Demonstration of Cost Benefit of Adaptation based on existing Heuristic Vulnerability Curves.

Vulnerability of Australian Residential Buildings to Severe Wind

Introduction

Historically Australian houses have been damaged by severe winds. To adapt to higher wind speeds as predicted by climate change science, it may be necessary to retrofit existing residential buildings to improve their resilience to severe wind. The work herein reported demonstrates a methodology by which the effectiveness of such adaptation work may be economically assessed.

This section of the report provides the background, context, broad methodology and results for the work carried out under Schedule 6, Phase 3. Detailed descriptions of the methodology and detailed results are provided in the Technical Report at Attachment A.

Background to Hazard Definition

Forces exerted by wind on buildings are proportional to the square of the wind speed at the location and height of the building. Typically, the wind hazard is specified by the 3 second gust wind speed at 10m height at the site of the building in question. The change in wind speed from 10m height to the height of the building's roof is taken into account during the calculation of the wind forces.

The wind hazard (i.e. 3 second gust wind speed at 10m height) is defined in the design standard AS 1170.2:2002 *Structural design actions Part 2; Wind actions*. The value it provides is influenced by:

(a) regional location within Australia;

(b) the probability of exceedance within the building's life;

(c) the roughness of the terrain within which the building is sited;

(d) the regional variation of wind speed with wind direction;

(e) the shape of the topography around the building and

(f) the presence of upwind structures that may shield the building from wind.

To define regional variations in wind speeds, Australia is divided into regions A,B,C,D, within which the wind speed is broadly similar with all other factors being equal. Figure 1 is an extract from AS 1170.2:2002 that spatially defines the four regions. Regions C and D are those where the hazard is dominated by tropical cyclones, region A is affected by synoptic and thunderstorm downburst winds only and region B is an intermediate region. The regional wind speed increases from region A to D.

The higher a wind hazard at a location (i.e. higher wind speed) the less often it will occur within a given period of time, or, conversely, the lower its annual probability of occurrence. Furthermore, the longer a building exists the more likely it is to be exposed to a given severity of wind. Hence, structures that are expected to be serviceable for longer periods of time (e.g. bridges), or structures for which the community has a greater expectation of being serviceable after a storm (e.g. hospitals) are designed for higher wind speeds. This is expressed either as a return period or as a probability of exceedance within a given time period. The Building Code of Australia specifies that residential buildings be designed for wind speeds with a 1 in 500 probability of annual exceedance, i.e. a return period of 500 years [BCA Table B1.2b].

The nature of the wind storm also has an effect on the building: cyclonic winds are more demanding of structures than synoptic winds of the same wind speed due to the repetitive nature of cyclonic wind gusts. During a cyclonic storm a structure will be subjected to numerous gusts at or close to the maximum wind speed while in a synoptic storm, a much smaller number of gusts at or close to the maximum wind speed will be experienced. Thunderstorm downbursts that dominate wind hazard in some capital cities have very few peak wind gusts associated with them. Sustained cyclic loading can lead to the phenomenon of fatigue in certain elements of a building.

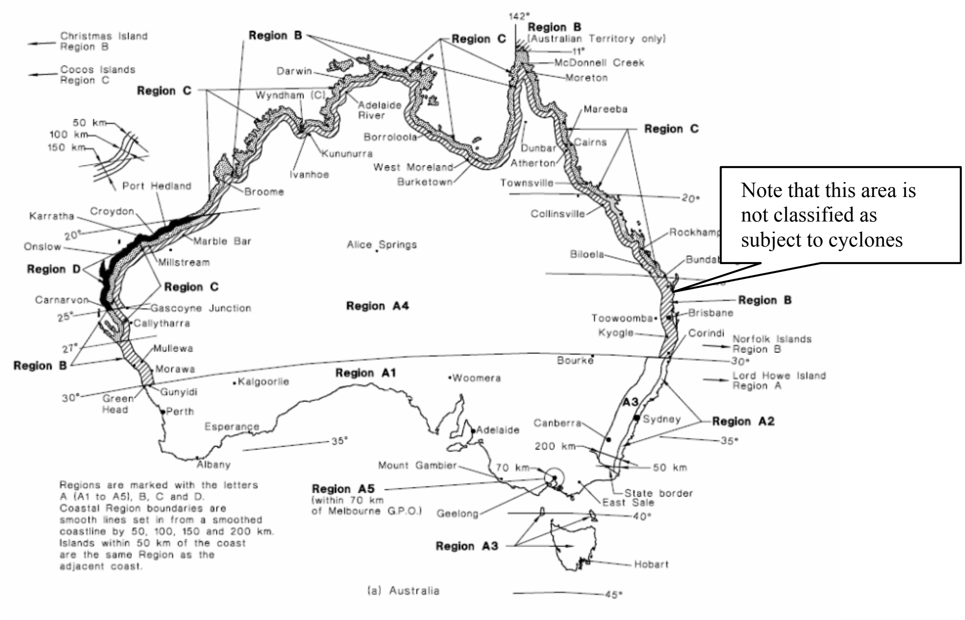


Figure 1. Extract from AS1170.2 showing wind regions. Note that one of the possible results of climate change is that the Sunshine Coast in south-east Queensland becomes susceptible to cyclonic winds; a large change in wind hazard.

The roughness of the terrain upwind of where a building is sited affects the wind speed it experiences, thus a building sited in an open field will be subjected to higher wind speeds than a nearby similar building sited well inside a densely built suburb.

In different regions of Australia, strong winds come from certain predominant directions. This can be used to advantage in building design utilising the appropriate factors specified by AS 1170.2.

The topography around a building will influence the wind speed to which it is subjected, thus a building situated close to the crest of a hill will experience a higher wind speed than a nearby similar building sited on flat ground. AS 1170.2 provides guidance on assessing the effect of topography on wind speed.

Nearby buildings situated upwind of a building in question will tend to shield the building from incident wind, thereby reducing the wind speed to which it is subjected. The magnitude of shielding afforded to a building is dependent on the size, number and spacing of upwind buildings. AS 1170.2 provides guidance on assessing the effects of shielding.

In Australia, a simplified methodology for assessing wind forces on houses is specified in *AS 4055-2006 Wind loads for housing*. This standard takes account of all the above hazard factors and expresses the wind hazard as a single wind class (N1 to N6 or C1 to C4). This class can then be used by other standards (e.g. *AS 1684.2-2006*

Residential timber-framed construction) to prescribe requirements for house framing or other elements. Refer to Figure 2 for an extract from AS 4055 showing the wind classes.

DESIGN GUST WIND SPEED (V_h) FOR CLASSIFICATION

Wind class		Design gust wind speed (V_h) at height (h) m/s	
Regions A and B (non-cyclonic)	**Regions C and D (cyclonic)**	**Serviceability limit state ($V_{h,s}$)**	**Ultimate limit state ($V_{h,u}$)**
N1	—	26	34
N2	—	26	40
N3	C1	32	50
N4	C2	39	61
N5	C3	47	74
N6	C4	55	86

Figure 2. Extract of AS 4055 showing wind classes and their associated design wind speeds.

The wind hazards set out in AS1170.2 and AS4055 are so chosen that a building designed and constructed to resist the wind hazards will have an acceptably small probability of failure over its lifespan. However, legacy buildings that do not comply with the modern standards and older buildings that may have suffered decay over time typically have higher probabilities of failure than modern code compliant buildings. Furthermore, if the wind hazard changes over time, perhaps due to climate change, even houses compliant with current standards may acquire an unacceptable high probability of failure. More simply, this can be expressed as: damage suffered by houses during large storms may become unacceptably severe.

As work to determine the likely hazard change due to climate change is not mature, arbitrary hazard changes were adopted for this work to demonstrate the methodology. These were as follow:

1. A change from a N1 hazard to a N3 hazard. This was considered representative of a N1 house being subjected to synoptic storms of greater intensity. This might be represented by a tiled roof house in any city in southern Australia.
2. A change from N2 hazard to a C2 hazard. This was considered representative of a N2 house in a region currently subjected to synoptic winds being subjected to medium strength cyclonic winds. This might be represented by a sheet roofed house on a flat site on the Sunshine Coast.
3. A change from N3 hazard to a C2 hazard. This was considered representative of a N3 house in a region currently subjected to synoptic winds being subjected to medium strength cyclonic winds. This might be represented by a sheet roofed house on a more exposed site on the Sunshine Coast.

Background to Vulnerability

Vulnerability defines the expected degree of damage to a building from a hazard (in this case the 3 second gust wind speed at 10m height). It is normally expressed as a S shaped curve relating *damage index* to the wind hazard. Damage index is defined as the repair cost divided by the replacement cost for the particular type of building in question. Thus the closer the damage index (DI) is to 1.0, the more heavily the house population is damaged. It is important to note that within the population of buildings there will be significant variation in building geometry, construction quality, maintenance and orientation to wind with each permutation possessing its own vulnerability. Thus a vulnerability curve describes the average vulnerability of the whole population, not individual properties.

For this work, vulnerability curves, representative of three house types (described below), were taken from the Phase 1 work where heuristic vulnerability curves were developed for a wide range of Australian house types.

Wind damage to houses is strongly related to connection failures and, to a lesser extent, the failure of critical members which do not have sufficient strength to perform their function. That is, under wind loading components often fail by their connections to other components failing (e.g roofing screws pull out, rafter tie-downs fail and roofs are lifted off), rather than the members themselves failing. Failures are usually tensile failures as wind loads on house roofs are usually upwards, trying to lift the roof off.

The sample houses for this work, as set out below, were chosen to suit the hazard changes described above. All the houses were assumed to be compliant with modern standards which reflect the current wind hazard. This enabled their current construction to be easily identified via reference to standards such as AS1684. The following types were used:

1. Brick veneer single storey house with tiled roof typical of southern Australian suburban environment (Hazard change N1 to N3).
2. Brick veneer single storey house with metal sheeting roof typical of south-eastern Queensland (Hazard change N2 to C2).
3. Brick veneer single storey house with metal sheeting roof typical of south-eastern Queensland (Hazard change N3 to C2).

For each house the set of critical connections was identified as shown in Figure 3 and listed in Table 1. These connections were those in the chain of connections resisting wind loads whose failure would lead to significant damage to the house.

For each connection the work required to upgrade it for the house to be code compliant to the future wind hazard was identified and costed using the manual *Construction Cost Guide, Rawlinsons, 2009*. The results are shown in Table 2. Costs were assessed both if the work was done on its own and if the work was done as part of a re-roofing project. The latter has the advantage that some of the upgrade cost is absorbed by the roof works which affords needed access to the roof space.

Vulnerability is also affected by decay. As a house ages the strength of connections may reduce due to corrosion and rot, thereby leaving the house with an increased vulnerability with time.

Vulnerability also needs to take into account the effects of the nature of hazard change. If the hazard changes from non-cyclonic to cyclonic then the effective strength of connections will be reduced due to the phenomenon of fatigue and the increased probability of internal pressurisation due to perforation of a building's envelope by flying debris. These are significantly more numerous during a cyclone than during a synoptic storm.

Details of how the above effects were taken into account are provided in the technical report.

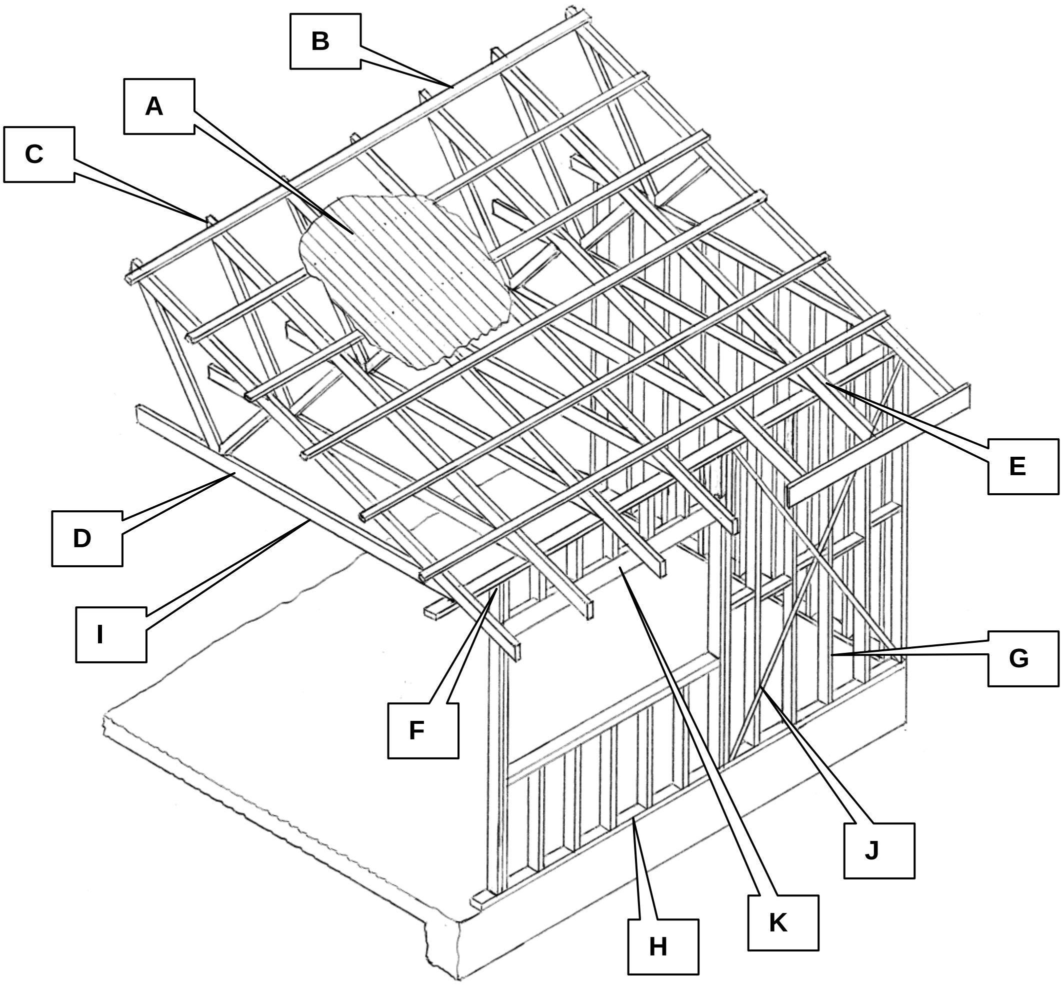


Figure 3. Generic location of critical connection and member types.

Connection	Name	Notes
A	Roofing to batten connection	
B	Batten size	
C	Batten to rafter connection	
D	Roof truss bottom chord size	
E	Roof truss to top plate connection	
F	Top plate to stud connection	
G	Stud size	
H	Bottom plate to foundation connection	
I	In-plane bracing size	Not shown for clarity
J	Vertical bracing size	
K	Lintel size	

Table 1. Identification of critical connection and member types

Elemental costs

Element	Description	Extg BV / tile N1	Extg BV / metal N2	Extg BV / metal N3	New work BV / metal C2: Description	Work to upgrade from N2	Work to upgrade from N3	Upgrade cost from N2 extg roof	Upgrade cost from N2 new roof	Upgrade cost from N3 extg roof	Upgrade cost from N3 new roof	New work BV / tile N3: Description	Work to upgrade from N1	Upgrade cost with extg roof	Upgrade cost with new roof	Element	Builder's work N2-C2/sheet: extg roof	N2-C2/sheet: new roof	N3-C2/sheet: extg roof	N3-C2/sheet: new roof	N1-N3/tile: extg roof	N1-N3/tile: new roof
A	Sheeting to batten / Tile to batten	Nail every second tile	3 screws per sheet	3 screws per sheet	5 larger screws per sheet with cyclone washers	Replace all screws with larger + washers + 2 extra per sheet	Replace all screws with larger + washers + 2 extra per sheet	7628	0	7628	0	Nail every second tile	Nil	0	0	A	2513	0	2513	0	0	0
									Incl in new roof		Incl in new roof											
B	Batten size	35 x 70 @ 330	45x 70 @ 900	45 x 70 @ 900	45 x 70 @ 450 ctrs in edge zone	2 extra rows of battens	2 extra rows of battens	1219	1219	1219	1219	35 x 70 @ 330	Nil	0	0	B	4437	0	4437	0	0	0
C	Batten to rafter	1/65 x 2.8 dia nail	2/75 x 3.75 dia def shank nails	1/Type 17 14-90 screw	1/Type 17 14-90 screw	Install screw at each connection	Nil	865	865	0	0	2/65x 2.8 dia nails	Extra nail at ecah connection	1007	1007	C	0	0	0	0	2009	0
																	Incl at B		Incl at B			
D	Bottom chord restraint	1 row per span	1 row per span	2 rows per span	3 rows per span	Add 2 rows of restraint	Add 1 row of restraint	1044	1044	522	522	1 row per span	Nil	0	0	D	0	0	0	0	0	0
																	Incl at B		Incl at B			
E	Truss to top plate	1 framing anchor per truss	2 framing anchors per truss	2/30 x 0.8 GI strap per truss	1/30 x 0.8 GI looped strap	Install looped strap per truss end	Install looped strap per truss end	1220	1220	1220	1220	2 framing anchors per truss	Install 2nd anchor	1188	1188	E	0	0	0	0	1452	0
																	Incl at B		Incl at B			
F	Top plate to stud	2/90 x 3.05 dia nails	30 x 0.8 GI strap @ 900 ctrs with 2/2.8 dia nails each end	30 x 0.8 GI strap @ 900 ctrs with 4/2.8 dia nails each end	M10 cyclone bolts @ 900 ctrs to foundation	Install cyclone bolts	Install cyclone bolts	3619	3619	3619	3619	2 framing anchors @ 900 ctrs	Install frmaing anchors	2377	2377	F	9657	9657	9657	9657	0	0
																					Incl at E	
G	Studs @ 450 ctrs size	70 x 35	70 x 35	70 x 35	70 x 45	Double every 3rd stud	Double every 3rd stud	935	935	935	935	70 x 35	Nil	0	0	G	0	0	0	0	0	0
																	Incl at F	Incl at F	Incl at F	Incl at F		
H	Bottom plate tie-down	Concrete nail	M8 chemical anchor	M8 chemical anchor	M10 cyclone bolt from eaves level	Install cyclone bolts	Install cyclone bolts	0	0	0	0	M8 chemical anchor	Install chemical anchors	867	867	H	0	0	0	0	3464	3464
								Incl in F	Incl in F	Incl in F	Incl at F						Incl at F	Incl at F	Incl at F	Incl at F		
I	In-plane roof bracing	1/ 30 x 0.8 GI strap set	1/ 30 x 0.8 GI strap set	1/ 30 x 0.8 GI strap set	2 / 30 x 0.8 GI strap set	Install extra set	Install extra set	794	794	794	794	1/ 30 x 0.8 GI strap set	Nil	0	0	I	0	0	0	0	0	0
																	Incl at B		Incl at B			
J	Racking walls bracing (m of ply bracing panel)	11.3	15.5	23.9	36.2	Add 20.7m of bracing	Add 12.3m of bracing	1306	1306	776	776	23.9	Add 8.4m of bracing	530	530	J	1064	1064	632	632	1519	1519
K	Lintel to 2.4m wide opening	2/170x45	170x35	170x35	170x45	Plate extg lintels with 19mm ply	Plate extg lintels with 19mm ply	1884	1884	1884	1884	2/170 x 45	Nil	0	0	K	1634	1634	1634	1634	0	0

Table 2. Table of costs in dollars to upgrade each type of connection for different future wind hazards.

Results

Benefit-cost ratios were computed for the three house / hazard increase combinations considering the hazard change and house structure degradation over the next 100 years. Benefits of adaptation were evaluated as the reduced annualised losses for wind hazard as a result of the retrofit. This was undertaken using standard economic evaluation methods with future benefits discounted at 7% to present value. It was assumed that the upgrade is undertaken at current time and not deferred until later. Future studies could use the proposed methodology to explore different timing and staging of retrofit along with consideration of other discount rates. Also assumed is that the house under consideration is a modern house and has not suffered any prior structural degradation. Three levels of upgrade were considered: roof space, intermediate and full. Roof space considered upgrading those connections in the roof space that were easily accessible. Intermediate upgrade additionally considered those connections at the top of walls and the roof structural members. Full upgrade considered all connections down to foundation level.

The results are presented in Table 3 showing the benefits versus costs for different levels of upgrade. The larger values represent the greater benefit for the cost of adaptation.

The economic advantage of carrying out the upgrade work as part of another contract when a house's roof is replaced can be clearly seen by the higher values in the right hand table. This is expected as the cost of building work necessary to provide access to connections for upgrade is paid for by another contract, namely that of replacing the roof.

The greatest cost benefit is realised for the tile roof house where the costs of undertaking the necessary upgrade work are smaller than for the sheet roof houses.

For a given house the greatest benefit-cost ratio is typically achieved for the roof space upgrade indicating that the extra cost of intermediate or full upgrades (that involve more invasive work on difficult to access elements of the house's structure) is not recovered by the incrementally lower level of vulnerability achieved.

Upgrade without roof replacement

House	Upgrade level	Benefit-cost ratio
N1/tile to N3/tile	Roof space	9.3
	Intermediate	6.9
	Full	4
N2/sheet to C2/sheet	Roof space	0.7
	Intermediate	0.5
	Full	0.5
N3/sheet to C2/sheet	Roof space	0.2
	Intermediate	0.2
	Full	0.2

Upgrade with roof replacement

House	Upgrade level	Benefit-cost ratio
N1/tile to N3/tile	Roof space	24
	Intermediate	12.1
	Full	5.2
N2/sheet to C2/sheet	Roof space	3.7
	Intermediate	1
	Full	0.7
N3/sheet to C2/sheet	Roof space	1.7
	Intermediate	0.5
	Full	0.4

Table 3. Tables of benefit-cost ratios

Note that the results presented here are based on increases in wind hazard that have been generated to demonstrate the methodology only. Furthermore, the vulnerability models used are first order with considerable scope for improvement. Nevertheless the annualised losses (presented in the technical report) appear to be quite high in dollar terms.

Typically the greatest contribution to the annualised loss is provided by the shorter return period winds. Even though they produce low levels of damage, wind speeds that recur frequently contribute the largest component to the total annualised loss.

A vulnerability curve represents the average damage incurred by a population of houses. Within that population there will be houses that have slight levels of damage (maybe below the excess) while others will have higher levels of damage. The use of vulnerability curves does not capture the beneficial effect of the fraction of the population that suffers damage that falls below the excess and thus overestimates the annualised loss. To explore this, a single house / upgrade / time slice instance was assessed using fragility curves rather than a vulnerability curve and the results assessed. Fragility curves show the proportions of the population of houses that fall into different damage states at each wind speed, i.e. what percentage of houses have no damage, what percentage are slightly damaged, etc.

The annualised loss was recomputed using the fragility curves with the results presented in Table 4 for the N1/tile house without upgrade at time slice 1, i.e. current wind hazard, and a $500 excess.

Comparison of predicted Annualised Losses for N1/tile roof base house at time slice 1	
Method used to assess Annualised Loss	Annualised Loss
Vulnerability Curve with no Excess Deduction	$1928
Fragility Curve with Excess Deduction	$300

Table 4. Results of comparison of methods for assessing annualised loss.

It is clear that the use of fragility curves has reduced the annualised loss to a more realistic level. However, it is to be remembered that the fragility curves used here have not been based on survey results or other quantitative basis other than they are broadly consistent with the vulnerability curve derived from the Phase 1 work. To be of broader use, fragility curves would be required for a range of houses and be produced by a quantitative process.

Summary

Structural adaptation strategies for buildings need to be developed on the basis of a quantitative understanding of changing wind hazard, current building vulnerability, time-dependent structural degradation and how vulnerability will be improved through retrofit options. This output of Schedule 6 has demonstrated how options for adaptation can be prioritised as to effectiveness based on engineering, quantity surveying and economic analysis techniques. The focus has been on the evaluation process rather than the actual numbers produced as the inputs have required significant assumptions. Notwithstanding this limitation, several observations can be made:-

1. The hazard level changes that were adopted for this demonstration were large. Severe hazard changes without adaptation result in significant increases in annualised loss and large benefits for adaptation costs. Emerging knowledge of how hazard likelihood will be affected by climate change can be seamlessly inserted into the methodology proposed and demonstrated.

2. The implementation of adaptation in conjunction with other maintenance related building activity markedly improves the effectiveness of the retrofit investment. In this work the high cost of gaining roof space access for structural upgrade of the roof system was avoided as the cost was already carried by the roof sheeting replacement works. This is a useful outcome for the development of adaptation strategies for high risk coastal communities.
3. Most wind related losses are due to roof damage and associated water ingress. More extensive structural damage is rare and results from more catastrophic wind events. This study has shown that the benefit-versus-cost of more extensive retrofits that affect more of the building structure are smaller. The improvements have less influence on the total annualised loss as they are associated with much rarer wind events.
4. Finally, the influence of insurance excesses as a transferral of risk from the insurance company to the policy holder had a great impact on the benefits due to adaptation. Using the fragility functions assumed for this study, the application of the insurance excess to the numerous lightly damaged building claims resulted in a marked reduction of annualised loss. Reduced benefits of adaptation to insurers is noted and this observation decreases the premium incentives that could be passed on to policy holders should they adapt.

Further study is recommended in the following areas:-

- Fundamentally the assessment of adaptation options requires a knowledge of how the vulnerability will change due to physical degradation with time and with a wide range of retrofit options. The stepped changes to the vulnerability curves assessed for this methodology demonstration may not be as great if the variability in the building population and wind effects is more rigorously considered. This needs to be enabled in a reliable quantitative way otherwise any economic analysis results will be a function of the assumptions made.
- Some structures under present climate have acceptably low likelihoods of damage. Other legacy structures already present unacceptable levels of risk to occupants and communities. These is a need to explore a broad range of retrofit approaches to both categories of structures including staging of improvements, the investment in retrofit ***options*** (in-building the opportunity to improve a structure at less cost in the future with greater initial cost of the initial building) for new construction (including what this means in physical terms) and the consideration of a range of discount rates.
- There is a need quantify ***all*** the benefits of adaptation. Injury related medical care emergency management costs need to be included as society meets these. Economic activity disruption also needs to be considered where the building houses business activity or indirectly the community damage affects labour supply and essential services. A more holistic quantification of benefits may also increase the contributions to annualised loss made by rare but credible storm events.
- The business behaviours of the insurance industry need to be studied more carefully in the context of an improved understanding of vulnerability and through direct engagement of key insurers. Using more reliable fragility relationships the effect of adaptation of insurance loss can be evaluated and the contributions that the industry can and cannot make to driving community

adaptation into the future be better understood. This knowledge is a fundamental component of what is needed for policy formulation.

Attachment A
DCC Schedule 6, Phase 3 Reporting
Demonstration of Cost-Benefit of Adaptation based on existing Heuristic Vulnerability Curves.

Technical Report

Aim

To demonstrate the methodology of assessing the cost-benefit of adapting houses to better resist wind hazard of increasing severity by use of heuristic vulnerability curves.

Introduction

The vulnerability of buildings to damage caused by severe wind is normally described by an S shaped curve relating the damage index (defined as repair cost / building replacement cost) to the 3 second gust wind speed at 10m height ($V_{10m,3sec}$) at the building's location. The curve is termed a vulnerability curve and has been described in [1] by an equation of the following form:

$$V_{10m,3\sec} = e^{\beta}\left(-\ln\left(1-DI\right)\right)^{\alpha} \qquad (1)$$

where DI is the damage index, α and β are parameters describing the curve's shape and position. Parameters for such curves were estimated for 203 different house types during phase 1 of the Schedule 6 work [1].

The general consensus is that the wind hazard in Australia will increase in severity due to climate change. This raises the question as to whether existing legacy housing should be structurally upgraded to better resist the increased wind speeds to which they are expected to be exposed. It is important to note that the forces acting on a house due to wind are proportional to the square of the wind speed. Thus even a 10% increase in maximum gust wind speed will cause a 21% increase in load on a building structure. This is a significant increase, particularly for older houses whose structure would not comply with current Building Code of Australia (BCA) requirements, i.e. they are not capable of resisting the maximum gust wind speeds currently specified for the design of residential structures.

A further aspect of wind hazard change is a potential change in wind environment; a cyclonic wind is a more severe hazard than a synoptic wind of the same speed due to the cyclic nature of the cyclonic wind repeatedly loading the house structure close to its capacity and thus fatiguing connections so that they fail at a load below their static strength. Thus if the wind hazard were to change from a synoptic wind to a cyclonic wind, the increase in vulnerability of a house with no retrofit, would be more severe than would be expected from just the increase in wind speed alone. This effect has been considered in the examples used to demonstrate the methodology.

The methodology set out below allows the benefits of adaptation to be assessed economically within the accuracies of the heuristic curves used to represent the vulnerability of particular types of houses. Currently the economic assessment only considers the cost of the house fabric. It does not consider the cost of damage to contents, hospitalisation of injured occupants, or down-stream effects such as absence of staff from the workplace due to loss of accommodation or injury. For the purposes of this study, cost benefit is defined as:

Sum (((Annualised loss (base house) – Annualised loss (upgraded house))* present value factor)/Upgrade cost

Methodology

The detailed methodology is set out below. Broadly, the process was to select three example house types, decide what modifications were required to adapt the structures to a more severe wind hazard, cost those modifications, and then assess the annualised losses before and after modification. The process was repeated at three time steps representing current climatic conditions, mid-century conditions and end of century conditions. Each time step involved an increase in wind hazard, a change of the dominant severe storm type and a loss of strength due to decay.

The magnitude of wind hazard was represented as a change in region (to AS 1170.2) and a change in wind speed multiplier. Note that this process is purely a construct to generate an increased wind hazard. Any increased wind hazard expressed as an increased probability for gust wind speeds could be chosen.

All three example houses were single storey with the same footprint but with different constructions as described below. A diagram of the house is given in Appendix 1. Timber framing was considered to be MGP10 which is commonly used in domestic construction in Australia apart from lintels which were considered to be F17 hardwood, consistent with common construction practice.

The detailed process is set out below.

1. <u>Select three house types</u>

The three house types chosen are as follows:

- A tiled roof brick veneer house constructed to the BCA for wind class N1 as defined in AS 4055 [2].
- A metal roof brick veneer house constructed to the BCA for wind class N2 as defined in AS 4055 [2].
- A metal roof brick veneer house constructed to the BCA for wind class N3 as defined in AS 4055 [2].

The first house (tile roof) was considered to be broadly representative of domestic housing in region A while the second and third houses (metal roof) were considered to be broadly representative of domestic housing in region B.

2. <u>Assign vulnerability curves to each type from existing suite of heuristic vulnerability curves</u>

This step necessitated a selection of representative house types for the base (no upgrade) houses listed above and also the upgraded house in each case, i.e. six curves in total. Curves were selected from the phase 1 work for the following houses.

- House 1 (N1 tile roof) upgraded to the N3 standard of construction
- House 2 (N2 metal roof) upgraded to the C2 standard of construction
- House 3 (N3 metal roof) upgraded to the C2 standard of construction

3. <u>Characterise each house type in terms of size, construction and replacement cost</u>

The characteristics of each house were determined as follows:

- Size: all three houses were taken to be the same size as described in Appendix 1.

- Construction: the size of all structural members and connections were taken from AS 1684.2 [3] and AS 1684.3 [4] and relevant supplements. The support and fixing requirements for roofing were taken from AS 2050 [5] for roof tiles and published recommendations from Lysaght [6] for metal deck roofing that was assumed to be Lysaght Custom Orb.
- Replacement costs were calculated from data in Rawlinsons Construction Cost Guide, 2009 [7] assuming that the houses were located in Brisbane.

4. <u>For each type of house, determine the scope of work for each level of upgrade</u>

Three levels of upgrade were identified for each house: roof space only, intermediate and full upgrade. Eleven critical members or connections were identified in the load path between roof and foundations, these are shown diagrammatically in Figure 3 and listed in the results in Appendix 2.

The eleven critical elements were divided amongst the levels of upgrade as follows:

- Roof space: A,B,C,E
- Intermediate: A,B,C,D,E,F
- Full upgrade: A to K

Full upgrade resulted in a house that was fully compliant with the BCA for the increased wind hazard.

The necessary work to upgrade each critical element to comply with current standards for the increased wind hazard was quantitatively identified for each house type. Refer to the table in Appendix 2.

5. <u>Cost each upgrade to each house</u>

For each of the eleven critical elements in each house type, the identified scope of work for upgrade was costed using costing data from [7]. The necessary building work to enable the upgrade work to be undertaken was included, e.g. removal and replacement of plasterboard for access to wall bracing. Two scenarios were considered: (a) the upgrade work was done in isolation, and (b) the upgrade work was done in conjunction with roof replacement undertaken for maintenance purposes. Scenario (b) typically reduced the building work cost as removal of the existing roof enabled ready access to many elements requiring upgrade. The costs for relevant critical element upgrade were summed to provide upgrade costs for each level of upgrade for each house for the two scenarios; 18 costs in total. Refer to the table in Appendix 2 for data.

6. <u>Generate vulnerability curves for all combinations of house type, upgrade level and time slice</u>

Vulnerability curves for different levels of upgrade were generated by the following process:

- Vulnerability curves for the base (no upgrade) house and full upgrade house were selected from the phase 1 work [1] as described in stage 2 above.
- The onset of damage is typically associated with the initial links in the load path (e.g. sheeting and purlin to rafter connections) failing. Hence, lesser levels of upgrade that address the strength of the initial links in the load path

tend to improve the lower part of the vulnerability curve while leaving the upper part unchanged. Data points on the vulnerability curve for roof space upgrade were taken as 1/3 of the distance between the base house vulnerability curve and the full upgrade vulnerability curve at 1% and 20% damage while the data point at 90% damage was taken as lying on the base house curve. A curve was then fitted to these three points to produce the roof space upgrade curve. Similarly, data points on the vulnerability curve for intermediate upgrade were taken as ½ of the distance between the base house vulnerability curve and the full upgrade vulnerability curve at 1% and 20% damage while the data point at 90% damage was taken as lying on the base house curve.

- The above process was repeated for each of the three house types.

Figure 4 shows this process in schematic form.

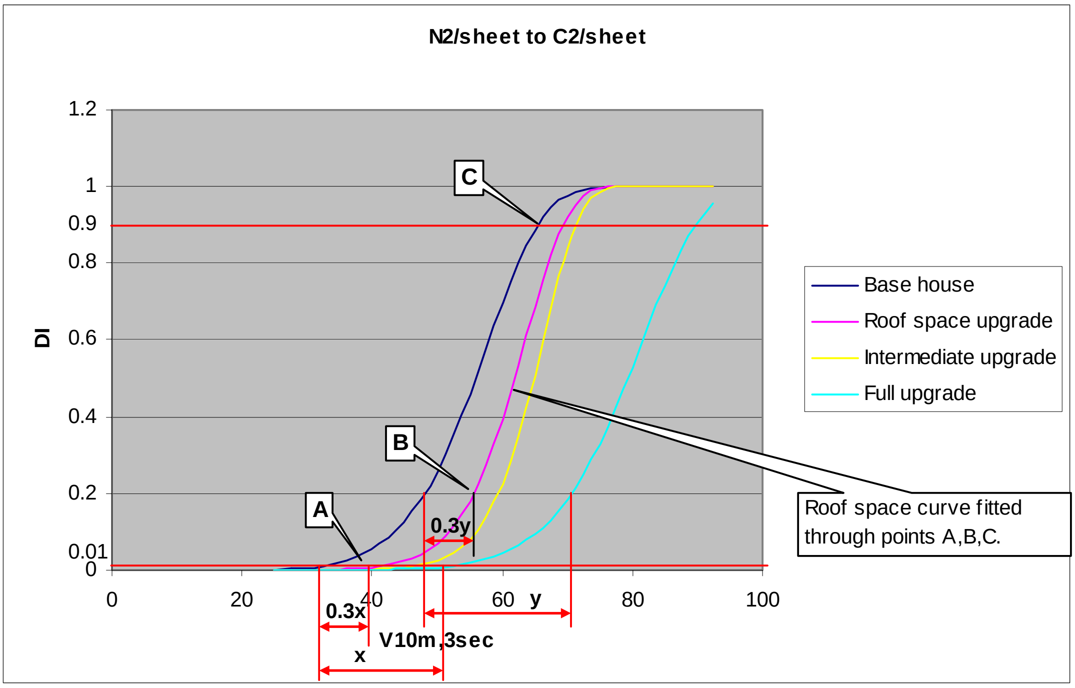


Figure 4. Method for producing vulnerability curves for roof space and intermediate levels of upgrade.

In order to be able to assess annualised loss for each instance it is necessary to develop a vulnerability curve for each combination of house type, level of upgrade and time slice (36 curves). The effect of time slice is threefold:

- If the wind environment changes to one of cyclonic wind conditions then, for a non-upgraded house, the effects of fatigue loading must be accounted for. Fatigue primarily affects the roofing screws where the thin metal roof sheeting fatigues and cracks around the screw heads. Calculations for the roof sheeting indicated that fatigue resulted in shifting the lower part of the vulnerability curve 22.5% to the left.

- If the wind environment changes to one of cyclonic wind conditions then there is an increased probability of internal pressurisation of the house due to a dominant opening forming in the windward wall due to either debris damage (e.g. shattered windows) or gross structural failure of windows due to wind pressure. AS4055 does not consider internal pressurisation for determination of wind loads for N class houses, but it does for C class houses. Calculations indicated that internal pressurisation resulted in shifting the vulnerability curve for an non-retrofitted house 25% to the left. Thus the effect of internal pressurisation masked the effect of fatigue.

- Increased house age means an increased likelihood of decay affecting the structural strength of members and connections due to rot of timber elements or corrosion of metal fasteners. While little data is available to quantify this effect, field surveys have noted that decay tends to affect the elements closest to the roof envelope such as roof, roofing screws, battens and their connections rather than elements lower down in the load path. Typically the design life for structures is 50 years however there are many examples of houses older than this figure suggesting that decay could be an important factor affecting the vulnerability of older houses. To account for this affect, vulnerability curves were skewed to the left by 20% at 1% damage for time slice 3 (lesser amounts for higher damage indices and time slice 2) while the upper part of the vulnerability curves were not moved for decay. This gave a good representation of decay affecting the elements higher up in the load path while lower elements were not affected.

Table 5 gives the factors used for modelling the above effects. Figure 5 shows a schematic of how vulnerability curves were adjusted using the factors in Table 5 to model the above effects.

Fatigue & Cpi factors

		Upgrade level			
House	Time slice	Base	Roofspace	Intermediate	Full
1	1	1	1	1	1
1	2	1	1	1	1
1	3	1	1	1	1
2	1	1	1	1	1
2	2	0.85	0.85	0.95	1
2	3	0.75	0.75	0.85	1
3	1	1	1	1	1
3	2	0.85	0.85	0.95	1
3	3	0.75	0.75	0.85	1

Decay factors

House	Time slice	V1 factor	V20 factor	V90 factor
1	1	1	1	1
1	2	0.9	0.922	1
1	3	0.8	0.844	1
2	1	1	1	1
2	2	0.9	0.922	1
2	3	0.8	0.844	1
3	1	1	1	1
3	2	0.9	0.922	1
3	3	0.8	0.844	1

Table 5. Factors used to model the effects of fatigue, internal pressurisation and decay on vulnerability curves.

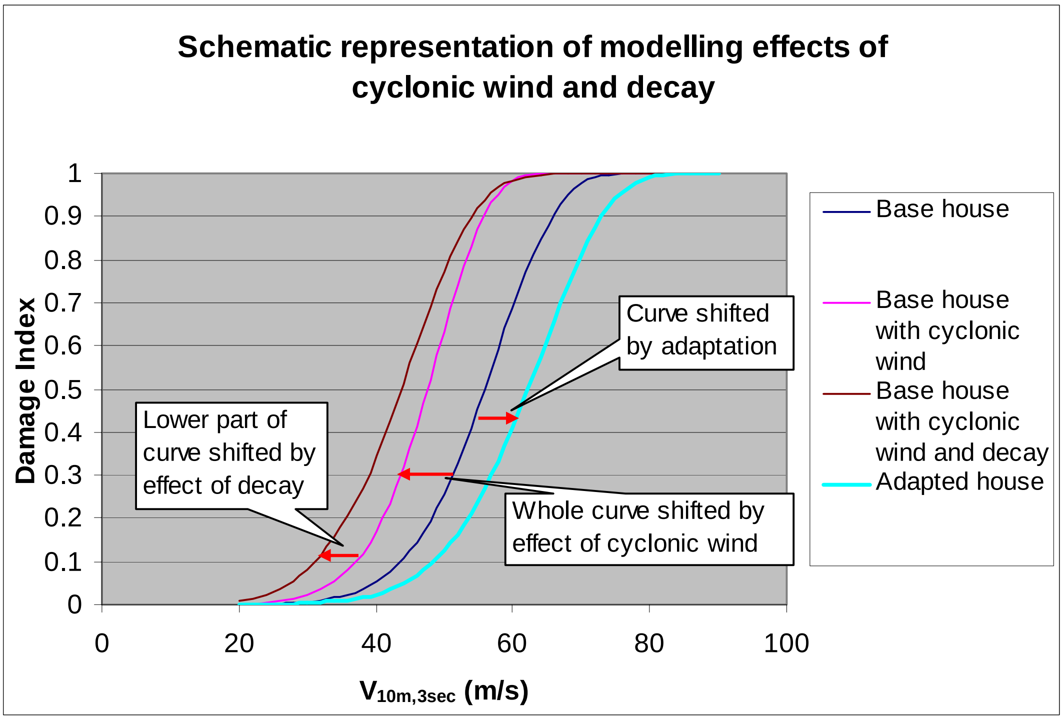


Figure 5. Method for modelling effects of cyclonic wind and decay.

Finally, the above effects, i.e. differing levels of upgrade, change in wind regime (fatigue and Cpi factors) and decay were combined to produce a vulnerability curve for each combination: 3 house types, 4 levels of upgrade (base house, roof space, intermediate and full), and three time slices producing 36 vulnerability curves. This was achieved by taking the vulnerability curve for each house type / upgrade level combination and applying the fatigue / Cpi factor and decay factor (relevant to the time slice being considered) to the wind speed at 1%, 20% and 90% damage to produce three new data points to which a curve was fitted to produce the appropriate vulnerability curve for the particular house type / upgrade level / time slice combination.

7. <u>Assign probabilities to each wind speed at each time scale</u>

In order to model the effect of changed wind hazard, it is necessary to quantify the increased probability of recurrence of a given wind speed. Furthermore, it is necessary to assign the probabilities of recurrence for the full range of wind speeds that a particular house is likely to experience. For the purposes of this exercise the change in wind hazard was represented as a change in wind region and / or a change in site factor (here taken as a single factor representing Mz,cat x Ms x Mh x Mt) in the notation of AS1170.2. Revised or updated return periods were calculated by the formulas given in Table 3.1 of AS1170.2 for the relevant region and probabilities of annual exceedance calculated as the inverse of the return periods. A range of regional wind speeds were considered from 20m/s to 90m/s. These were factored to a 3sec gust at 10m at the house site by a site factor relevant to the house type and time slice under consideration. Return periods for the local wind speed were then calculated using the relevant formula from AS 1170.2 table 3.1 for the appropriate region. Table 67 gives the factors used in the above calculations.

Site Factors

House Time slice	N1/tile to N3/tile Region A		N2/sheet to C2/sheet Region B to C		N3/sheet to C2/sheet Region B to C	
1	$V_{500,region}$=	45	$V_{500,region}$=	57	$V_{500,region}$=	57
2	$V_{500,region}$=	45	$V_{500,region}$=	63.2	$V_{500,region}$=	63.2
3	$V_{500,region}$=	45	$V_{500,region}$=	69.3	$V_{500,region}$=	69.3
Time slice	$V_{500(AS4055)}$	Site factor	$V_{500(AS4055)}$	Site factor	$V_{500(AS4055)}$	Site factor
1	34	0.755556	40	0.701754	50	0.877193
2	42	0.933333	50.5	0.799051	55.5	0.878165
3	50	1.111111	61	0.880231	61	0.880231

Wind return period parameters R=EXP((LN(Coeff2-(V/Coeff1))-LN(Coeff3))/-0.1)

House	Timeslice	Region	Combined	Coeff1	Coeff2	Coeff3
1	1	A	11	1	67	41
1	2	A	12	1	67	41
1	3	A	13	1	67	41
2	1	B	21	1	106	92
2	2	B/C	22	1.025	114	98
2	3	C	23	1.05	122	104
3	1	B	31	1	106	92
3	2	B/C	32	1.025	114	98
3	3	C	33	1.05	122	104

Table 6. Factors used to model change of wind hazard.

8. Calculate annualised loss

For each of the 36 combinations of house type, upgrade level and time slice the annualised loss is computed as the integral of the likelihood versus loss curve. Where the loss is equal to the damage index multiplied by replacement cost and the likelihood is the probability of recurrence for a given peak gust wind speed within one year.

9. Calculate benefit / cost ratio

For each of the 18 combinations of house type, upgrade level and whether the upgrade is undertaken in conjunction with a roof replacement contract, the benefit-cost ratio was computed over the next 100 years of hazard change and structural degradation.

10. Examine the effects of variation in damage within a population

Vulnerability curves represent the average damage across a population of similar buildings. The annualised losses calculated above assume each house with the population suffers the average damage. Within the population some individual houses will suffer less damage than the average while others will suffer more than the average. If the effects of an insurance excess is considered, utilising an average damage approach will overestimate the annualised loss as some of the houses within the population will suffer slight damage that is below the excess and hence have effectively zero damage. To investigate this effect, a single house / upgrade / time slice instance was assessed using fragility curves rather than a vulnerability curve and the results assessed. Fragility curves were derived from cumulative lognormal distribution curves for Slight, Moderate, Extensive and Complete damage with damage indices of 0.06, 0.3, 0.75 and 1.0 respectively. The fragility curves were generated to match as far as possible the vulnerability curve; that is, the sum of the (population fraction x damage level) as represented by the fragility curves should equate to the vulnerability curve. Equality was achieved within the lower half of the lower portion of the vulnerability curve but could not be achieved in the upper part of the curves as shown in Figures 6 and 7. However, as observed above, the upper portion of the vulnerability curve does not contribute as significantly to the annualised loss as the lower portion as the wind speeds at the upper portion have lower likelihood.

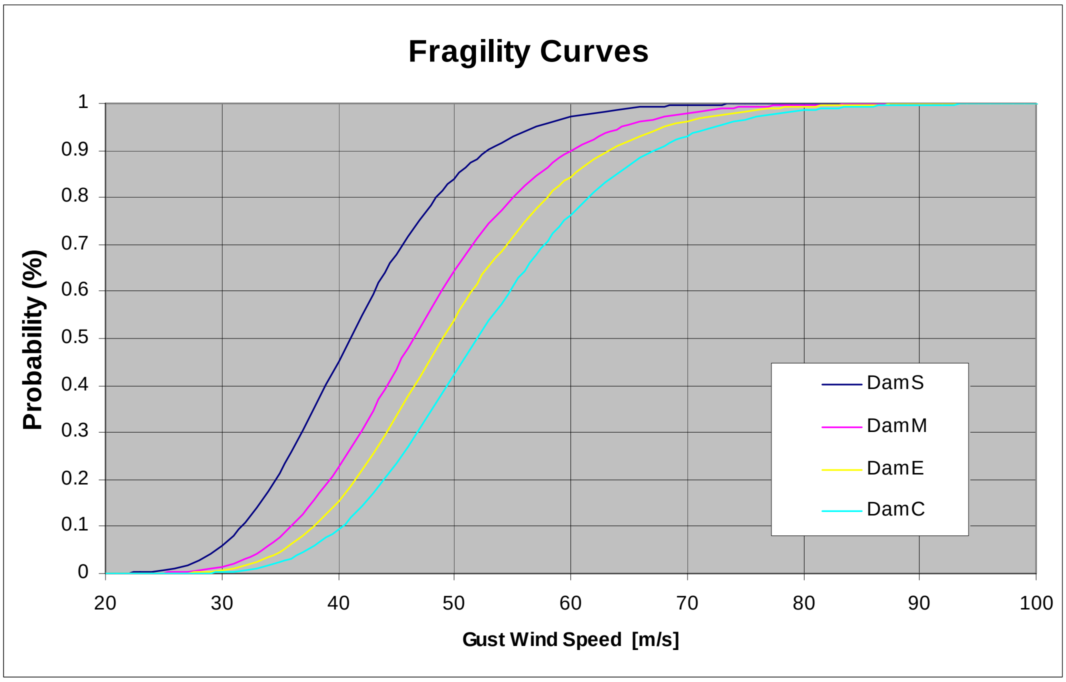


Figure 6. Fragility curves used for assessment of annualised loss.

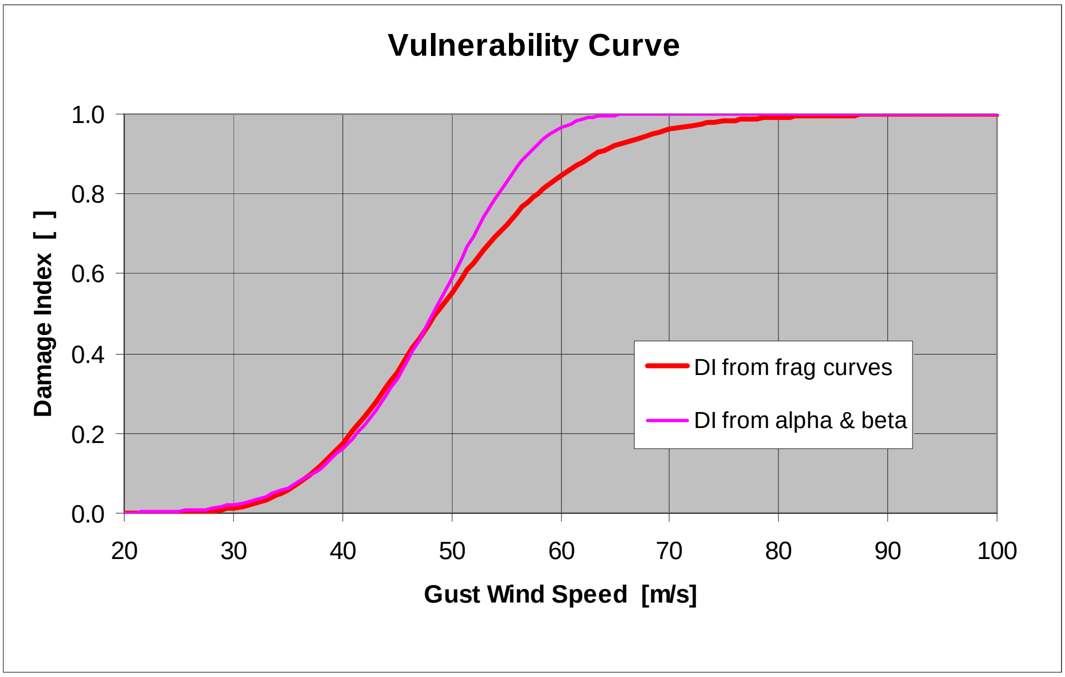


Figure 7. Comparison of vulnerability curves derived from fragility curves and from alpha and beta values.

Results

The detailed results are given in the appendices as summarised below.

Appendix 1: Plan of generic single story house

Appendix 2: Upgrade elemental costs

Appendix 3: Vulnerability curve parameters for all combinations of house type, upgrade level and time slice

Appendix 4: Annualised losses

Appendix 5: Annualised losses using fragility curves

Appendix 6: Benefit-cost ratios

Discussion

Consider the results given in Appendix 6 showing the benefit-cost ratios for different levels of upgrade. The larger values represent the greater benefit-cost ratio.

The economic advantage of carrying out the upgrade work as part of another contract when a house's roof is replaced can be clearly seen by the higher values in the right hand table. This is expected as the cost of the building work necessary to provide access to connections for upgrade is paid for by another contract, namely that of replacing the deteriorated roof.

The greatest benefit-cost ratio is realised well into the future where the greatest increase in wind hazard has occurred. Indeed, there is small benefit-cost ratio realised where a modern code compliant house is upgraded but only subjected to the current wind hazard, refer to the time slice 1 results.

For a given house and time slice the greatest benefit-cost ratio is typically achieved for the roof space upgrade indicating that the extra cost of intermediate or full upgrade (that involve more invasive work on difficult-to-access elements of the house's structure) is not recovered by the lower level of vulnerability achieved.

Note that the results presented here are based on increases in wind hazard that have been generated to demonstrate the methodology only. Nevertheless the annualised losses appear to be quite high in dollar terms. Typically the greatest contribution to the annualised loss is provided by the shorter return period winds, i.e. even though they produce low levels of damage, winds that recur frequently contribute the largest fraction to the annualised loss. This is not unexpected as a vulnerability curve represents the average damage incurred by a population of houses. Within that population there will be houses that have slight levels of damage (maybe below the excess) while others will have higher levels of damage. The use of vulnerability curves does not capture the beneficial effect of the fraction of the population that suffers damage below the excess and thus overestimates the annualised loss.

Consider the results shown in Appendix 5. It is clear that the use of fragility curves has reduced the annualised loss to a more realistic level. However it is to be remembered that the fragility curves used here have not been based on survey results or other quantitative basis other than they are broadly consistent with the vulnerability curve derived from the Phase 1 work. In the future fragility curves would be required for a range of houses and be produced by a quantitative process.

References

[1] Report to the Department of Climate Change on Schedule 6, Quarter 1, Development of a nationally consistent set of vulnerability curves for the Australian residential building stock, Geoscience Australia, 2010

[2] AS 4055 Wind loads for housing, Standards Australia, July 2008

[3] AS 1684.2 Residential timber-framed construction Part 2 Non-cyclonic areas, Standards Australia, Nov 2006

[4] AS 1684.3 Residential timber framed construction Part 3 cyclonic areas, Standards Australia, Nov 2006

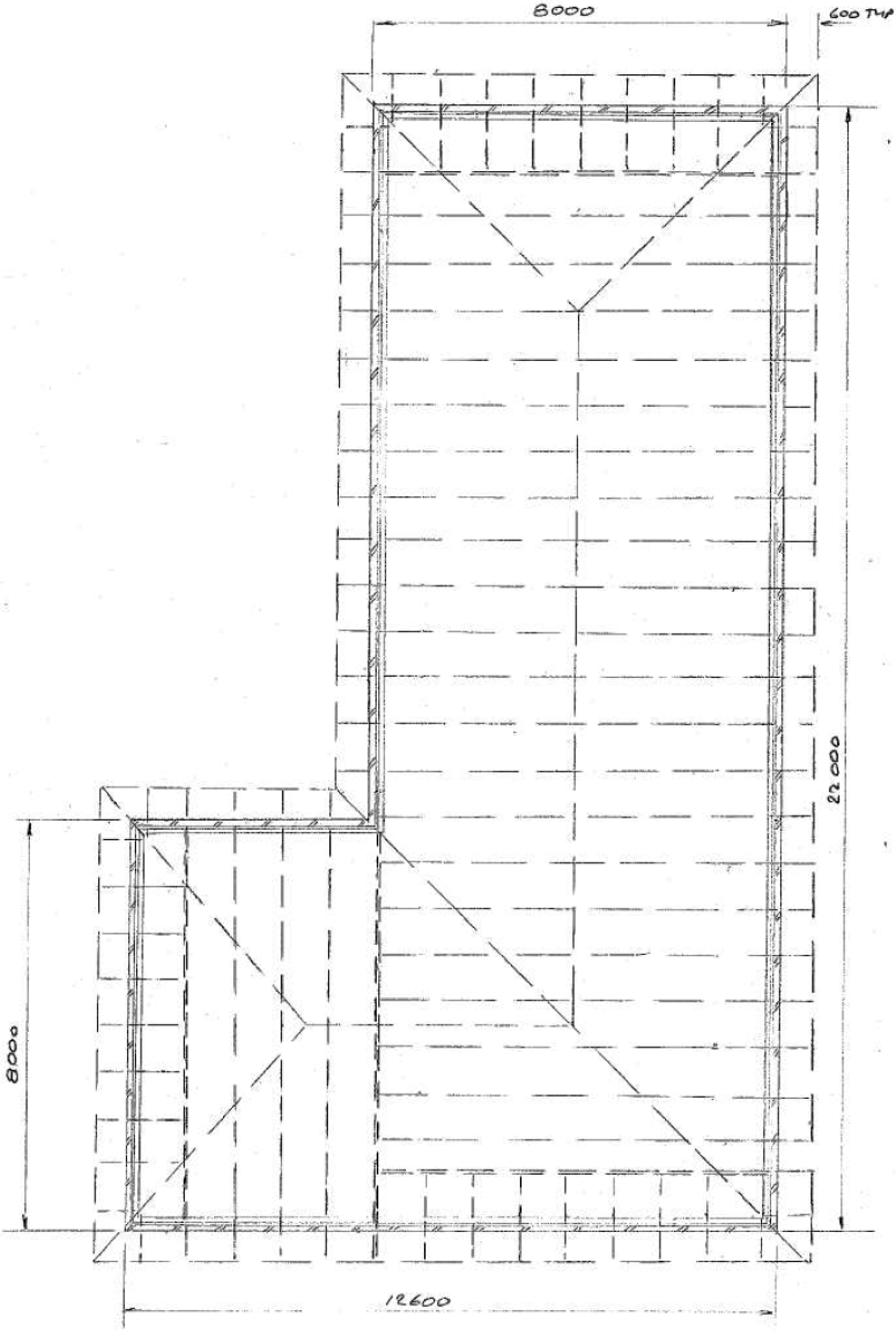
[5] AS 2050 Installation of roof tiles, Standards Australia, Dec 2005

[6] Using steel roofing and walling in cyclonic areas, Lysaght, May 2009

[7] Construction Cost Guide, Rawlinsons, 2009

Appendices

Appendix 1 Plan of generic single story house



Appendix 2 Upgrade elemental costs

Elemental costs

					New work BV / metal C2							New work BV / tile N3					Builder's work					
																	N2-C2/sheet		N3-C2/sheet		N1-N3/tile	
Element	Description	Extg BV / tile N1	Extg BV / metal N2	Extg BV / metal N3	Description	Work to upgrade from N2	Work to upgrade from N3	Upgrade cost from N2 extg roof	Upgrade cost from N2 new roof	Upgrade cost from N3 extg roof	Upgrade cost from N3 new roof	Description	Work to upgrade from N1	Upgrade cost with extg roof	Upgrade cost with new roof	Element	extg roof	new roof	extg roof	new roof	extg roof	new roof
A	Sheeting to batten / Tile to batten	Nail every second tile	3 screws per sheet	3 screws per sheet	5 larger screws per sheet with cyclone washers	Replace all screws with larger + washers + 2 extra per sheet	Replace all screws with larger + washers + 2 extra per sheet	7628	0	7628	0	Nail every second tile	Nil	0	0	A	2513	0	2513	0	0	0
									Incl in new roof		Incl in new roof											
B	Batten size	35 x 70 @ 330	45x 70 @ 900	45 x 70 @ 900	45 x 70 @ 450 ctrs in edge zone	2 extra rows of battens	2 extra rows of battens	1219	1219	1219	1219	35 x 70 @ 330	Nil	0	0	B	4437	0	4437	0	0	0
C	Batten to rafter	1/65 x 2.8 dia nail	2/75 x 3.75 dia def shank nails	1/Type 17 14-90 screw	1/Type 17 14-90 screw	Install screw at each connection	Nil	865	865	0	0	2/65x 2.8 dia nails	Extra nail at ecah connection	1007	1007	C	0	0	0	0	2009	0
																	Incl at B		Incl at B			
D	Bottom chord restraint	1 row per span	1 row per span	2 rows per span	3 rows per span	Add 2 rows of restraint	Add 1 row of restraint	1044	1044	522	522	1 row per span	Nil	0	0	D	0	0	0	0	0	0
																	Incl at B		Incl at B			
E	Truss to top plate	1 framing anchor per truss	2 framing anchors per truss	2/30 x 0.8 GI strap per truss	1/30 x 0.8 GI looped strap	Install looped strap per truss end	Install looped strap per truss end	1220	1220	1220	1220	2 framing anchors per truss	Install 2nd anchor	1188	1188	E	0	0	0	0	1452	0
																	Incl at B		Incl at B			
F	Top plate to stud	2/90 x 3.05 dia nails	30 x 0.8 GI strap @ 900 ctrs with 2/2.8 dia nails each end	30 x 0.8 GI strap @ 900 ctrs with 4/2.8 dia nails each end	M10 cyclone bolts @ 900 ctrs to foundation	Install cyclone bolts	Install cyclone bolts	3619	3619	3619	3619	2 framing anchors @ 900 ctrs	Install frmaing anchors	2377	2377	F	9657	9657	9657	9657	0	0
																					Incl at E	
G	Studs @ 450 ctrs size	70 x 35	70 x 35	70 x 35	70 x 45	Double every 3rd stud	Double every 3rd stud	935	935	935	935	70 x 35	Nil	0	0	G	0	0	0	0	0	0
																	Incl at F	Incl at F	Incl at F	Incl at F		
H	Bottom plate tie-down	Concrete nail	M8 chemical anchor	M8 chemical anchor	M10 cyclone bolt from eaves level	Install cyclone bolts	Install cyclone bolts	0	0	0	0	M8 chemical anchor	Install chemical anchors	867	867	H	0	0	0	0	3464	3464
								Incl in F	Incl in F	Incl in F	Incl at F						Incl at F	Incl at F	Incl at F	Incl at F		
I	In-plane roof bracing	1/ 30 x 0.8 GI strap set	1/ 30 x 0.8 GI strap set	1/ 30 x 0.8 GI strap set	2 / 30 x 0.8 GI strap set	Install extra set	Install extra set	794	794	794	794	1/ 30 x 0.8 GI strap set	Nil	0	0	I	0	0	0	0	0	0
																	Incl at B		Incl at B			
J	Racking walls bracing (m of ply bracing panel)	11.3	15.5	23.9	36.2	Add 20.7m of bracing	Add 12.3m of bracing	1306	1306	776	776	23.9	Add 8.4m of bracing	530	530	J	1064	1064	632	632	1519	1519
K	Lintel to 2.4m wide opening	2/170x45	170x35	170x35	170x45	Plate extg lintels with 19mm ply	Plate extg lintels with 19mm ply	1884	1884	1884	1884	2/170 x 45	Nil	0	0	K	1634	1634	1634	1634	0	0
					Roof space upgrade		A,B,C,E	10932	3304	10067	2439			2195	2195		6950	0	6950	0	3461	0
					Intermediate upgrade		A,B,C,D,E,F	15595	7967	14208	6580			4572	4572		16607	9657	16607	9657	3461	0
					Full upgrade		A to K	20514	12886	18597	10969			5969	5969		19305	12355	18873	11923	8444	4983

Total costs new work + builders work excl prelim

N2-C2/sheet		N3-C2/sheet		N1-N3/tile	
Extg roof	New roof	Extg roof	New roof	Extg roof	New roof
17882	3304	17017	2439	5656	2195
32202	17624	30815	16237	8033	4572
39819	25241	37470	22892	14413	10952

Appendix 3 Vulnerability curve parameters for all combinations of house type, upgrade level and time slice

Curve parameters alpha

			Upgrade level			
House	Timeslice	Combined	Base	Roofspace	Intermediate	Full
1	1	11	0.13721	0.103062733	0.086954	0.10663
1	2	12	0.15849	0.124342335	0.108234	0.12791
1	3	13	0.182151	0.148003385	0.131895	0.151571
2	1	21	0.13257	0.094691764	0.078018	0.10214
2	2	22	0.15385	0.115971367	0.099298	0.12342
2	3	23	0.177511	0.139632417	0.122959	0.147081
3	1	31	0.10663	0.091327672	0.084068	0.10214
3	2	32	0.12791	0.112607274	0.105348	0.12342
3	3	33	0.151571	0.136268324	0.129009	0.147081

Curve parameters beta

			Upgrade level			
House	Timeslice	Combined	Base	Roofspace	Intermediate	Full
1	1	11	3.92861	4.006413	4.057989	4.22856
1	2	12	3.895211	3.973014	4.024589	4.195160593
1	3	13	3.859035	3.936838	3.988414	4.158984995
2	1	21	4.07149	4.160565	4.201225	4.41193
2	2	22	3.875572	3.964647	4.116533	4.378530593
2	3	23	3.714233	3.803308	3.969131	4.342354995
3	1	31	4.22856	4.273072	4.294282	4.41193
3	2	32	4.032642	4.077153	4.209589	4.378530593
3	3	33	3.871303	3.915815	4.062188	4.342354995

Appendix 4 Annualised losses

House	Level of Upgrade	Time slice	Annualised loss ($)
N1/tile to N3/tile	Base	1	1928
		2	18815
		3	89507
	Roofspace	1	169
		2	1451
		3	34634
	Intermediate	1	27
		2	1394
		3	17352
	Full	1	27
		2	847
		3	9032
N2/sheet to C2/sheet	Base	1	271
		2	6784
		3	42167
	Roofspace	1	26
		2	2295
		3	23572
	Intermediate	1	6
		2	479
		3	8792
	Full	1	3
		2	115
		3	1260
N3/sheet to C2/sheet	Base	1	196
		2	3318
		3	18808
	Roofspace	1	71
		2	1902
		3	13341
	Intermediate	1	40
		2	569
		3	5437
	Full	1	29
		2	244
		3	1261

Appendix 5 Annualised losses using fragility curves

Comparison of predicted Annualised Losses for N1/tile roof base house at time slice 1	
Method used to assess Annualised Loss	Annualised Loss
Vulnerability Curve with no Excess Deduction	$1928
Fragility Curve with Excess Deduction	$300

Appendix 6 Benefit-cost ratios

Upgrade without roof replacement

House	Upgrade level	Benefit-cost ratio
N1/tile to N3/tile	Roof space	9.3
	Intermediate	6.9
	Full	4
N2/sheet to C2/sheet	Roof space	0.7
	Intermediate	0.5
	Full	0.5
N3/sheet to C2/sheet	Roof space	0.2
	Intermediate	0.2
	Full	0.2

Upgrade with roof replacement

House	Upgrade level	Benefit-cost ratio
N1/tile to N3/tile	Roof space	24
	Intermediate	12.1
	Full	5.2
N2/sheet to C2/sheet	Roof space	3.7
	Intermediate	1
	Full	0.7
N3/sheet to C2/sheet	Roof space	1.7
	Intermediate	0.5
	Full	0.4