Housing damage in windstorms and mitigation for Australia

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ABSTRACT: Windstorms cause most of the damage to housing in Australia. Population growth is exposing more people and buildings to risks from these wind hazards. Houses and components are currently designed and built to standards aligned with the Building Code of Australia. Regulatory measures including building inspections are meant to ensure acceptable quality of construction. Inspections and post windstorm damage surveys have consistently shown that contemporary houses (post 1980) perform better than older houses (pre 1980) in cyclone and non cyclone areas. However, errors in design and construction found during recent surveys, reduce the resilience of contemporary housing. Geoscience Australia is developing a software tool for assessing the vulnerability of housing, using empirical models, expert opinion, and engineering methods. These models could be used to assess vulnerability of a range of house types and also recommend adaptation measure to account for increases in the intensity of windstorms in Australia.

KEYWORDS: Cyclone, Windstorm, Vulnerability, Housing, Standards, Codes, Damage

1 INTRODUCTION

Windstorms are recognized as the natural hazard that causes most of the damage to buildings in Australia [1]. In addition to economic losses, these events also inflict a social cost on the community. Population growth is exposing more people and buildings to risks from these wind hazards. This risk is dependent on the frequency and intensity of windstorms, the number of buildings exposed and their vulnerability.

Houses and other buildings are currently designed and built to codes and standards aligned with the Building Code of Australia [2]. These are built to a nominal “lifespan” with a specified level of hazard, based on data available at that time. In many cases, wind load is the critical environmental design load and most buildings (including houses) are constructed to withstand a “500yr return period” ultimate limit state wind speed. Older houses were built with limited engineering input, during periods when the regulatory framework was less stringent. Such buildings could be highly susceptible to wind damage and hence are prime candidates for adaptation measures especially for climate change scenarios that predict increases in wind speed.

The vulnerability of buildings can be estimated using either an engineering method based on structural analysis, strength of materials and statistics, or empirical methods based on observed levels of damage for the type of building, obtained from damage survey data and full scale tests [3]. These damage assessments require information such as building type, structural system, method of construction and age. Findings from post windstorm damage surveys and full-scale house tests carried out by the Cyclone Testing Station (CTS) are used to assess and validate the vulnerability of a range of house types to windstorms. This data is also used for developing and revising codes and standards.

House frames are complex structures consisting of multiple building elements and connections that cannot be easily analyzed using simple structural analysis techniques. The roof of a house is generally subjected to the largest wind load and is most vulnerable to wind damage. Geoscience Australia (GA) in partnership with the CTS and JDH is developing a software tool able to estimate the vulnerability of buildings to wind damage using engineering models developed by the CTS for a range of house types. This software will be applied to a given population of buildings (i.e. house stock in a town) to assess their vulnerability, and also used to analyze effects of predicted changes in wind intensity or frequency, and to recommend adaptation strategies (i.e. building retrofit).

The CTS and GA have surveyed houses in many parts of Australia and also accessed the database of house types available from the Australian Bureau of Statistics. Furthermore, GA has developed a national definition of residential building categories as part of their National Exposure Information System [4]. The system included building attributes such as age, wall type and roof types which permit a mapping of wind vulnerability to buildings. The vulnerability of houses to windstorms is estimated by defining the structural components, and identifying critical connections and their strengths, for each house type. In addition, the wind loads on these components and their variability with increasing wind speeds are determined, and predictions of damage verified using house damage data. Results obtained from this analysis are applied to the mix of houses in a particular region (e.g. selected postcodes within a city) to estimate the extent of damage and also the type of damage for specified events. This analysis also accounts for the progressive damage to the housing stock with respect to the storm track. These results can be used by Emergency Services to assess the vulnerability of the housing stock to a range of predicted wind speed events (including those that may result from climate change) and determine effective adaptation strategies.

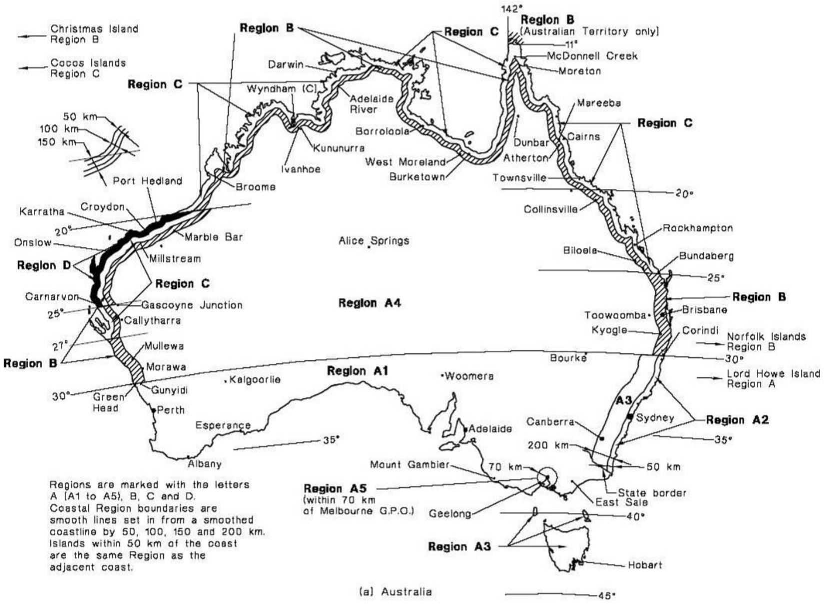
This paper presents a summary of work carried out in the area of wind and structural engineering in Australia, with the aim of mitigating wind related damage of domestic housing. Section 2 describes the wind climate and the types of windstorms that cause damage, Section 3 gives an overview codes and standards and the design philosophy. Section 4 reviews the vulnerability methods used by industry, Section 5 summarizes finding from recent damage surveys, and recommendations and conclusions are given in Section 6.

2 WIND CLIMATE AND WINDSTORMS

Windstorms can broadly be classified according to their meteorological parameters as, tropical cyclones, thunderstorms, tornados and gales. Thunderstorms and tornados are short-lived local events with their influence affecting distances of up to tens of kilometers. Cyclones generally impact coastal regions in the tropics, and extend hundreds of kilometers, therefore having the potential to cause the most damage.

Parts of Australia experience different types of windstorms and are characterized as either cyclonic or non-cyclonic wind regions in the wind load standard AS/NZS 1170.2 [5]. AS/NZS 1170.2 which excludes tornados from its scope of wind actions, classifies Australia into several regions, as shown in Figure 1, and provides data for calculating wind loads used in the design of structures (e.g. houses). The cyclonic regions are identified with increasing severity as C and D extending 50km inland along Australia’s western, northern and eastern tropical coastlines. Non cyclonic regions are classified as A1 to A5 and cover the southern parts and the interior of Australia. Decaying cyclone regions are classified as intermediate Region B.

Tropical cyclones develop over the warm oceans to Australia's north, during the summer months from November to April, and can generate destructive winds, heavy rain and flooding to many coastal areas in Western Australia, Northern Territory and Queensland, shown in Figure 2. Tropical cyclones in which winds rotate clockwise around a low pressure eye with a diameter generally of about 20-50 km, track overland at varying speeds, before decaying into a low-pressure system. The passage of a cyclone past a given location will generate increasing then decreasing winds along with changing wind directions, over a period of a number of hours. The impact of a cyclone is generally felt over an area of hundreds of square kms, over many days with the most destructive winds experienced just outside the eye. These destructive winds can cause extensive property damage and generate windborne debris. The Bureau of Meteorology categorizes cyclones with increasing severity from 1 to 5 according to the maximum expected wind speed and minimum central pressure, as shown in Table 1.



Regions are marked with the letters A (A1 to A5), B, C and D. Coastal Region boundaries are smooth lines set in from a smoothed coastline by 50, 100, 150 and 200 km. Islands within 50 km of the coast are the same Region as the adjacent coast.

(a) Australia

Figure 1. Wind Regions of Australia [5]

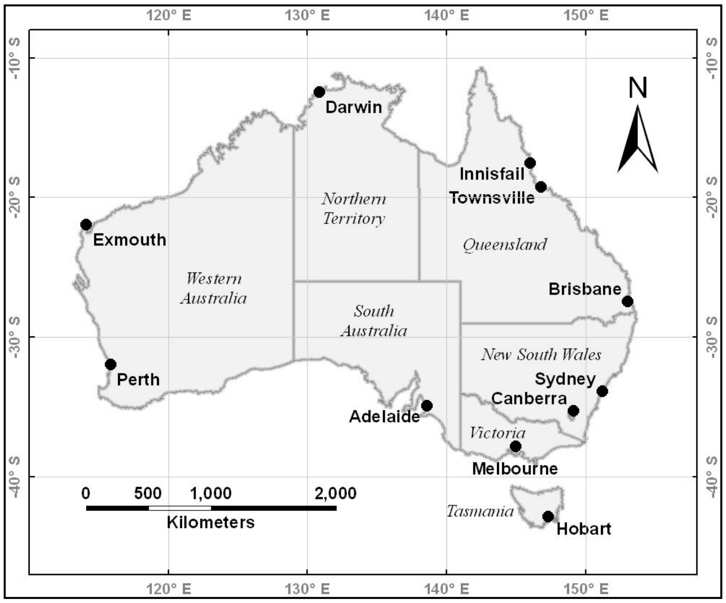


Figure 2. Map of Australia

Table 1. Bureau of Meteorology Cyclone Categories

Cyclone Category	Gust Wind Speed at 10 m height in flat open terrain			Central Pressure
	km/h	knots	m/s	hPa
1	90-125	49-68	25-35	990
2	125-164	68-89	35-46	970-985
3	165-224	89-121	46-62	950-965
4	225-279	121-151	62-78	930-945
5	>280	>151	>78	<925

Historical data on tropical cyclones show erratic tracks and varying rates of decay following landfall. However, there is a scarcity of wind speed measurements, as there have only been a small number of landfalling cyclones that have passed over meteorological stations. Therefore, probabilistic wind speed forecasts made from this limited data have a large level of uncertainty, which is accounted for by using factors when calculating design wind speeds in the wind loading standard AS/NZS 1170.2 [5]. Some analysis methods such as those used for future climate change predictions simulate many thousands of years of synthetic tropical cyclone events, based on the limited measurements from the Bureau of Meteorology.

Other types of windstorms that cause damage are thunderstorms, severe synoptic low-pressure systems, and tornadoes. Thunderstorms and tornadoes only affect a few square kilometers, while synoptic storms can cause damage over thousands of square kms. Thunderstorms are typically short lived (up to tens of minutes) and occur in all parts of Australia. Synoptic storms mostly affect the southern parts, and persist for days. Most thunderstorms occur during the warm summer months, whilst some thunderstorms in Western Australia, South Australia, Victoria and Tasmania are linked to cold fronts. Severe thunderstorms are most common in New South Wales, Queensland and parts of Western Australia, and least common in Tasmania. Synoptic low-pressure storms categorized as mid-latitude lows form in the westerly wind band over the Southern Ocean. These affect Tasmania and the southern parts of Western Australia, South Australia, Victoria and New South Wales. They occur mainly between winter and early summer and commonly produce gale force winds. East coast lows form along the east coast from southeast Queensland to Tasmania usually during autumn and winter. Decaying tropical cyclones can also impact non-cyclonic areas (Region A and B) and cause significant damage.

Some preliminary studies of the influence of climate change on tropical cyclones suggests increases in intensity and more southward tracks, but reduced occurrences. Other studies indicate negligible influence of climate change effects on cyclone behaviour and occurrence. The current state of knowledge in this area is discussed by McBride [6]. Large cities such as Brisbane, Gold Coast and Sunshine Coast in Queensland and Perth in Western Australia are located close to the cyclone regions, and there is a possibility that a tropical cyclone will impact these locations either directly or during transition to a low pressure system. Holmes [7] has reviewed papers on the effects of climate change to the wind climate, and the implications for the boundaries of cyclonic regions in Figure 1.

Current research suggests climate change may cause a decrease in severe thunderstorm risk for southern Australia, but a marked increase in thunderstorm risk for the east coast. The tracks of synoptic storms are projected to move southward, with fewer but possibly more intense systems occurring in southern Australia.

3 REGULATIONS, CODES AND STANDARDS

The Australian Federal government formulates national disaster management policies and provides states and territories with support during a natural disaster. State and territory governments are responsible for natural disaster management in their jurisdictions, including developing relevant policies, warning systems, awareness and education, and response and recovery. Local governments, in collaboration with State and Federal Government agencies, often lead the development of regional emergency management and disaster response plans. They also conduct community awareness and preparedness programs aimed at reducing the impacts of severe storms. Professional bodies, consultative groups such as the Queensland Tropical Cyclone Consultative Committee (QTCCC) and a range of industries provide advice on the management of natural hazards. The engineering profession plays a crucial part in mitigation, via Engineers Australia and Standards Australia. Research into natural hazards and their impact is undertaken at many universities. Consulting companies provide a range of services including developing risk assessments, and analyzing hazards and structural response.

State and territory governments are responsible for administering the planning laws and building regulations (formulated by the Australian Building Codes Board (ABCB)) to ensure that infrastructure and housing are built to an acceptable level of resistance to windstorms. State and territory governments, through the relevant emergency services agencies (e.g. EMQ), work closely with the community to develop plans to minimize impacts of windstorms. Northern Territory, Queensland and Western Australia state government departments conduct educational programs for builders and allied professionals on these issues.

Designers and builders are required to comply with the Building Codes of Australia provisions under the appropriate state or territory legislation. The Australian Building Codes Board sets the level of risk for building performance in the Building Code of Australia (BCA), with the primary objective of safeguarding people from injury arising from structural failures, and includes loss of amenity and the protection of property. The BCA [2] structural performance requirements specify that a building or structure, to the degree necessary, must resist the wind actions to which it may reasonably be subjected and remain stable and not collapse, prevent progressive collapse, minimize local damage and loss of amenity, and avoid causing damage to other properties.

The level of risk is evaluated depending on the location and type of structure. Most buildings including domestic housing are given an Importance Level 2 (as is specified in the Guide to the BCA). These buildings are designed to resist an ultimate limit state wind speed which has an annual probability of exceedence of 1:500. Importance Level 3 buildings that are designed to be occupied by a large number of people, and Importance Level 4 buildings or structures that are essential to post disaster recovery or associated with hazardous facilities are designed to resist an ultimate limit state wind speed which has an annual probability of exceedence of 1:1,000 and 1:2,000, respectively. The Queensland government guidelines require that cyclone shelter buildings should be designed to resist an ultimate limit state wind speed which has an annual probability of exceedence of 1:10,000.

Standards Australia produces relevant design standards, such as the suite of ASNZS 1170 loading standards. AS/NZS 1170.0 [8] stipulates combinations of loads including wind actions to be applied on structural system components that are checked against their design strength. Failure occurs when the combined load exceeds the component's strength. Structures designed according to AS/NZS 1170.0 should have a very small probability of failure (i.e. < 0.001 or as a percentage, < 0.1 %) at ultimate limit state loads, that is, failures of structural elements would not be expected to occur at the ultimate limit state design load. However, some component damage is expected at wind speeds close to the design loads. The wind load standard AS/NZS 1170.2 [5] is the primary standard referenced in the BCA that provides design wind speeds for each wind region of Australia. The standard, 10 m height gust wind speed (V_R) as defined in AS/NZS 1170.2, for a 1:500 probability in cyclonic region C and D are 69 and 88m/s m/s, respectively. The corresponding design wind speeds in Regions B and A1-A5 are 57 and 45 m/s, respectively. These wind speeds have a nominal probability of exceedence of about 10% in 50 yrs. In most cyclone and non cyclone regions, the determination of wind loads for housing is carried out using the standard on wind loading for residential housing, AS 4055 [9]. This standard and other related standards for building components, such as; the timber framing manual AS 1684 [10], windows AS 2047 [11], and garage doors AS 4505 [12] etc that reference the standard AS/NZS 1170.2, are used by engineers and builders for designing appropriate components and connections in a house.

Criteria adopted in structural design standards used in Australia, are related to a specified limit state, such as the ultimate limit state of component or structural failure. The basic framework for probability based, limit state design is provided by reliability theory described by Ellingwood et al [13]. In this approach, the loads and resistances are taken as random variables and the required statistical information is assumed to be available. Pham et al [14], Holmes [15], Pham [16], Leicester et al [17] and Melchers [18], used this probabilistic approach, to formulate the limit state design standards currently used in Australia. AS/NZS 1170.0 provides calibrated combinations of factored, permanent (dead), imposed (live) and wind actions (loads) to be applied on structural components and checked against their factored resistances. Component failures take place when its strength, is exceeded by the load. Statistical parameters are used to account for the uncertainty and variability associated with loads and component strengths. Data on loads and component strengths are required in order to calculate the risk of component failure or reliability.

Wind load effects for the design of components of buildings are based on pressures derived from Equation 1, using nominal pressure coefficients, provided in AS/NZS 1170.2. Here ρ is the density of air, V_h is the design gust wind speed at mid-roof height and C_{fig} is the aerodynamic shape factor. Quasi-steady external and internal pressure coefficients combined with factors are used to determine C_{fig} values for internal and external pressures. External and internal design pressures acting over the tributary area are combined to get the nominal, net design wind load, W_N from which the wind load effect is calculated. The nominal, design gust wind speed at 10m elevation in terrain category 2 approach, is modified by wind direction, terrain/height, shielding and topography multipliers to calculate V_h.

$$p_{design} = 0.5\rho V_h^2 C_{fig} \tag{1}$$

4 HOUSING VULNERABILITY

The vulnerability of a community to windstorms is dependent on the exposure of houses, infrastructure and services. In this paper, only the vulnerability of domestic houses is examined, acknowledging that other services and infrastructure are also at risk, in windstorms. Townships comprise a range of house types, with differences in shape, size, cladding type, window size, roof shape and slope, materials, method of construction, and age. Each of these features influence the vulnerability of a house to wind damage. Houses also have varying degrees of exposure to wind, with those located in a suburban environment sheltered by surrounding structures as opposed to more exposed houses near the sea or open terrain. Topographic features such as hills can also speed-up or slow-down the wind flow. Housing vulnerability to wind is significantly influenced by the regulations in force at the time of construction. Cyclone regions have experienced the introduction of more stringent regulations in house design since the 1980s that have led to significant reductions of wind vulnerability. The regulatory changes have been more varied across non-cyclonic regions and therefore the changes to house vulnerability in these areas are also more variable. The age of a house could be used to identify regulations that are likely to have influenced its construction, as well as other factors such as the likely deterioration of materials. The classification of houses into pre and post 1980 relates to the introduction of revised engineering deemed-to-comply provisions in Appendix 4 of the Queensland Home Building Code [19].

The insurance industry in Australia is involved in the development of models for assessing building vulnerability to windstorms. For a chosen wind speed, these models simulate the pattern of wind damage, in terms of the cost of repairing or replacing the damaged building. A review of the current state of vulnerability modeling by Walker [20], describes the evolution of techniques since the 1970s and the present state of capabilities. Most of the models used in the insurance industry are proprietary, empirical models, based on fitting curves to data on damage, in the form of damage loss ratio versus the wind speed. In general, buildings are classified according to classes commonly used in the insurance industry which may include age, type of building, the form of structure and type of material, with separate models for each. This approach was used by Walker [21] to develop vulnerability models for houses built before 1980 and after 1980, in northern Australia. Empirical models are modified based as much on expert opinion as statistical analysis to accommodate significant changes that are made to house construction standards or when data is not available. A typical approach is to assume the shape of vulnerability curves for buildings of similar types, and validate these using available loss data or engineering judgment. As damage data at the higher wind speeds is often unavailable, considerable amount of expert opinion is needed to generate these curves. Henderson and Harper [22] produced vulnerability curves for a range of house types in cyclone regions of Queensland using a similar approach.

There is less data on the vulnerability of houses exposed to windstorms outside cyclonic regions. Geoscience Australia facilitated a series of wind vulnerability expert workshops to consolidate available information. These workshops served to categorize the Australian residential building stock as presented in Table 2 based on the wind region, the building age, the local wind hazard category from AS 4055 [8] (for modern construction only) and the building envelope materials. Out of session, the same expert group was engaged in a relative ranking exercise using the reference curves in Figure 3 which were derived from earlier workshop activity. The overall ranking of vulnerability, expressed as a relative positioning to the curves in Figure 3, is also presented in Table 2. In order to be used reliably, these heuristic models based on expert opinion need to be validated with reliable data. The insurance industry has commented that the present ranking over-predicts wind vulnerability as they understand it. Some validation can be made by application of engineering analysis and testing. Further improvements are made from engineering models that are being produced as part of the software tool being developed by GA.

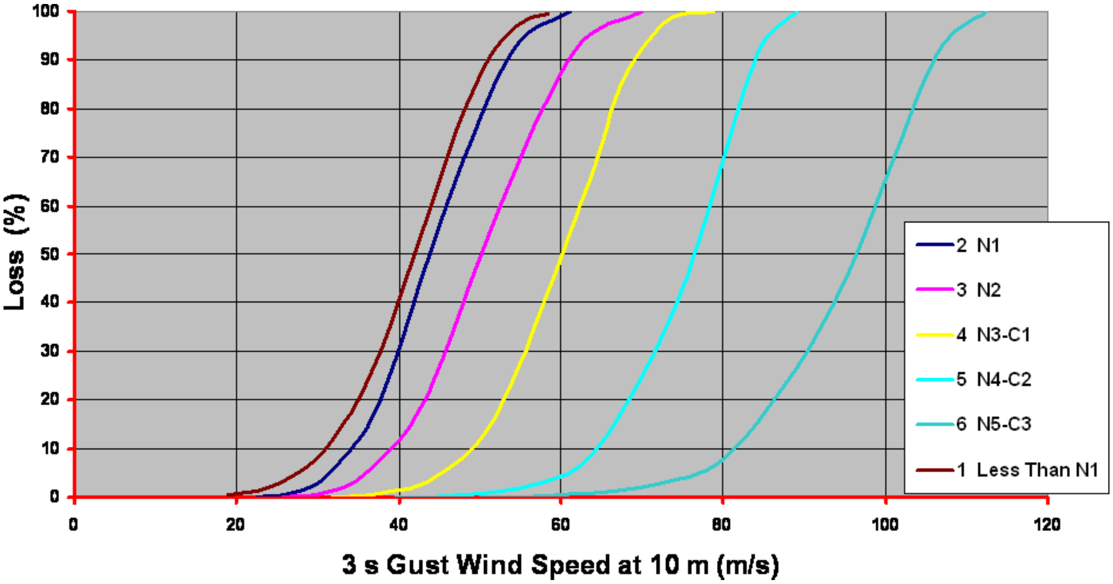


Figure 3. Reference curves for heuristic ranking process by expert group engaged through workshop activity

Table 2. Categorization of residential building stock derived from expert workshop consultation. (Values presented are the draft lower bound relative ranking of wind vulnerability based on the reference curves in Figure 3 and expert consensus)

Jursidiction and Wind Region	Age	AS 4055 Classification	Roof	Wall Material					
				Brick Veneer	*Reinforced Masonry*	*Cavity Double Brick*	*Timber or Metal Clad*	*Fibre Cement Clad*	*Solid Brick and Stone*
Queensland, WA and Northern Territory Regions C and D	1980 to Present	C1	Sheet Metal	4.0	4.2	N/A	4.0	N/A	N/A
			Tile	4.2	4.2	N/A	4.2	N/A	N/A
		C2	Sheet Metal	4.5	4.9	N/A	4.5	N/A	N/A
			Tile	4.4	4.7	N/A	4.4	N/A	N/A
		C3	Sheet Metal	5.1	5.2	N/A	5.2	N/A	N/A
			Tile	4.9	5.1	N/A	5.0	N/A	N/A
		C4	Sheet Metal	5.4	5.7	N/A	5.6	N/A	N/A
			Tile	5.2	5.2	N/A	5.2	N/A	N/A
	1960 to 1979	N/A	Sheet Metal	3.1	3.4	2.9	3.1	2.9	N/A
			Tile or Slate	3.0	3.3	2.8	3.0	2.8	N/A
			Fibre Cement	2.9	3.2	2.7	2.9	2.7	N/A
	1946 to 1959	N/A	Sheet Metal	3.3	N/A	2.9	3.2	2.8	N/A
			Tile or Slate	3.2	N/A	2.8	3.0	2.8	N/A
			Fibre Cement	3.0	N/A	2.8	3.0	2.7	N/A
	1914 to 1945	N/A	Sheet Metal	N/A	N/A	3.0	3.1	2.8	N/A
			Tile or Slate	N/A	N/A	2.7	2.8	2.7	N/A
			Fibre Cement	N/A	N/A	2.5	2.8	2.7	N/A
	1891 to 1913	N/A	Sheet Metal	N/A	N/A	N/A	3.0	N/A	2.7
			Tile or Slate	N/A	N/A	N/A	2.3	N/A	2.3
	1840 to 1890	N/A	Sheet Metal	N/A	N/A	N/A	2.8	N/A	2.5
			Tile or Slate	N/A	N/A	N/A	2.3	N/A	2.3
Queensland Region B	1996 to Present	N2	Sheet Metal	3.1	3.3	2.9	3.1	3.1	N/A
			Tile	3.0	3.1	2.8	3.0	3.0	N/A
		N3	Sheet Metal	3.7	4.0	3.6	3.7	3.7	N/A
			Tile	3.6	3.9	3.4	3.6	3.6	N/A
		N4	Sheet Metal	4.6	4.7	4.4	4.6	4.6	N/A
			Tile	4.0	4.4	3.9	4.0	4.0	N/A
		N5	Sheet Metal	5.2	5.4	4.9	5.2	5.1	N/A
			Tile	4.7	4.9	4.4	4.7	4.7	N/A
Queensland Region B	1980 to 1995	N/A	Sheet Metal	3.2	3.5	3.1	3.2	3.1	N/A
			Tile or Slate	3.1	3.3	3.1	3.1	3.0	N/A
All Other States, Terroritories Age Groups and Wind Regions	1996 to Present	N1	Sheet Metal	2.0	2.0	2.0	2.0	1.9	N/A
			Tile	1.9	2.0	1.9	2.0	1.7	N/A
		N2	Sheet Metal	2.6	2.6	2.5	2.6	2.3	N/A
			Tile	2.6	2.5	2.6	2.6	2.3	N/A
		N3	Sheet Metal	3.4	3.4	3.3	3.4	3.2	N/A
			Tile	3.2	3.1	3.2	3.2	2.9	N/A
		N4	Sheet Metal	4.2	4.5	4.3	4.5	4.3	N/A
			Tile	4.0	4.0	4.0	4.0	3.7	N/A
	1980 to 1995	N/A	Sheet Metal	2.4	2.2	2.3	2.2	2.0	N/A
			Tile or Slate	2.0	2.0	2.0	1.9	1.8	N/A
	1960 to 1979	N/A	Sheet Metal	1.8	1.7	1.7	1.8	1.5	N/A
			Tile or Slate	1.8	1.7	1.8	1.7	1.6	N/A
			Fibre Cement	1.5	1.4	1.4	1.5	1.4	N/A
	1914 to 1959	N/A	Sheet Metal	1.6	N/A	1.5	1.4	1.3	N/A
			Tile or Slate	1.5	N/A	1.4	1.5	1.2	N/A
			Fibre Cement	1.2	N/A	1.1	1.2	1.1	N/A
	1891 to 1913	N/A	Sheet Metal	N/A	N/A	N/A	1.5	N/A	1.5
			Tile or Slate	N/A	N/A	N/A	1.5	N/A	1.5
	1840 to 1890	N/A	Sheet Metal	N/A	N/A	N/A	1.5	N/A	1.5
			Tile or Slate	N/A	N/A	N/A	1.5	N/A	1.5

4.1 *Engineering models – Probability of failure*

Engineering vulnerability models estimate the damage caused by wind loads of varying intensity by applying mechanics of materials and structural engineering techniques. This requires reliable estimates of spatial and temporal variations in wind loads on a building and the structural (including all component and connection) responses. Knowledge of the possible modes of failure, including effects such as component fatigue, and the redistribution of forces as a result of component failures, is also required. These models are based on reliability analysis where the loads and component capacities are given in probabilistic terms.

In practice, engineering based vulnerability models use a combination of engineering and expert opinion. This approach has been used by Henderson and Ginger [23] to develop a vulnerability model for a typical northern Australian house built prior to the adoption of current building standards. They modeled both the probability of damage occurring from different modes of failure as the wind speed increased and the probabilities of various levels of damage occurring at different wind speeds as a result of progressive failure, including the effect of debris damage and consequent internal pressurization. Good agreement was obtained with recorded information from damage surveys undertaken following major tropical cyclones which have impacted this form of housing in northern Australia.

In this approach the wind load, effect W acting on components is given by the probabilistic model in Equation 2, where V is the maximum gust velocity at 10m height in terrain category 2 in 50 yrs (lifetime) and the parameter B includes all the other parameters (including the tributary areas, pressure coefficients, factors accounting for surrounding terrain, topography and shielding and uncertainties in analysis methods) of the wind load effect. Pham et al [14] and Holmes [15] used a similar model to describe the wind load component in the limit state design approach used in developing AS/NZS 1170.2. The nominal values of these parameters (obtained from codes etc) are combined to give B_N which is used to deduce the nominal design wind load effect, W_N from Equation 3, where V_N is the ultimate limit state design wind speed.

$$W = B\,V^2 \tag{2}$$

$$W_N = B_N\,V_N^{\,2} \tag{3}$$

Probabilistic descriptions of each of the variables contained in B deduced from surveys and other studies are applied to obtain a probability distribution of the random variable B. In these assumptions, values in AS/NZS 1170.2 are generally considered conservative, on average, especially when calculating design wind load effects on the primary structure. However pressures on small tributary areas near windward roof edges can be underestimated and shielding benefits over-estimated on parts of the roof, by codes.

The probability of failure of a component, as a result of its strength being exceeded by the wind load, can be obtained by comparing the wind load W with corresponding resistance R. The wind load W and resistance R are represented by random variables with probability density functions $f_W(W)$ and $f_R(R)$, with means μ_W and μ_R, as shown in Figure 4. Failure occurs when the wind load exceeds the resistance of the component. Hence, the aim of design is to ensure that the likelihood of $R < W$ is very small for the life of the component. Therefore, the reliability can be measured in terms of the probability, P $[R > W]$.

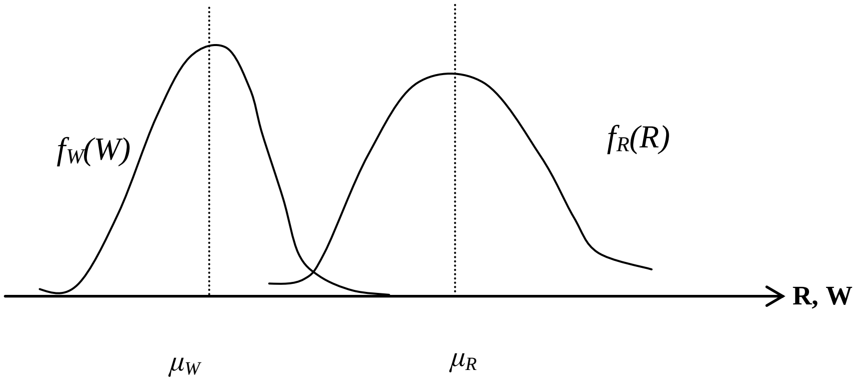


Figure 4. Probability distributions for wind load *W* and component resistance *R*

Assuming that *W* and *R* are statistically independent, the probability of failure is given by Equation 4.

$$p_f = \int_{-\infty}^{\infty} F_R(W) f_W(W) dW \tag{4}$$

where, $F_R(R)$ is the cumulative probability distribution, such that $F_R(W) = \int_{-\infty}^{W} f_R(R) dR$

The probability of failure of each of the components of the house and progressive failures were determined by combinations of experimental testing of populations of components, examination of full scale testing, engineering analysis and detailed statistical observations following damage surveys. Wehner et al [24] describe the alpha version of a software tool being developed by Geoscience Australia for assessing the vulnerability of buildings in Australia.

The creation of a dominant opening during a windstorm by the failure of a window or door can significantly increase the internal pressures thereby often increasing the probabilities of failure of the affected components. Such scenarios add to the uncertainty in the estimation of wind loads on individual components for a given incident wind speed. Failure of individual components leads to a redistribution of forces which further increases uncertainty and affects the sequence of progressive failure. Windborne debris, which can consist of items such as tree branches or elements from damaged upwind buildings, can also contribute to the vulnerability. Furthermore, the damage to components such as garage doors, facias and guttering etc is independent of structural design wind speed, as was observed in Cyclone Larry [25].

Unanwa et al [26] also used probabilistic methods including modeling the consequence of the failure of one component on the probabilities of failure of other components. They outlined a method for establishing a fully probabilistic engineering based vulnerability model for a building using fault trees to link possible modes of failure and their interaction with each other. They assumed wind loads were deterministic and given by formulas in a code. Similar methods were used by Pinelli et al [27] to develop vulnerability estimates for the Florida Public Hurricane Loss Model, and calibrate against recorded loss data, from hurricane damage in Florida.

The development of a comprehensive engineering based wind vulnerability models is restricted by the availability of adequate knowledge on the structural behaviour of building systems under wind loads, including both component behaviour and the consequential structural behaviour following failure of individual components. Further complications arise because small variations in component details can significantly change structural response, especially in domestic houses, and as damage to the structure could also change the pressure distributions acting on the house.

The development of performance based design of structures has resulted in a number of recent studies focusing on the vulnerability of structural systems under wind loads. Many of these such as those by Ellingwood et al [28], Rosowski and Ellingwood [29], Henderson and Ginger [23] and Jayasinghe and Ginger [30] are analyzing the behaviour of critical components and their connections and on the integration of this information to model the vulnerability of sub-systems such as the roof.

5 DAMAGE INVESTIGATIONS

This section summarizes the findings from some recent damage investigations carried out by the CTS, and highlights recurring issues that arise with respect to performances of houses and the provisions in the BCA and relevant Standards. Tropical cyclones Althea and Tracy impacted the Northern Australian towns of Townsville in 1971 and Darwin in 1974, respectively. These events, especially Tropical Cyclone Tracy caused significant damage to domestic housing as detailed by JCU [31], Walker [32] and Leicester and Reardon [33]. As a consequence, regulations were introduced to improve design and construction of housing to be able to withstand cyclonic wind loads.

Evidence of the resulting improvements to housing standards is found from the comparatively better performance of newer construction in recent windstorms. However, shortcomings in some aspects of design and construction mean that there is still a risk to contemporary housing, including those in non-cyclonic regions. A significant proportion of roller doors in newer buildings failed under wind loads resulting in dominant openings. Wind damage was more widespread among buildings that were built prior to the release of the Queensland Home Building Code Appendix 4. In many cases, these buildings had been refurbished since the 1980s, but structural details remained the same. Guidance for reconstruction is available from publications such as HB132.2 Structural upgrading of older houses - Part 2: Cyclone areas [34].

- Tropical Cyclone Winifred [35]

Tropical Cyclone Winifred crossed North Queensland coast near Innisfail (Region C) on 1 February 1986. It was the most damaging cyclone in Queensland since cyclone Althea. Wind gusts in the order of 30 m/s or more were experienced over a front of about 150 km between Cairns and Cardwell. The maximum wind gust speeds were estimated to have been in the order of 50 m/s. Damage to buildings was generally less than original estimates, and houses built to new regulations suffered little damage. Older buildings often had roofing removed frequently with battens still attached.

- Tropical Cyclone Vance [36]

Tropical cyclone Vance hit the small Western Australian township of Exmouth (Region D) on 22 March 1999. The Bureau of Meteorology designated Vance a category 5 cyclone, and it recorded a gust wind speed of 267 km/h (74 m/s) at Learmoth Airport 35 km south of Exmouth. The wind speeds impacting the buildings in Exmouth were estimated to range between 55 and 69 m/s. About 70% of the houses had virtually no damage. Transportable houses performed poorly. The newer houses performed better than the average. However, water ingress caused significant damage to contents even in houses that did not suffer structural damage.

- Tropical Cyclone Ingrid [37]

During March 2005, Cyclone Ingrid travelled across parts of Queensland, the Northern Territory and Western Australia (Region C) before degenerating into a rain depression. The Bureau of Meteorology classified this cyclone as varying in intensity between Category 3 and Category 5 during its erratic path across the three states. Cyclone Ingrid mostly tracked across sparsely populated areas and so the potential for damage to housing and infrastructure was limited. The damage survey focusing on the small Minjilang community of about 300 residents found that gust wind speeds were about 200 to 250 km/h (55-70 m/s). Most houses resisted wind forces, and failures that were observed, were attributed to inadequate, missing or corroded structural components. However, there was extensive tree and vegetation damage.

- Tropical Cyclone Larry [25]

Tropical Cyclone Larry made landfall on 20 March 2006 near Innisfail in North Queensland (Region C) causing significant damage to buildings in the surrounding areas. A survey of nearly 3000 houses, conducted by the Cyclone Testing Station and Geoscience Australia enabled quantification of the housing stock and the extent and types of damage sustained. The peak gust wind speeds in the study area were estimated at 50 to 65 m/s. Damage to the housing stock was estimated at about 20% (excluding water ingress). Contemporary housing fared considerably better than older housing, reflecting marked improvement of construction detailing and better structural condition, and satisfactory performance of relevant standards. Failure of roller doors, loss of roof battens when fastened to rafters with one or two nails and loss of rafters or trusses when anchored to top plates with skew nails only, were common. Houses on or near hill-tops that that did not have fixings to account for higher wind speed caused by topography had significant damage. Debris impact caused damage, whilst some window and door fixings failed under wind load. Structural component failures of under-designed cold formed steel sheds and garages were also widespread. Tropical Cyclone Larry was a fast moving event, hence, minimizing the potential for fatigue failure of metal cladding, debris impact as well as reducing the period in which rain was being driven into buildings.

- Tropical Cyclone George [38]

Tropical Cyclone George crossed the Pilbara coast east of Port Hedland in WA (Region D) on 8 March 2007. The period of high winds lasted for four to five hours. Estimates of the maximum gust wind speed were up to 270 kph (~75 m/s). Fewer than 2% of buildings sustained structural damage. The worst structural damage observed was loss of the roof in older buildings. Structural damage was caused by deterioration of older structural elements, inappropriate re-roofing practices, not following current practice for this area, failure of non-structural elements such as flashings and trims. Most buildings constructed to current codes and standards performed well though there were some concerns about light gauge metal trusses and battens.

- Tropical Cyclone Ului [39]

Tropical Cyclone Ului travelled across the islands of the Whitsunday group, including Hamilton Island and crossed the coast in the early hours of 21 March 2010 with its eye passing over Proserpine in Queensland (Region C). The peak gust wind speeds in the coastal regions surveyed were estimated to be in the order of 140 to 160 km/h (~45 m/s). There was minimal structural damage, and in the few cases where structural failures were caused by wind loading, the damage was attributed to inadequate, missing or corroded structural components. Wide spread tree and vegetation damage (i.e. fallen trees) led to some structural damage. There were many instances of failures of ancillary elements such as flashings, guttering, advertising signage, shade-cloth and vents.

- Dubbo Thunderstorm [40]

A damage investigation was conducted by AGSO and CTS in the Eastern suburbs of Dubbo (Region A) following a thunderstorm on 6 January 2001. The peak gust wind speed was estimated to be about 40 m/s, and there was significant damage to residential and commercial structures due to the wind load, debris impact, heavy rain and hail. The survey of housing, showed that approximately 5% suffered structural damage, mostly to tiled roofs from wind loads and debris impact, compared to the more extensive damage suffered by commercial and industrial buildings. Most of this damage was instigated by the failure of windows or doors generating large internal pressures. The poor performance of engineered construction is attributed to application of low internal design pressure based on the assumption that the buildings would remain nominally sealed.

- Perth Storm [41]

Outer suburbs of Perth in WA (Region A) experienced tornadoes from two separate events in June 2008. Both tornadoes damaged buildings and vegetation. Although tornadoes are not covered in AS/NZS1170.2, the estimated wind speeds generated by the tornadoes were similar to or less than the design wind speed for all affected houses. Deficiencies in structural capacity were noted in the batten to rafter connections, rafter to top plate connections, roof structure connections, top plate to masonry connections and verandah details. This investigation also showed that some houses were given incorrect site wind classifications. Even short duration wind events such as tornadoes generate wind borne debris. Some of this debris was instrumental in causing internal pressurization, which in turn lead to significant structural damage. In other cases, failure of doors and windows lead to internal pressurization.

- Brisbane Storms [42]

The Bureau of Meteorology recorded a significant level of storm activity in the South-East part of Queensland (Region B) during the period 16 to 20 November 2008. These storms caused damage to housing in many parts of Brisbane, where the peak gust wind speeds were estimated to about 45 m/s. Street surveys performed on a sample of houses in The Gap (suburb of Brisbane) indicated that Post 1980 houses performed better than Pre 1980 houses. The most common types of damage observed was caused by falling trees, and water ingress, either through failed doors or windows, or by differential pressure across doors or windows that had not failed, or through intact unsarked tiled roofs. Structural failures resulted from inadequate tie-down, wind borne debris breaking windward windows or doors causing an increase in internal pressure, sometimes leading to more damage, some cases of windows or doors not being adequately fixed to their supporting structural members and allowing the complete door or window to fail.

5.1 *Lessons learnt*

Findings from these damage surveys have provided data on the structural performance of a range of house types in various cyclonic and non-cyclonic parts of Australia. A summary of these findings are; overall, contemporary houses performed well in resisting the wind loads (for wind speeds that were less than the regions design wind speed). Generally, these newer buildings had damage mainly to roller doors and attachments such as guttering, facias etc. There was extensive water ingress in both damaged and "undamaged" buildings. Where structural failures were observed on contemporary houses, they were associated with poor construction practice or application of incorrect site classification (i.e. low design wind speed), breaches in the building envelope (from failed doors or windows, or debris impact) exacerbated the potential for failure from the resulting high internal pressure. Corrosion or rot of connections and framing elements initiated failures. The damage surveys showed that the majority of contemporary houses remained structurally sound protecting their occupants, thereby meeting the life safety objective of the BCA. However, these buildings were subjected to water ingress resulting in a loss of amenity, in addition to failures of elements (i.e. doors, fascias, guttering, etc) with the potential to impact other buildings, thus failing to meet some performance requirements of the BCA.

- Design Issues

Further investigations and recent design detail audits of low-rise houses have shown errors by designers when selecting parameters, from AS/NZS 1170.2 and AS 4055. These errors have included the use of low design site wind speed, local pressure factors on the roof and internal pressure coefficient. The underestimation of these design parameters results in the use of components and connections of inadequate strength to withstand the design wind loads and consequently an increased vulnerability.

Internal pressurization of the building can occur from failure of an element (door, window, soffit, etc) from direct wind pressure or from wind borne debris impact. The damage investigations revealed that; (a) some elements (roller doors, awnings, etc) did not have an adequate wind load rating and therefore did not conform to the relevant standard, and (b) in some cases the debris impact load was significantly higher than test criteria that are specified in the AS/NZS 1170.2. The wind resistance of buildings could be improved significantly by applying design internal pressures resulting from a dominant opening.

- Construction Issues

Inspections of houses under construction in both cyclonic and non-cyclonic regions have revealed common construction faults that can significantly reduce the capacity of structural elements, leading to the failure of the structure. Typical faults were missing framing anchors, misalignment of truss cleats, minimal fixings for windows and incorrect truss spacings and poor fixing installations. Design standards and manufacturers data do not account for these types of faults and poor construction practices. This is a reason for higher than expected failures of contemporary construction. A missing or poorly installed fastener can result in the failure of significant portions of a building, as adjacent fixings are overloaded and can fail in a cascading manner.

- Water Ingress – Loss of Amenity

Water ingress can cause damage to internal linings, resulting in costly repairs, potential long term durability concerns and mould growth, in addition to the loss of amenity. Water ingress and associated damage to "non-structural" components of the house can be expected when heavy rain occurs with wind speeds greater than about 30 m/s. This damage will arise from the ingress of wind driven rain-water caused by a pressure difference across the envelope (i.e. net positive pressure across the roof and wall), and also from the envelope being damaged by flying debris or failure of soffits, gutters and fascias.

The pressure developed across the building envelope during windstorms frequently exceed the serviceability test pressures specified in AS 2047 for window resistance to water ingress. Therefore if a severe storm event is accompanied by rain, water ingress can be expected. The only means of minimizing water ingress is by incorporating adequate seals for all windows, vents, doors, flashings, etc. However, this solution may be untenable, partly because of the prohibitive cost and the impracticality of completely sealing the envelope. Resilience of the building could however be improved by a combination of (a) reducing water ingress by complying with a higher serviceability test pressure, (b) using water resistant internal linings and (c) occupant education to the likelihood that wind driven rain will enter the house.

5.2 *Recommendations*

Post windstorm damage surveys have shown that houses designed and built to the revised standards since the 1980s, perform better structurally than houses built prior to that. These studies have also indicated that the current suite of loading, design and construction standards are effective without being overly conservative. However, there were examples of houses designed and built that did not conform to the relevant standards, because of the;

- Use of unconservative design parameters, such as not accounting for high internal pressure caused by a dominant opening, or use of incorrect wind speed up or shielding multipliers.
- Poor or faulty construction practices such as unattached or missing fasteners, overdriven nails, component or connection spacings in excess of specified minimum distances.
- Inappropriate use of materials for durability requirements (corrosion, rot, etc), and
- Use of products that have not been designed, tested or installed for appropriate wind region (unrated roller doors and awnings, cladding and battens that have not been fatigue tested).

Education and awareness of the consequences of making unconservative design assumptions, and of faulty construction (e.g. damage to property and risk to life) is required in every step of the building process (regulation, design, construction, certification and maintenance) and by all parties (designer, builder, certifier, and owner).

Education and awareness is needed in the areas of;

- Correct interpretation of BCA provisions and application of design standards,
- Testing and certifying building materials, connections, etc to the relevant standards,
- Diligent construction practices, and correct application of materials and components as per manufacturer’s instructions,
- Appropriate inspection and certification at time of construction, and
- Ongoing inspections and maintenance for serviceable life of building.

6 CONCLUSIONS

Windstorms cause most of the damage to housing in Australia. Population growth is exposing more houses to risks from these wind hazards. Houses are currently designed and built to AS4055 aligned with the BCA. In many cases, domestic houses are designed to withstand a 500yr return period ultimate limit state wind speed. Regulatory measures including building inspections are meant to ensure acceptable quality of construction. Inspections and post windstorm damage surveys have consistently shown that contemporary house perform better than older (pre 1980) houses in cyclone and non cyclone areas. However, errors in design and construction as documented following surveys, reduce the resilience of recently built housing. The vulnerability of housing is assessed using empirical models developed by the insurance industry, expert opinion, engineering models and approaches incorporating all of these. Climate change effects may result in changes to the intensity and the frequency of windstorms in Australia, possibly requiring the revision of wind regions in AS/NZS1170.2.

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