Role of building codes and construction standards in windstorm disaster mitigation

David Henderson and John Ginger from James Cook University, examine the role of Australia's building code and construction standards in a number of windstorm disaster mitigation situations.

Abstract

It seems the incidence of severe weather resulting in damage to buildings and infrastructure — causing distress and hardship to communities — is on the increase. Is this reported damage indicating deficiencies in Australia's building standards?

Recent damage surveys have shown that the majority of contemporary structures remained structurally sound protecting their occupants, thereby meeting the life safety objective of the Building Code of Australia. However, there were examples of houses designed and built that did not conform to the relevant standards, because of the use of incorrect design parameters, poor construction practices, and inappropriate materials. It is recommended that continuing education is required in all steps of the building process.

Introduction

Tropical Cyclone Larry crossed the North Queensland coast in the early morning of Monday 20th March 2006, causing severe damage to buildings, agriculture, and infrastructure for power, communications and services in the Innisfail region (Figure 1). Wind damage extended well into the Atherton Tablelands and flooding was reported in the Innisfail area, the Tablelands and into the Gulf country.

The cyclone caused significant community disruption within the affected area. Lifelines (e.g. power, phones, and roads) were severely disrupted. It took weeks to restore communications and power, with some properties un-connected for months. The repair of houses has continued into its second year.

The Australian Building Codes Board (ABCB) sets the societal risk for the performance of buildings, in the Building Code of Australia (BCA-2007), with the objectives of safeguarding people from injury arising from structural failures, loss of amenity and protecting property. This paper discusses wind loading on buildings, the BCA's structural provisions, and assesses these with observed damage to low-rise structures in windstorms.

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Figure 1: Damage in Mourilyan from TC Larry.

The Building Code of Australia

The BCA's (2007) 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,
- Minimise local damage and loss of amenity, and
- Avoid causing damage to other properties.

The Australian Building Codes Board sets the societal risk for the ultimate limit state strength of a structure, in the Building Code of Australia (BCA, 2007). The level of risk is evaluated depending on the location and type of structure as shown in Table 1. For example, a hospital has a higher level of importance (Level 4) that an isolated farm shed (Level 1). From Table 1, the design level for housing (Importance level 2 as noted in the Guide to the BCA 2007) is to be a minimum annual probability of exceedance of 1:500. The Wind loads for housing standard (AS-4055, 2006) derives its wind loads for housing based on housing being Level 2 importance.

Accordingly, a house is required withstand its ultimate limit state design wind speeds thereby protecting its occupants. For cyclonic region C (Figure 2) as defined in AS/NZS 1170.2-2002, the regional 10 m height 3 second gust wind speed (VR) for a 1:500 probability is 69 m/s, a mid-range Category 4 cyclone. This wind speed has a nominal probability of exceedance of about 10% in 50 yrs.

AS/NZS 1170.0:2002 provides designers with load combinations including wind actions to be applied on structural components and checked against their design strength. Failure occurs when the combined load exceeds the component's strength. Structures designed according to AS/NZS 1170.0:2002 should have a negligible 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.

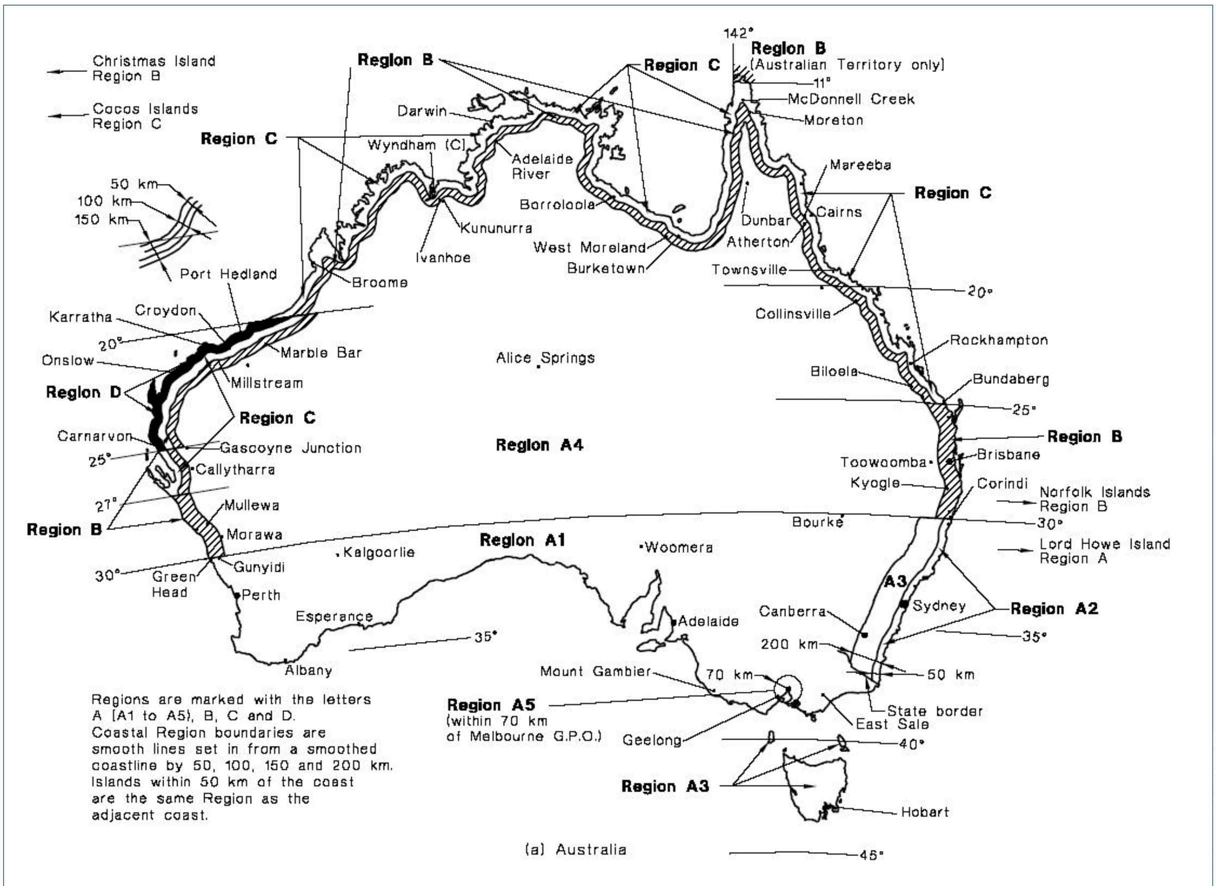

Figure 2: Wind Regions of Australia (AS/NZS-1170.2, 2002)

Wind regions for design

Windstorms can broadly be classified according to their meteorological parameters as: tropical cyclones, thunderstorms, tornados, monsoons and gales. Different parts of the world are influenced by these various types of storms. Cyclones generally impact on coastal regions in the tropics, and extend hundreds of kilometres and therefore have the potential to cause the most damage. Thunderstorms and tornados are much more local, with their influence affecting distances of up to 10's of kilometres. A tornado impacting on a community in Australia is a relatively rare occurrence, compared to that of the US. Nevertheless, tornadoes can generate extremely high wind speeds and cause extensive destruction in local areas. For more detailed information on the different types of windstorms see texts such as Crowder (1995) and Holmes (2001).

These variations in weather systems are accounted for in the Australian and New Zealand Standard for structural design wind actions, AS/NZS 1170.2:2002, which divides Australia into several regions, as shown in Figure 2. Wind loads used in the design of structures (e.g. houses, shops, large storage sheds, 4 to 5 storey apartments, etc) are calculated from the data specified in AS/NZS 1170.2 which excludes tornados from its scope of wind actions.

Wind loads

The design wind speed, for a particular site must take account of factors that can either increase or decrease the local wind speed (i.e. building height, topography, shielding from other structures, suburban terrain, etc). As the pressure experienced on a structure is proportional to the wind speed squared, a small increase in wind speed gives a much larger increase in load. Therefore a building on a hill-top location, that is designed without proper consideration for the increase in wind speed over the hill, is at an increased the risk of failure.

Figure 3 is a representation of the pressures acting on a simple structure showing the high suction pressures at the leading edge of the roof. If there is a breach in the building envelope on a windward face such as from a broken window or failed door, the interior of the house is suddenly pressurised. These internal pressures act together with the external suction pressures significantly increasing the load on the cladding and structure. Depending on the geometry of the building, the increase in internal pressure caused by this opening can double the load on the structure, thereby increasing the risk of failure especially if the building has not designed for a dominant opening.

Damage from recent events

Significant damage to buildings and other structures has been reported following the impacts of cyclones and thunderstorms in recent years. This section will detail the findings from some recent investigations, to highlight recurring themes that are used for assessing the provisions in the BCA and relevant Standards.

Tropical Cyclone Larry

The CTS conducted a detailed study of the performance of buildings in the Innisfail region and relevant codes and standards following the category 4 Tropical Cyclone Larry (Henderson et al., 2006). The study estimated that peak gust wind speeds that impacted on the region were in the order of 50 to 60 m/s (referenced to 10 m height in open terrain), as shown in Figure 4, which is less than the region's ultimate limit state design wind speed of 69 m/s.

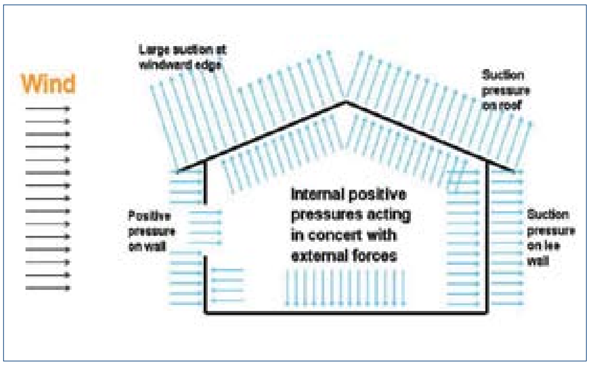

Figure 3: Wind forces with a dominant opening in windward wall

An external survey of nearly 3000 houses, was conducted by the Cyclone Testing Station and Geoscience Australia in order to obtain an overview of the extent of the damage to housing. The survey enabled quantification of the housing stock and the types of damage sustained, in terms of the damage classes and the percentage of damage as shown in Figure 5. The classification of houses into pre and post 1985 relates to the introduction of revised engineering deemed to comply provisions in Appendix 4 of the Queensland Home Building Code (1981).

Most of the contemporary houses (post 85) were slab-on-ground houses, with reinforced masonry walls. Figure 5 shows contemporary housing suffered less structural damage than pre-1985 housing as a result of the improvements specified in the revised standards.

Figure 5 shows about 5% of post-85 houses suffered failures from wind loading (Damage Class 3-7). These failures were generally caused by under strength connections details resulting from incorrect AS4055 site classification (e.g. building a C1 house on a C3 site), the use of inappropriate building materials, errors in construction or poor maintenance. There were examples of structural damage to contemporary elevated houses shown in Figure 6 which is attributed to their hill-top locations which experience higher wind loads than the structural detailing catered for. Many adequately designed contemporary houses which were subjected to higher wind speeds due to topography had minimal damage.

An external damage survey of commercial and industrial sheds showed that approximately 30% of these "engineered" buildings suffered damage ranging from loss of cladding through to complete collapse. This amount of damage is concerning, especially as these failures took

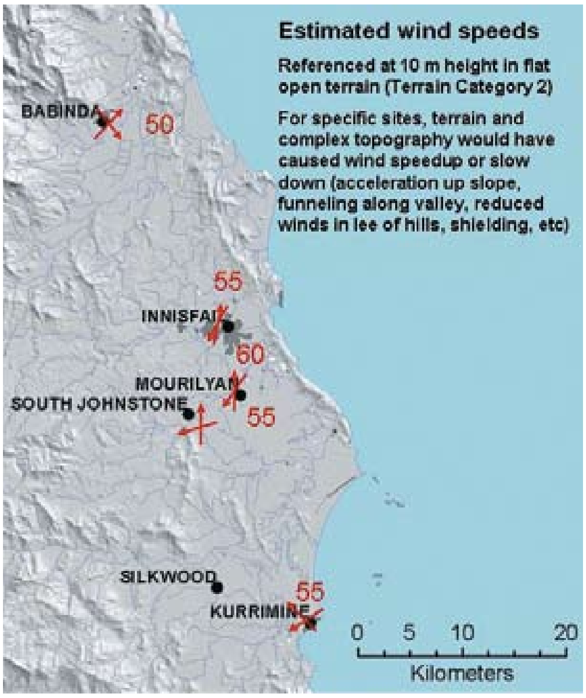

Figure 4: Estimates of wind speed in flat open terrain (Henderson et al., 2006)

place at wind speeds significantly lower than the design value, exceeding the level of failures acceptable according to the BCA and relevant Standards. Of the buildings that had roller doors, 60% had failed doors, often causing additional internal damage and in some cases leading to structural failures. The major structural failures were mainly in the thin cold formed steel frame sheds (Figure 7). The heavier hot-rolled steel framed sheds performed better, notwithstanding the failure of the roller doors, or failures due to corrosion of elements.

Cyclonic wind induced fatigue of metal cladding and battens can greatly reduce the material's strength eventually leading to its failure. The reduction in capacity which can be as much as half of the static strength was documented following Cyclone Tracy (Walker, 1975). Since then, the various Codes and Standards have prescribed fatigue load criteria in order to evaluate products that are used in cyclonic regions.

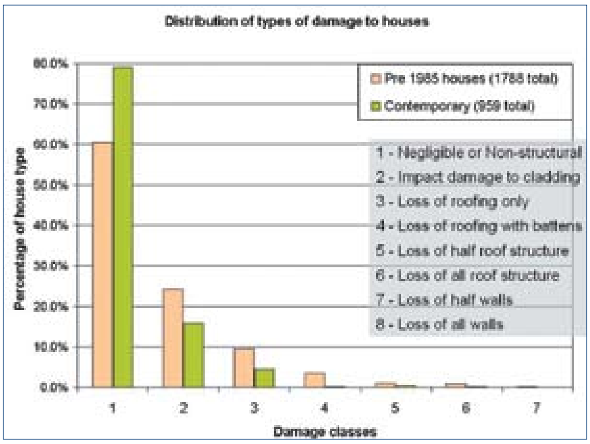

Figure 5: Damage to houses following Cyclone Larry (Henderson et al., 2006)

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Figure 7: Failure of cold formed steel frame shed

Fatigue failure of metal cladding was observed in a few instances, but for these cases the cladding was not installed correctly with fixing centres exceeding the required spacing.

Although Figure 5 showed that about 80% of contemporary housing suffered minimal structural damage it was noted that many houses were subjected to water ingress as shown in Figure 8. A recent GA and CTS supported survey conducted by Melita (2007), details building envelope failures during TC Larry. He found that approximately 75% of post-85 houses suffered water ingress through breaches in the building envelope (broken windows, punctured cladding, failed fascia or guttering, etc) or through window "seals", vents and under flashings. In many cases this has necessitated the refurbishment or replacement of internal linings and building contents.

Tropical Cyclone Larry was a fast moving event, which meant that the duration of strong winds was relatively short. Hence, buildings experienced fewer wind pressure fluctuations and less debris impact as well as a shorter period in which rain was being driven into buildings. The reduced duration of intense winds also minimised the potential for fatigue failure of metal cladding, fixings and battens. Had the cyclone been travelling slower but with the same gust wind speeds, the debris damage, water penetration and cladding damage would have been worse.

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Figure 6: Elevated house on side of hill

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Figure 8: Ceiling damaged by water ingress from debris impact to gable

Dubbo thunderstorm

A damage investigation was conducted by AGSO and CTS in the Eastern suburbs of Dubbo following a thunderstorm on the 6th January 2001. The peak gust wind speed was estimated to be about 40 m/s which is slightly lower than the region's design wind speed. There was significant damage to residential and commercial structures due to the wind load, debris impact, heavy rain and hail (Stehle and Henderson, 2001).

An external survey of housing, showed that approximately 5% suffered damage, mostly to tiled roofs from wind loads and debris impact (note that this excludes internal damage from water ingress, etc), in stark contrast to the more extensive damage suffered by commercial and industrial sheds. Figure 9 shows a shed with loss of cladding, buckled top hat purlins and buckled plates at the portal frame knees following the failure of the windward roller door. Note that the door has been laid back mostly in place following the event.

Approximately 50% of the sheds in the surveyed industrial area suffered some damage. The damage was mostly to roof and wall cladding and to roller-doors, with the damage levels ranging from negligible to structural collapse. There were a large number of roller door and window failures, which instigated more severe damage. It appears that the poor performance of engineered construction may be attributed to application of low internal pressure based on the assumption that the buildings would remain nominally sealed. This assumption is invalid when considering the large percentage of roller door failures at lower than design level wind speeds..

Damage Investigations – Learning the same lesson

These damage surveys have resulted in findings similar to those carried out after TC Winifred (Reardon et al., 1986), TC Vance (Reardon et al., 1999), TC Ingrid (Henderson and Leitch, 2005), and TC George (Boughton and Falck, 2007). A summary of these findings are;

- Overall, contemporary construction performed well in resisting the wind loads (as it should have as the wind speeds were less than the regions design wind speed). Generally these newer buildings had external damage mainly to roller doors and attachments such as guttering, facias etc.
- There was extensive water ingress in both damaged and "undamaged" construction.
- Where structural failures from wind forces were observed on contemporary houses, they were associated with poor construction practice or application of incorrect (ie low) site 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.

Performance of the BCA

Findings from the damage surveys show the majority of contemporary houses remained structurally sound protecting their occupants, thereby meeting the life safety objective of the BCA. However, even 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 objectives and performance requirements of the BCA.

Design Issues

Damage investigations and recent design detail audits of low-rise industrial sheds and 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 and internal pressure coefficient. The misinterpretation of these design criteria results in the use of components and connections of inadequate strength to withstand the design wind loads and consequently a higher probability of failure.

Figure 9: Structural failure of shed from failure of roller door on windward wall

Internal pressurisation of the building can occur from failure of an element (door, window, soffit, etc) from direct wind pressure or from wind driven debris impact. The damage investigations revealed; (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 the 4 kg mass projected at 15 m/s that is specified in the AS/NZS 1170.2 test criterion. The wind resistance of buildings could be improved significantly by applying 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 shown in Figures 10 and 11. Design standards and manufacturers data do not account for these types of faults and poor construction practices. This is another reason why damage surveys show higher than expected failures of contemporary construction. A missing or poorly installed fastener can result in the failure of a building, as adjacent fixings are overloaded and fail in a cascading effect.

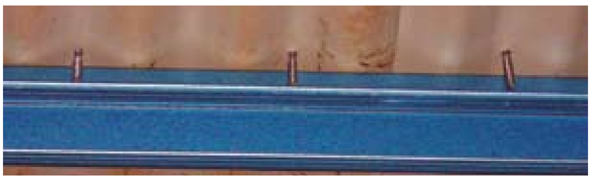

Figure 9: Roofing screws missed top hat batten.

Figure 10: Gun nails over driven in bracing panel.

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 rain-water with 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 (1999) 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 minimising water ingress is by incorporating adequate seals for all windows, vents, doors, flashings, etc. However, this solution maybe 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 fact that wind driven rain will enter the house. It is recommended that cost effective methods of improving the resilience of buildings against water ingress during severe storms be examined.

Conclusions and recommendations

Post windstorm damage surveys have shown that houses designed and built to the revised standards since the mid-eighties, perform better structurally than houses built prior to that. The 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, for example 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 in 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,
- Correct 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 manufacturers instructions, and
- Appropriate inspection and certification at time of construction, and
- Ongoing inspections and maintenance for serviceable life of building.

We are all a part of disaster mitigation. The resilience of our communities is up to all of us.

Acknowledgements

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