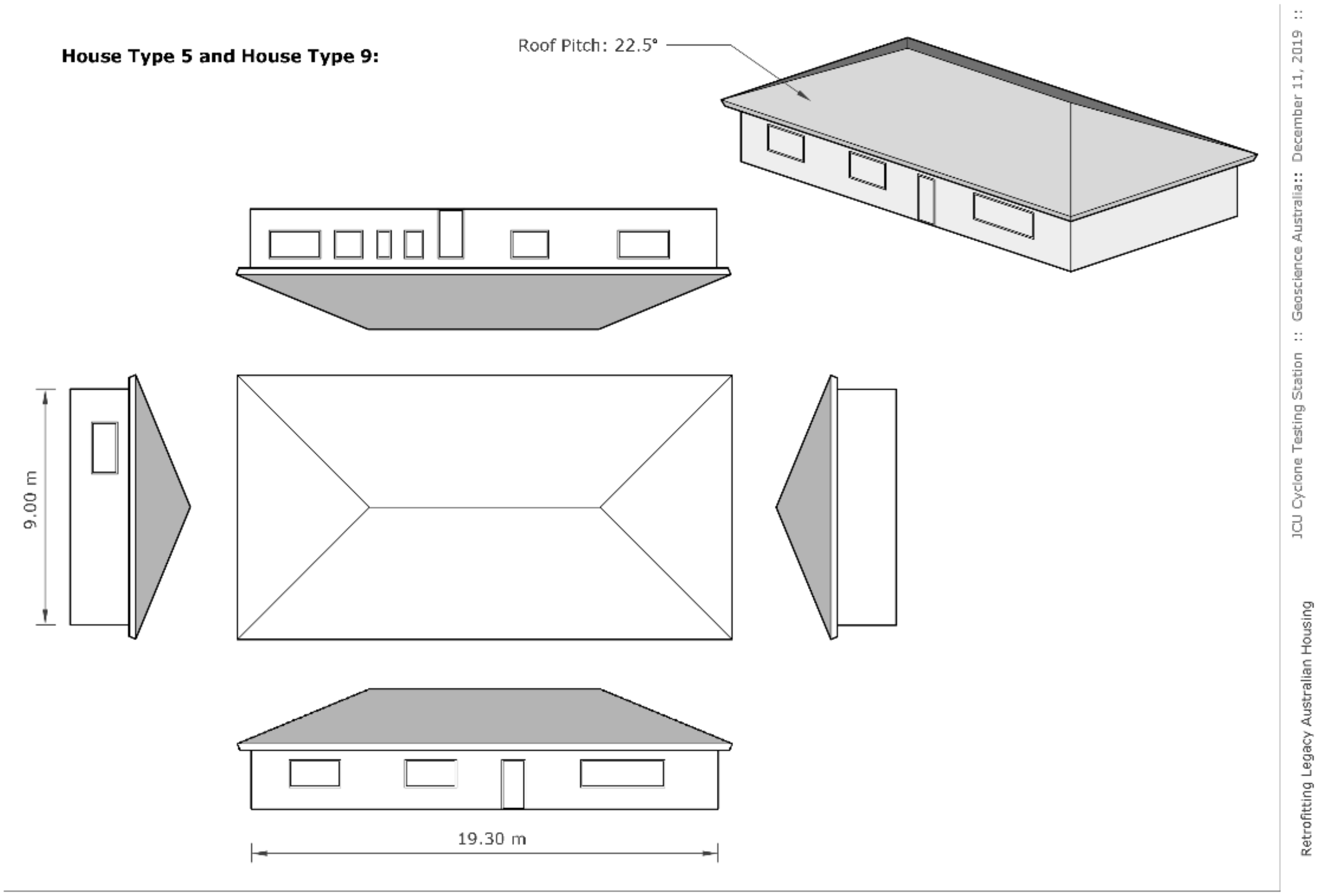
APPENDIX A: GENERIC HOUSE TYPES



House Type 1 - Highset Northern Australian House


Retrofitting Legacy Australian Housing
JCU Cyclone Testing Station :: Geoscience Australia:: December 11, 2019 ::
House Type 3 and House Type 7:
Roof Pitch: 22.5°
19.3 m
9.00 m

House Type 5 and House Type 9:



APPENDIX B: RETROFIT OPTIONS AND COSTS

The costs to retrofit the ten house types are presented in Table B1. Note that the apparent unintuitive result of some retrofit scenarios costing more in non-cyclonic regions than in cyclonic regions is due to higher rates for work in southern states.

House Type	Retrofit Scenario	Cost to retrofit in non-cyclonic region ($)	Cost to retrofit in cyclonic region ($)
1	1. Window and door protection	15865	15016
	2. Roof sheeting upgrade	27784	26812
	3. Roof sheeting and batten upgrade	29233	28210
	4. Full roof upgrade	35592	34346
	5. Full roof upgrade and door and window protection	51457	49752
2	1. Window and door protection	15865	15406
3	1. Window and door protection	15865	15406
	2. Roof sheeting upgrade	39714	38324
	3. Roof sheeting and batten upgrade	42193	40716
	4. Full roof upgrade	51851	51843
	5. Full roof upgrade and door and window protection	67716	67248
4	1. Window and door protection	15865	15406
	2. Installation of sarking	43610	43950
	3. Tile clips and batten connection upgrade	43358	43770
	4. Tile clips, batten connections and roof structure upgrade	53015	54896
	5. Full roof upgrade and sarking and door and window protection	70951	72299
5	1. Window and door protection	15865	15406
	2. Roof sheeting upgrade	47189	45538
	3. Roof sheeting and batten upgrade	50007	48257
	4. Full roof upgrade	60182	60375
	5. Full roof upgrade and door and window protection	76048	75781
6	1. Window and door protection	15865	15406
	2. Installation of sarking	45106	45331
	3. Tile clips and batten connection upgrade	44853	45151
	4. Tile clips, batten connections and roof structure upgrade	55029	57269
	5. Full roof upgrade and sarking and door and window protection	72964	74672

House Type	Retrofit Scenario	Cost to retrofit in non-cyclonic region ($)	Cost to retrofit in cyclonic region ($)
7	1. Window and door protection	15865	15406
	2. Roof sheeting upgrade	39714	38324
	3. Roof sheeting and batten upgrade	42193	40716
	4. Full roof upgrade	51851	51740
	5. Full roof upgrade and door and window protection	67610	67146
8	1. Window and door protection	15865	15406
	2. Installation of sarking	43610	43950
	3. Tile clips and batten connection upgrade	43359	43770
	4. Tile clips, batten connections and roof structure upgrade	54313	53156
	5. Full roof upgrade and sarking and door and window protection	69148	70559
9	1. Window and door protection	15865	15406
	2. Roof sheeting upgrade	47189	45538
	3. Roof sheeting and batten upgrade	50007	48257
	4. Full roof upgrade	60359	60546
	5. Full roof upgrade and door and window protection	76225	75952
10	1. Window and door protection	15865	15406
	2. Installation of sarking	45106	45331
	3. Tile clips and batten connection upgrade	44853	45151
	4. Tile clips, batten connections and roof structure upgrade	52666	54983
	5. Full roof upgrade and sarking and door and window protection	70595	72386

TABLE B1 ESTIMATED RETROFIT COSTS

APPENDIX C: BENEFIT-COST

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

TABLE C1 ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 1

Retrofit scenario	Benefit-cost in a non-cyclonic wind region	Benefit-cost in a cyclonic wind region
1. Window and door protection	0.00	0.18

TABLE C2. ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 2

Retrofit scenario	Benefit-cost in a non-cyclonic wind region	Benefit-cost in a cyclonic wind region
1. Window and door protection	0.00	0.58
2. Roof sheeting upgrade	0.00	0.00
3. Roof sheeting and batten upgrade	0.00	0.25
4. Full roof upgrade	0.00	0.68
5. Full roof upgrade and door and window protection	0.00	0.58

TABLE C3. ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 3.

Retrofit scenario	Benefit-cost in a non-cyclonic wind region	Benefit-cost in a cyclonic wind region
1. Window and door protection	0.04	5.87
2. Installation of sarking	0.02	3.53
3. Tile clips and batten connection upgrade	0.02	0.60
4. Tile clips, batten connections and roof structure upgrade	0.01	0.50
5. Full roof upgrade and sarking and door and window protection	0.02	2.35

TABLE C4. ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 4.

Retrofit scenario	Benefit-cost in a non-cyclonic wind region	Benefit-cost in a cyclonic wind region
1. Window and door protection	0.00	0.72

2. Roof sheeting upgrade	0.00	0.00
3. Roof sheeting and batten upgrade	0.00	0.03
4. Full roof upgrade	0.00	0.46
5. Full roof upgrade and door and window protection	0.00	0.42

TABLE C5. ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 5.

Retrofit scenario	**Benefit-cost in a non-cyclonic wind region**	**Benefit-cost in a cyclonic wind region**
1. Window and door protection	0.05	5.92
2. Installation of sarking	0.02	3.24
3. Tile clips and batten connection upgrade	0.01	0.50
4. Tile clips, batten connections and roof structure upgrade	0.01	0.44
5. Full roof upgrade and sarking and door and window protection	0.02	2.24

TABLE C6. ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 6.

Retrofit scenario	**Benefit-cost in a non-cyclonic wind region**	**Benefit-cost in a cyclonic wind region**
1. Window and door protection	0.00	0.72
2. Roof sheeting upgrade	0.00	0.00
3. Roof sheeting and batten upgrade	0.00	0.31
4. Full roof upgrade	0.00	0.83
5. Full roof upgrade and door and window protection	0.00	0.71

TABLE C7 ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 7.

Retrofit scenario	**Benefit-cost in a non-cyclonic wind region**	**Benefit-cost in a cyclonic wind region**
1. Window and door protection	0.05	7.14
2. Installation of sarking	0.03	4.03
3. Tile clips and batten connection upgrade	0.02	0.82
4. Tile clips, batten connections and roof structure upgrade	0.02	0.70
5. Full roof upgrade and sarking and door and window protection	0.03	2.95

TABLE C8. ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 8.

Retrofit scenario	**Benefit-cost in a non-cyclonic wind region**	**Benefit-cost in a cyclonic wind region**

1. Window and door protection	0.00	0.89
2. Roof sheeting upgrade	0.00	0.00
3. Roof sheeting and batten upgrade	0.00	0.04
4. Full roof upgrade	0.00	0.54
5. Full roof upgrade and door and window protection	0.00	0.50

TABLE C9 ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 9.

Retrofit scenario	Benefit-cost in a non-cyclonic wind region	Benefit-cost in a cyclonic wind region
1. Window and door protection	0.06	6.88
2. Installation of sarking	0.02	3.74
3. Tile clips and batten connection upgrade	0.01	0.83
4. Tile clips, batten connections and roof structure upgrade	0.01	0.74
5. Full roof upgrade and sarking and door and window protection	0.02	2.95

TABLE C10. ESTIMATED BENEFIT-COST RATIOS FOR RETROFIT TO HOUSE TYPE 10.