Department of Climate Change and Energy Efficiency - Schedule 7

Wind Vulnerability Model Development for Adaptation Studies on Specific Residential and Industrial Buildings

GEOSCIENCE AUSTRALIA

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Executive Summary

Australian residential buildings have been damaged by severe wind events historically. Coastal communities with older residential building stock are particularly vulnerable to severe wind and this vulnerability and related risk is expected to be exacerbated in many Australian regions by climate change. This was particularly evident following Tropical Cyclone Larry which impacted Innisfail, Queensland, in March 2006. Most of the residential building losses were associated with older construction that had not benefitted from the significant changes made to Queensland building regulations in 1981. Furthermore, modern residential construction that performed well in the winds of Tropical Cyclone Larry, which were below design levels, may become compromised in the future by increased wind speeds. Such empirical knowledge of residential vulnerability gained from past severe wind events points to adaptation of both existing buildings and the regulations for new buildings. Such adaptation should be informed by tools that enable quantitative assessments of the wind vulnerability changes accompanying a range of adaptation strategies for representative Australian building types.

Adaptation strategies include structural changes effected through retrofit of existing buildings and the staged improvement of building regulations for new construction. While there are typically several adaptation options, some may be more cost-effective than others. Tools that enable quantitative assessments and rankings of options can be used to identify optimal choices for physical improvements and regulatory changes, along with the best timing for implementation. The use of such objective measures can ensure that limited resources for adaptation are used to the greatest effect subject to the limitations on current available data.

The wind vulnerability development program at Geoscience Australia (GA) was recently supplemented by the Department of Climate Change and Energy Efficiency (DCCEE) through Schedule 7 to their joint Collaborative Heads of Agreement with GA. The work funded through this schedule has provided key modelling components of a future capability that will permit the assessment of building vulnerability to severe wind. Geoscience Australia has funded software development which will ultimately fully enable the Schedule 7 deliverables in a loss assessment software tool. The prototype software developed is called the **V**ulnerability **A**daptation to **W**ind **S**imulator and is known by the acronym VAWS.

The deliverables from Schedule 7 will permit the VAWS software tool to simulate the wind vulnerability of three common Australian building types. The deliverables have been developed through two contractual engagements of recognised Australian wind engineering expertise undertaken by Geoscience Australia on behalf of DCCEE. The Cyclone Testing Station of James Cook University (JCU) developed engineering models for three common building types; a high-set north Queensland house typical of the 1960's, a modern north Queensland industrial shed and a two storey brick veneer house with a tiled roof typical of western Sydney. Dr John Holmes of JDH Consulting produced separately, through the second contract, profiles of wind speed variability with height, shielding models to adjust local wind speeds for the effects of upwind structures and a detailed wind debris model. Completed elements were integrated into the modelling software along with pre-existing GA research. Preliminary validation of VAWS was undertaken through a process that compared the software's output to that of empirically derived models and post disaster observations.

Cyclonic events have shown the 1960's house type modelled in VAWS to be already compromised under present climatic hazard [see, for example, references 1,2,3]. Using this house type the utility of the modelling products developed and enabled in the VAWS software were finally demonstrated. Three levels of retrofit of the house type were considered and the construction costs for each evaluated as summarised in Table E1. The strength improvements effected by the retrofits were subsequently incorporated into the VAWS structural models and the vulnerability of the overall building re-simulated. The portion of the vulnerability curve for the existing building and the corresponding curves for each retrofit option are presented in Figure E1 for wind speeds up to 60m/s. These show a progressive reduction in vulnerability for successively more extensive retrofit options. The four curves converge at higher wind speeds (refer to section 6.2 of the main report) as failures at higher wind speeds relate to failures of housing components such as piers and wall bracing that are unaffected by the retrofit options considered here. Economic analysis has indicated that variations in vulnerability curves at lower wind speeds have the greatest influence on annualised loss. Although lower wind speeds produce lower levels of loss they have a higher probability of annual recurrence and hence contribute more to annualised loss than rarer, though more damaging, higher wind speeds. Finally, the benefit-versus-cost of adaptation was evaluated for two hypothetical scenarios of climate induced wind speed accentuation (Figure E2), two economic discounting rates (4% and 7%) and two retrofit timings (2010 and after 20 years) in a building life of 50 years from the present. The outcomes are summarised in Tables E2 and E3.

Table E1. *Upgrade strategies and costs for retrofit of 1960's north Queensland house type.*

RETROFIT OPTION		**UPGRADE COST**
Number	Description	
1	*Roof sheeting*: upgraded by the use of cyclone washers with the fixing screws	$786
2	*Roof sheeting and battens*: battens upgraded by improving their connection to the rafters with a metal strap in addition to (1)	$2,172
3	*Roof sheeting, battens and roof structure*: roof space structure upgraded by improving the rafter to ridge connections, the rafter to top plate connections and the collar tie connections in addition to (2)	$4,414

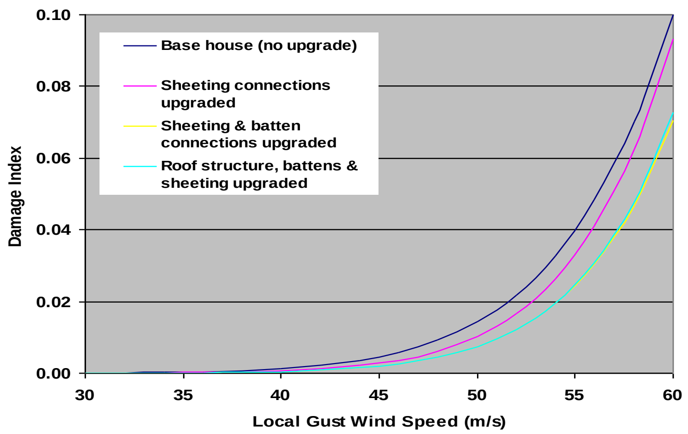

Figure E1:- *Vulnerability curves simulated using VAWS for the suite of retrofit options considered. Note the lack of improvement in moving to full roof structure upgrade due to failures in walls or piers overshadowing the improved resilience of the roof structure. Other non-roof related retrofit options for the building type are therefore pointed to, such as strengthening of wall bracing or piers..*

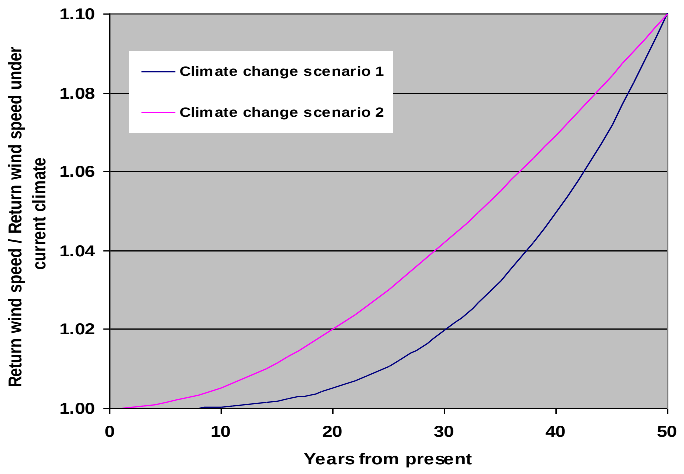

Figure E2:- *Increased wind speeds for the two hypothetical climate change scenarios considered.*

Table E2. *Benefit /cost ratios with a discount rate of 7%.*

RETROFIT OPTION	CURRENT CLIMATE WIND HAZARD		CLIMATE CHANGE SCENARIO 1		CLIMATE CHANGE SCENARIO 2	
	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS
1) Roof sheeting	0.83	0.76	0.85	0.81	0.87	0.84
2) Roof sheeting and battens	0.96	0.87	1.01	1.04	1.07	1.17
3) Roof sheeting, battens and roof structure	0.42	0.38	0.44	0.44	0.46	0.48

Table E3. *Benefit /cost ratios with a discount rate of 4%.*

RETROFIT OPTION	CURRENT CLIMATE WIND HAZARD		CLIMATE CHANGE SCENARIO 1		CLIMATE CHANGE SCENARIO 2	
	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS
1) Roof sheeting	1.26	1.03	1.30	1.11	1.33	1.16
2) Roof sheeting and battens	1.45	1.18	1.59	1.47	1.71	1.65
3) Roof sheeting, battens and roof structure	0.64	0.52	0.68	0.61	0.72	0.67

While the software is in its prototype form and the climate influences have been assumed, the results do highlight the utility of VAWS as a fundamental input to evaluating several influences on the assessed benefits of adaptation. Specifically, the following observations on the analysis outcomes are made:-

- Retrofit of roof sheeting connections alone (Retrofit Option 1) does not realise optimal benefits as the strengthening of one connection type transfers the type of failure from loss of sheeting to loss of both sheeting and battens. The overall outcome (loss of weatherproofing) is essentially the same whether the roof sheeting connections are retrofitted or not.
- Higher discounting rates (7% versus 4%) greatly reduce the assessed benefits of climate change adaptation. For Retrofit Option 2 the higher rate points to delayed retrofit to a time when climate change effects have significantly increased annual benefits, i.e. when increased wind hazard due to climate change has significantly increased the annual loss suffered by the base house when compared to the loss suffered by the retrofitted house.
- More expensive retrofit deeper into the structural system (Retrofit Option 3) is less attractive as the greater cost of the works is not offset by corresponding benefits.
- Retrofit Option 2 is the most cost-effective which entails upgrade of both sheeting and batten connections. This option is marginally viable under climate change if 7% discount rates are used but is shown to deliver significant return on retrofit investment if benefits are discounted at 4%. Investment returns are improved if retrofitting is immediately implemented rather than opting for delayed action for a 4% discount rate. The reverse is true for a 7% discount rate.

While the above “findings” result from a demonstration of the preliminary software using hypothetical data, the study establishes that there is potential for use of this model in assessing the viability of adaptation options.

Future work has been recommended that entails activity in the three key areas:-

- Refinement of the VAWS tool with a broadening of the range of modelled building types to better investigate building vulnerability changes with adaptation across a larger portion of the national building stock.
- Insurance industry engagement to incorporate their methods for the provision of insurance and setting of insurance premiums.
- Assessment of the benefits of adaptation to a selected high vulnerability house type in a selected Local Government Authority Area (LGA)

In summary, the targeted funding from Schedule 7 has bridged from the deliverables of an existing collaborative research program led by Geoscience Australia to a suite of modelling components that can be used in concert with others to evaluate building vulnerability. The simulation approach enabled in VAWS for a single Australian building type represents world best practice in the catastrophic loss modelling field. It is base capability that can be further validated and expanded to meet the key information needs of Australian decision makers for climate change adaptation. Recommendations have been made on how this capability can be taken forward and its utility demonstrated at local government level.

1. Introduction

Knowledge of the degree of damage to residential and industrial buildings caused by severe wind is fundamental to an understanding of the benefits derived from adaptation strategies. These strategies are needed to respond to expected changes in wind severity due to climate change that will impact upon more vulnerable infrastructure. Government, the insurance industry and emergency services require this capability for information on the impacts, risk and logistics they will need to manage now and in the future. Essential to the development of adaptation strategies is the ability to quantitatively assess the benefits of structural improvements through the retrofit of existing buildings and as a result of improved building regulations for new construction.

The Department of Climate Change and Energy Efficiency (DCCEE) Schedule 7 work has provided key components of a future capability that will permit the assessment of building vulnerability to severe wind. In parallel with this work, Geoscience Australia (GA) has funded software development as a complement to the scheduled work that will ultimately fully enable the Schedule 7 deliverables in a loss assessment software tool. A single residential type building has been enabled in the preliminary software to date and modelling components for another residential type building and an industrial building have been produced through the schedule for future integration. Finally, the utility of the tool has been demonstrated for the enabled residential building with three retrofit options in economic terms.

In this document the key reporting requirements of the DCCEE have been addressed. The deliverables developed by the contractual engagements and the outcomes of the three workshop activities are reported along with the timelines and financial statement. However, these are presented in a more informative reporting context which provides background to the drivers for this development, descriptions of how, with software enablement, the deliverables will fit into an adaptation framework, a report on parallel GA funded software development and a demonstration of the utility of the combined outcomes.

2. Background

Historically, Australian residential buildings have been damaged by severe wind events associated with cyclones, thunderstorms and larger synoptic storm systems. Coastal communities with older residential building stock are particularly vulnerable to severe wind and this vulnerability and risk is expected to be exacerbated with the effects of climate change in many Australian regions. This was particularly evident in the case of TC Larry which impacted Innisfail, Queensland, in March 2006. Most of the residential building losses were associated with pre-1980 construction that had not benefitted from the significant changes to building regulations in Queensland in late 1981. Older homes of this type are likely to be even more susceptible in the future if climate change increases local wind hazard. Further, modern residential construction that performed well in TC Larry may become compromised as building regulations are linked to current wind hazard and not the winds that may be experienced later in the life of the structure. Clearly, there is a need for tools that can quantitatively assess the changes to vulnerability associated with a range of adaptation strategies.

Similar adaptation of building regulations may be required for industrial buildings. While these structures benefit from specific engineering design, building regulations may need to progressively change ahead of climate change induced increases in wind hazard. Tools are needed to quantify the benefits derived through the life of a structure due to increased investment at the time of construction or strategies for retrofit later.

This work advances an existing substantial body of work that has been undertaken by recognised wind engineering experts and funded by Geoscience Australia. It builds on existing research to develop several key modelling components required for a process that can model the vulnerability of buildings to wind. The work is directed at developing a software application that can evaluate the current vulnerability of building structures and capture the wind resilience benefits of changing the structural system by retrofit strategies. The process involves simulating a large population of houses and/or light commercial (industrial) shed structures of the type of interest and capturing the variability that exists between buildings as to local wind effects and member strengths. The process then simulates the wind loading and component failures at staged increases in wind speed which are then aggregated into overall damage scenarios (including water ingress damage). Finally, the reparation cost is quantified. The results from a large number of simulations can then be used to generate vulnerability curves that can be input into a wind risk assessment to ascertain the benefits of adaptation strategies in economic terms.

3. Deliverables and Timelines

The deliverables for this project are key modelling components needed to permit a simulation process to be enabled for three common Australian building types. They have been developed through two contractual engagements undertaken by Geoscience Australia on behalf of the Department of Climate Change and Energy Efficiency and are reported on in two report documents. The scopes of the contracts were agreed at a pre-Schedule workshop held at the Cyclone Testing Station of James Cook University and are summarised below. Minutes from the workshop are attached at Appendix 3. The collaborative development process was also to be facilitated by three workshop activities.

1. Cyclone Testing Station of James Cook University (JCU) to:
    a. Develop for a high-set north Queensland type of house typical of 1960's construction a set of data and logic that characterise the house sufficiently to enable GA to enable the wind vulnerability software for this type of house. Undertake calibration of the output of the software against available data.
    b. Develop for a north Queensland type of industrial shed a set of data and logic that characterise the house sufficiently to enable GA to enable the wind vulnerability software for this type of house.
    c. Develop for a two storey brick veneer house with a tiled roof typical of western Sydney a set of data and logic that characterise the house sufficiently to enable GA to enable the wind vulnerability software for this type of house.
    d. Review the implementation by GA of the debris damage model.
    e. Review the implementation by GA of the water ingress damage model.
2. Dr John Holmes of JDH Consulting (JDH) to:
    a. Develop suites of boundary layer wind profiles which capture the anticipated variability in wind speed with height for cyclone and thunderstorm events;
    b. Provide recommendations for variation in shielding for individual houses within a level suburb;
    c. Provide recommendations for differential shielding between different building envelope surfaces where an individual structure is shielded;

d. Provide recommendations for a suitable debris damage impact model including necessary parameters to enable GA to develop computer code for the model.

All these elements were completed in a form that will enable their utilisation in a structural adaptation tool. The two reports of the modelling components developed are contained in Appendices 1 and 2.

The above two deliverables and associated reporting were to be completed and reports forwarded to Geoscience Australia by 20 June 2010. Geoscience Australia's covering report was to be complete by the project termination date, 30 June, 2010. The draft final report was submitted to DCCEE for comment on 22 July, 2010. The delay was due to late completion of one of the above deliverables. The extension was approved by DCCEE (email Ian Foster to Mark Edwards 13 July, 2010).

4. Benefits of the Model Development and Software Enablement

The advantage of developing models and a software tool is that vulnerability is calculated quantitatively in a way that takes account of the variability present in many components of a building type of interest. These features are detailed in section 5. The effects of adaptation strategies can be examined quantitatively by varying the probability distributions that the software tool samples for the strength of the key building components as part of a structural system. The effects are expressed as changes in the overall building vulnerability and fragility curves produced by the tool. Figure 1 shows how the software tool is used within the overall risk assessment process.

5. Development of the Software Tool

In parallel with the development of the two deliverables outlined above GA commenced the development of the software tool to quantitatively model vulnerability of residential and industrial buildings to severe wind. The tool has been developed to incorporate the majority of the outputs of the deliverables. However, some salient features, such as the modelling of wall collapse, still need to be incorporated. Notwithstanding this, the output of the tool in the current state of development is able to be calibrated against observed data as described below.

5.1 OVERALL LOGIC

The tool takes a component-based approach to modelling building vulnerability. It is based on the premise that overall building damage is strongly related to the failure of key connections.

The tool generates a house with values for component/connection strengths, external and internal pressure coefficients, shielding coefficients, wind speed profile, building orientation, debris damage parameters, and component weights randomly sampled from predetermined probability distributions. Then, for successive gust 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 which it costs, and thus calculates a damage index for that wind speed.

Failure of roof sheeting or roof batten connections triggers a redistribution of load to adjacent intact connections, thus making allowance for member continuity in these elements. Failure of roof structure connections revises the influence coefficients for the roof structure load effects depending on the specific connection that failed, thus making allowance for redistribution of forces within the roof structure. Connections that have failed and the effects of redistribution are preserved for successive wind speed increments, thus ensuring that increasing wind loads act on the damaged structure rather than beginning anew with an intact structure.

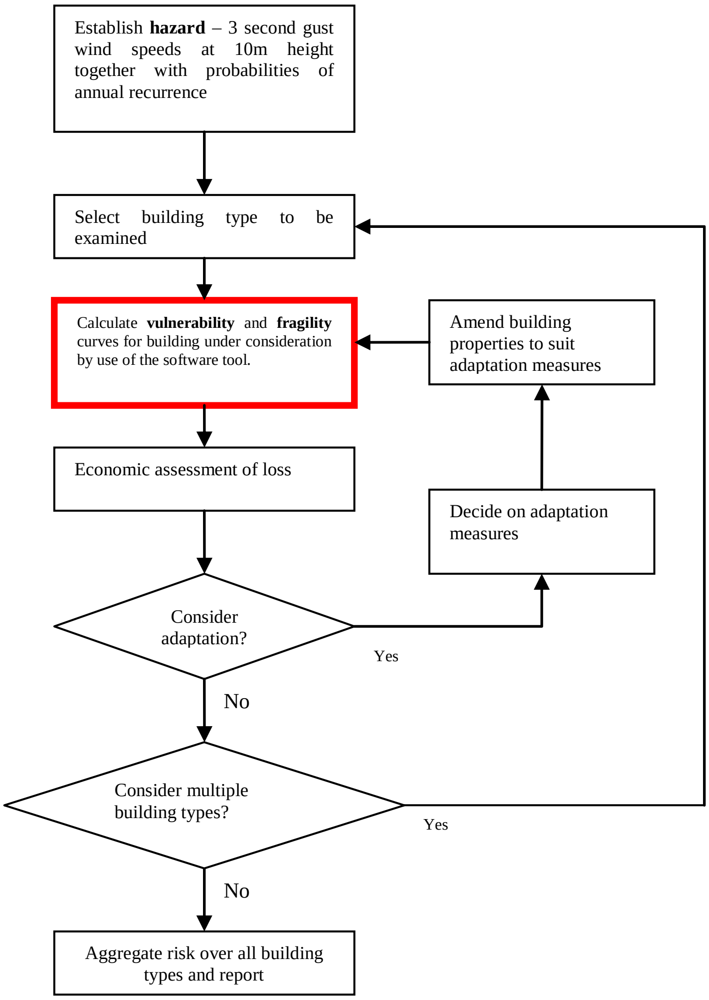

Figure 1: *Flowchart showing where the software tool lies in the risk assessment process (red box). The software tool is used to calculate the losses experienced by a building across the range of hazard magnitudes.*

The effect of high level structural (i.e. cladding) failures removing load from lower level structure (i.e. batten) is modelled by a hierarchical approach to assessing component failures at each wind speed. Roof sheeting connections are assessed first, and any necessary distribution from failed roof sheeting connections is undertaken before loads are calculated on batten connections, which are then assessed and redistributed before loads on roof structure connections are calculated, and the connections assessed. Hence, if an area of roof sheeting were to fail (lift off), the underlying battens and rafters would not receive any load from that area. Similar approaches are used to determine failures in wall cladding, wall structure and lower storey structure.

Once the tool has determined which connections have failed, it transposes the extent of damage in a group of connections to a percentage damage for a building damage scenario such as loss of roof sheeting, damage to wall cladding, loss of roof structure, etc.

The tool's debris damage section calculates the damage from windborne debris [refer JDH Deliverable d].
The simulation tool's water ingress section calculates the damage to internal linings via predefined cumulative normal distribution curves relating water ingress to gust wind speed and degree of envelope damage.

A costing module then gives a total repair cost for the accumulation of damage scenarios at a particular gust wind speed. After the set maximum wind speed is reached, a new, undamaged, house is generated with new randomly selected parameters and the process repeated.

At the completion of the simulation of a user specified number of houses of the same basic type, each at a number of wind speeds, a vulnerability curve is generated and fragility curves calculated.

5.2 PROBABILITY DISTRIBUTIONS FOR AN EXAMPLE RESIDENTIAL BUILDING

Various types of probability distributions are used in the tool to generate wind loading and house component strength parameters. The capture of the variability is described below.

5.2.1 Wind speed profiles

Variation in the profile of wind speed with height is captured by the random sampling of a profile from a suite of 10 profiles for a given terrain category [refer JCU Deliverable a]. The wind speed used for vulnerability curves is the 3 second gust at 10m height however calculation of wind loads requires the wind speed at mid-roof height. The appropriate factor to account for the change in wind speed from 10m to the house's mid-roof height is selected from the chosen profile.

5.2.2 Shielding coefficients

Variability in shielding to a house within its surroundings is accounted for by modifying the incident wind speed. The modifying factor is randomly chosen from a population of shielding coefficients for suburban houses developed from suburban wind speed field observations [refer JDH deliverable b]. Variability in the degree of shielding applied to different house surfaces is accounted for, modifying the external pressures using factors obtained from wind tunnel experiments [refer JDH deliverable c].

5.2.3 External and internal pressure coefficients (previous GA funded work)

Pressure coefficients for different zones of the house surfaces are randomly chosen from a Type III extreme value distribution with specified means for different zones of the house envelope, and specified coefficients of variation for different load effects: cladding, structural member, internal pressure (no openings), and internal pressure (with openings) [5]. The tool samples pressure coefficients for every zone of each house surface simulation for each wind direction and each load effect; approximately 6,500 coefficients.

5.2.4 Building orientation

For each simulated house, its orientation with respect to the wind is chosen from the eight cardinal directions either randomly, or chosen by the user.

5.2.5 Connection strengths

Connection strengths for generated houses are sampled from log-normal probability distributions for each type of connection. The mean and coefficient of variation (CoV) values have been developed from testing and damage survey work [refer JCU Deliverable a].

5.2.6 Debris model parameters

The debris impact modelling has several variables. These are sampled in a similar fashion to the other variables described above using probability distributions developed under Schedule 7 [refer JDH Deliverable d].

5.3 RESULTS

Examples of the simulation tool output are given in Figures 2 and 3 for a north Queensland high-set, fibro clad type house with corrugated steel roof cladding, timber battens at 900mm centres and timber framed roof structure consisting of timber rafter pairs at 900mm centres with collar ties to every second pair. A picture of an example of the modelled house is given in Figure 4. The roof structure connections modelled are rafter to top plate, rafter to ridge board and collar tie to rafter. The outputs are given in two parts:

1. Graphical view of results of Damage Index (DI) versus wind speed with a fitted vulnerability curve. Results from simulations on 20 houses (simulations at each wind speed increment approaching from a single direction) are shown in Figure 2. The curve is described by Eq. (1) and fitted to the mean DI values.

$$DI = 1 - \exp\left[-\left(\frac{V_{10m,3\sec}}{e^{\beta}} \right)^{\frac{1}{\alpha}} \right] \tag{1}$$

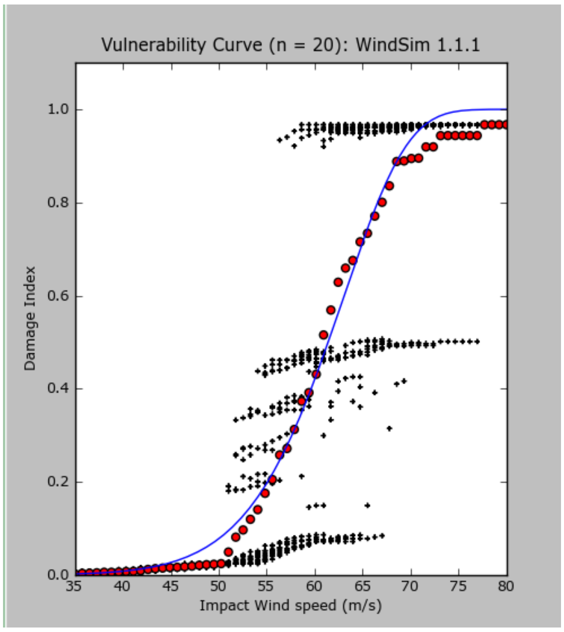

Figure 2:*. Output of simulation tool showing the DI versus $V_{10m,3sec}$ (m/s) vulnerability curve. The small black dots are individual simulation - wind speed increment results. The large red dots are mean DI at each wind speed increment. The large jump in DI between about 0.5 and 0.9 is due to failure of lower storey structure.*

2. Graphical view of calculated Fragility Curves for slight, medium and total damage is shown in Figure 3.

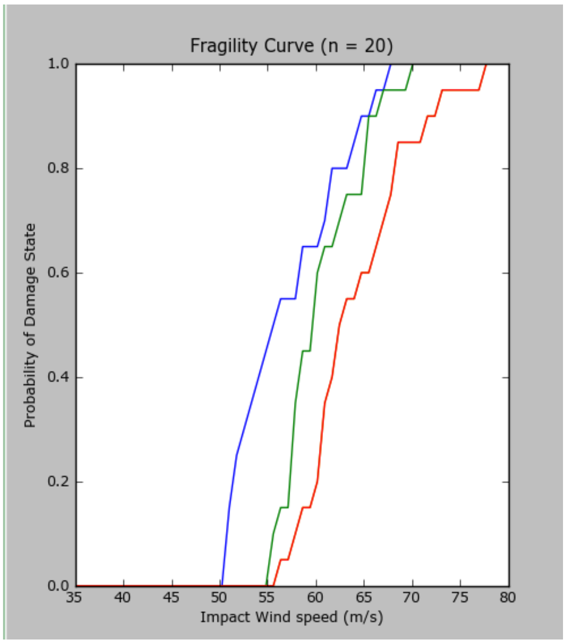

Figure 3: *Output of simulation tool showing fragility curves calculated from the results shown in Figure 2. The curves capture the spread of results about the mean vulnerability curve and show the proportion of houses expected to suffer no damage, slight damage, medium damage, and total damage at each wind speed. The stepped nature of the curves results from the low number of simulations (20 in this case). The DI defining the threshold of each level of damage is arbitrarily set.*

The simulation tool was calibrated by comparing the results of the high set north Queensland house type to damage observations following cyclones. Post disaster damage investigations describing the performance of the high set house type are largely limited to Cyclone Althea, which hit Townsville in 1971 [2] and Cyclone Tracy which made landfall in Darwin in 1974 [3]. The calibrations are conducted by comparing damage extent on a given house as well as the overall percentage of failure for the housing stock [4].

Calibration work to date has indicated that the overall vulnerability and fragility modelled by the tool matches observed damage reasonably well. However, the results for damage to specific components of the Group 4 house is not modelled as well with the simulation tool typically predicting later onset of damage and a steeper rise of damage extent with increasing gust wind speed.

Figure 4: *Example of the type of Queensland high-set house for which data has been enabled into the simulation tool.*

5.4 SUMMARY

To date the tool has been developed to model the damage to roof sheeting, roof battens, roof structure, wall cladding, lower storey structure, damage from windborne debris and damage from water ingress. Future work will involve extending the scope of the tool to include damage to wall structure, as well as further calibrating results against damage observed during post-storm surveys.

Data has been enabled into the tool for a single house type: a high-set, fibro clad Queenslander type house dominant in residential building structures in the 1960's and early 1970's from south-east Queensland to Darwin. Future work will involve enabling data sets for two further building types developed under Schedule 7: a portal frame industrial shed typical of north Queensland and a two-storey tiled-roof brick veneer house typical of western Sydney.

6. Adaptation Assessment Demonstration Using VAWS Software Tool

6.1 INTRODUCTION

The preliminary VAWS software tool has been used to evaluate the economic benefits of adaptation as a demonstration of its utility. The tool has been run multiple times for a given house type using different connection strengths to model the effects of connection upgrade works as options for adapting the house's structure to increasing wind hazard. An economic analysis was then undertaken for each retrofit option – wind hazard combination to determine the benefit-cost ratio and, hence, whether the upgrade work is effective in adapting the house to the wind hazard considered. The economic analysis can be based on either the vulnerability curves or fragility curves output by the simulation tool. In this instance the fragility curves have been used as they afford more detailed information on the damage to a population of houses of nominally the same type.

In this demonstration a high-set north Queensland type house similar to that shown in Figure 4 was modelled in the preliminary simulation tool. Three wind hazards were considered:

1. current Region C wind hazard as defined by AS 1170.2 [6];
2. a hypothetical increased wind hazard with a 10% increase in gust wind speed after 50 years and an initially slow increase (refer Figure 5); and,
3. a second hypothetical profile of increased wind hazard with a 10% increase in gust wind speed after 50 years and faster initial increase (refer Figure 5).

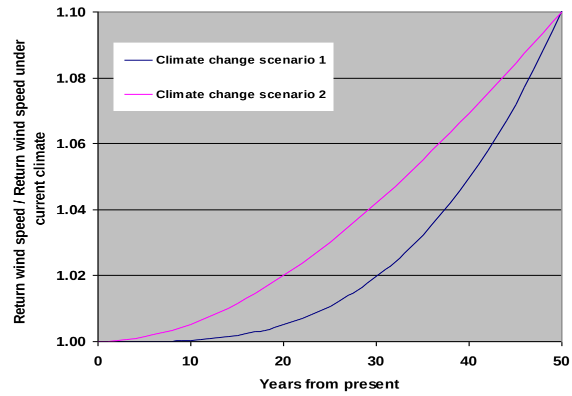

Figure 5: *Increased wind speeds for the two hypothetical climate change scenarios considered.*

The house was considered to be situated in Terrain Category 2 (representative of being located on the edge of a suburb). Three retrofit options were considered as briefly described below with more detail presented in Appendix 7:-

1. Roof sheeting upgraded by the use of cyclone washers with the fixing screws,
2. Battens upgraded by improving their connection to the rafters with a metal strap in addition to the work describe in Retrofit Option 1,
3. Roof space structure upgraded by improving the rafter to ridge connections, the rafter to top plate connections and the collar tie connections in addition to the work describe in Retrofit Option 2.

The costs of the upgrade works are presented in Table 1 and were calculated from Rawlinsons construction cost data [9] and assuming that all retrofit works were undertaken during scheduled roof replacement. Hence the costs of removing the roof sheeting and replacement with new were not included in the costs for the retrofit works. The house replacement cost was $214,952 and no excess was assumed in order to model the total cost to society. Benefits were calculated over a 50 year period using two alternative discount rates of 7% and 4% to bring benefits and costs to a present value.

Table 1:-. *Construction costs of retrofit options. Costs assume that the works will be undertaken in conjunction with roof sheeting replacement and so represent the incremental additional cost.*

RETROFIT OPTION	UPGRADE COST
1. Roof sheeting	$786
2. Roof sheeting and battens	$2,172
3. Roof sheeting, battens and roof structure	$4,414

The effects of internal damage from water ingress were neglected in this demonstration as the method used in the preliminary software tool to assess loss from water ingress is coarse and would not accurately model the change in water ingress afforded by the adaptation work.

6.2 RESULTS

The results are shown in Tables 2 and 3 and Figures 5 to 9.

Table 2. *Benefit /cost ratios with a discount rate of 7%.*

RETROFIT OPTION	CURRENT CLIMATE WIND HAZARD		CLIMATE CHANGE SCENARIO 1		CLIMATE CHANGE SCENARIO 2	
	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS
Roof sheeting	0.83	0.76	0.85	0.81	0.87	0.84
Roof sheeting and battens	0.96	0.87	1.01	1.04	1.07	1.17
Roof sheeting, battens and roof structure	0.42	0.38	0.44	0.44	0.46	0.48

Table 3. *Benefit /cost ratios with a discount rate of 4%.*

RETROFIT OPTION	CURRENT CLIMATE WIND HAZARD		CLIMATE CHANGE SCENARIO 1		CLIMATE CHANGE SCENARIO 2	
	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS	UPGRADE UNDERTAKEN NOW	UPGRADE UNDERTAKEN IN 20 YEARS
Roof sheeting	1.26	1.03	1.30	1.11	1.33	1.16
Roof sheeting and battens	1.45	1.18	1.59	1.47	1.71	1.65
Roof sheeting, battens and roof structure	0.64	0.52	0.68	0.61	0.72	0.67

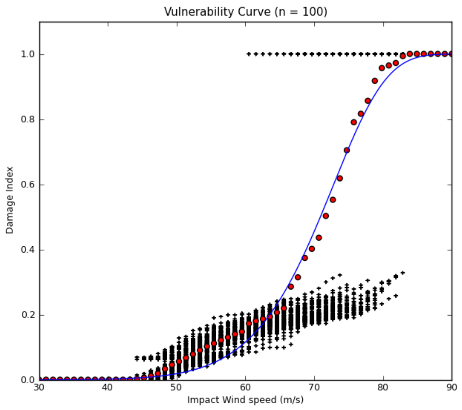

Figure 5. *Vulnerability results from simulation tool for base house (no upgrade).*

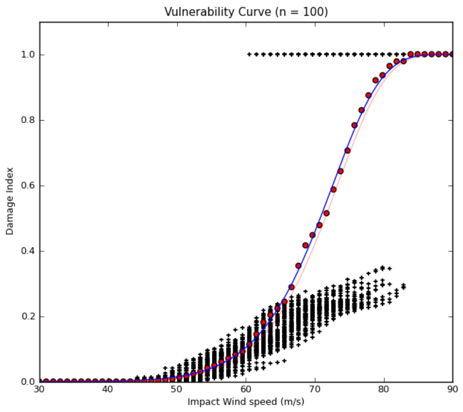

Figure 6. *Vulnerability results from simulation tool for Retrofit Option 1 (roof sheeting upgrade).*

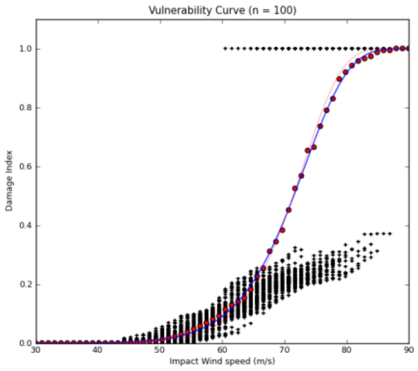

Figure 7. *Vulnerability results from simulation tool for Retrofit Option 2 (roof sheeting and batten upgrade).*

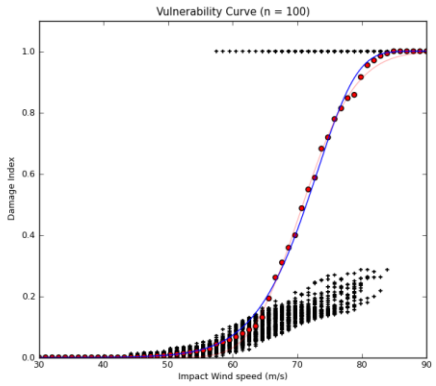

Figure 8. *Vulnerability results from simulation tool for Retrofit Option 3 (roof sheeting, batten and roof structure upgrade).*

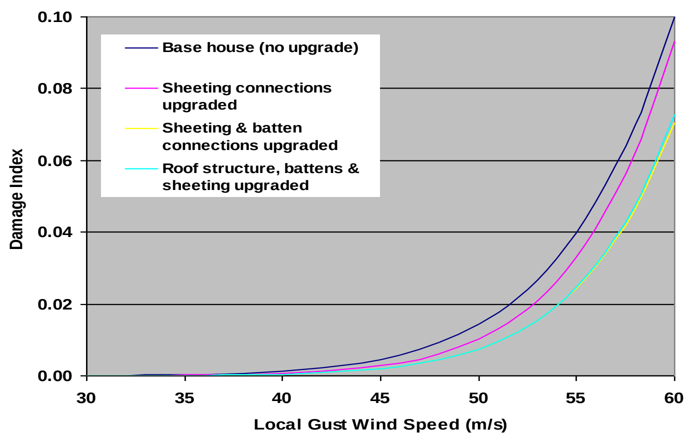

Figure 9. *Detail of vulnerability curves from figures 5 to 8 showing the shift in vulnerability curves due to upgrade works. Note the lack of improvement from roof structure upgrade due to failures further down the load path (in walls or piers) overshadowing the improved resilience of the roof structure.*

6.3 DISCUSSION

The results from this demonstration show the greatest economic return is achieved by upgrading roof sheeting and batten to rafter connections although the magnitude of the return is strongly influenced by the discount rate.

The Retrofit Option 1 result indicates that if only the roof sheeting fasteners are upgraded there is an increased likelihood that the roof sheeting will be blown off with the battens attached (i.e. the mode of failure changes from one of loss of roof sheeting to one of failure of the batten to rafter connection).

The Retrofit Option 3 result indicates that the greater cost of upgrading the roof space structure is not warranted. Although substantially increasing the strength of the roof structure the upgrade work does not improve the overall vulnerability of the house sufficiently to generate an increased benefit – cost ratio. This is because failures further down the load path (in walls or piers) overshadow the improved resilience of the roof structure.

Furthermore the economic analysis indicated that only a small shift of the vulnerability curve is required to generate an economic benefit highlighting the need for calibration of heuristically developed curves. The benefit / cost ratio is sensitive to the discount rate with lower discount rates tending to improve the return on retrofit investments.

7. Workshops

During the development of Schedule 7 work, GA facilitated three workshops that were held at the Cyclone Testing Station (CTS) of James Cook University (JCU) on 12/13 October, 2009; 17/18 February, 2010; and 26/27 May, 2010. The workshops were attended by GA, CTS of JCU and JDH Consulting. The workshops were held to facilitate the development of the collaborative work, monitor the progress of the deliverables, and to brief CTS and JDH Consulting on software development work undertaken by GA. Minutes of the workshops are attached at Appendices 4, 5 and 6.

8. Contracts and Statement of Financial Records

9. Recommendation for Future Application

Adaptation information needs to reach and influence decision makers faced with the option to adapt. For residential homes which have featured prominently in wind related damage, the individual home owner is typically that person, subject to the influences/incentives he or she may experience from local government and their insurer. Future work is recommended to translate what has been achieved through Schedule 7 to information that can be used. The activity entails four key areas:-

- Refinement of the VAWS tool with a broadening of the range of modelled building types to better represent building vulnerability changes with adaptation across a larger proportion of the nation's building stock.
- Insurance industry engagement to incorporate their key drivers and potential incentives.
- Assessment of the benefits of adaptation to a selected high vulnerability house type in a selected Local Government Authority (LGA) area

10. References

[1] JCU (2006) "Tropical Cyclone Larry, Damage to buildings in the Innisfail area", CTS Technical report TR51

[2] JCU (1972) "Cyclone Althea", Report and recommendations prepared by the Engineering Department, James Cook University for the Queensland Government.

[3] R.H. Leicester & G. Reardon (1976) "A Statistical Analysis of the Structural Damage by Cyclone Tracy", Civil Engineering Transcripts, IE Aust., **CE18**, pp. 50-54.

[4] D.J. Henderson & J.D. Ginger (2007) "Vulnerability model of an Australian high-set house subjected to cyclonic wind loading" Wind & Structures, **10 (3)** pp. 269-285.

[5] JDH Consulting 2007 Effective wind pressure coefficients for two house types – report prepared for Geoscience Australia.

[6] AS/NZS 1170.2:2002 "Structural design actions Part 2: Wind actions", Standards Australia, 2002.

[7] AS 1684.3-2006 "Residential timber-framed construction", Standards Australia, 2006.

[8] AS 1720.1-1997 "Timber structures Part 1: Design methods", Standards Australia, 1997.

[9] Rawlinsons Construction Cost Consultants and Quantity Surveyors, "Construction Cost Guide for Housing, Small Commercial and Industrial Buildings", Rawlinsons Publishing, 2009

Appendix 1

Appendix 2

Appendix 3

Appendix 4

Appendix 5

Appendix 6

Appendix 7

Description of Adaptation Measures

Description of Adaptation Measures

This appendix describes the measures considered for each of the retrofit options.

The connections considered to be strengthened for the different retrofit options considered are shown in Table 1. Details of the upgrade work to each connection type are given in Figures 1 to 6.

Table 1. Connections considered to be strengthened by retrofit option.

RETROFIT OPTION	CONNECTIONS STRENGTHENED
1. Roof sheeting	Connections type A in Figure 1
2. Roof sheeting and battens	Connections type A and B in Figure 1
3. Roof sheeting, battens and roof structure	Connections type A, B, C, D and E in Figure 1

Strengths for the upgraded connections were determined from [7] and [8]. Such strengths were considered to be 95% pass values (i.e. 95% of actual connections would have strengths larger than these). Connection strength means and standard deviations for the upgraded connections were derived from these values assuming a log-normal distribution and a coefficient of variation of 0.35.

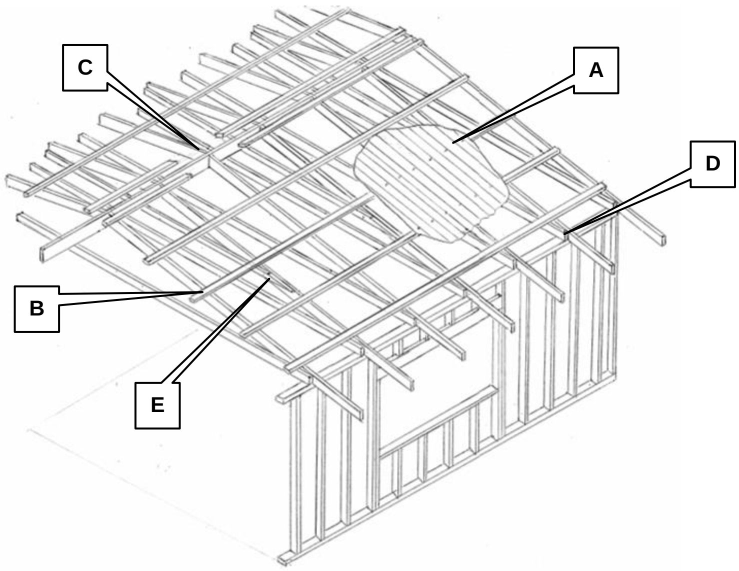

Figure 1. *Schematic of north Queensland house upper storey structure identifying types of connections considered to be strengthened to improve the house's resilience to severe wind.*

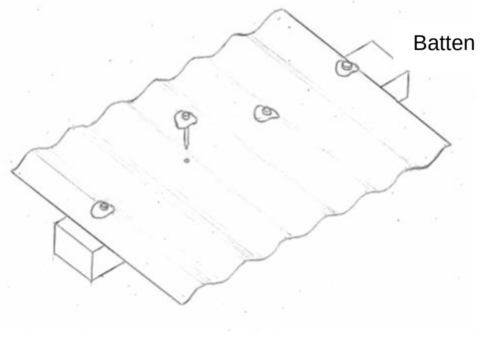

Figure 2. *Upgrade A, installation of roofing screws with cyclone washers.*

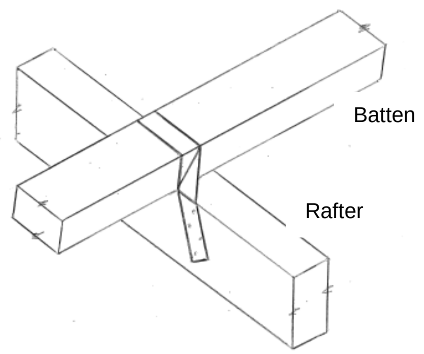

Figure 3. *Upgrade B, improvement of connection of battens to rafters by use of a 30 x 0.8mm GI strap with 4 x 2.8mm diameter nails each end.*

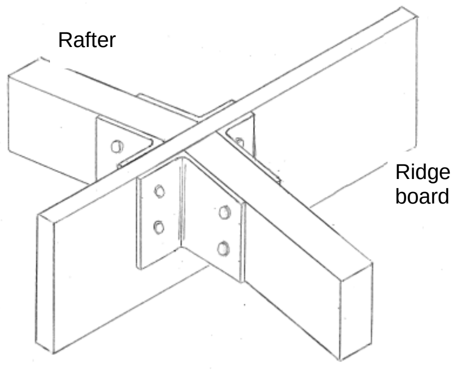

Figure 4. *Upgrade C, improvement of connection of rafters at the ridge by installation of 4 No. 100 x 50 x 10 UA brackets with 8 M12 bolts.*

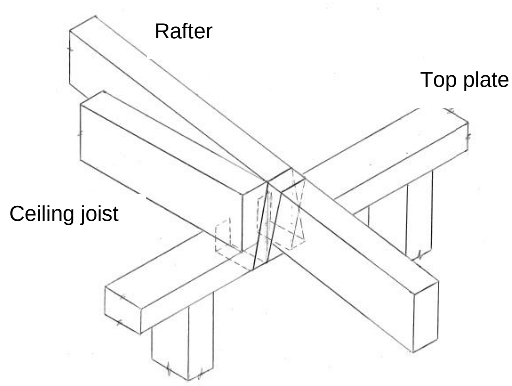

Figure 5. *Upgrade D, improvement of connection of rafters to top plate by installation of a 30 x 0.8mm GI looped strap with 3 x 2.8mm diameter nails each end.*

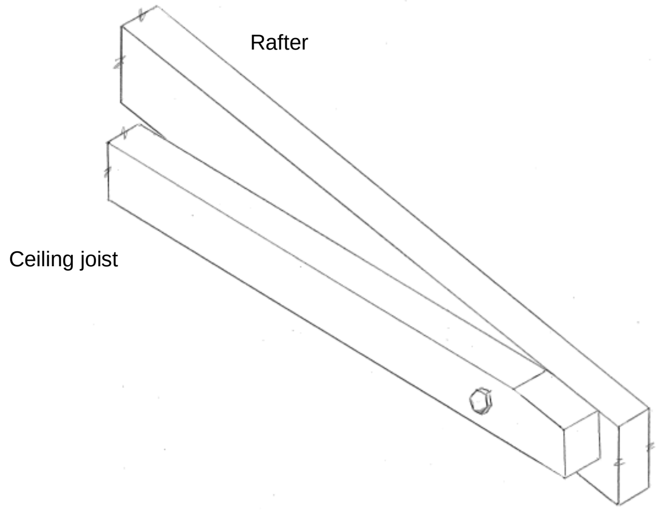

Figure 6. *Upgrade E, improvement of connection of collar ties to rafters by installation of 1 M12 bolt.*