Tropical Cyclone Yasi
Structural damage to buildings

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CYCLONE TESTING STATION

SCHOOL of ENGINEERING and PHYSICAL SCIENCES
JAMES COOK UNIVERSITY

TECHNICAL REPORT NO. 57

Tropical Cyclone Yasi
Structural damage to buildings

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Tropical Cyclone Yasi: Structural damage to buildings

Executive Summary

Tropical Cyclone Yasi (TC Yasi) made landfall in the early hours of Thursday 3rd February 2011 with the eye passing over the Mission Beach region. The maximum wind gusts at the standard 10 m reference height in flat open country (i.e. Terrain Category 2 per AS/NZS 1170.2), were estimated to be 140 to 225 km/h with a 10% error margin, across the area stretching from Townsville to Innisfail. The range of wind speeds across the impacted region is equivalent to 55% to 90% of typical housing's ultimate limit state design wind speed (V_{500}) which is nominally 250 km/h. The localities away from the Mission Beach to Cardwell region experienced gust wind speeds towards the lower end of the stated range.

A destructive storm surge was recorded between Clump Point and Lucinda but fortunately it did not coincide with a high tide. Even so significant damage to several structures resulted from storm surge. There was little surge North of Clump Point and a reduced surge was recorded along the coast, South of Lucinda. Planning and the development of new construction requirements for buildings within a storm surge zone are recommended in order to reduce the risk of structural damage in future events.

Under wind load actions, buildings correctly designed and constructed to the standards/requirements introduced in the 1980s performed well. The exceptions were roller doors, tiled roofs and water entry. Each of these has been specifically addressed in the report, including recommendations for improvement in each case.

Typically less than 3% of all Post-80s houses in the worst affected areas experienced significant roof damage, although more than 12% of the Pre-80s housing inspected had significant roof damage. More than 20% of the Pre-80s housing in some towns had significant roof loss. Inspections for possible hidden structural damage are suggested. Recommendations are made for the upgrading of Pre-80s housing to improve the resilience of communities along with ongoing maintenance programs.

The generally low incidence of damage in the Post-80s buildings indicates that the current building practices are able to deliver a satisfactory outcome for most of the building structure at these load levels, as should be expected since the wind speeds were less than the design criteria.

The study reinforced the need to design the whole low rise building envelope, including cladding, doors, windows, roller doors, eaves lining and skylights to resist the expected ultimate limit states wind forces. It also highlighted the role of dominant openings in determining the internal pressures in buildings.

The report recommends changes to AS 4055 with respect to calculating topographic classes. It also suggests an investigation into requirements in AS/NZS 1170.2 for determining internal pressures in tropical cyclone-prone areas. It details recommendations for improving AS/NZS 4505 on roller doors and AS 2050 on roof tiles. Other key recommendations relate to construction of a 'strong compartment' within each residence for protection of life in case the building envelope is breached by large wind-borne debris and/or wind speeds exceeding design levels.

With current design requirements, water ingress through the building envelope is inevitable at wind speeds near the ultimate limit state, and unless new water-tightness requirements are developed, materials and fittings should be selected with a view to their resilience to wind-driven rain.

The report has highlighted the inadequacy of the sparse anemometer network along the tropical coast. Due to the importance of determining the wind speeds that impacted the communities for building code development and emergency response planning, the report recommends that systems be put in place to establish more anemometers providing better coverage during tropical cyclone events.

Tropical Cyclone Yasi: Structural damage to buildings

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Acknowledgements

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The CTS field team comprised Geoff Boughton, who led this investigation, John Ginger, Cam Leitch, David Henderson, Peter Kim, Chana Jayasinghe, Ulrich Frye, Bipin Sumant, and Dennis Smith from the CTS, JCU Adjunct Professors John Holmes and George Walker, Lex Somerville from BMCC Services, Erroll Holdsworth from the ABCB and Matt Mason and Ryan Crompton from Risk Frontiers. JCU engineering graduate Josephine Zammit was part of the Innisfail phase of the investigation. Graeme Stark from the CTS was the Base Operations Manager, stationed in Townsville.

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1. Introduction

Tropical Cyclone Yasi (TC Yasi) was a severe tropical cyclone with a relatively large diameter that crossed the Queensland coast near Mission Beach in the early hours of Thursday 3 February 2011. The media reported damage of varying severity between Townsville to Cairns, with the most severe damage located between Cardwell and Innisfail. Figure 1.1 shows the Babinda to Ingham region that contains the study area.

Cyclone Yasi was initially predicted to have a very significant storm surge associated with it, mainly because of the large extent of the system and its relatively low central pressure. Fortunately, the peak storm surge did not coincide with high tide and so the actual sea water rise was significantly less than it may have been for the worst case scenario.

Nonetheless, TC Yasi produced structural storm surge damage and structural wind damage at various locations between Innisfail and Townsville. As the warnings of the event were widely reported and because the predictions were very dire, there was an evacuation of low-lying areas between Cairns and Townsville. Many houses were also evacuated as people made decisions as to which of their friends' houses looked and felt strongest. Due in no small part to this community response to the event, there were no casualties due to structural wind or storm surge damage, though casualties may have occurred if some of the buildings that were badly damaged had been occupied during the event.

1.1 Field investigation

Teams from the Cyclone Testing Station (CTS) conducted field surveys to investigate the performance of buildings (housing, larger residential structures and sheds) under the actions of TC Yasi.

The study area extended from Innisfail in the North to Halifax in the South along the coastline and extending inland to Tully and the Bruce Highway as shown in Figure 1.1.

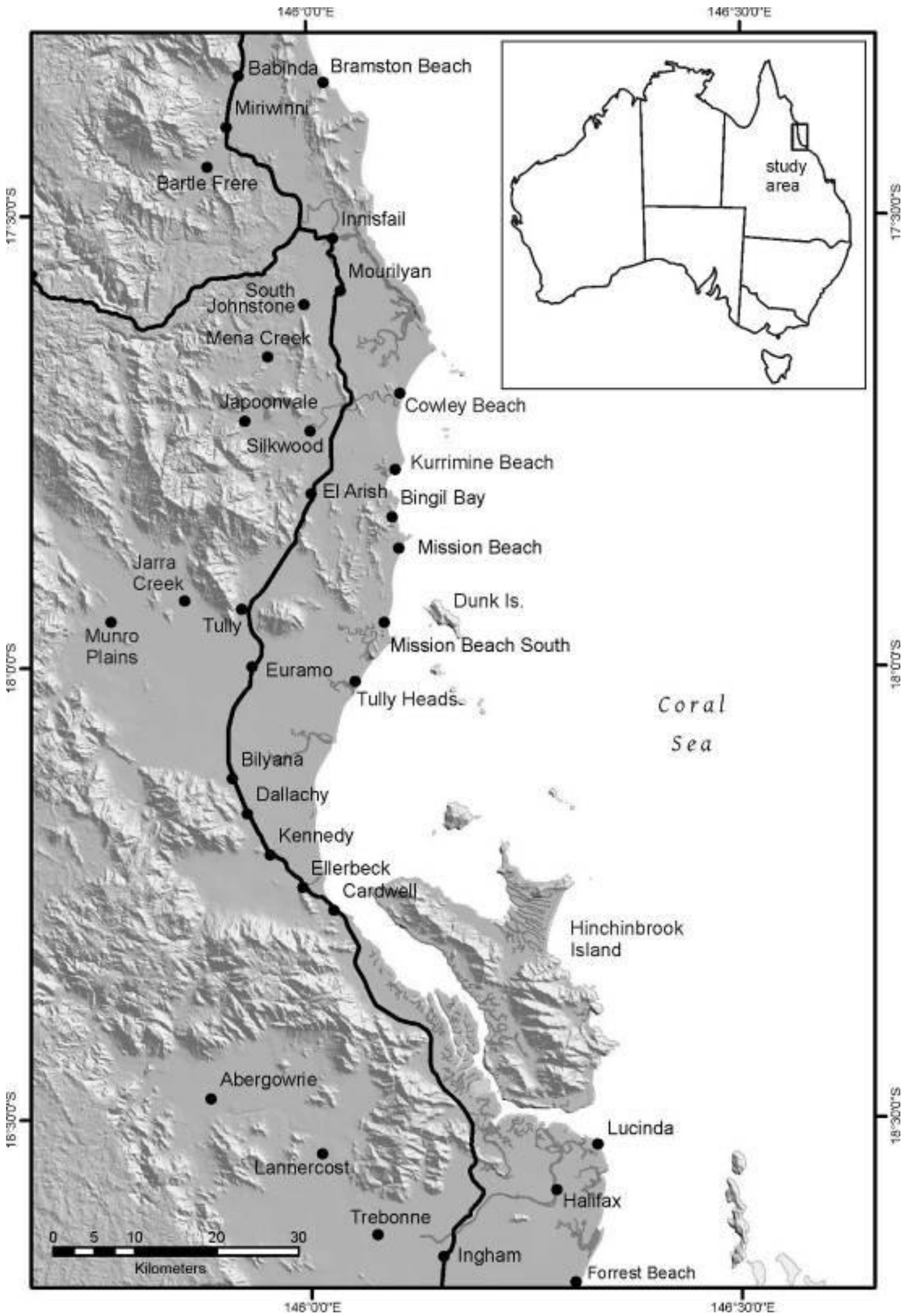


Figure 1.1 Region of investigation

The field study commenced on Friday 4 February with the first phase complete on Friday 11 February 2011. A follow-up data collection phase was undertaken from Tuesday 22 February to Friday 25 February. The field study:

- Used 'windicators' to estimate the peak gust experienced at a number of different locations within the study area. This data would augment any anemometer data from the bureau and lead to a better understanding of the wind field experienced in the study area.
- Examined contemporary buildings to determine whether their performance was appropriate for the estimated wind speeds they experienced. Where damage was greater than that expected, common failures were documented in sufficient detail to allow recommendations for changes to regulations or construction methods as appropriate.
- Examined patterns of damage to determine whether there are any types of structure that appear to have systematic weaknesses.
- Evaluated the performance of structures that had been repaired following Tropical Cyclone Larry to determine whether the repair methods had offered any improvement in structural performance.
- Investigated the performance of larger residential structures such as resorts or holiday units.
- Assessed the ability of the building envelope to withstand wind loading and debris impact loading.
- Determined the extent of structural damage from storm surge in the study area.
- Conducted street surveys to map patterns of damage and its relationship to characteristics of the built environment

1.2 Meteorological information

In late February 2011, the Bureau of Meteorology published the following information on their website: http://www.bom.gov.au/cyclone/history/yasi.shtml

> Information repeated here with thanks to the Bureau of Meteorology:
>
> ***Summary***
>
> *Severe Tropical Cyclone Yasi began developing as a tropical low northwest of Fiji on 29th January and started tracking on a general westward track. The system quickly intensified to a cyclone category to the north of Vanuatu and was named Yasi at 10pm on the 30th by Fiji Meteorological Service. Yasi maintained a westward track and rapidly intensified to a Category 2 by 10am on 31st January and then further to a Category 3 by 4pm on the same day.*
>
> *Yasi maintained Category 3 intensity for the next 24 hours before being upgraded to a Category 4 at 7pm on 1st February. During this time, Yasi started to take a more west-southwestward movement and began to accelerate towards the tropical Queensland coast.*
>
> *Yasi showed signs of further intensification and at 4am on 2nd February and was upgraded to a marginal Category 5 system. Yasi maintained this intensity and its west-southwest movement, making landfall on the southern tropical coast near Mission Beach between midnight and 1am early on Thursday 3rd February. Being such a strong and large system, Yasi maintained a strong core with damaging winds and heavy rain, tracking westwards across northern Queensland and finally weakened to a tropical low near Mount Isa around 10pm on 3rd February.*
>
> *Yasi is one of the most powerful cyclones to have affected Queensland since records commenced. Previous cyclones of a comparable measured intensity include the 1899 cyclone Mahina in Princess Charlotte Bay, and the two cyclones of 1918 at Mackay (January) and Innisfail (March).*

Wind Damage

At the time of writing there are no verified observations of the maximum wind gusts near the cyclone centre. However a barograph at the Tully Sugar Mill recorded a minimum pressure of 929 hPa as the eye passed over suggesting wind gusts of about 285 km/h were possible. This is supported by measurements (subject to verification) from instrumentation operated by the Queensland Government (Department of Environment and Resource Management) at Clump Point (near Mission Beach) which recorded a minimum pressure of 930hPa. Significant wind damage was reported between Innisfail and Townsville where the destructive core of the cyclone crossed the coast. Tully and Cardwell suffered major damage to structures and vegetation with the eye of the cyclone passing over Dunk Island and Tully around midnight on 2nd February.

The largest rainfall totals were near and to the south of the cyclone and were generally in the order of 200-300mm in the 24 hours to 9am Thursday. These rainfall totals were experienced in the area between Cairns and Ayr, causing some flooding. The highest totals were; South Mission Beach 471mm, Hawkins Creek 464mm, Zattas 407mm, Bulgun Creek 373mm along the Tully and Herbert River catchments.

Storm Tides

A 5 metre tidal surge was observed at the Department of Environment and Resource Management (DERM) storm tide gauge at Cardwell, which is 2.3 metres above Highest Astronomical Tide (HAT). The anomaly occurred at about 1.30am on a falling tide, averting more serious inundation. Some significant, yet far less substantial sea inundation occurred on the late morning high tide on 3rd February between the Cairns Northern Beaches and Alva Beach, with peak levels measured at DERM's Townsville tide gauge close to the expected 0.6m above HAT causing inundation of parts of the city.

****All information relating to intensity and track is preliminary information based on operational estimates and subject to change following post analysis****
** All times mentioned is Australia Eastern Standard Time (EST)*

Coastal Crossing Details
Crossing time: *12 am - 1am EST, 3 Feb 2011*
Crossing location: *Near Mission Beach, 138km S of Cairns*
Category when crossing the coast: 5

Extreme Values During Cyclone Event (estimated)
Note that these values may be changed on the receipt of later information

Maximum Category: *5*
Maximum sustained wind speed: *205 km/hr (estimated)*
Maximum wind gust: *285 km/hr (estimated)*
Lowest central pressure: *929 hPa*

Figure 1.2 shows the Bureau of Meteorology’s estimates of track and intensity of TC Yasi, both as it approached the coast and as it dissipated whilst travelling over land.

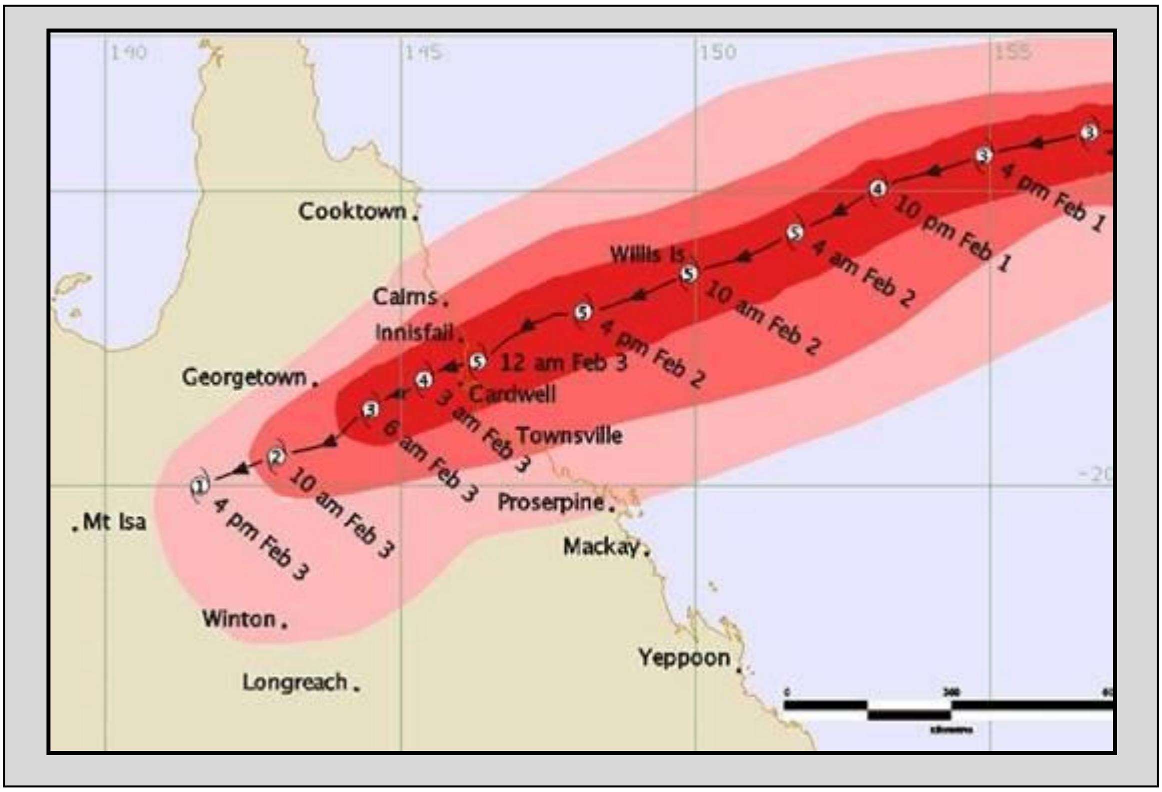


Figure 1.2 Track and intensity information for Tropical Cyclone Yasi
(Image courtesy Bureau of Meteorology)

1.3 Purpose of the report

This report presents the outcomes of the CTS field investigations into structural effects of Tropical Cyclone Yasi. It focuses on the following issues that are important to the continuing safety of buildings in cyclone-prone regions of Australia:

- Structural performance of buildings constructed under the current regulations. This gives feedback as to whether the current regulations are targeting an appropriate level of structural safety.
- Individual structural details that may need to be addressed through Codes and Standards to ensure that their performance is adequate. This includes some items (such as garage doors and tiles) that have shown poor performance in previous events.
- The performance of buildings that had been repaired after structural damage in a previous tropical cyclone. Some areas affected by TC Larry (2006) and TC Yasi over-lapped and some buildings that had been damaged in TC Larry and repaired were subjected to similar loads in TC Yasi. The investigation had a rare opportunity to evaluate the effectiveness of these repairs.
- Identification of hidden damage in previous events. The investigation sought structures that were damaged at lower wind speeds in TC Yasi but reported no damage at higher wind speeds in TC Larry. The premature failures of these structures during TC Yasi could be attributed to undetected weakening of structural elements following a previous severe event. Also signs of partial failures of connections were also sought from damage that may have been caused by TC Yasi.
- Structural storm surge damage. TC Yasi generated a significant storm surge that impacted on buildings in a number of different settlements.

2. Estimation of wind speeds and directions

Three approaches were used to estimate the maximum values of 3-second gusts reached at the main centres affected by Cyclone Yasi. These were as follows:

a) Use of anemometer data from the Bureau of Meteorology, or other agencies, where available
b) A field investigation of failed and non-failed road signs ('windicators')
c) Use of the standard Holland wind field model to predict wind speeds.

Methods (a) and (b) were used to calibrate and adjust the parameters of the Holland model, enabling it to be used as an interpolation tool to obtain realistic and consistent estimates of wind speed and direction in the region of interest.

2.1 Analysis of wind data

2.1.1 Anemometer data

Data was available from the following anemometers:

- *South Johnstone*. The anemometer is located at the Research Station of the Queensland's Primary Industries and Fisheries (part of the Department of Employment, Economic Development and Innovation). The measurement height is the standard 10 metres. However, the site is estimated as Terrain Category 2.5 and affected by a range of hills to the south (Basilisk Range) with a peak at 252 metres above sea level, and the sugar mill to the north-west. The anemometer and direction vane appeared to function correctly during the event.
- *Lucinda Point*. The anemometer is located at the end of a 5-kilometre long conveyor jetty. The 3-cup anemometer head is located about 4 metres above the roof of the loading shed, which is itself 27 metres above mean sea level. The direction vane appeared to malfunction at the height of Cyclone Yasi.
- *Cairns Airport*. Data was available from an automatic weather station (AWS) with 3-cup anemometer, at this location. The height of this is 10 metres.
- *Townsville Airport*. Data was available from both an AWS and a Dines anemometer at this location. Both instruments are at 10 metres above the airport terrain.
- *East Innisfail*. Wind speed and direction data was supplied by Mr. James Begg, a member of the Weather Underground, from his WMR2000 weather station located at East Innisfail. The anemometer head was located at about 1 m above a house roof ridge.
(http://www.wunderground.com/weatherstation/WXDailyHistory.asp?ID=IQLDEAST2)

In addition to these stations, hardware for a weather station exists at the Army Firing Range at Cowley Beach, including a 3-cup anemometer and direction vane, but unfortunately no recording equipment has been connected to it for several years, and no data was obtained in Cyclone Yasi.

Table 2.1 shows the maximum values of 10-minute mean wind speed, 3-second gust wind speed and direction and times of occurrence, during Cyclone Yasi for each of the recording stations listed earlier.

Table 2.1 Readings from recording anemometers

Station	Maximum 10-minute mean (km/h)	Direction	Maximum 3-second gust (km/h)	Direction (degrees)	Time of max gust (EST)
South Johnstone	95	NW	130	WNW	12.17 am
Lucinda Point	137	?	185	?	11.31 pm
Cairns Airport	61	W	93	NW	12.43 am
Townsville Airport	106	E	135	E	1.23 am

The above values have had no corrections applied to them. However, in the comparisons described following, the maximum gust from South Johnstone was corrected to standard conditions (terrain category 2) by assuming the surrounding terrain was Terrain Category 2.5 and dividing the measured value by 0.915. The East Innisfail anemometer readings were corrected to allow for terrain and non-standard height of the anemometer.

2.1.2 ‘Windicator’ data from failed road signs

Over a 100 failed road signs were inspected during the course of the field investigation. Many of these were found to have failed as a result of a footing failure and were ignored. Detailed dimensions were obtained from those that had shown a permanent deformation resulting from generation of a plastic moment at, or near, ground level. In those cases, a suitable non-failed sign was sought in the general vicinity, although this was not always possible. In this way, lower and upper limits of gust wind speed were derived.

In the investigation, cases where signs with one, two, or even three, support poles have been used, and also cases where non-rectangular plates are installed, and some cases with more than one plate on the same sign have been used. Figure 2.1 shows an example of a failed road sign used in this investigation. Figure 2.2 shows an upright ‘diamond’ sign. The calculated failure wind gust speed for this common type of sign is 65 to 68 m/s (235 to 243 km/h). No examples of failures by wind loading of signs of this type were found anywhere in the survey area, thus establishing 240 km/h as a likely overall maximum upper limit of gust speed anywhere affected by TC Yasi.

Appendix A.2 gives background on the analysis method for calculating wind speed from ‘windicators’. For each location where a number of potential ‘windicators’ had been measured only the highest wind velocity calculated from failed signs and the lowest wind velocity calculated from upright signs were tabulated in Appendix A. Their values give the narrowest range of estimated wind speeds at this location.

Figure 2.1 Failed road sign with increased signage area compared to upright sign in background

Figure 2.2 Upright 'diamond' road sign on Bruce Highway near Kennedy

Table 2.2 summarises the results from the ‘windicator’ study. Figure 2.3 shows the location of the ‘windicators’ and their readings over the study area (between Innisfail and Cardwell).

The averages of the lower and upper limits shown in Table 2.2, give a general indication of the maximum expected gusts at the various locations – with values of 225-227 km/h at Tully and South Mission Beach shown.

The lower limit of 148 km/h estimated from a signpost at Townsville Airport can be compared with the airport anemometer readings. The 3-cup anemometer at the Townsville Airport read 135 km/hr as shown in Table 2.1. However, the Dines anemometer at Townsville Airport concurrently showed a maximum gust of 163 km/h, this larger value reflecting that this apparatus measures gusts over a shorter time period than the 3-cup anemometer. The lower limit from the failed sign lies between these two values.

Table 2.2. Summary of ‘windicator’ results

ID	Location	Lower limit (km/h)	Upper limit (km/h)	Average (km/h)
A	Mourilyan	140	202	171
B	Cowley Beach	194	-	-
C	Silkwood	173	187	180
D	Japoon	-	198	-
E	El Arish	173	187	180
F	Kurrimine	133	230	182
G	Bingil Bay	194	202	198
H	Mission Beach	187	-	-
I	S. Mission Beach	209	245	227
J	Tully	216	234	225
K	Jarra Creek	-	198	-
L	Euramo	-	176	-
M	Munro Plains	187	-	-
N	Dallachy-Bilyana	166	194	180
O	Kennedy	180	245	212
P	Cardwell	198	220	209
Q	Halifax-Macknade	144	184	164
R	Townsville	148	-	-

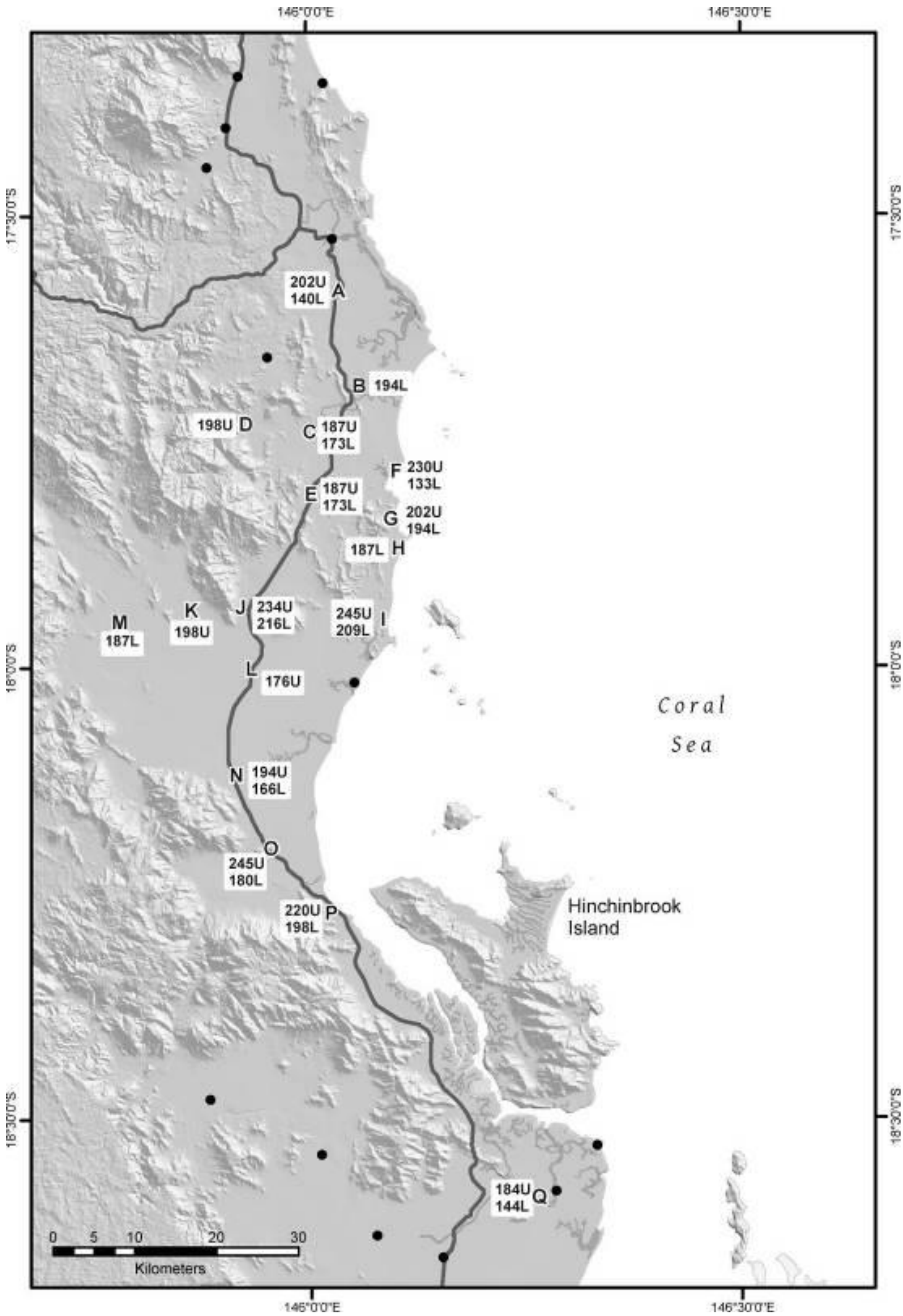


Figure 2.3 Upper and lower limits from "windicators" (km/h)

2.1.3 Holland wind field model

In order to provide a more complete picture of the wind field generated by Cyclone Yasi at landfall, the well-known Holland model (Holland, 1980) was employed, primarily as an interpolation tool for the data from the anemometers and backed up by the "windicators". Details of the Holland model, such as choice of parameters used, calibration and sensitivity analysis are given in Appendix A.1.

2.2 Wind field

Figures 2.4 to 2.6 show the expected maximum gusts in the region from Innisfail to Cardwell for three locations of the centre of the cyclone, calculated using the standard Holland model, with the parameters given previously, calibrated to best fit the anemometer and 'windicator' data as discussed in previous sections:

- 20 kilometres from landfall,
- at landfall when the centre of the cyclone was over Mission Beach,
- 20 kilometres after landfall when the centre of the cyclone was located over Tully.

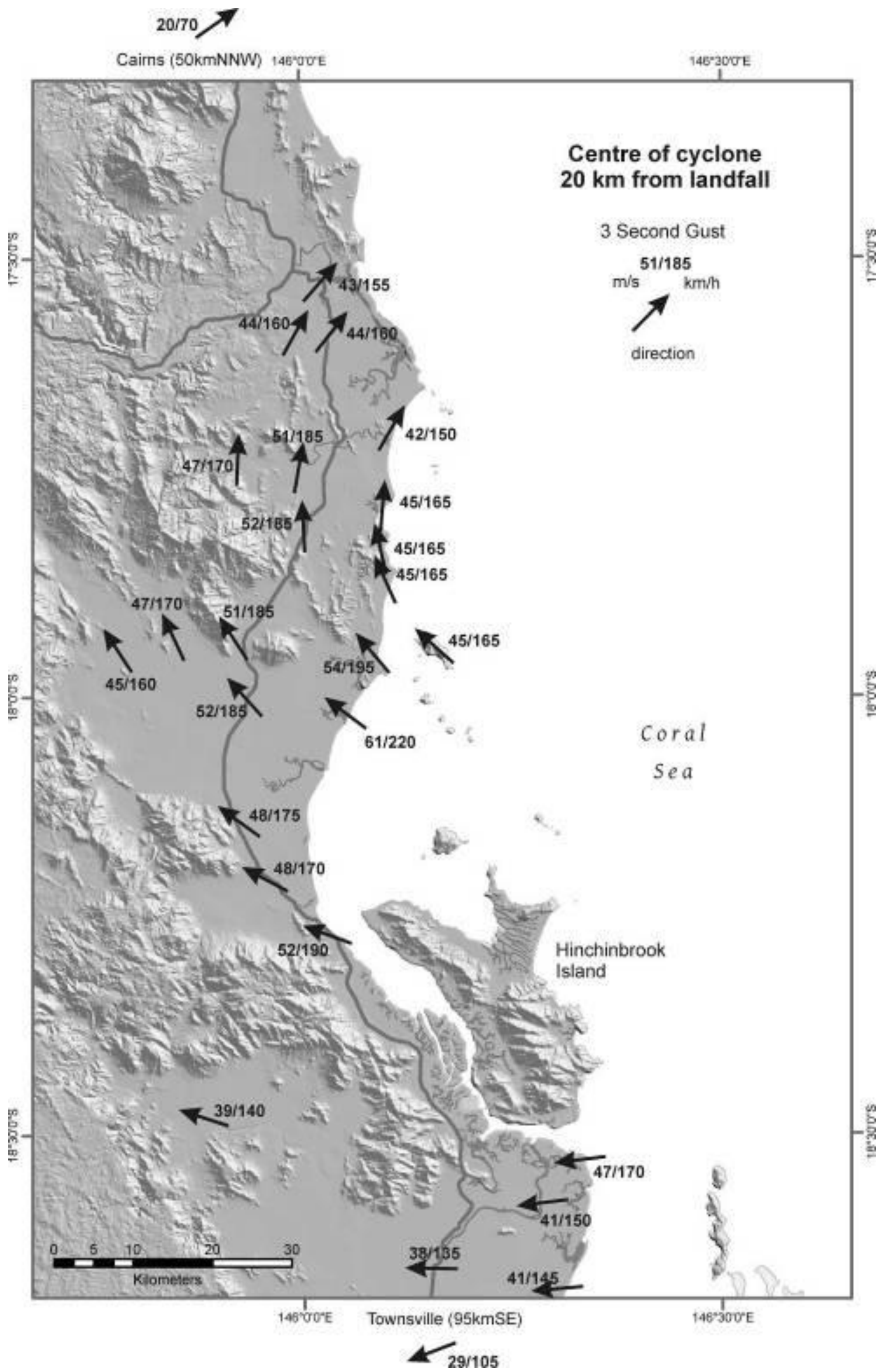
Figure 2.4 shows that coastal locations between Wongaling Beach and Tully Heads experienced strong south-easterly off-water gusts, when the centre of Cyclone Yasi was 20 km from landfall. Tully was experiencing gusts from the SSE at that time, while Cardwell received gusts from the ESE. Innisfail and Mourilyan experienced peak gusts of 155-160 km/h from the south-west when the cyclone was in that position.

As Cyclone Yasi made landfall (Figure 2.5), beachside locations from Kurrimine to South Mission Beach experienced the eye and very low winds. The winds at Tully turned more southerly, and Cardwell is predicted to have received its strongest gusts from the east at that time, although these may have been shielded by Hinchinbrook Island. Wind gusts at Innisfail and Mourilyan turned more westerly.

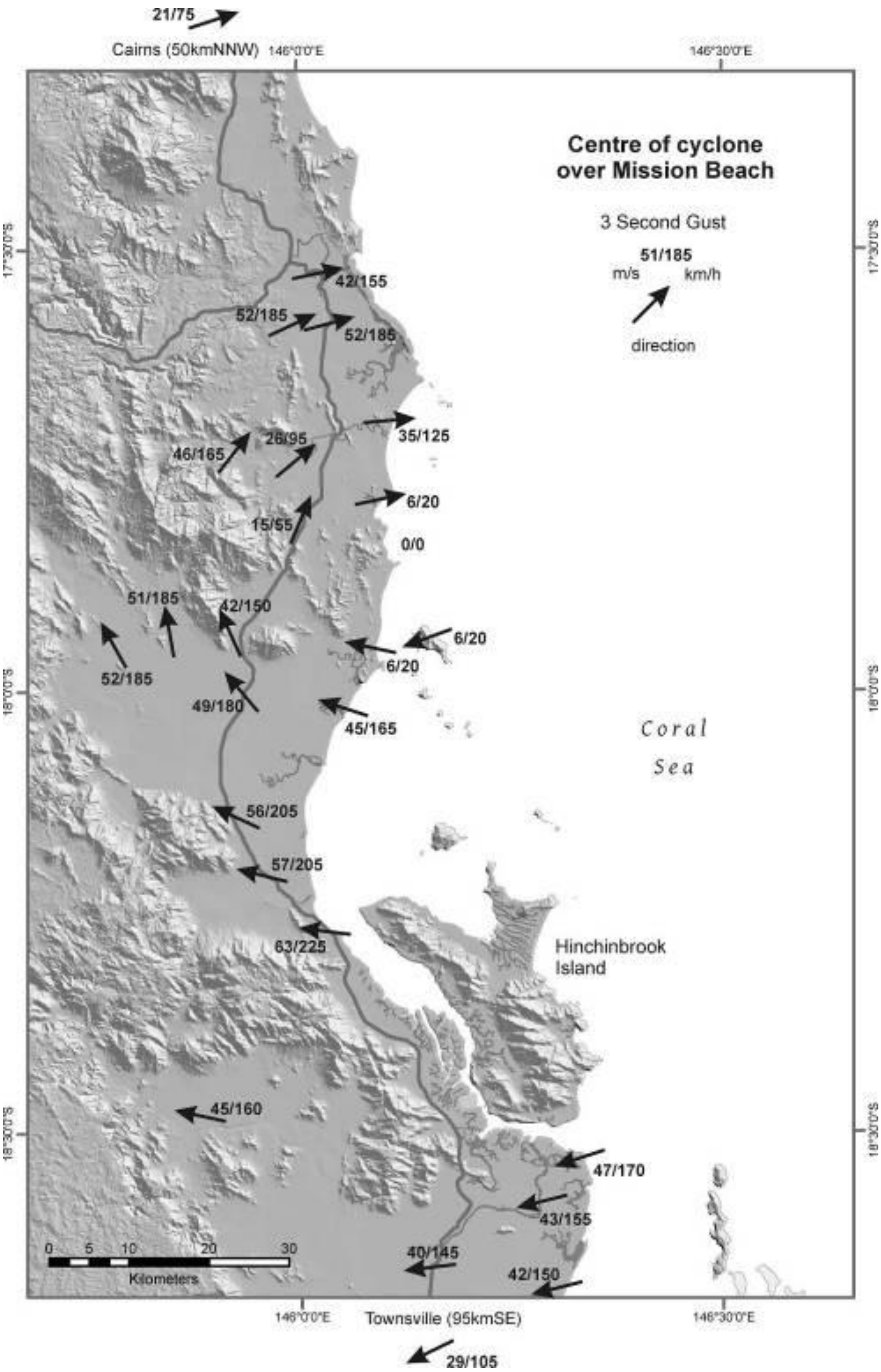
When the eye of the cyclone was centred over Tully (Figure 2.6), wind gusts were more northerly at the beachside locations from Kurrimine to Tully Heads. Winds at Innisfail, Mourilyan and Silkwood were from the WNW. Tully itself experienced the eye, and, of course, very low winds at that time.

Figure 2.7 shows approximate contours of the highest estimated gusts that occurred at any time during the event. The highest gusts of 215-225 kilometres per hour are estimated to have occurred at South Mission Beach, Tully Heads and Cardwell. Tully itself is estimated to have experienced lower maximum gusts. However, it should be noted that large-scale topographic effects have not been included in the predictions from the Holland model which show expected maximum 3-second gusts at 10 metres height over Terrain Category 2 in AS/NZS 1170.2. It is possible that channeling between Mount Tyson and Mount Mackay produced some amplification of gusts at Tully. On the other hand, some shielding of easterly winds at Cardwell by Hinchinbrook Island was likely.

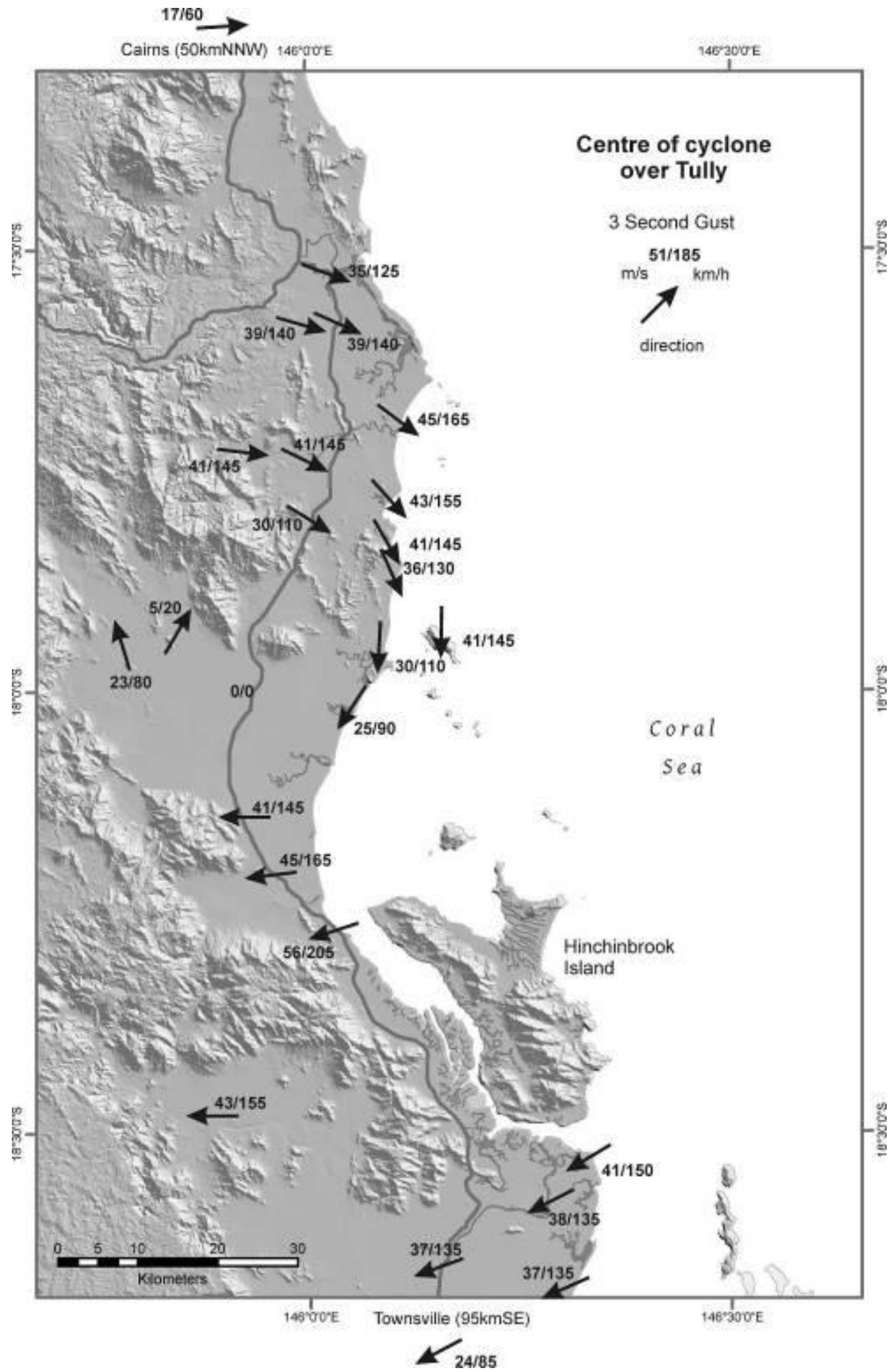
Maximum gusts in the range of 140 to 170 kilometres per hour are estimated to have occurred in the Ingham-Halifax-Lucinda area, and at Abergowrie in the Herbert River valley.



Figures 2.4 Wind directions and gust speeds from Holland model – prior to landfall
(Topographic effects not included and values rounded to 1 m/s and 5 km/h)



Figures 2.5 Wind directions and gust speeds from Holland model – at landfall
(Topographic effects not included and values rounded to 1 m/s and 5 km/h)



Figures 2.6 Wind directions and gust speeds from Holland model – after landfall
(Topographic effects not included and values rounded to 1 m/s and 5 km/h)

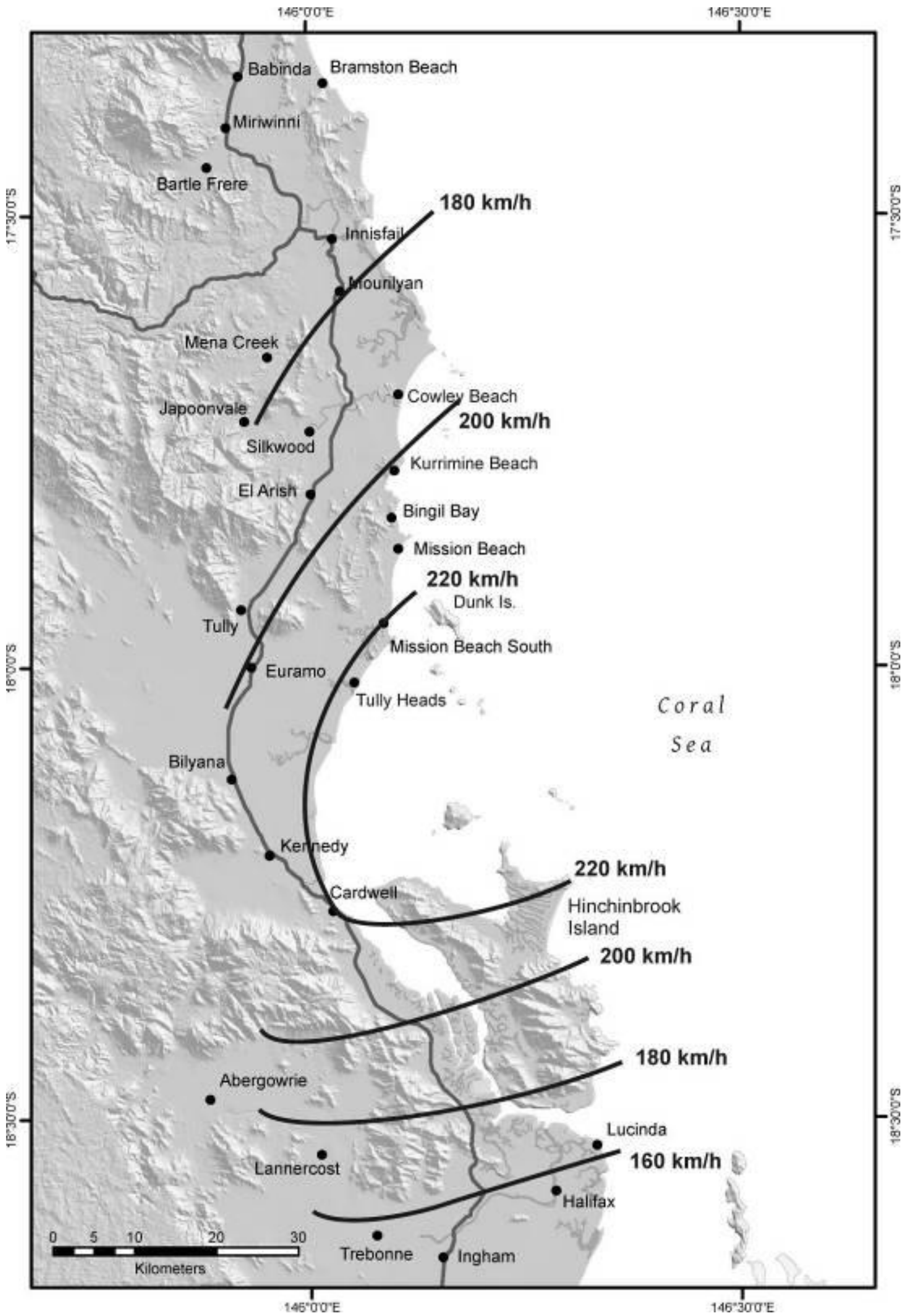


Figure 2.7 Approximate contours of maximum 3-second gust at any time during the event (Topographic effects not included.)

2.3 Maximum wind gusts

The wind field on the land at the landfall of Cyclone Yasi has been assessed using a combination of anemometer measurements, 'windicators' (i.e. failed road signs) and the well-known Holland model of the vortex wind field of tropical cyclones. The model has been 'tuned', and the variable parameters adjusted to give the best agreement with the measured maximum gusts.

The model indicates maximum 3-second gusts of 225 kilometres per hour, with the highest values predicted to have occurred on the south side of the storm at South Mission Beach, Tully Heads and Cardwell. It is possibly that slightly lower gusts occurred at Cardwell than those predicted, due to some shielding of easterly winds by Hinchinbrook Island. Conversely, the north and south wind gusts at Tully may have been higher than predicted, due to 'channelling' or 'funnelling' between Mounts Tyson and Mackay.

The maximum 'best-estimate' winds are about 10% below the design wind speeds (V_{500}) for most buildings (i.e. Importance Level 2 in the BCA). The estimated wind speeds in this section are generally compatible with the assessment of damage to buildings discussed elsewhere in this report.

In the absence of reliable anemometer measurements in the centre of the storm, the maximum *random* errors in the individual estimates at particular locations may be around 10%. This includes the possible local effects of topography which have not been explicitly incorporated, and possible local wind phenomena such as downdrafts. However, given the good general agreement with the measurements, the overall *bias* in the predictions are likely to be less than 5%.

There is some uncertainty in the parameters selected for use with the Holland model. The method of combining the forward speed of the storm with the vortex wind speeds also has a significant effect. Including this uncertainty leads to a general assessment of a maximum error of around +10% for estimates of extreme gust at individual locations in the main damage zone shown in Figure 2.8 (i.e. Innisfail to Cardwell). This overall error also includes possible asymmetry effects on the vortex, which are not captured by the axisymmetric nature of the Holland model, either in the standard or double form, and the possible occurrence of downdrafts embedded in the cyclone which may have led to increases in wind gusts at certain localities. Local asymmetry effects may have contributed to the gust wind speed at Townsville being greater than that predicted by the Holland model.

Although there are uncertainties associated with the estimated maximum gusts produced by Cyclone Yasi, an indication from the available evidence that the maximum gusts over the mainland did not exceed 240 km/h is given by the non-failure of any common yellow 'diamond' road signs (Figure 2.2).

2.4 Recommendations for wind measurements in future events

As detailed elsewhere in Section 2, there are various uncertainties in the estimation of the cyclone's wind speed when there are no anemometers. It is essential for these investigations to know whether the wind speed is greater or less than the design wind speed – so, wind speed estimates have to be made from what information is available.

2.4.1 Automatic Weather Stations

The availability of direct measurements of wind speeds and directions from anemometers is very desirable. Harper *et al.* (2008) reported that less than 2% of all tropical cyclone peak intensities in the Australian region have been directly measured from instrumented eye passages. This event has again highlighted the inadequacy due to the sparse locations of weather stations along the tropical coast for the purposes of reliably determining peak wind speeds. Similar findings were also made in 1986 and 2006 following Cyclone Winifred and Cyclone Larry, as well as many other events across the cyclonic regions of Australia (Reardon *et al.*, 1986; Boughton, 1999; Henderson *et al.*, 2006).

Accurate measurements of wind speeds that impacted the built environment are crucial for the continuing development of building regulations and Standards to provide appropriate safety and resilience of buildings, and allow a targeted and efficient process in the rebuilding and retrofitting of structures.

It is recommended that in order to provide a minimum level of information so this can occur, Automatic Weather Stations should be installed at sizeable communities and within 50 km of the next AWS. For example, the string of AWS locations relevant to the current study could be near Ingham, then Cardwell, then Mission Beach/Tully region, with the next location being the existing AWS at South Johnstone (Innisfail locale). An existing anemometer at the Army Firing Range at Cowley Beach, is well situated and with permanent staff on site, should be reconnected (having not functioned during both Tropical Cyclones Larry and Yasi).

Each AWS needs to be robust and remain functioning throughout severe cyclonic events. Each new AWS should be situated at 10 m height in a flat open area such as airfield, race track oval or farm land. However, well documented adjustments to the wind speed measurements can be made to account for buildings and other changes in terrain for upwind directions (Ginger and Harper 2004, Masters *et al* 2010). Site selection should take account of potential upwind sources of wind driven debris. The Bureau of Meteorology report an AWS to cost approximately $40,000 per unit.
(http://www.bom.gov.au/inside/services_policy/pub_ag/aws/aws.shtml)

2.4.2 Re-locatable anemometers

In addition to the proposed AWS coastal chain, re-locatable anemometers could be deployed ahead of a cyclone's predicted landfall to get a finer resolution of wind speeds across the impacted region. This data could also be relayed in real time to the Department of Emergency Services as an aid to planning and asset deployment/management (in association with vulnerability models). Systems such as the 15 m mobile towers and the StickNet system have been successfully deployed for land falling hurricanes across the southern states of the US (Schroeder and Weiss, 2008). The StickNet system has an estimated cost of $10,000 per unit (private correspondence). In addition to use along the Northern Queensland coast, the transportable nature of these devices means that the units could be crated and transported by air for deployment out of NT and WA cities and towns such as Darwin, Broome, and Karratha.

2.4.3 Options for improvement

The increased density of anemometers (both the proposed robust AWS chain and re-locatable units) enables the measurement of wind speeds rather than relying on the estimation using 'windicators'. Therefore, the increased density reduces the research cycle time, improves our knowledge of the real risk associated with these severe events and thus better informs the design process.

It is recommended that the CTS be commissioned to engage with other appropriate stakeholders to investigate and operate a system of re-locatable anemometers. This includes number, type, siting requirements and deployment capabilities.

3. Structural wind damage to buildings

Section 2 indicated that maximum gust wind speeds of 225 km/h were experienced. Wind damage to structures was observed across the Townsville to Innisfail region. At the extremities of this area, the damage was very isolated with maximum wind gusts in the order of 140 km/h, and in the main study area, the damage was more frequent with estimated maximum wind gusts of 225 km/h.

Two levels of investigation into structural wind damage were carried out:

- Street Surveys: These used a one line evaluation of each building from the street to obtain a rough, quantitative estimate of the extent of damage and the distribution of building categories. These surveys were mainly performed from vehicles, but where the damage was more concentrated or the community was judged to be very sensitive, the surveys were undertaken on foot. The information gathered and the results of the street surveys are presented in Section 3.1.
- Detailed studies: Specific buildings of interest were selected for careful assessment of the order in which the failure took place, the identified weak points in the structure, and any issues associated with compliance with building codes and standards. These investigations required estimations of parameters that affect the site wind speed e.g. shielding and topography, and measurements of key dimensions to enable engineering analysis. The results of the detailed studies are presented in Section 3.2.

3.1 Patterns of damage

Patterns of the damage could be assessed in a number of different ways. Initially, reports from the Emergency Management Queensland were used to direct the study teams to areas in which most significant structural damage was to be expected. Figure 3.1 shows an early estimation of the extent of damage to buildings from this source.

This information enabled the investigation team to select the following locations for street surveys:

- Bingil Bay
- Mission Beach
- Wongaling Beach
- South Mission Beach
- Hull Heads
- Tully Heads
- Tully (part survey)
- Cardwell (part survey)
- Upper Murray (part survey)

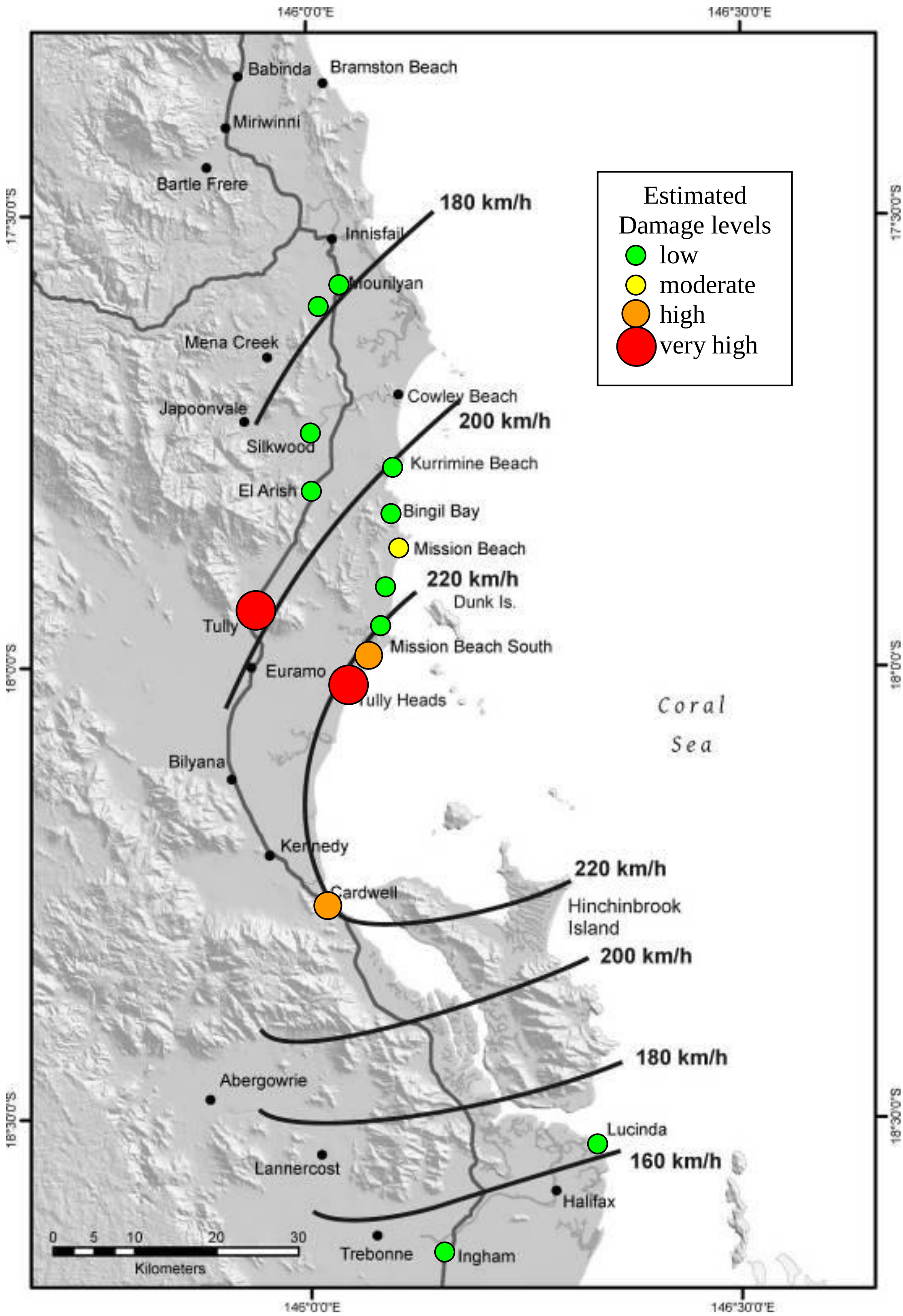


Figure 3.1 Representation of early estimates of reported damage by EMQ overlaid on estimated wind field.

A total of 1963 buildings were surveyed. The following information on each building in the survey area was obtained from a quick visual inspection from the street side:

- Estimated decade of construction or last major renovation. (This data was used to sort the buildings into pre-1980s and post-1980s construction.)
- Style of construction (high-set, slab on grade, low set etc.)

- Orientation of the building on site
- Wall cladding materials
- Whether the building had large windows (full height or greater than 3 m^2 per window).
- Roof geometry and roof materials
- Three digit Damage Index (Roofing (R), Openings (O), Walls (W))

The Damage Index used in the study is shown in Table 3.1.

Table 3.1 Three category Damage Index

No	Roof (R)	Openings (O)	Walls (W)
0	None	none	none
1	Gutters downpipes	debris not pierced	debris not pierced
2	Debris damage to roof	debris pierced	debris pierced
3	lifted < 10%	windows/doors leaked	Carport /verandah damage
4	lost roofing < 50%	Windward broken < 30%	One wall panel fallen
5	lost battens < 50%	frames lost < 30%	> 1 wall panels fallen
6	lost battens > 50%	Windward broken 30%-70%	racking damage, cladding attached
7	lost battens > 50% and lifted rafters	Windward broken > 70%	racking damage and lost cladding
8	lost battens > 50% and damaged tie-down	Windward broken > 70% and suction loss	only small rooms intact
9	lost roof structure > 50% including ceiling	100% broken / missing	no walls remaining

Using this system, each building returned a three digit number as the Damage Index (DI) with the first digit representing the roof damage, the second representing the damage to openings and the third digit representing damage to walls.

Subsequent to the Street Survey, the location of each building was used to assess a topographic classification according to AS 4055:2006. The topographic classification was used together with an estimate of the Terrain Category and Shielding classification to assign a C-rating to each site. This work was performed as a desk-top study using satellite images and topographic maps and would not have had the same rigor as an individual wind speed assessment for each site.

Throughout the rest of this report, buildings will be classified by age into Pre-80s and Post-80s buildings. This distinction is particularly important for houses, as the Queensland Home Building Code Appendix-4 (1981) brought significant structural improvements to housing designed to resist strong winds. Houses built in the Post-80s era have had to demonstrate that there is a continuous load path for tie-down from roof cladding to the ground and that all of the lateral forces from wind can be resisted by bracing walls and bracing at all levels of the structure.

3.1.1 Geographical location

The building and damage characteristics of each of the settlements have been presented in Table 3.2. Appendix C presents the methodology of the analysis.

The building and damage characteristics of each of the towns have been presented in Table 3.2. The table shows:

1. Number of Pre-80s houses is the number of buildings judged to have been built or had the last substantial renovation prior to 1980.
2. Number of Post-80s houses is the number of buildings judged to have been built or substantially redeveloped since 1980.
3. Average Damage Index for Roofing, Openings, or Walls was obtained by averaging the digit representing that Damage Index category for all the houses within the groups. (Refer to Appendix C for method).
4. Average topographic class was obtained by averaging the topographic class for all buildings within the group as described in Appendix C.

Table 3.2 shows that in Tully and Hull Heads more buildings constructed prior to the 1980s were inspected than Post-80s buildings. At Cardwell, roughly similar numbers were inspected in each class. This somewhat reflects the demographics of the areas.

Table 3.2 Damage Street Survey classification for each locality

	Pre-80s					Post-80s				
Locality	**No**	**avg R**	**avg O**	**avg W**	**avg Topo**	**No**	**avg R**	**avg O**	**avg W**	**avg Topo**
Bingil Bay	69	0.96	0.77	0.23	1.13	129	0.49	0.16	0.05	1.32
Mission Beach	22	2.36	0.18	0.00	1.00	217	0.53	0.06	0.05	1.12
Wongaling Bch	62	0.73	0.15	0.00	1.00	356	0.51	0.10	0.06	1.06
Sth Mission Bch	26	1.12	0.42	0.42	1.23	277	0.45	0.15	0.10	1.58
Hull Heads	32	0.59	0.19	0.00	1.00	14	0.07	0.00	0.00	1.00
Tully Heads	73	1.70	3.71	1.78	1.00	129	0.71	1.28	0.61	1.00
Cardwell	162	1.70	0.49	0.07	1.00	176	0.51	0.10	0.02	1.00
Tully	146	1.08	0.38	0.14	1.27	44	0.43	0.09	0.00	1.73
Total	592	1.30	0.82	0.32	1.09	1371	0.51	0.22	0.11	1.21

Table 3.2 also shows that a greater proportion of Post-80s buildings have been built on sites where topographic effects cause higher winds.

The average Damage Index for Post-80s buildings was significantly lower than that for Pre-80s buildings for both roof and openings damage. There was not as much of a difference for wall damage. This is explored in more detail in Section 3.1.2.

Figure 3.1 shows the EMQ early estimates of housing damage overlaid with this report's estimated wind field. Tully Heads and Hull Heads experienced significant storm surge damage and are covered in Section 4 of this report. The higher proportion of damage to the housing in Tully may be due to the greater proportion of older housing and topographic effects (wind speed up on slopes) when compared to the damage at Kurrimine Beach and Bingil Bay which are estimated to have experienced similar wind speeds.

3.1.2 Performance of Post-80s buildings

As indicated previously, building standards in Queensland's cyclone prone regions underwent a step change in the early 1980s with the introduction of Appendix 4 of the Building By-laws. As a result, buildings constructed since the 1980s would have been built to a very similar level as that required in the current Codes and Standards.

Table 3.2 showed the differentiation between damage sustained by Pre-80s and Post-80s construction. It is further illustrated in Figure 3.2.

Figure 3.2 presents the data for all buildings contained in the Street Survey. The buildings have been subdivided into Pre-80s and Post-80s buildings and the Damage Index is for roofs as detailed in Table 3.1.

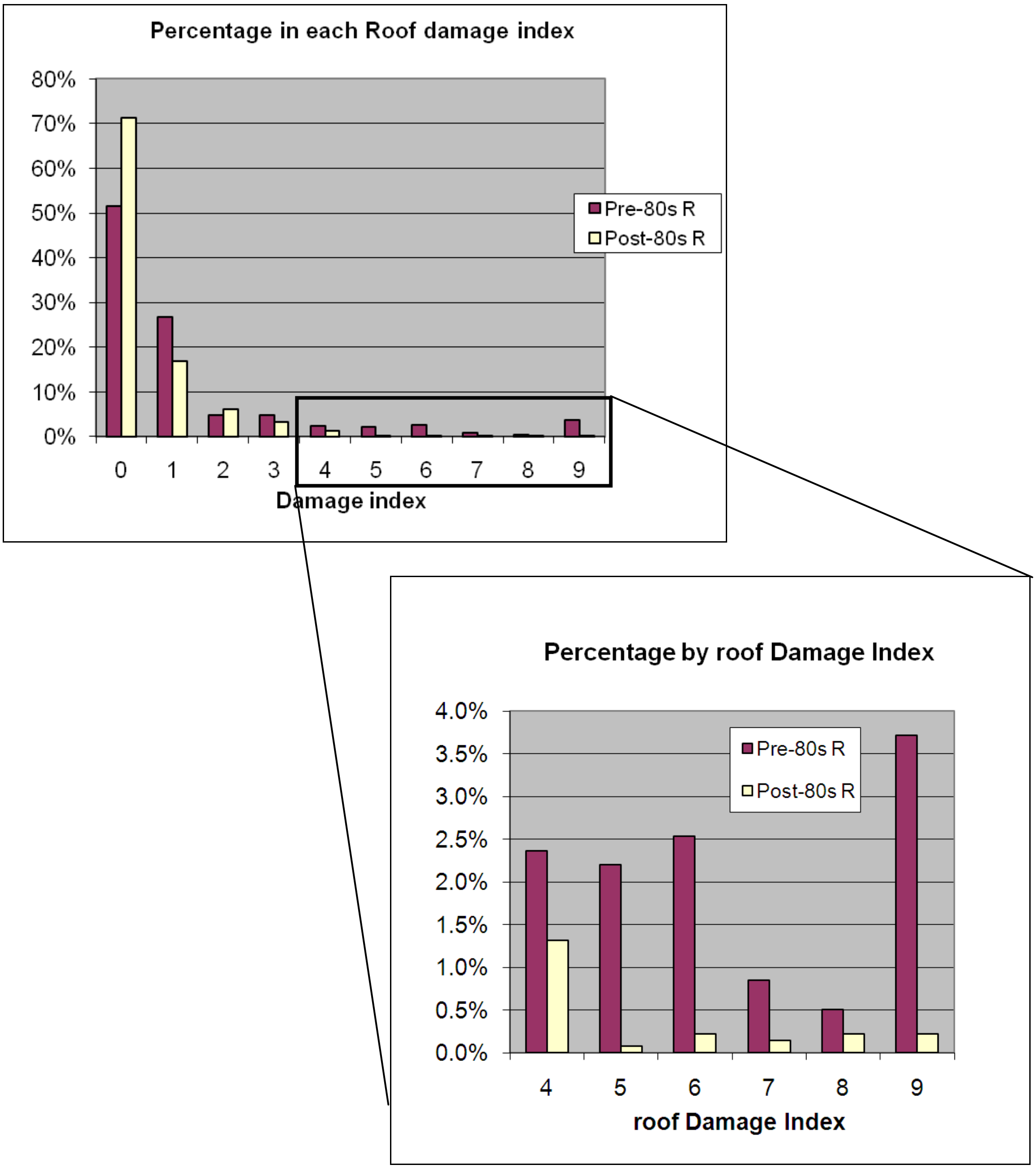


Figure 3.2 Comparison of roof Damage Index by construction era across the study area (Refer Table 3.1 for Damage Index values)

Figure 3.2 shows that just more than 70% of Post-80s buildings sustained no roof damage compared with just more than 50% of Pre-80s buildings. Serious roof damage has an index of four or more, and this region of the graph is highlighted in the inset in Figure 3.2. It shows that Pre-80s buildings have consistently greater frequency of severe roof damage compared with Post-80s buildings.

A student-t test was performed to check that there was a statistically significant level of damage between the two age classes of buildings and Table C.2 shows that it was significant for the entire area at much better than the 5% level, for all three damage indices. Table C.2 shows that the difference was significant at each location at better than the 10% level except for Openings at Wongaling Beach and Walls at Hull Heads, Mission Beach and Wongaling Beach.

Figure 3.3 shows the estimated gust wind speed expressed as a percentage of V_{500}, the design wind speed for Importance Level 2 buildings (the class which includes housing). This figure shows that the area that sustained the highest gusts (South Mission Beach to Cardwell) received approximately 90% of the design wind speed for housing. The percentages indicated in the street surveys of Post-80s houses that sustained a roof Damage Index of 4 or more for each town studied is also marked on the map.

The street survey across the whole study area showed that around 12% of Pre-80s buildings sustained roof damage at Damage Index 4 or more compared with around 2% of Post-80s buildings. This level of damage is consistent with estimated wind speeds of between 80% and 90% of the design wind speeds for houses as shown in Figure 3.3.

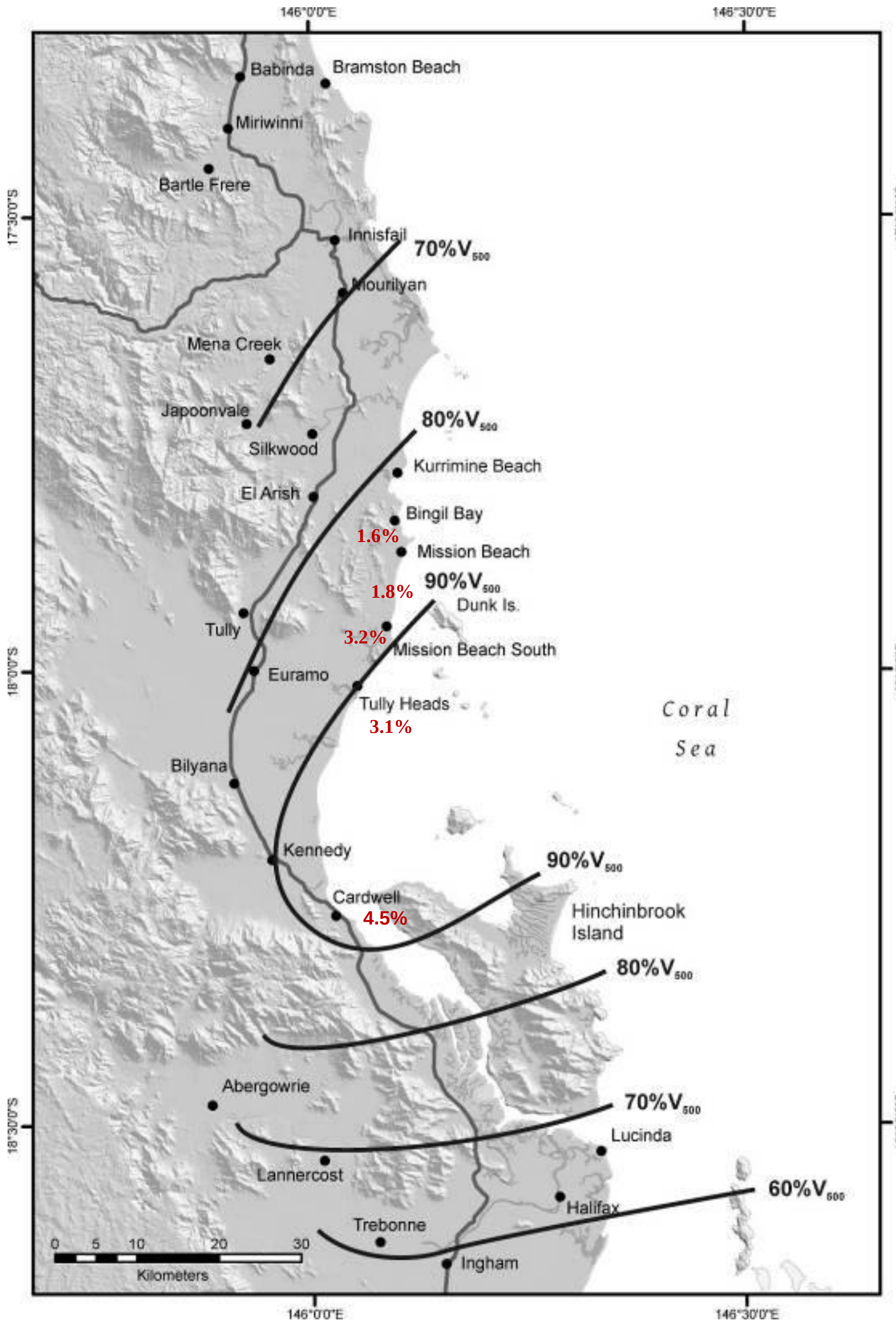


Figure 3.3 Estimated gust wind speed as a percentage of design speed for houses (Map also shows percentage of Post-80s houses in street surveys with roof DI >3)

3.1.3 Effect of topography

Table 3.2 showed that a greater percentage of Post-80s buildings in the street surveys had higher topographic classes than Pre-80s buildings. No Post-80s buildings were assessed as having a topographic class greater than T1 in the towns of Wongaling Beach, Hull Heads, Tully Heads, Cardwell and Upper Murray.

Figure 3.4 shows a comparison between the damage to buildings and their topographic class as derived from AS 4055:2006, in the towns of Bingil Bay, Mission Beach, South Mission Beach and Tully, where there were some buildings in the street survey that were assessed a topographic class of T2 or higher.

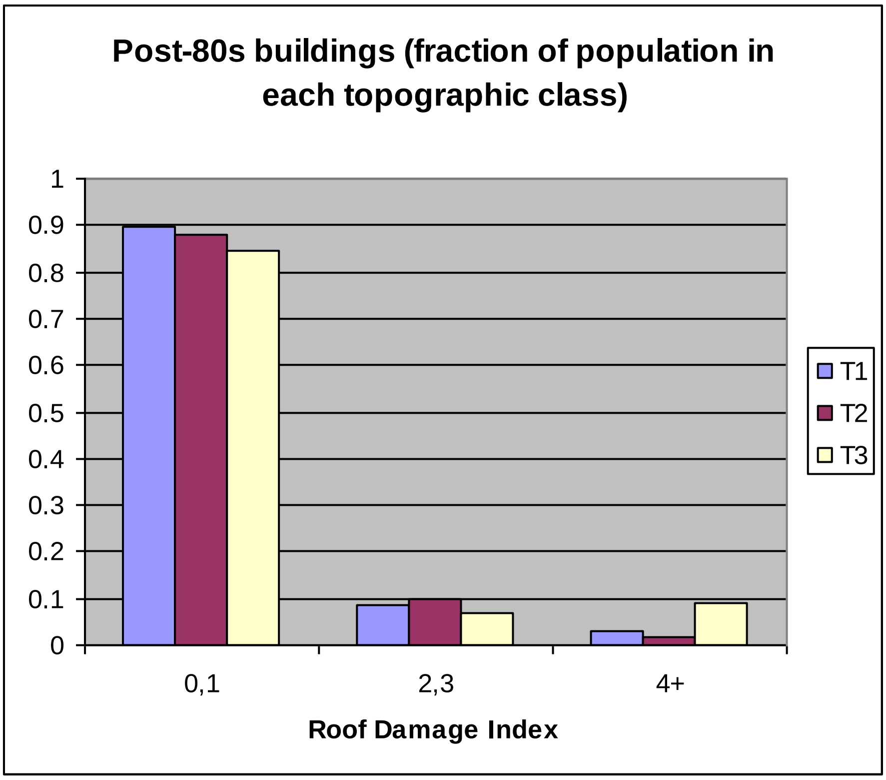


Figure 3.4 Roof damage and topographic class for Post-80s houses (Refer Table 3.1 for Damage Index values)

Figure 3.4 shows that the roof Damage Index for Topography class T1 and T2 are similar, but that for T3, the extent of serious damage (Damage Index 4 or more) is 9% compared with 3% and 2% for T1 and T2 respectively. The incidence of serious damage was 3 times as great on exposed sites compared with normal sites.

Figure 3.5 shows a very similar trend for window Damage Index. The more serious DI for openings (4 and above) shows that around 9% of buildings in Topography class T3 sustained this level of damage, compared with less than 2% for both T1 and T2 Post-80s buildings.

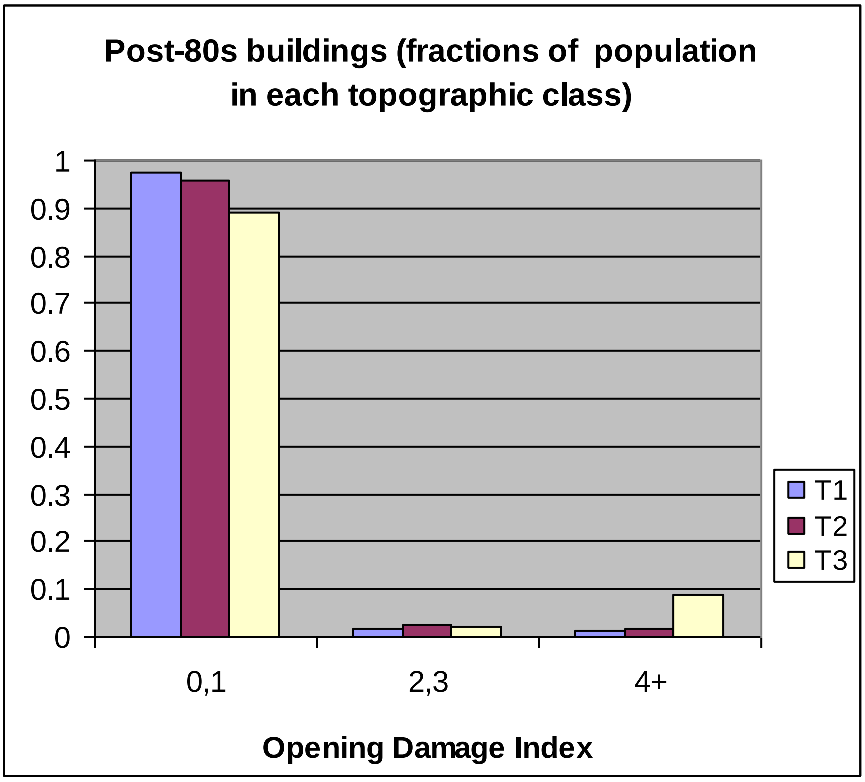


Figure 3.5 Openings damage and topographic class for Post-80s buildings (Refer Table 3.1 for Damage Index values)

3.2 Specific issues in structural damage

While conducting the Street Surveys or while driving through the study area, some buildings were identified as worthy of a more detailed study. In general, it was a single feature of the building or its damage that prompted the greater level of detail in the study.

Where possible in this Section, the individual issues will be related to the output from the Street Surveys to identify the scale of the issues raised.

3.2.1 Repairs following TC Larry

Part of the area affected by TC Yasi also experienced very strong winds in TC Larry (Henderson *et al.* 2006). Figure 3.3 shows the estimated maximum wind gust in TC Yasi expressed as a percentage of V_{500} (the normal regional design wind speed used for houses).

The region around Kurrimine Beach and Silkwood experienced much the same maximum wind gusts in the two tropical cyclones. The town of Innisfail experienced lower gust wind speeds in TC Yasi compared with those in TC Larry, and towns to the south of Silkwood and Kurrimine Beach experienced higher wind speeds in TC Yasi compared with those estimated at the same locations in TC Larry.

The buildings in and around Innisfail and Kurrimine Beach with failures documented by CTS in TC Larry were checked for their performance in TC Yasi. Each building was visited and discussions with the owners or neighbours established where the builder responsible was based and how the repairs had performed. The performance of these buildings was examined separately for the two towns as the conclusions from each must be different because of the different relativities of the gust speeds in TC Larry and TC Yasi.

3.2.1.1 Innisfail

TC Larry gust wind speeds in Innisfail were estimated at between 55 and 65 m/s (Henderson *et al*, 2006), and 60 m/s will be used as a reasonable approximation. The estimated gust wind speeds in Innisfail during TC Yasi were around 45 m/s. This is 75% of the wind speed experienced at the same location in TC Larry and around 56% of the wind load experienced in Larry. Wind directions were different in each of these events, which may have introduced some differences in topography or shielding and hence some differences in multipliers used to determine the appropriate site wind speed. However, the site wind speed at all of the inspected sites was less for TC Yasi than that experienced in TC Larry.

Twenty different buildings in Innisfail had been subjected to detailed assessment of failure following TC Larry. Each of these sites was visited with the intention of evaluating the performance of the repairs under lower wind speeds than the ones that caused the initial damage. In cases where there was damage to the repaired structure, then there was a problem with the adequacy of the repair.

Table 3.3 Effectiveness of repairs Innisfail

Subsequent Repair / Replace / Demolish of original following TC Larry	No	Performance in TC Yasi	Problems caused by repairs following TC Larry
Demolished	4	na	
Replaced	4	Satisfactory	
	1	Damage to roofing	Not fixed in accordance with manufacturer requirements
Repaired	7	Satisfactory	
	2	Damage	Windows not properly fixed Roller door – rails not properly fixed and louvres not properly fixed.
	2	Damage	Door furniture failure

Table 3.3 shows that from the limited Innisfail data available to the study team:

- Replaced buildings had a 4 in 5 success rate from the small sample, and
- Repairs had a lower success rate with 7 in 11 from the small sample.

All of the damage indicated in Table 3.3 was relatively minor as shown in Figure 3.6, but in each case resulted in significant entry of wind-driven water with consequential damage to furnishings and contents.

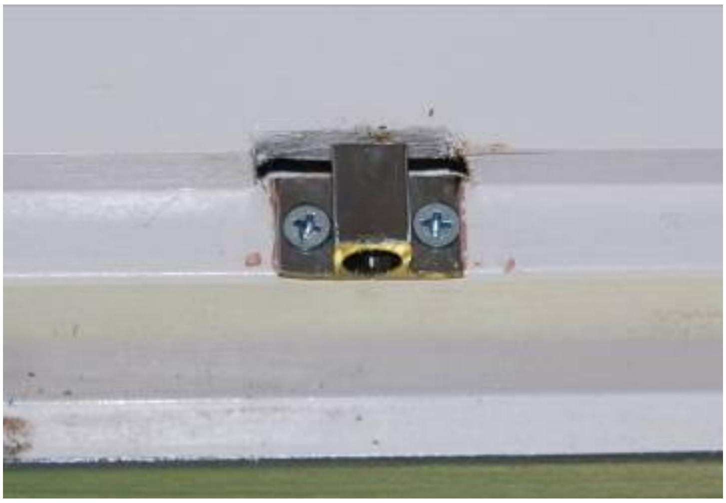


Figure 3.6 Door keeper connections not strong enough (broken screws have been replaced with bigger screws by owner but latch is still too small for wind loads)

3.2.1.2 Kurrimine Beach

The estimated gust wind speed in Kurrimine Beach was around 55 m/s during both TC Larry and TC Yasi. This is within the error bands of the two estimates so the wind speed in the two events can be considered around the same value. Wind directions were different in each of these events, which may have introduced some differences in shielding and hence some differences in multipliers used to determine the appropriate site wind speed. None of the sites inspected required any modification of wind speed to account for topography. Hence the site gust wind speed at all of the inspected sites was very similar in TC Yasi compared with the gust speed in TC Larry.

Eight different buildings in Kurrimine Beach had been subjected to detailed assessment of failure following TC Larry. Each of these sites was visited with a view to evaluating the performance of the repairs under similar wind speeds than the ones that caused the initial damage. The survey results are summarised in Table 3.4.

Table 3.4 Effectiveness of repairs Kurrimine Beach

Subsequent Repair / Replace of original following TC Larry	No	Performance in TC Yasi	Problems caused by repairs following TC Larry
Demolished	1	na	
Replaced	2	Satisfactory	
	2	Damage	Roof batten loss
Repaired	1	Satisfactory	
	2	Damage	Roof sheeting loss Roof batten loss

The sample size in Kurrimine Beach was even more limited than that in Innisfail, but the results show that:

- Replaced buildings had a 2 in 4 success rate from the small sample, and
- Repairs had a lower success rate of 1 in 3 from the small sample.

Figure 3.7 Roof and batten loss for a second time

In Kurrimine Beach, where damage occurred it was greater as the wind speed was higher. In a number of cases there was loss of a substantial part of the roof (for example the house shown in Figure 3.7). Comparative success rates for new construction were higher than those for repairs in both Innisfail and Kurrimine Beach. However, the higher wind speeds experienced in TC Yasi at Kurrimine Beach reduced the success rates of both.

In some cases, the damage to the repaired house originated in a part of the house that had been regarded as undamaged in the previous event. (Figure 3.7 shows the part of the roof that was undamaged in TC Larry, and still had roof battens secured using two nails, while the portion of roof that had been replaced previously used framing anchors.) This underlines the importance of a thorough inspection of all buildings after a cyclone to ensure that there is no hidden damage, and that all parts of the structure have adequate residual strength. (Hidden damage is considered in more detail in Section 3.2.2.2)

3.2.1.3 Mission Beach Area

While no formal attempt was made to examine the repairs to buildings damaged in TC Larry in other areas, in four other cases, when discussing damage to a house with the owner or a friend of the owner, the CTS inspectors were made aware that the damage sustained in TC Yasi was similar to the damage in TC Larry.

Figure 3.8 Same gable lost in TC Larry and TC Yasi

In Mission Beach and the surrounding area, the wind speeds in TC Yasi were higher than those in TC Larry, so the second failure may have been at a higher load than the first. In this case conclusions about the quality of the repair after TC Larry cannot be drawn, so the data for Mission Beach has not been included with the data from the areas with comparable or lower gust wind speed in TC Yasi compared with those in TC Larry.

3.2.1.4 Options for improvement

The results from this limited survey indicate that the performance of repaired buildings was lower than that of newly constructed buildings. This highlights the difficulties of working within an existing structure, and the importance of thorough inspections for damage and for bringing all important structural details to current requirements whether they have been damaged or not.

Some of the repairs inspected were made by the owners, and some by registered builders. Data from discussions with owners and neighbours indicated that owner repairers had lower success rates than registered builders. This indicates there may be a need for more information and training. A number of owners who repaired their own homes made reference to using their “mates” for help with the more technical aspects of the job. Where the “mates” were well versed in the requirements for buildings in this area, they became part of the information path.

Data from our discussions with the owners and neighbours indicated that repairs conducted by builders from within the cyclone region may have had higher success than those based outside it. It is clear that the study used a very small sample compared with the total number of repairs undertaken after TC Larry. A more detailed study of the performance of repaired buildings may establish whether some builder groups had a significantly different success rate than others (for example registered builders as compared to owner repairers, or builders located within the cyclone area compared to those located outside of it).

This information will make it possible to better target information dissemination programs to improve the performance of repair and rebuilding.

3.2.2 Performance of Pre-80s buildings

Houses types are defined by construction era, which also correlates with the style of construction. A study carried out by Henderson and Harper (2003) categorized the house stock in the cyclonic areas of Queensland and assessed their vulnerability to windstorms based on style of construction and age. Damage investigations carried out after TC Larry (Henderson *et al*, 2006) clearly showed that the Post-80s houses suffered less damage and this has also been demonstrated in for TC Yasi.

3.2.2.1 Types of Pre-80s houses

The types of Pre-80s houses are indentified and their general performance discussed in this section.

Pre-1950s Queenslander

A common style of this era was a central square core with verandahs on two or three sides. The house was supported clear of the ground on stumps. The roof of the core is high pitched and often pyramid shaped with no ridge-line. Roof framing consists of rafters spanning from the top plates of the core walls to the apex or ridge. The roof of the verandahs has a lower pitch. Wall framing was mortice and tenon construction. Generally, walls were clad only on the inside of the frame using vertical joints (VJ) boards. This VJ lining plays a significant role in providing tie down for the roof structure against wind uplift forces, by extending from bottom wall plate to top wall plate. In addition, some boards continue upwards, being fastened to an over-batten on top of the rafter and directly over the wall, and downwards to the subfloor where it was fastened to a joist or bearer. Usually, the only bolts included in the construction were used to attach the bearers to timber stumps.

From the 1930s to the 1950s, houses became larger, but the construction technique remained much the same. They were no longer square, or even rectangular, in plan which resulted in complex roof shapes with multiple hips and gables. External cladding was introduced at this time (usually timber weatherboards). Some houses have cyclone rods, mainly in the corners.

1950s and 1960s Houses

In the post war era, VJ timber lining became un-economical and was replaced by flat sheet internal lining material. This was easier to fix and provided a smooth surface for painting, but had lower structural strength compared to VJ lining. In these houses cyclone rods are present in perimeter walls at about 3 m spacing. Alternatively, a specific number of rods were stipulated for a house. In some cases, the rods were extended to over-battens, but the holding nuts interfered with the roofing and hence were often embedded in the batten, weakening it severely. These houses still had large often irregular, floor plans. Their roof structure generally featured a high ridge-line, and weatherboards were often used as external wall cladding. Mostly these houses were high set, with sufficient room underneath for some habitable rooms.

1960s and 1970s Houses

In the pursuit of reducing construction costs further, houses became simpler and smaller. A typical house of this period was of rectangular shape, timber framed, elevated on stumps about 2.5 m high, with external walls clad with fibre-cement or timber weatherboards and internal lining of either hardboard or plasterboard. The roofing was usually metal sheeting on a relatively low to flat pitch. This period also saw the introduction of single storey brick veneer construction.

Simple joints were used in the frame construction, and tie-down rods were installed regularly in these houses. The very low roof slope excluded the use of tiles, and roof slope was often achieved with graded purlins. Damage caused to these types of houses during TC Althea (Townsville 1971) and TC Tracy (Darwin 1974) introduced awareness for wind resistance in house design (Walker, 1975).

3.2.2.2 Damage to Pre-80s houses in TC Yasi

Section 3.1.2 has shown that there was a statistically significant difference between the structural performance of Pre-80s houses and Post-80s houses. The higher levels of damage to Pre-80s houses were most obvious in the towns of Tully where gust wind speeds were around 80% of the design value for housing and Cardwell that experienced maximum gusts near 90% of the design wind speed for housing. However, the same trend was also seen where the wind speeds were as low as 50% of the design wind speed for housing.

In some cases, the creation of a dominant opening on the windward wall (from wind pressure or windborne debris impact) and the resultant high internal pressures were responsible for the failure of roofing components. Inadequate design or deteriorated connections were generally evident in most of the failures of Pre-80s houses.

In some cases, older houses had been partially renovated. In most of these, new roof cladding was attached to battens in accordance with current standards (such as AS 4040.3:1992 or BCA). However, the batten to rafter connections, and the rafter to wall plate connections were rarely upgraded using HB132.2:1999. Any weak points in the roof hold-down chain remained after the partial upgrade, and the house continued to have a high possibility of failure of large parts of the roof (at the weak batten-rafter connection) at wind speeds significantly less than design wind speeds.

Figure 3.9 shows a high-set fibre-cement 12 m x 8 m house in Townsville where peak gust wind speeds were estimated as 55% of the V_{500} wind in AS/NZS1170.2:2002, with a low slope corrugated steel roof cladding fixed every 4^{th} corrugation with one 75 mm nail to 75 x 40 mm battens spaced 900 mm apart. These battens were nailed with two 75 nails to 125 x 50 mm rafters spaced 1100 mm apart. The failure of a glass pane created large positive internal pressure pushing-in the ceiling access-hole and lifting all the battens with the cladding attached and depositing it approximately 25 m downwind. The member sizes and spacings were appropriate for the estimated wind loads, but the connections were not.

Figure 3.9 Batten to rafter failure at 55% design wind speed

Figure 3.10 shows an ocean front 11×6.5 m flat roofed house in Cardwell which experienced winds near 90% of the design wind speed. The 11m wall, facing ocean exposure, consisted of louvered windows “protected” by steel mesh and a single door entrance. The aluminium roof cladding was screwed with cyclone washers to 75×50 mm timber battens spaced 1000 mm apart and fixed to 125×50 mm timber rafters by two 75 mm nails. The rafters spanning across 6.5 m to the walls and spaced 1200 mm apart were fixed to the external and internal wall top plates by 4 nails.

The roof structure suffered significant damage. The failure of the door lock for winds normal to that wall created a dominant windward opening and generated large internal pressure which contributed to the failure of the entire roof. A significant part of the roof travelled a distance of about 100 m downwind over neighbouring houses and impacted a 2-storey recently constructed house damaging its envelope. Figure 3.11 shows parts of the roofing with battens still attached that impacted the new house. As for the house in Figure 3.9, the weaknesses in this house were the connections. Member sizes were adequate, so had the connections been upgraded, the roof structure would have been sufficient to resist the estimated wind loads. This house had metal screens over the windows, but still was exposed to internal pressures from dominant openings because of failure in door furniture.

Figure 3.10 Roof loss after door failure

Figure 3.11 Roofing with battens attached from house shown in Figure 3.10

Figure 3.12 shows a damaged Pre-80s house that has experienced batten loss. It is typical of a number that were seen in which the roofing had been replaced since the 1980s but the batten to rafter connection was not upgraded at the time the sheeting was replaced. Houses from a similar period can be seen in the background without any significant damage.

Figure 3.12 Batten loss

Figures 3.13 and 3.14 show some of the older houses that appear to have sustained only minor or negligible structural damage. There are a number of reasons for this;

- In most cases, the envelope of the house was intact and hence resulted in low internal pressures or considerable venting occurred e.g. via large vented eaves etc
- In some cases the relevant roof structure upgrades had been performed.
- In other cases there was a favourable orientation of the house and/or shape of the roof to approaching winds.
- In few cases reduced local wind speeds (due to shielding, terrain or topography) may also have been factors.

Figure 3.13 High exposure site with minimal damage to Pre-80s house

Figure 3.14 mixed performance of Pre-80s housing

Hidden damage in a structure that externally appeared undamaged in the form of separation of some of the battens from rafter within the roof was observed in TC Larry (Henderson *et al.* 2006). As the battens had not separated from the rafters, the damage was not obvious from an external examination, and it did not become apparent until several months later during reconstruction. Evidence is mounting following TC Yasi of cases with partial separation of the battens from the rafters in roofs, which look fine when viewed from the outside (see also Section 3.2.8.1). The presence of this type of damage can only be detected by a roof space inspection. If not repaired, this type of partial damage may precipitate early failure in a future severe wind event.

3.2.2.3 Consequences of the damage

Many towns (such as Tully) have a housing stock that is dominated by Pre-80s houses. The higher levels of damage sustained by this type of housing means that the total relative damage sustained by these communities is higher. The damage to those buildings compromised the safety of those communities during the event and increased the demand for sheltering in community evacuation centres. The demand on reconstruction services will be higher and the recovery task in these communities is also higher.

It was also seen that the loss of significant areas of roofing also released some high mass debris into the air stream which caused further damage to buildings down-wind of the initial failure.

3.2.2.4 Options for improvement

The main reasons for the failure of the Pre-80s buildings at loads less than the current design load can be addressed by inspection, maintenance and upgrading of these buildings:

- Roof space inspections should be undertaken to detect partial failure of batten to rafter connections. These inspections should be performed on all buildings that have experienced high winds even if they appear to be undamaged.

- Where designs have not taken into account internal pressures from a dominant opening, the use of tie-down details presented in AS 1684.3(2010) will improve performance in future events. Use of optional robust window shutters (see Section 3.2.10) will offer some level of protection to windows as well.
- Where there has been deterioration of connections or members, this should be detected during the inspections. For example, whenever the roof cladding is removed (e.g. for replacement), the whole roof structure should be inspected and members or connections in which deterioration is found should be replaced.

These steps will improve the performance of any Pre-80s houses in regions C and D. The investigation has demonstrated that housing of this era is more vulnerable than Post-80s houses, so the resilience of these houses to future events can be improved by taking these steps on all Pre-80s houses. Information on upgrading structural performance in Pre-80s houses can be found in Standards Australia Handbook HB 132.2.

3.2.3 Window and door performance

Overall, little wind damage was observed with windows and doors in both Pre-80s and Post-80s houses – a result expected with estimated gust wind speeds less than the design wind speeds. The failures observed were:

- Window glass breakage from either wind pressures or debris impact.
- Window or door frame separation from the building.
- Failure of furniture used to secure the door or window closed allowing it to open during the high winds.

3.2.3.1 Glass failure

Wind-borne debris noted in TC Yasi included a large range of building elements from individual roof tiles to whole roofs. Unprotected glass showed some debris failure as shown in Figure 3.15.

Figure 3.15 Broken window due to concrete roof tile impact

Figure 3.16 shows two separate types of window failure:

- The sliding door panels had become disengaged from their tracks. It appears that the window glass was not broken until the panels hit the floor as the tinted glass from these panels was still within the panel frame.

- The side windows of the unit (visible just to the left of centre of the photograph) had both had the glass broken. None of the broken glass was inside the unit, it was all outside indicating that the glass had broken under the differential pressure from the inside to the outside of the building.

In both of these cases, there was no sign of any debris impact. Both types of failures had been caused by differential air pressure.

Figure 3.16 Sliding door and window glass failures

There were some other cases reported where window glass that was protected by undamaged security screens failed due to high wind pressure.

3.2.3.2 Separation of frames

Window and door frames must be securely anchored to the building fabric to ensure that the building envelope is secure. Where the window or door frame became separated from the building, a large opening was created. In some cases the large opening led to other failures.

Figure 3.17 shows a modern house in an exposed location in which a number of window frames on the side wall (aerodynamically) of the building were sucked out of the building. A failure of some window glass under wind pressure on the windward wall allowed internal pressurization of the building that contributed to the failure of the large frames. This house was in a very exposed location and the frames should have been anchored against the required higher pressures.

Figure 3.17 Loss of window frames under differential pressure

Two complete timber casement window frames detached from the supporting frame and were blown in on a Post-80s house as shown in Figure 3.18. The connection between the timber window frame and the timber house frame was inadequate. The failure of the windows resulted in significant water ingress.

Figure 3.18 Window frame failure due to inadequate anchorage

3.2.3.3 Door and window furniture

There were a number of observed cases where door and window furniture failure meant that a previously closed door or window became an opening. This furniture included latches, bolts and hinges. These items are not traditionally thought of as structural elements, but are crucial to the satisfactory performance of the building envelope.

The double solid entrance doors in Figure 3.19 were rebuilt after TC Larry and close a substantial opening. The fixing at the centre is by a barrel bolt top and bottom. The screws securing the keepers for these bolts all failed (see Figure 3.6) and allowed the doors to swing inwards. In this case the load on the doors was substantially less than the design loads on the house. Significant water damage followed the failure of the door latch.

Figure 3.19 Door furniture failure

While this detail was very simple, a similar sized opening with semi concealed barrel bolts in a pair of solid doors failed because the bolts broke out of the door under lateral loading as shown in Figure 3.20. There did not appear to be any contributing impact damage on the doors. The swinging of the now unrestrained doors contributed to one the doors tearing off its hinges. In both of these cases, the failure of the furniture contributed to a dominant opening in the building envelope.

Figure 3.20 Door bolt and hinge failure

Figure 3.21 shows a door furniture failure that caused damage to the entire hollow core door. Here the forces on the lock had pried the inner and outer faces away from the frame.

Figure 3.21 Failure of door around the lock

These failures demonstrate that dominant openings can develop following damage to fittings not often regarded as structural elements.

The investigation also found window furniture failure associated with locks and movement of windows within frames. Figure 3.22 shows a sliding window that had been lifted by the applied wind pressure, causing it to become jammed in the opening. While it did not create a large opening, a narrow opening (highlighted by the pen) will contribute to water ingress.

Figure 3.22 Jamming of window in the frame

Figure 3.23 shows some catches that opened during the maximum winds without causing any permanent damage to the latch, the window or frame. The latch may have opened due to flexing of the Western Red Cedar timber frame. On some larger Western Red Cedar doors, the flexing had cracked the glass.

Figure 3.23 Window latch disengagement

3.2.3.4 Consequences of window or door damage

Damage to window and doors during cyclones can create a dominant opening and allow large internal pressures that may lead to the failure of the roof system. Figure 3.24 shows a building in which windows 7.7m wide were blown in. The loss of windows allowed the wind to internally pressurise the units causing loss of the roof cladding and failure of the first internal beam connection to the wall.

Figure 3.24 Consequences of window failure

The structural design principle of robustness AS/NZS 1170.0(2002) indicates that the consequences should be related to the initial failure. The principle of robustness implies that:

- It is reasonable to expect to replace a window after it has failed.
- It is not reasonable to expect to replace the whole roof after a window has failed.

Even in cases where openings are protected, the failure of door or window furniture under wind loads can lead to the development of a dominant opening. Dominant openings cause significant increases in loads on other elements in buildings.

Even where windows failure did not cause damage to the roof system, evidence of substantial water ingress through these openings was observed in the investigation. Consequences of water ingress itself are investigated in Section 3.2.11.

3.2.3.5 Options for improvement

Because doors and windows are part of the building envelope they are important elements for separating internal and external pressures in buildings. They should be designed to resist the differential pressures that may exist across them. This includes not only the glazing, but also the frame and any furniture that secures opening panels.

However, the study has demonstrated that they can be damaged by impact from wind-borne debris or blow open due to failure of fittings/furniture and so in order to ensure that the building as a whole remains robust, the structure should be designed to remain intact in spite of the development of a dominant opening by failure of a door or window.

3.2.4 Large Access Doors Including Roller Doors

Roller and sectional doors were the most common types of large access doors seen in this investigation. Other types of doors are also briefly discussed. The focus is primarily on doors in residential garages and sheds but the discussion is also relevant to large doors in most other buildings.

Large access doors are doors that cover large openings for vehicular access. In the study they were most commonly used in garages or in commercial and industrial buildings. A few large access doors were also used in community buildings, sports halls and assembly halls.

Four different types of large access doors were observed in the study and are illustrated in Figure 3.25.

- The most common was the roller door which was used in garages and in light industrial buildings as well as public buildings such as community centres.
- Sectional doors (panel type doors) were only used in garages.
- Tilt doors were less commonly seen in this investigation.
- A few large, side-hinged doors were observed. These were only seen in industrial sheds and hangars.

(a) roller door (b) sectional door

(c) tilt door (d) side-hinged door

Figure 3.25 Illustrations of large access doors.

Previous reports on wind damage in cyclonic and other high wind events have reported on the generally poor performance of large access doors (Henderson *et al*, 2006; Leitch *et al*, 2009).

The Street Surveys showed that across the study area, less than 3% of Post-80s housing sustained significant roof damage. This can be compared with 6% of sectional doors that were damaged and 29% of roller doors. The discrepancy in performance of the roller doors is significant.

Failures in roller doors were observed throughout the entire study area where estimated gust wind speeds ranged from 70% of the design wind speed to over 90% of the design wind speed (equivalent to a range of 50% to 80% of the design wind pressure). While doors are not specifically mentioned in the Building Code of Australia, it is a requirement of the BCA that all parts of the building envelope including cladding, windows, personnel and other doors are designed and installed to resist the design wind pressure in the specific location.

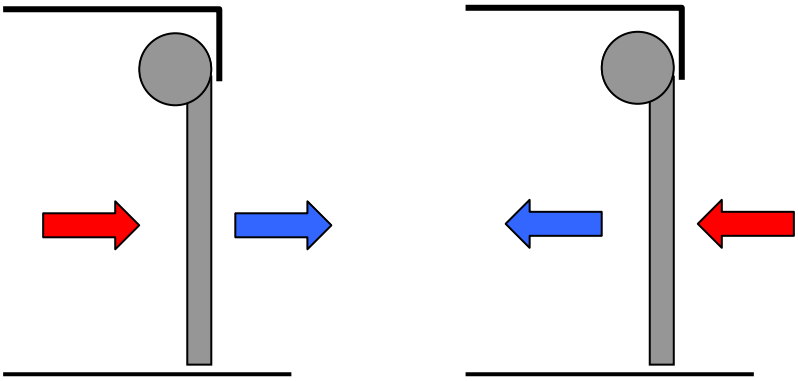
The evidence of poor performance of doors has been evident in post disaster damage investigations by the CTS, suggests the BCA requirement is not being correctly interpreted and addressed.

3.2.4.1 Forces on Doors

There are some simple principles that are relevant to the ability of all doors to resist wind pressures. One of the most important is that a door is likely to experience similar inward or outward pressures in a cyclone and this is also true for other severe wind events such as thunderstorms. These pressures are illustrated in Figure 3.26:

- A combination of positive internal pressure and negative external pressure is illustrated in Figure 3.26 (a), and may arise if the door is on a leeward or side wall.
- A combination of negative internal pressure and positive external pressure is illustrated in Figure 3.26 (b), and may arise if the door is on a windward wall.

The forces on the door are approximately equal in magnitude for the two scenarios illustrated. The door must be designed to resist these forces in both directions.



(a) net outward pressure (b) net inward pressure

Figure 3.26 Net pressure across large access doors

3.2.4.2 Roller Door Performance

The most common failure mechanism observed in TC Yasi was disengagement of the door from its tracks. This left the door free to flap in the opening and in some cases caused other damage to the structure.

Many roller door failures were observed in which the door had become first disengaged from the guides, then detached from the drum and become wind-borne debris. Figure 3.27 shows a door that has damaged the roof of the shed (highlighted with the red ellipses) after becoming disengaged from the guides and then detaching from the drum.

Figure 3.27 Roller door detachment from drum

It was observed that roller doors that incorporated wind locks to restrain them in the guides offered better performance than those that did not have these devices. However, some failures of large doors where wind locks had been fitted were observed, but in most of these cases, the doors had torn the guides away from the rest of the structure as shown in Figure 3.28.

Wind locks anchor the edges of the door curtain to the guides and enable the deflected door to develop in-plane tensions. The deflected door uses bending and catenary action to carry the wind forces to the sides of the opening. The tension force develops secondary forces in the guides that must be successfully transitioned to the rest of the structure and safely carried to the ground. Where wind locks are used, it is essential that the guides and the supporting structure are designed to accept the large lateral forces (forces in the plane of the door) than can occur in a severe wind event.

Figure 3.28 Roller door guide failure

Another failure mode for roller doors fitted with wind locks or supported with struts involved generation of cracks in the door itself. The combined tension and bending in the door curtain and the repeated loading can lead to the development of cracks.

Figure 3.29 Failure of door curtains under repeated combined bending and tension loads

3.2.4.3 Sectional Door Performance

The Street Surveys indicated that sectional or panel-type doors that are used commonly in house garages had a significantly lower failure rate than roller doors in similar applications. One advantage of sectional doors in resisting wind loads is that each panel is rigid, having reasonable inherent stiffness and depth. Performance can be further enhanced by adding battens or other stiffeners to the inside of each panel but it should be noted that this is best done by the manufacturer, as the springs in the door mechanisms are reasonably sensitive to the mass of the door. Most of the sectional doors observed during the detailed inspections had these stiffeners.

Figure 3.30 shows a sectional door that had failed after being struck by debris. The failure was caused by disengagement of the door rollers from the guides.

Figure 3.30 Sectional door failure after debris impact.

3.2.4.4 Consequences of Large Access Door Failure

Failure of large access doors created a large opening in the building envelope. In most buildings, this opening became a dominant opening, and would have dramatically influenced the internal pressure:

- Few cases of failure of house roofs following the failure of a garage door were found in this investigation.
- However, in a number of cases, sheds suffered consequential cladding damage following a roller door failure.

3.2.4.5 Improvement of Large Access Door Performance

Large access doors are part of the envelope of the building to which they are fitted. They must therefore be designed and installed to resist the appropriate wind pressures. The current poor performance in an event that had lower wind pressures than the design event indicates that many manufacturers need to develop stronger door systems.

Wind locks demonstrated that they were able to prevent the main failure mode of roller doors – disengagement from the guides. However, they may develop other failure modes. They place large lateral forces on both the door curtain and the guides as the door flexes and put the wind locks in tension. The shape of the deflected door can mean that these tension forces are much larger than the ones parallel to the direction of the wind. The configuration of the door and its fixings can affect the loads that must be resisted by the remainder of the building structure. The curtain must also be able to resist the repeated bending and tension stresses developed by the door anchored by the wind locks.

Other systems such as temporary braces must be developed for strengthening existing doors. Some occupants used their cars to brace their large access doors in TC Yasi. This method really only resisted inward acting forces, but separate bracing systems should be developed to offer resistance to both inward acting and outward acting forces.

These systems will rely on occupiers correctly installing them prior to the wind loads so that they can support the door under wind actions. Braces can be horizontal or vertical but in either case, care is needed to ensure that points of attachment are capable of accepting the forces involved and engineering guidance is appropriate.

A large number of large access doors failed in TC Yasi. As these doors have demonstrated that they cannot resist winds lower than the design winds, the damaged doors should be replaced with stronger doors rated to the pressures developed by the design wind.

Correct performance of these doors relies on effective communication between engineers, building designers, door suppliers and door manufacturers:

- The wind classification for the building site must be established in accordance with AS/NZS 1170.2 or AS 4055 and be communicated to the door supplier.
- Manufacturers must have designed and tested the features of their doors to resist specific wind load requirements and have marked each door with the wind rating of the door.
- Suppliers can therefore match wind requirements for the site with wind capacity and certifiers can check that the door has an appropriate rating for its role in the building.

To facilitate this process, AS/NZZS 4505 must be aligned with AS/NZS 1170.2. Incompatibilities have been identified between these documents.

Section 3.2.10 indicates that all Region C and D low-rise structures will satisfy robustness provisions if designed for dominant opening internal pressures. Hence internal pressures obtained from dominant opening assumptions should be used in determining the wind requirements for large access doors. A number of cases were observed in TC Yasi where side windows on garages had failed and the roller doors had been lost. Similar observations were made in other recent events.

While these options have been presented in the context of damage caused by TC Yasi, they apply for all large access doors in Wind Regions C and D. Damage to doors has been observed in all recent major wind events.

3.2.5 Tiled roofs

Damage to concrete and terracotta tile roofs was observed in some parts of the study region. Figure 3.31 presents an analysis of the Street Survey data which shows that damaged tile roofs are over-represented when compared to metal clad roofs for houses of similar age and location. The survey results clearly show the higher rate of failure of tiled roofs associated with elevated and exposed building locations. The Australian Standard AS 2050-2002 “Installation of roof tiles” specifies that every full tile shall be mechanically fastened for AS 4055 wind classification C2 and C3 and states that for higher wind classification refer to manufacturer’s specifications. No specifications for fixing of roof tiles in region C4 are provided in the technical manuals published by the major tile suppliers.

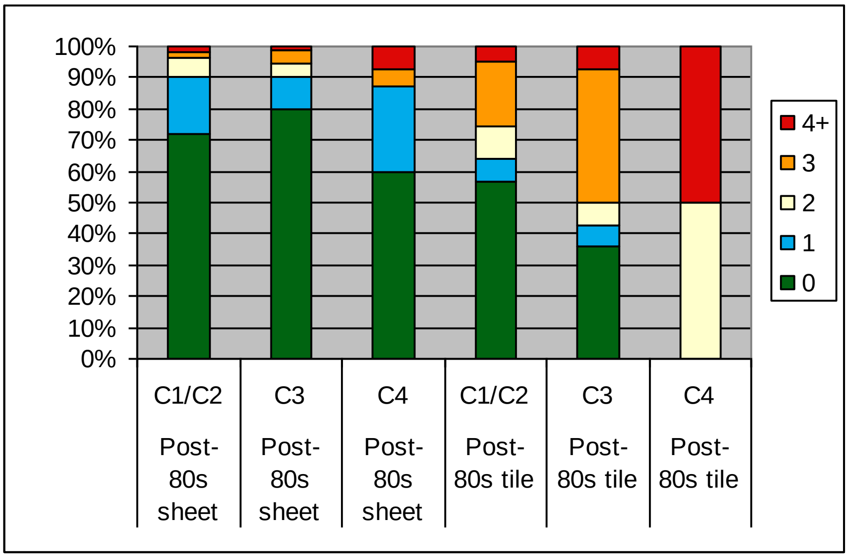


Figure 3.31 Roof Damage Index for Post-80s houses (Refer Table 3.1 for Roof Damage Index values)

3.2.5.1 Tile clips on normal roof tiles

Of the few opportunities that were available for inspection of damaged tile roofs, the inspections showed tiles clips generally in place with missing or dislodged tiles. The damaged tile roofs that were inspected were all sarked, as per building requirements.

One notable example was a tiled roof house in an exposed location that had the tile roof replaced after Cyclone Larry due to tile roof damage only to have lost a major portion of the tile roof following Cyclone Yasi. Figure 3.32 shows the original stainless steel clips still in the battens next to the heavier gauge galvanized clips installed for the re-roof after Cyclone Larry. A neighbouring tiled roof house also suffered loss of tiles.

Figure 3.32 Failed tile roof with clips from initial installation and an upgrade

3.2.5.2 Ridge tiles

A number of damaged tile roofs had lost ridge (both apex and hip) capping. An example of a house in a C2 site is shown in Figure 3.33. On this house and on most that had lost ridge capping, no mechanical fixings such as clips or screws on the ridge tiles were observed. The fixing method appeared to be the flexible pointing adhesive. The dislodgement of the ridge or other tiles generally led to additional damage to the tile roof and to adjacent structures. The barge tile fixings can be seen still in the fascia.

Figure 3.33 Failure of ridge capping

3.2.5.3 Consequences of tile damage

Where tiles were dislodged, they frequently became wind-borne debris. This debris often caused damage to other parts of the same roof or windows on the tiled building and in some cases, impacted on neighbouring structures. The damage caused by tiles as debris is outlined in Section 3.2.10.

Loss of tiles causes debris damage to the same roof and this can put holes in the sarking and allow water to enter the ceiling space. Most houses with damaged tile roofs showed water damage to ceilings below the tile damage as illustrated in Figure 3.34. The inset shows the area above the ceiling damage on leeward side of roof where damage was caused by wind-borne tiles from the same roof.

Figure 3.34 Ceiling damage under tile damage

3.2.5.4 Options for improvement

The higher levels of damage sustained by Post-80s tiled roofs indicate that there are some issues that need to be resolved. In particular:

- It was observed that ridge capping was not anchored using mechanical fasteners such as clips or screws. The use of flexible adhesive fixing systems does not appear to have been successful in resisting the cyclonic winds particularly at C3 and C4 sites.
- It is only full tiles that are required to be fixed in manufacturer’s recommendations, yet under the hip lines, each tile is cut and therefore not fastened. This area of the roof experiences high suction, and ridge adhesive systems glue the ridge to these unsecured tiles. A number of cases of damage at the hip lines were observed and manufacturers will have to revise their recommendations in this area.
- High exposure sites had significantly lower tile performance. Section 3.2.8 presents comments on buildings in exposed sites; however, the problems on exposed sites with

tiled roofs are significantly greater than those in Post-80s sheet roofs on exposed sites. A close examination of tile anchorage in very exposed sites is necessary.
- In the event of tile damage, the tile could bend the clip or slide out from under it, and become wind-borne debris. Fastening systems that do not allow detachment of damaged tiles would prevent these tiles from causing further damage to the same roof or to nearby structures.

Tile anchorage systems use elements that could be sensitive to fatigue under wind actions. Some tiles may “wriggle” free under the actions of successive gusts. The intent of clause 2.5.5 in AS/NZS 1170.2 is that all cladding systems that may be subject to progressive deterioration under load and unload cycles should be tested for their resilience under simulated cyclonic loading. Tiles and tile anchorage systems should demonstrate that they can resist load sequences such as those presented in AS 4040.3 or the BCA. This demonstration should apply for all aspects of tiled roofs including:
- Full tiles in the body of the roof
- Ridge tiles
- Barge tiles
- Cut tiles along the edge of a hip

These were all areas in which tile damage was observed in TC Yasi.

This type of demonstration of performance needs to support the recommendations for fixing tiles that are published in Standards or in manufacturer’s information for all Wind Classifications.

There are some areas of AS 2050 that may require some revision:
- Clause 2.3.1 in AS 2050 indicates that some flexible pointing material can be marked as “*adhesive mechanical fastening*” and used to anchor tile elements. However this seems at odds with note 1 under Table 4 which states “*In most instances of mortar bedding and pointing, a truly long-term adherent bond does not exist.*” The evidence of lost ridge capping in TC Yasi would support the note rather than clause 2.3.1.
- Table 4 allocates the same fixing requirements to N3 and C1. These wind classifications share the same design velocity, but the internal pressure used in C1 should be significantly more than that in N3. Thus the anchorage requirements for C1 should be higher than those for N3.
- Clause 3.3.2 allows a reduction of one wind class for the use of sarking under the tiles. It is a requirement that all tiled roofs in the cyclone areas be sarked, so this is in effect a reduction in the wind classification of all tiled roofs in the cyclone region. The higher levels of damage to C3 and C4 tiled roofs suggest that such a reduction in anchorage requirements is not appropriate.

These issues should be referred to the relevant Standards committee for decisions.

3.2.6 Sheet roofs

Overall, metal roof cladding, which includes metal roof tiles as well as continuous sheet cladding such as corrugated and rib-pan profile, performed well. The vast majority of cladding remained attached to the roof battens. This should be expected as the estimated wind speeds were less than design loads.

Attachments such as flashings and guttering are discussed in Section 3.2.9. Failures of batten to rafter connections are discussed in Sections 3.2.2 and 3.2.8.

3.2.6.1 Fatigue in sheet roofs

The roof of a low-rise building experiences both the large wind loads and also large fluctuations in the load over time in sustained strong winds. The combination of internal positive pressures with negative external pressures has already been cited in this report as initiating roof structure damage (see Section 3.2.2). Investigations in the aftermath of Cyclone Tracy in Darwin found that low-cycle fatigue cracking of metal roofing and the disengagement of the sheet through the fastener heads typically initiated failures in the sheeting itself (Beck and Stevens, 1979).

The fatigue loading test criteria, Technical Record TR440 (1978) was developed to enable manufacturers to test their product's suitability for use in cyclonic regions. TR440 formed part of the stringent standards that have been applied for contemporary housing constructed since the early 1980's, in cyclonic regions of Queensland. This has been superseded by the Low-High-Low (L-H-L) test regime defined in the BCA since 2006, which requires the metal roof cladding to withstand a cyclic load regime that has increasing then decreasing pressure cycles approximating the passage of a cyclone. This repeated loading criteria test uses the design wind loads calculated from AS/NZS 1170.2 (2002).

A few cases of fatigue damage to cladding adjacent to fasteners were observed. However in all the observed cases, the damage was because the fastener spacings were greater than manufacturer specifications. Figure 3.35 shows an example from a re-roofed shed with fastener spacing 50% greater than the recommended spacing for the product used. Figure 3.36 shows detachment from fasteners in a modern detail with no flashings and with edge fixing too far from edge.

Figure 3.35 also shows that some fasteners have broken out of the side of the timber purlin. With only partial embedment, these fasteners did not have the necessary holding strength as and would have caused the adjacent fasteners to be overloaded.

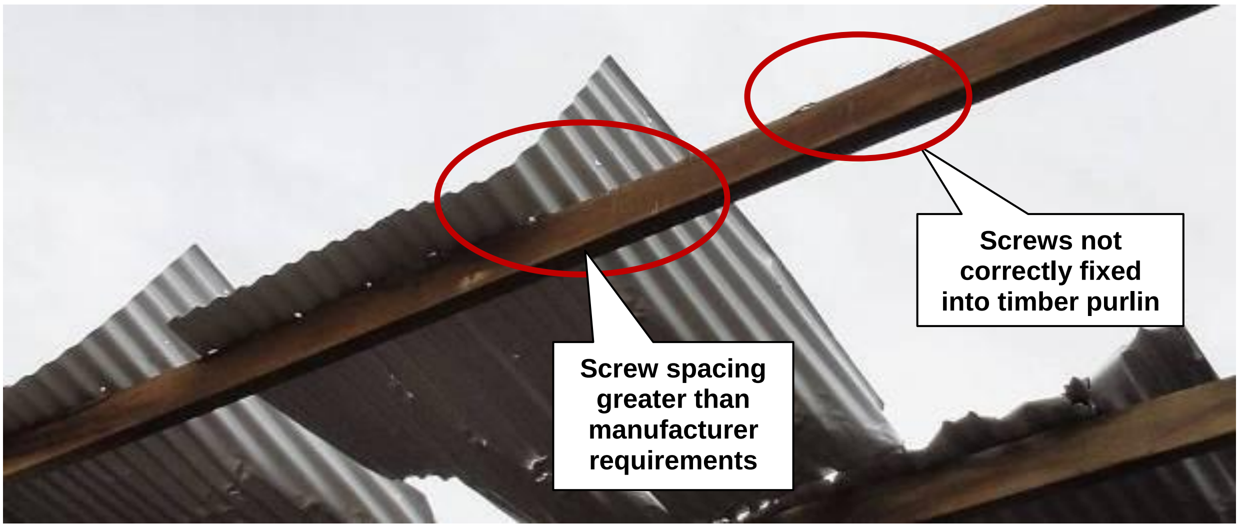


Figure 3.35 Large fastener spacings led to fatigue failures of sheeting

Figure 3.36 Large edge distance led to fatigue failures in sheeting

Several undamaged roofs across the study area were visually inspected for signs of onset of permanent deformation such as creasing and dimpling, which can be precursors to fatigue damage. No observed deterioration was noted in this limited inspection. In order to arrive at a more definitive conclusion a more detailed examination, which would have involved removal of the cladding fixings, is required. It is recommended that a few potential candidate roofs in the region affected by both TC Larry and TC Yasi be selected and a detailed investigation be conducted on the cladding and battens. In these roofs there will be cladding that has been subjected to two significant wind loading events. Experimental programs on cladding fatigue have demonstrated fatigue damage is cumulative (Henderson 2010).

3.2.6.2 Secret fixed cladding

Failures of secret-fixed (or clip-fixed) cladding were observed. Secret-fixed cladding refers to the cladding that is “clipped” on to a series of clips that are fastened to the support purlins. Loss of cladding was observed from a warehouse in Townsville where wind speeds were significantly less than the ultimate design speed. The edge details and clip spacings were not as per manufacturer specifications. Damage to flashing may have also influenced the outcome for the sheeting on this building.

Extensive loss of secret-fixed cladding was observed on an apartment building shown in an aerial view in Figure 3.37. The cladding was subjected to dominant opening internal pressure and normal external pressures. On closer examination a rafter had become dislodged from its supports into the structure’s masonry block wall indicating that the cladding resisted the large wind loads and transferred them into the purlins then rafter. The manufacturer’s recommended stiffened overhang fixing for the cladding edge was not observed.

As for pierced fixed metal cladding, the failures observed involved systems that were not installed to specifications and in some cases flashing damage may have influenced the outcome.

Figure 3.37 Failure of secret fixed roofing.

3.2.6.3 Consequences

Loss of cladding is a perforation of the building envelope. It allows changes to the internal pressure in the building and removes a potential structural membrane for redistribution of other forces. It also allows large amounts of water into the building with other adverse consequences as indicated in Section 3.2.11.

Loss of cladding has the potential to damage other buildings as well as it contributes to the wind-borne debris load as discussed in Section 3.2.10.

3.2.6.4 Options for Improvement

Failures of incorrectly installed roofing systems, indicates that there is a continuing need for education of installers and certifiers. For example, increasing the spacing of fasteners by 50% increases the tributary area of a single fixing by the same amount and reduces capacity by more than the factor of safety. Installers must be sure that all fasteners penetrate the purlin or batten properly so that they can be relied on for their full capacity.

Losing cladding at wind speeds significantly lower than design is a cause for concern. Inspection of secret fixed roofing to ensure correct installation is more involved than that of pierced fixed cladding as there is no visual check for engagement of the sheeting in the clips.

3.2.7 Sheds

Observations were made on the performance of rural and industrial sheds, as well as steel-clad residential garages. No observations were made on the performance of larger factory or warehouse buildings.

3.2.7.1 Construction

The separation of the shed type into “hot rolled” or “cold formed” is derived from the primary framing elements of the shed’s portal frame which are either of hot rolled steel members or cold formed steel elements.

- The hot rolled steel members typically had welded base plates and knee and apex joints.
- The cold formed sheds generally were smaller than the hot rolled sheds. The smaller portal frame joints in cold formed sheds typically employed screws through gusset plates to connect members at knees and apexes.

Both the hot rolled and cold formed sheds used cold formed purlins and girts. In many cases, large cold formed top-hat batten sections were used as purlins and girts in the cold formed sheds compared to the C and Z sections that used a cleat plate to connect to the hot rolled portal frames.

3.2.7.2 Damage

There were a range of failure modes and performance issues observed in both cold-formed and hot rolled steel framed sheds. Where failures were observed, damage could be aggregated into the following:

- Roller door failures resulting in damage to the inside of the roof and wall cladding (as well as contents) due to the door curtain being whipped back and forth in the severe wind gusts and eddies where the door had blown inwards. An example of this type of damage is given in Figure 3.27.
- Buckling of purlins and cladding were observed together with door or window failures. The failure of the windward building envelope results in the windward edge bay of the roof being subjected to the large combined internal and external pressures. Failures were in the form of buckled purlins and cladding, with extreme cases involving the loss of the entire roof envelope as shown in Figure 3.38.
- Failures of non-enclosed sheds (i.e. sheds with two or three walls) were observed. These failures occurred when the severe winds aligned with the shed opening direction and often for hot rolled sheds, resulted in buckled purlins and cladding loss as shown in Figure 3.39. (In this case the wind was normal to the opening, and the load on the fascia bent the brackets at the end of the overhang.)
- Windward end-wall failures were observed in a few cases. These failures consisted of buckled purlins due to the combined loading of uplift on the end bay purlins from the suctions on the roof and compression from the wind ward positive pressure on the end-wall. However, Figure 3.40 shows the failure of the end wall into the shed where a few self drilling screws were the only fixings connecting the end wall columns to the portal frame.
- Foundation and base plate failures were observed. Figure 3.41 shows the remains of two different hot rolled shed after being lifted clear of the ground with concrete footings still attached. Figure 3.42 details the corrosion associated with base plate welded to light gauge cold formed portal frame.

Figure 3.38 Loss of roofing envelope after purlins buckled

Figure 3.39 Buckling of purlins and loss of cladding.

Figure 3.40 loss of end wall under lateral loads

Figure 3.41 Farm sheds with footings removed intact

Figure 3.42 corrosion of base plate previously welded to cold formed column

3.2.7.3 Consequences

Many of the sheds inspected could not be considered as isolated sheds and so the assumption of minimal risk to human life in the event of a failure was not valid. Examples include:

- A number farm sheds that had been built very close to houses and in some cases, debris from damaged sheds had travelled up to 200 m before impacting and damaging nearby housing. In one case the shed itself had struck the house and caused substantial damage.
- Some sheds were clearly being used as accommodation.

Importance Level 1 should only apply to buildings that are well away from any people or to buildings of a temporary nature. The risks to life from selecting an inappropriate Importance Level during the design phase are obvious where sheds are in close proximity to habitable buildings.

3.2.7.4 Options for Improvement

Shed performance has been highlighted in a number of recent investigations into building damage following tropical cyclones, and improvements in shed performance have been made in some areas.

The majority of the sheds inspected were within 200 m of habitable buildings. Under these circumstances, they should be designed as Importance Level 2 buildings. Even many of the farm sheds were close to houses. It was not possible to find the design criteria for the sheds that were inspected, but it is important to note that in the region covered by the study, that sheds that satisfied the requirements of an Importance Level 1 building were very much the exception.

Sheds contain a number of elements that may be sourced from other suppliers. These may include; windows, doors and roller doors, and each of these externally sourced items need to satisfy the wind loads themselves. As well, each of these items transmits wind forces to the structure of the shed and it must be specifically designed to carry those forces to the ground. The communication process outlined for large access doors in Section 3.2.4.5 also applies for roller doors fitted to sheds.

Sheds should be designed for dominant openings. In a number of cases, the shed is completely open on one of more sides, but in others, nominally enclosed sheds can have a dominant opening develop during a tropical cyclone through impact on windows or the cladding, or through failure of latches on windows and doors.

Some elements of sheds need to be checked for their performance under combined actions. This includes purlins in end bays where the members must resist compression forces introduced by bracing requirements of the building together with bending actions due to the out-of-plane forces on the roof due to internal and external pressures.

The Steel Shed Group has undertaken a program in recent years to develop engineering guidelines called ShedSafe™ (http://shedsafe.com.au/) and an audited accreditation program for members. This program already specifies design for full internal pressure, which addresses one of the issues discussed above.

3.2.8 Other structural failures

Sections 3.2.1 to 3.2.7 have covered the more commonly observed structural failures. This section describes some other observed failures that deserve discussion.

3.2.8.1 Batten to rafter connections

Nailed batten to rafter connections have been identified as potential weak links in Pre-80s buildings in Section 3.2.2.2. In many of these cases it was clear that a failure had occurred as the roofing with battens attached had been separated from the rest of the building. However, Figure 3.43 shows a case in which the loads had started to lift the battens from the rafters (hidden damage). This connection would not be capable of providing its full capacity in another cyclonic wind event. It is only by conducting inspections inside the roof space that the extent of this type of failure can be determined.

Figure 3.43 Partial withdrawal of nails in batten to rafter connection

3.2.8.2 Corrosion of steel elements

Corrosion of cladding and purlins was observed in rural sheds and coastal properties. The loss of the soffit lining on a beach frontage house revealed corrosion of the eaves top hat batten as shown in Figure 3.44. The corrosion was located in the lower flange and adjacent to fixings. The house was less than ten years old. Its capability to resist further loads may be compromised by the extent of the corrosion.

Figure 3.44 Corrosion of eaves top hat section in beach-front house

Even more advanced corrosion was seen on older buildings and in connections where water, salt and dust could be trapped and held.

In some exposed coastal areas, nails and nail plates were observed to have corroded. Figure 3.45 shows an anchorage for a truss from a seaside shelter in which the metal brackets securing the trusses to beams were corroded. The heel of the truss itself is shown in the inset. Stainless steel brackets should have been specified for sites very close to the sea.

Figure 3.45 Corrosion of nail plates and anchorages on a truss adjacent to the beach

In coastal locations, sea spray is contained in the wind stream from the tropical cyclone, so salt can be blown well into the structure including the roof space. This salt remains even though the structural elements dry out. There is the potential for corrosion to increase after a cyclonic event. It is recommended that a study be undertaken to examine structural components including those in the roof space of buildings that may have been subjected to this salt intrusion.

3.2.8.3 Deterioration of timber

In a number of cases, timber in the very wet environment of the study area had deteriorated due to rot.

The heel of the truss, shown in Figure 3.45 exhibits signs of advanced deterioration. This may have been accelerated by the corrosion products from the tie down boot, but the moisture trapped in the boot may have caused the rot without any assistance from the iron oxides generated by the corrosion of the steel.

In other cases leaking gutters had kept timber near the edge of roofs continually damp and led to conditions perfect for fungal growth, as shown in Figure 3.46. Deterioration of timber near the highly loaded edge of the roof may have contributed to rapid onset of damage to the structure.

Figure 3.46 Deterioration of timber at the very edge of a roof

3.2.8.4 Splitting failures in timber - tension perpendicular to the grain

Wind loads in previous events have caused tension perpendicular to grain failures in rafters where the battens were anchored to the top half of the rafter and the anchorage at walls or beams only engaged with the bottom half of the rafter. Such failures were also observed in TC Yasi.

Figure 3.47 shows a rafter with a tension perpendicular to grain failure running immediately under the connections between the rafters and the purlins. This type of failure could have been prevented if the connection to the column anchored the very top of the rafter.

Figure 3.47 Tension perpendicular to grain failure in rafter

3.2.8.5 Reinforced masonry construction

A few issues were observed with reinforced masonry block construction. Figure 3.48(a) shows a bond beam that has large plastic conduits running inside the core filled wall which would significantly reduce the bending capacity of the bond beam at that point. Like all other design and construction details, masonry construction needs to be compliant with codes, Standards and industry recommendations.

With the large number of masonry block houses in the study area, many buildings had used expanding masonry anchors to resist wind loads. A number of these failed. Cases observed included:

- Anchorage of hinges to walls at doors and windows.
- Anchorage of rafters to wall bond beams
- Anchorages of ledgers to walls.

Figure 3.48 (a) shows a failure of masonry anchors that secured a steel rafter to a 'single' bond beam, immediately below the half height blocks shown in the photo, in a large house. The masonry anchors which seemed to be too short to have engaged the concrete in the filled core have pulled out of the concrete at both ends. The top row of masonry anchors did not have sufficient edge distance to the top of the bond beam and the bottom row appeared to be below the bond beam. This utilization of the anchors was required to resist high loads. Figure 3.48(b) shows a lesser loaded feature in which loads from a light awning were transferred to a wall.

(a) between steel rafter and bond beam

(b) between awning and wall

Figure 3.48 Failure of expanding masonry anchors failures

Failures of unreinforced masonry construction were observed, notably parapets on older commercial buildings or unreinforced block work as infill panels on sheds.

3.2.8.6 Internal wall failures

Different internal wind pressures in different parts of the building lead to differential pressures across internal walls. Figure 3.49 shows an internal wall that had been shifted by internal pressures following breakage of windows.

Figure 3.49 Internal wall moved by differential air pressure

In this case, the wall was anchored to the ceiling and the top of the wall did not move, but the base of the wall required more nails to fix it to the floor.

More extreme cases of internal loadings were seen in storm surge penetration of buildings. Figure 3.50 shows an unreinforced blockwork wall that had been damaged by storm surge.

Figure 3.50 Internal unreinforced blockwork under storm surge loading

3.2.8.7 Resilient small rooms

Extreme wind damage can remove the roof structure and most of the walls in a building. However, often the smallest rooms remain because of the high connectivity between walls in these rooms.

This is the reason that advice given to occupants about sheltering in their own home is to stay in the smallest rooms. Very few houses in the study area were damaged to this extent, but Figure 3.51 shows a house that was demolished except for the bathroom and toilet.

Section 3.2.10.2 discusses the option of building a “strong compartment” into residential buildings and this Figure illustrates that the higher resilience of bathrooms toilets and in some cases laundries offers a starting point.

Figure 3.51 Small rooms remaining after extreme wind damage

3.2.8.8 Damage to houses from fallen trees

The cyclone caused widespread tree damage. There were many cases observed of damage to structures caused by falling trees. Figure 3.52(a) shows a house on which two trees had fallen. Both had caused damage to the roof and ceiling leading to significant water damage. Other examples are given in Figure 3.52(b).

Figure 3.52(a) Tree damage to housing

Figure 3.52(b) Tree damage to housing

3.2.9 Topographic effects

Section 3.1.3 presented some data that showed buildings sited in regions with a topographic class of T3 were more than 3 times more likely to suffer serious roof damage compared with those in topographic classes T1 or T2. In Section 3.1.3, the topographic class was determined as being the classification of the site considering only the two directions from which the maximum winds came and taking the maximum value of the two. This classification is not the method defined in AS 4055.

The higher incidence of damage on sites that were assessed in the investigation as T3 sites could have been due to:

- Problems with the method presented in either AS 4055 or AS/NZS 1170.2 to classify the topography of sites.
- Incorrect use of the standards to classify the topography of the site.
- Selection of incorrect details for the topographic class.
- Mistakes in installation of structural details.

These are investigated in the following sections.

3.2.9.1 AS 4055 topographic class

The philosophy of AS 4055 is to take a non-directional approach to all aspects of the site wind categorization. The designer is required to look at all three components of the wind classification independently:

- Terrain category is the representative of the lowest roughness category in any direction averaged over 500 m from the site.
- Topography class is based on the average hill slope for the upper half of the hill and is assessed independently to the terrain.
- Shielding is assessed based on the general building density around the location and again is assessed independently to the other two categories.

A single wind categorization (equivalent to a wind speed) results for the whole building.

The simplified methods in AS 4055 can be contrasted with the methods in AS/NZS 1170.2 where the terrain, topography and shielding must be assessed separately for eight directions, combined for each direction and then in design, the separately evaluated wind speeds for each direction are used to evaluate wind loads on the structure.

The simplification uses some conservative assumptions and some unconservative assumptions to ensure that the final wind classification is on average quite close to the value found from AS/NZS 1170.2.

In evaluating the terrain category, the selection of the lowest roughness direction for the whole site is a conservative assumption, but for the topography and shielding, the selection of the average with respect to direction can be unconservative.

In selecting the average slope in the top half of a hill, ridge or escarpment, wind from the steepest direction will always be understated by the topographic class. This is particularly the case for ridges and escarpments where the lowest slope is close to zero, so the averaging will return a slope of half of the steepest slope. In addition, the effect of the topographic class is also attenuated. The multiplier that is applied is the one appropriate to the midpoint of the class, rather than the highest slope in the class.

Some of the most badly damaged buildings in the high topography classes observed in the TC Yasi investigation were on ridges that were oriented at right angles to the direction of maximum wind. The topographic class found by averaging the ridge slope with zero slope was T2, and by not averaging T3. The AS/NZS 1170.2 topographic multiplier gave the same effect as T3 topographic class. This difference was enough for the houses concerned to change the C4 wind classification which represents the actual wind exposure, to a C3 if using the current AS 4055. Figure 3.53 shows the view from one of these sites looking towards the direction of maximum wind in TC Yasi.

Figure 3.53 View from ridge with T2 classification in AS 4055 but more severe wind loads

A more appropriate representation of topographic class is found by using the maximum slope rather than the average slope at the top of the topographic feature. This gives minimal change in the classification of sites on hills, but means that sites at the top of ridges and escarpments will be appropriately designed for winds that are normal to the ridge or escarpment.

3.2.9.2 Site wind classification and construction

For many buildings it was not possible to determine which site wind classification had been allocated in design, but in visiting a few houses that had been built on exposed sites in the past 10 years, the owners volunteered to show the drawings for the house. These drawings made no mention of topography or even a C rating but referred to a Category 1 site. This is not enough to have given the structure sufficient strength for the design winds at the site. Clearly there is a need for continuing education of some designers and certifiers in current categorization of sites.

In other cases, it was not possible to know what Wind Classification had been specified, but it was possible to see that one screw had been used for a batten to rafter connection which with the spans used, would have complied for a C2 categorisation but not a C4 or even a C3. There is a need for more awareness of the importance of site exposure on the detailing of structures for wind. Figure 3.54 shows buildings on a small hill top with damage to the roof while structures on the flat land in the foreground are relatively undamaged.

Figure 3.54 Damage to hill-top houses.

The higher levels of damage of exposed houses compared with houses in T2 topographic class as indicated in Section 3.1.3, shows that those involved in house design and construction need to be better informed of the requirements of wind classification and the details that must be used in constructing of houses in such sites.

For housing, AS 4055 is used to obtain the correct site classification and should be used and understood by designers and certifiers. However, the wind exposure of the site correlates well with the view from the site. Builders and tradespeople should be aware that a really great view means that the fixing details required may be different than what they typically use for C1 and C2 and they should be checking the drawings, relevant standard or manufacturers' literature for the appropriate fixing details. The following general guide was first published in TR51 and serves as a useful check on site classification, but can also be used as a rough guide for tradespeople in North Queensland:

- *No view – C1*. With no view, it is likely that the topography is flat and the site is well shielded with neighbouring (same size or bigger) houses.
- *Some view – C2*. This is likely to be the case if there are few shielding houses on gently rising ground, or if there are many surrounding houses and moderate slopes.
- *Good view – C3*. This is a view that adds significant value to the block and can only be achieved on moderate slopes with partial shielding or more steeply sloping ground with many surrounding houses. The anchorage and bracing loads for C3 classifications and below can be found in AS 4055.
- *Really great view – see an engineer*. Great views mean that the site is near the top of a steep slope. Any surrounding houses are not effective in shielding because of the slope, and a professional engineer must be used to design all structural aspects of the house.

The view shown in Figure 3.53 indicates that an engineer should have specified all of the anchorage requirements of the house at this location. Use of AS/NZS 1170.2 gave design wind speeds equivalent to a C4 classification.

3.2.9.3 Consequences of incorrect site/wind classification

Where the site wind classification is understated, then the construction will not have the required strength to resist the design winds.

As well as the correct classification and appropriate detailing on the design drawings, the installation of all of the important structural elements (including connections) must be correct to avoid failure in wind events that have speeds less than the design wind speed for the region.

3.2.9.4 Options for improvement

At present AS 4055 underestimates the topographic class of sites on ridges and escarpments. It is recommended that the Standard be amended so that the maximum slope is considered rather than the average of the maximum and minimum slope.

Training in the correct allocation of site wind classification is still needed throughout the industry. It is particularly important that designers, certifiers and builders can assess a site correctly. It is also of value if the trades working on the site also have an understanding of the needs of different wind classifications and rough ways of assessing them (e.g. the view approximation presented in Section 3.2.9.2).

3.2.10 Wind-borne debris impact and building envelope performance

Failed elements, such as roof structures and tiles, awnings, guttering, flashings, roller doors, etc, as well as unsecured items stored in residential yards and vegetation were blown by the wind. In some cases the roofing elements travelled hundreds of metres, highlighting the threat to life safety and potential for further damage to other structures.

Figure 3.55 shows a house, in the right of the photograph, which lost its roof. At the top left of the photograph is the house that was hit by the debris. The roof had cleared the shed and the trees in the middle of the photograph. The roof travelled as large pieces, but broke up a little after impact.

Figure 3.55 Roof as wind-borne debris

3.2.10.1 Tiles as debris

Observations were made of a number of tiled roof houses with significant number of tiles missing (see Figure 3.56). Many of these became wind-borne debris and impacted other houses, breaking windows (see Figure 3.15) and in one case penetrating a metal roof as shown in Figure 3.57.

Figure 3.56 Damaged tiled roof, each lost tile being a potential missile

Figure 3.57 Metal roof damaged by dislodged roof tile

3.2.10.2 Debris simulation and debris similar to the test piece

Wills, Lee and Wyatt (2002) have shown that for debris to become airborne in windstorms a certain threshold wind velocity must be exceeded. This value is governed by relationships of available debris geometry and density. The current (optional) test criterion for wind-borne debris impact in the wind load standard AS/NZS 1170.2 (2002) requires the envelope of buildings in cyclone regions to withstand the impact from a piece of 100 mm × 50 mm timber weighing 4 kg, and impacting at 15 m/s. The revised wind load standard that is to be released soon recognises the dependency of debris flight velocity on the wind speed (Lin, Holmes and Letchford, 2007) and will require the debris impact test velocity to be a percentage of regional wind speed. Essentially the proposed missile impact velocities for vertical surfaces (e.g. walls, window screens) will range between 25 m/s and 35 m/s for residential buildings in Regions C and D, respectively. However, the size and mass of the test missile will be unchanged.

Investigations of buildings damaged in TC Yasi, revealed that a number of those cases had been impacted by timber pieces of similar dimensions to the test missile. The response of impacted building envelope components varied from deformation only, to the external layer being punctured but essentially preventing further penetration, to missiles entering building interiors and thereby posing a serious threat to occupant safety.

Figures 3.58 and 3.59 show photographs of a building that sustained impact damage from debris similar to the test missiles but where the missiles had not penetrated through the cladding into the interior.

Figure 3.58 Impact damage on metal cladding without complete missile penetration

Figure 3.59: Impact damage on concrete block wall without complete missile penetration

Figures 3.60 to 3.61 show photographs of buildings that also sustained debris impact damage and the missiles had penetrated through the envelope and internal lining into the interior.

Figure 3.60 Debris complete penetration through steel roof (inset shows missile)

Figure 3.61 Complete penetration through window (Inset shows missile)

3.2.10.3 Large debris impact

Other instances of observed impact damage involved entire building or roof structures with their mass estimated between 500 kg and 4000 kg. An example of large debris is shown in Figure 3.62, where a shed became one piece of debris and it obviously had a significant effect on the house it hit.

Figure 3.62 Very large debris and the house it hit

As indicated in Section 3.2.6, there are fewer incidences of cladding failures, and with inadequate or deteriorated connections deeper into the structure triggering the failures, the debris released is significantly larger than that which featured in tropical cyclones in the 1970s and 1980s. The larger wind-borne debris carries significantly more energy and momentum.

Normal building envelope components or entire structures cannot be reasonably expected to withstand impacts by large debris, and testing debris with this energy in a simulated regime would prove very difficult.

The Street Survey information from Bingil Bay to South Mission Beach (the area in which all houses were surveyed), was used to identify the number of cases in which large debris caused consequential damage to structures.

Only buildings with a Roof Damage Index of 4 or more were selected from the data and these houses were used to identify whether or not the debris released from the damaged house caused consequential down-wind damage. Damaged Pre-80s houses were evaluated separately from damaged Post-80s houses.

- Where Pre-80s houses had lost substantial parts of their roof, around 20% of them caused damage to other houses. Most of the other houses damaged were also Pre-80s houses.
- Where the few Post-80s houses had lost substantial parts of their roof, around 40% of them caused damage to other houses. Most of the other houses damaged were also Post-80s houses.

These findings probably relate to the geography of the study area. Most of the Post-80s houses were in newer subdivisions where they were surrounded by other Post-80s houses. The newer subdivisions tended to have smaller block sizes and this gave a higher probability of the wind-borne debris impacting another house. Also in the newer subdivisions, trees tended to be smaller in size and may not have offered a form of buffer from wind-borne debris as the more established trees in the older parts of the towns.

These ratios may be slightly different for towns in which Pre-80s houses are in closer proximity to Post-80s houses. However, the study has shown that even in the areas where there were few Pre-80s houses, that large wind-borne debris can be released and when it is, the chances of it doing further damage are between 20% and 40%. This means that in the study area in which 2.2% of the Post-80s houses suffered major damage, between 0.5% and 1% of Post-80s houses would have sustained damage from large wind-borne debris. While this is a relatively small percentage, it is still significant considering the winds speeds were less than the design event and the significant consequence of damage resulting from the impact of large debris.

3.2.10.4 Consequences of debris impact

The instances above highlight the danger that is posed to building occupants by wind-borne debris. Seeking shelter in a small internal room, ideally without windows, is highly recommended for reasons of personal safety.

As well, debris impact has the potential to "snowball", or cause a cascade of additional wind-borne debris. Where the impact causes significant structural damage, this can cause more debris to be released into the air stream, which in turn increases the likelihood of even more damage to down-wind buildings. No evidence of "snowballing" of wind-borne debris was observed in this study but it remains a strong possibility where wind speeds are close to the design velocity.

3.2.10.5 Options for improvement

The structural performance of buildings in communities can be improved by minimizing the debris in the air stream. This can be achieved using two main strategies:

- Early preparation in the removal or securing potential objects and structures that could become wind borne debris was evident in most areas. These actions certainly played a part in minimising debris damage. However, in some cases the removal and securing of objects had been neglected, resulting in debris available to become airborne. It is essential that communities continue the practice of cleaning up prior to the cyclone season, and then again as cyclone warnings are issued.
- The risk of potential "snowballing" of the amount of wind-borne debris can be reduced by ensuring that all buildings can perform structurally after the impact of debris. It is clear that normal structures cannot remain sealed after the impact of very large debris. To achieve this, all buildings in cyclone regions should be designed for dominant opening internal pressures. This will minimize consequential damage after debris impact.

Having recognized that impact from large debris is possible in an ultimate limit states event, and that if impacted by large debris, the building envelope will be breached, consequential damage to structure will be minimized by designing it to resist the worst case scenario assuming dominant openings. However, there are two important implications that follow from this recommendation:

- Recognizing that large debris can penetrate well into a building as shown in Figure 3.62, an option for further minimising the threat to life by windborne debris would be to incorporate strong, specially designed shelter rooms into any newly constructed residential dwellings. Retrofitting existing buildings with components suitable to resist current testing standards could be rather difficult and costly and therefore it may not be feasible to implement. However, to integrate such a strong compartment in new construction is quite simple and can be achieved at relatively low cost. A number of suitable building components are readily available. Not only would a strong compartment protect occupants from wind-borne debris in events below or at the design level, but would also offer additional safety from windstorms that exceed the design level. These events have a low probability of occurrence but nonetheless possible.

- If the concept of a strong compartment is to be adopted and introduced, this will not negate the need for adequate design of the structure surrounding the strong compartment. Potential arguments to relax the design requirements for buildings that incorporate a strong room based on the presence of such an internal shelter would lead to drastic consequences. Such relaxations would increase the availability of debris and hence the damage caused by it. Whilst occupant safety might be provided to an adequate level, the additional load and associated cost on community recovery would thwart all advances in cyclone resistant construction that have been made in the preceding three decades.

3.2.11 Wind-driven rain

Wind-driven rain passed through the building envelope at openings such as windows and doors (even if closed), around flashings, through linings or where the envelope has been damaged. This discussion of this water entry is separate to the discussion of storm surge in Section 4.

Wind-driven rain has been mentioned in most previous damage investigations (Boughton, 1999; Henderson *et al*, 2006; Leitch *et al*, 2009). In some cases, wind-driven rain affected the structural elements of the building (e.g. complete or partial ceiling collapse). As the ceiling serves as a structural diaphragm to redistribute lateral loads to the tops of bracing walls in severe wind events, structural performance can be compromised.

3.2.11.1 Modes of Water Ingress from wind-driven rain

A high differential pressure between the inside and the outside of the building can be established in strong winds. This differential pressure can force water through gaps and spaces that it would otherwise not penetrate.

The air flow around and over a building in an extreme wind event can drag water upwards over the building envelope. The movement in a direction opposite to its normal movement means some flashings that channel downward-moving water away from the envelope, direct the upward-moving water into the building.

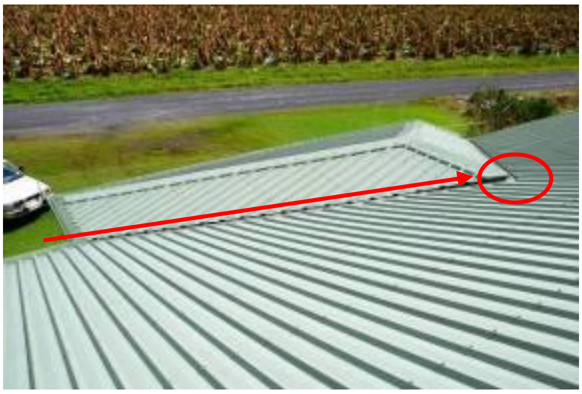
The following points of entry of water into buildings in TC Yasi were observed and are illustrated in Figure 3.63:

- Through ventilators. Ventilators in gables, soffits or in the roof surface normally keep out driven rain that has a significant downward component to its motion. However in extreme winds, the upward component in the driven rain means that the water was driven upwards through the soffit ventilators or between the slats in gable ventilators.
- Around doors and windows. The high differential pressure across the building envelope drove water through the small spaces around doors and windows and upwards through window weep holes. Some occupants reported a steady spray of water from the base of windows into rooms on the windward side of the house.
- Under flashings. Wind-driven rain moving upwards against the building envelope was pushed under flashings and into the building. This effect was particularly noticeable at the top of valley gutters. Water was driven up the valley gutter by wind where the direction of the gutter was aligned with the wind direction, entered the building near the top of the gutter and caused damage to the ceiling.
- Through perforations of the envelope. In the previous dot points, water ingress was observed in buildings with a perfect structural performance, but where the building

envelope had been damaged through either impact of debris or structural loss of cladding, water could bypass all of the normal water-tightness features of the building. Significant quantities of water entered the building by this method.

(a) roof ventilation

(b) window weep holes



(c) valley gutter

(d) envelope penetration

Figure 3.63 water ingress routes

3.2.11.2 Entry of Wind-driven Rain through Roofs

Regardless of the cladding material, roof complexity adds to the potential for water ingress. Valley gutters, box gutters and parapets, all require additional flashings and therefore more potential locations for water to be driven into the roof space

Sarking under tiled roofs can redirect water that has been driven under tiles by a combination of wind drag and differential pressure, back to the eaves gutter. Sarking under tiled roofs has also been able to redirect water that has overflowed valley gutters and flashings into the eaves gutters. Particular care is needed in detailing of the sarking into the gutters if water entry into the building is to be avoided. However, in some cases where the tiles had been lifted or broken, the sarking was also damaged and this allowed water to penetrate the sarked building.

Regardless of how water enters the roof space, it saturates the ceiling. Where plasterboard is used as the ceiling material, the combination of increased weight and reduced strength means that parts of the ceiling collapse as shown in Figure 3.64.

Figure 3.64 Loss of ceiling under damaged roof

3.2.11.3 Water Ingress under Eaves

A number of cases of soffit failure were observed. Some of these were the soffits under eaves, but an increasing trend is for large areas of soffit under an outdoor entertainment area. Figure 3.65 shows failure of soffit under a large balcony on a modern house. In this case, the water that gained entry through this space caused failure of ceilings inside the house.

Figure 3.65 Soffit failure under large outdoor entertainment area

3.2.11.4 Consequences of rain-water damage

Even small quantities of water ingress can affect furnishings such as curtains, carpets and bedding. Other types of potential water damage include some timber fibre products such as particle board or craft wood, where the uptake of water swells the wood and necessitates replacement.

Some wall and ceiling linings such as plasterboard are sensitive to water ingress. Where the ingress has been into the roof space, then the water saturated ceilings and ran down the inside of walls. Plasterboard ceilings and wall linings became saturated and within one week of the event had enabled mould growth in the linings and in some cases had separated from the framing. In previous events, these problems have rendered the buildings unsuitable for habitation and contributed to homelessness in the affected communities. Wet insulation holds water in the roof space and can prolong the high humidity conditions that encourage the growth of mould.

Other effects of water ingress include damage to electrical wiring and potential for corrosion of connections and other metal components in the structure. At the very least, once the structure has been soaked, an electrician’s certificate is required before it can be reconnected to the grid.

The speed with which a damaged building can be made weather-tight after a cyclone can dramatically affect the damage to the building and its subsequent occupancy. In cases where the damage has allowed water ingress, and the water can be kept out of the structure with tarpaulins, subsequent deterioration of furnishings, linings and even structural elements is minimized. However, where the building is left open for a number of weeks, then the continuing rain in the period after the cyclone means that mould, fungi and rot organisms become established in the building and this can limit subsequent use of the building.

3.2.11.5 Options for improvement

To reduce the risk of failure of soffits, they should be designed for the same pressure as the adjacent wall. This is a requirement in AS/NZS 1170.2, but is not explicitly stated in AS 4055.
Soffit linings are in regions of the building that experience extremes of pressure or suction (including local pressure effects) so need to be designed accordingly. Where they had failed or incorporated holes for ventilation, this allowed both wind and water entry to the roof space.

Windows and sliding doors manufactured in recent years should be tested for resistance to both wind and water pressure using a certification system developed by the Australian Window Association (www.awa.org.au). The AWA system for evaluating windows also addresses water ingress. However, under this system windows are only tested for resistance to water ingress based on serviceability pressure differentials. That is, they are tested to show that they can resist water under a differential air pressure that might exist on a normal windy day but they are not tested to ensure that they will not leak in an ultimate limit states design wind event such as a cyclone. Testing for weather tightness at or near the ultimate limit states wind speed will require development of a new test standard.

Where water-tightness requirements are extended to the ultimate limit state wind speed for windows, measures for reducing water ingress through guttering, flashings and vents should also be introduced.

Where more rigorous water proofing requirements are not adopted buildings can be made more resilient to the effects of wind-driven rain by selection of materials for linings and furnishings (e.g. floor coverings) that do not deteriorate when they get wet.

3.2.12 Ancillary items

Along with the main structural elements of buildings that include cladding and structural frame, there are a number of other elements that also impacted on the performance of buildings during or after the event. These are discussed in this section. Figure 3.66 shows some examples.

(a) Modern apartment block

(b) Pre-80s house

Figure 3.66 Ancillary Items

3.2.12.1 Guttering and flashings

While guttering and flashing are not structural components of buildings their damage in TC Yasi impacted their serviceability and the repair of these two items will significantly affect the speed of recovery for the community.

Figure 3.67 shows a building with some damage to openings, and to guttering. The damage to the windows and doors can be repaired from ground level, but repair to the guttering will require the roof to be accessed by scaffolding. This has the potential delay the commencement of the relatively simple repair of guttering. Also the high anticipated demand on scaffolding may mean that the work on guttering has the potential to delay the repair of structural damage to other buildings.

This case was not isolated, with approximately 20% of Post-80s buildings surveyed showing guttering damage. While not a structural problem, the high incidence of failure of guttering clips can delay full recovery of the community.

Figure 3.67 Guttering loss

Figure 3.68 shows a building that has started to lose some flashing. In this case water ingress meant that power could not be reconnected to the building before the building was made water-tight and an electrician's safety certificate was obtained.

In some cases, the loss of flashings had created a sail area that was sufficient to lead to the loss of roof sheeting. In these cases, the structural damage was as a consequence of damage to flashings. Any flashing damage will lead to water ingress during and after the event and therefore contribute to the problems discussed in Section 3.2.11.

Figure 3.68 Flashing loss

3.2.12.2 Solar hot water panels and solar photovoltaic panels

Figure 3.69 shows a building with photovoltaic cells (PV) on the left of photo and solar hot water (HW) panels on the right of photo. In this house, both the PV panels and the hot water panels were undamaged by the event and were fully operational immediately afterwards.

Figure 3.69 Solar panels

Figure 3.70 shows a case where some hot water panels remained, but one became detached and was lost. In this photograph, the lost panel was the right most panel in a group of three. A number of hot water panels were damaged by debris and remained in place, but with their glass covers broken or lost.

Figure 3.70 Solar hot water panels

A smaller number of buildings had solar photovoltaic panels, and their performance was variable. Many buildings had no damage at all, and others had one or more panels missing. Figure 3.71 shows one house with all of its panels intact and another with one panel only missing.

(a) no damage to panels

(b) one panel missing

Figure 3.71 Photovoltaic panels

There are many different suppliers of photovoltaic cells and systems in the market, and the current sample is too small to make generalizations. However, it is a rapidly growing market, and it is important that all installations in the cyclone area are designed and constructed to resist the appropriate design wind forces.

Not only do lost panels and damaged anchorages compromise the water-tightness of the structure on which they were originally fixed, but panels that have separated from a structure contribute to wind-borne debris.

3.2.12.3 Roof mounted air conditioning units

Not many roof mounted air conditioning units were observed in the study area, but the ones that were noted in the study were all significantly damaged. The damaged units allowed water directly into the building on which they had been located. Figure 3.72 shows the remains of an evaporative cooling unit.

Figure 3.72 Damaged roof-mounted evaporative air conditioning unit

3.2.12.4 Television aerials and satellite dishes

There were many television aerials and satellite dishes through the study area. Many of the aerials were undamaged as shown in Figure 3.73(a), but in a number of cases, when the aerial suffered some damage, which allowed water to enter the roof space as shown in Figure 3.73(b).

(a) undamaged television aerial

(b) damaged aerial and consequential roofing damage

Figure 3.73 Television aerials

The roof shown in Figure 3.73(b) was undamaged aside from the television aerial and some gutter loss, but there was plasterboard ceiling damage to two rooms.

Satellite dishes generally remained attached. Because of lack of power at the time of the survey, most occupants had not been able to check whether the dishes were still functional, but those who had power and dishes reported that minimal work was required to restore them to operation. Figure 3.74 shows a functional satellite dish on a roof that had sustained sheeting loss. The inset shows a rare case of a satellite dish that had become detached from the roof.

Figure 3.74 Satellite dishes

3.2.12.5 Fencing

The study area did not have a particularly high number of boundary fences and there were few cases observed of fences that had caused structural damage. Some had been damaged by wind, others by storm surge and others remained undamaged in spite of damage to buildings around them as shown in Figure 3.75.

In this study, there were not enough observations of fence damage to make a recommendation, but it has been observed that fences that remain attached to the ground after falling over do not contribute to wind-borne debris and so do not pose a risk to other structures.

Figure 3.75 Undamaged fencing among damaged buildings.

Figure 3.76 Failed fence

Figure 3.76 shows a fence that had failed but remained in its original location in spite of the complete failure of the post as shown in the inset.

Fencing that does not fail has the potential to catch debris as shown in Figure 3.75, but fencing that has failed has the potential to contribute to it.

4. Structural damage from storm surge

4.1 Introduction

The storm surge accompanying a tropical cyclone is a temporary but dramatic change in sea-levels produced by the combination of low pressure and strong winds. Some background information along with accounts of previous severe surge events is included in Appendix D.

4.2 Storm surge in TC Yasi

The maximum recorded storm surge height in TC Yasi was of the order of 5.4 m at Cardwell. Fortunately this occurred at about 1 AM at about quarter tide, as shown in Figure 4.1. This greatly reduced its potential impact with the maximum water level being about 2.2 m above the Highest Astronomical Tide (HAT). Had the maximum storm surge occurred at the next high tide the maximum water level would have been about 4.7 m above HAT.

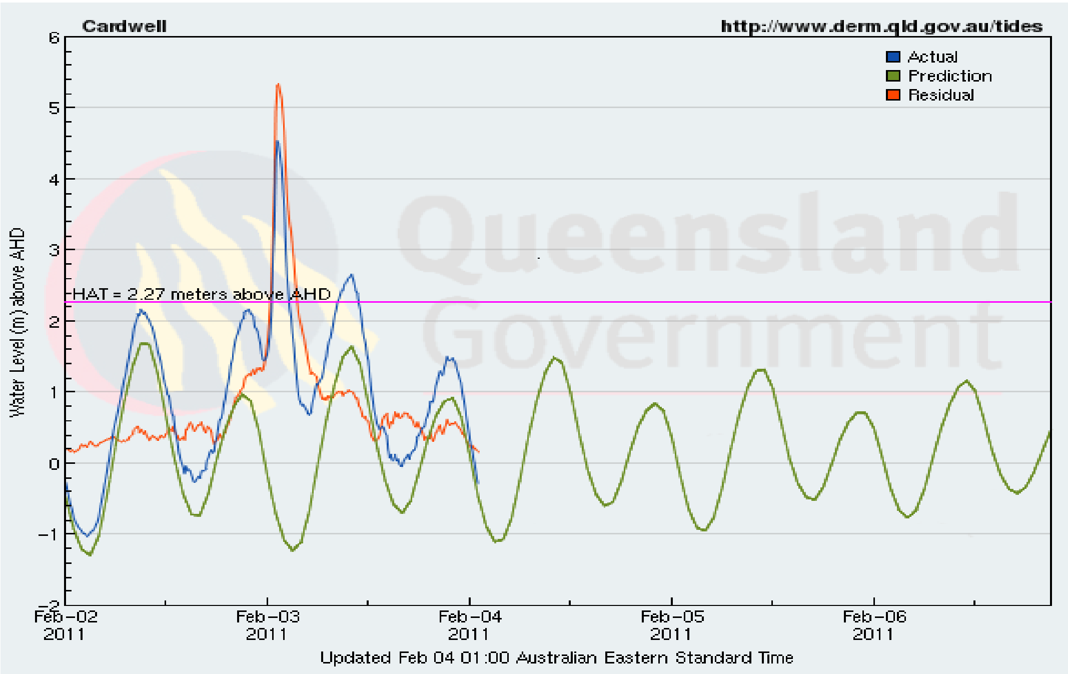


Figure 4.1 Cardwell tide gauge data (DERM, Qld Gov.)

The storm surge of 2.35 m at Townsville (refer Figure 4.2) which was approximately 180 km from Clump Point was only about half a metre lower than that recorded in Cyclone Althea which crossed the coast about 50 km north of Townsville. The storm surge was still greater than a metre at Bowen over 300 km south of Clump Point. Furthermore as shown in Figure 4.2 the peak storm surge in Townsville persisted for about 2 hours, and then continued at an elevated level for well over 12 hours. This gave a secondary peak of the order of 1.2 m at the following high tide and resulted in a maximum water level of 0.4 m above HAT at that time.

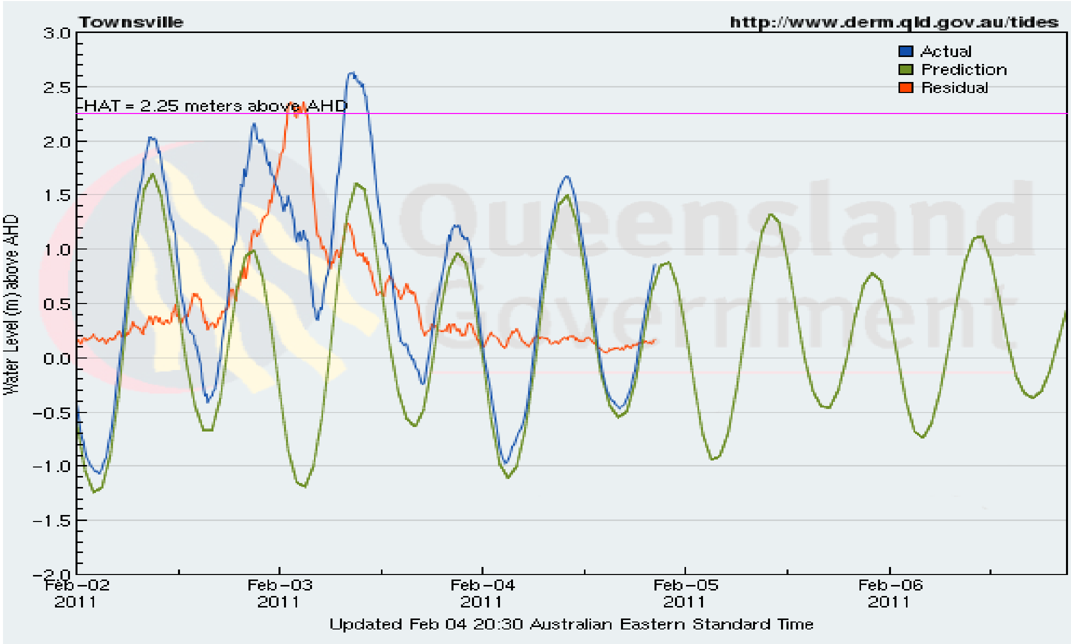


Figure 4.2 Townsville tide gauge record (DERM, Qld Gov)

Figure 4.3 shows a linear interpolation between the reported measured storm surge heights in TC Yasi (red line) at different locations along the east coast of Queensland relative to Clump Point which approximately corresponds to where the centre of the eye is estimated to have crossed the coast. Also shown is the actual maximum sea level relative to HAT (green line) which gives a better indication of the actual sea level at any locality, and the potential maximum sea level relative to HAT if the storm surge had coincided with the maximum adjacent high tide, which in this case was the following high tide around 9 hours later (blue line).

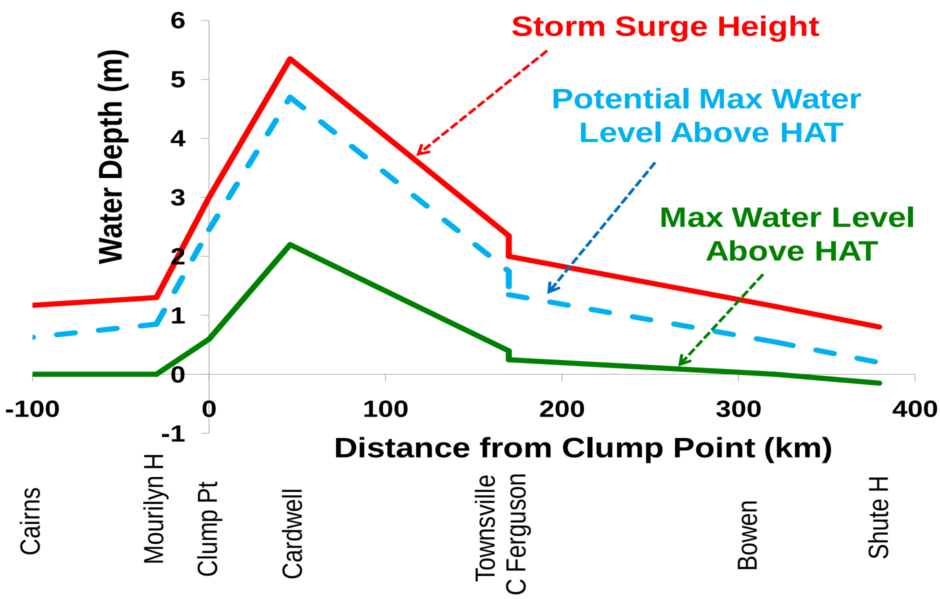


Figure 4.3 Simplified storm surge profile along coast interpolated between tide gauges

Figure 4.3 has been drawn without reference to any bathymetry or coastline features between the tide gauges that may affect the local storm surge height. It shows that as expected, the effects of surge are very significant to the south of the track and minimal to the north of the track. There was no sign of a negative surge to the north of the track.

The jump in levels between Townsville and Cape Ferguson probably demonstrates the effect of different local features, with Townsville facing north within Cleveland Bay with Cape Cleveland to the east and Magnetic Island to the north, and Cape Ferguson being on the southern side of the Cape Cleveland peninsula and facing south.

4.3 Patterns of damage

At Tully Heads many of the houses alongside the road parallel and closest to the beach suffered major damage from storm surge while at Mission Beach and at Cardwell there appeared to be very little structural damage from storm surge.

- At Tully Heads the storm surge penetration inland was approximately 500 m and reached around 1.5 to 2 m above HAT as the land sloped very gently away from the beach.
- At Cardwell the region behind the beach had a steeper slope which gave the surge a much lower penetration inland.

None the less there was damage to foreshore reserves and beach-front roads at all three locations and at other coastal communities in the study area.

Figures 4.4 and 4.5 contrast the coastal situation at Tully Heads and at Port Hinchinbrook in the Cardwell area. At Tully Heads the back lawn of beach-side houses shown is close to beach level, the rocks scattered about the lawn apparently coming from a destroyed seawall which was intended to protect the property. At Port Hinchinbrook the houses are on top of a bank significantly above beach level, and there is the same feature in Cardwell itself.

Figure 4.4 Back lawn at Tully Heads

Figure 4.5 Back lawn at Port Hinchinbrook

As a consequence of the low elevation of houses at Tully Heads, water surged through properties up to a depth of over a metre on the seaward side of the street and up to 0.8 m on the landward side of the street, cleaning out the ground floor of 2 storey houses as shown in Figure 4.6. Single storey houses were also cleaned out if not totally washed away as shown in Figure 4.7. In the Mission Beach and Cardwell areas, the maximum levels of inundation reported were of the order of 200 mm with minimal structural damage and generally only moderate damage to contents as shown in Figure 4.8.

Figure 4.6 Two storey house on seaward side of road at Tully Heads.
(Photo looking inland. Same back lawn as in Figure 4.4)

Figure 4.7 Single storey houses at Tully Heads – right hand one is washed away

Figure 4.8 Marks on chair leg and cane settee show depth of storm surge inundation at Port Hinchinbrook

The upper floor and roof of most 2 storey homes on the beach front at Tully Heads had suffered little or no structural damage due to storm surge, and one single storey house shown in Figure 4.9 appeared to have no observed structural damage as a consequence of its slightly elevated position and raised floor level. Significantly this latter house was on stumps which allowed the surge at this level to go under the house without putting significant forces on it.

Figure 4.9 Undamaged house at Tully Heads close to the sea

The following structural damage was observed:

- Failure of windows and doors that appear to have been breached. (See Figure 4.6.)
- Loss of internal linings such as plasterboard. (See Figure 4.10)
- Removal or movement of internal walls (including unreinforced masonry) as shown in Figure 3.50.
- Removal or movement of external walls. (See Figure 4.12.) This sometimes led to loss of the entire superstructure as shown in Figure 4.7.
- Removal of floors. (See Figure 4.7.)

Figure 4.10 Damage to internal linings and movement of internal walls

Figure 4.11 Damage to external wall due to water flow through shed

Figure 4.12 Damage to external walls on the seaward side of a house

4.4 Specific issues in structural damage

The pattern of damage highlighted a number of factors.

- The level of the ground floor of a building relative to the storm surge level was important in determining structural damage due to storm surge.
- Buildings could survive in storm surge locations if the ground floor is above the maximum water level experienced and the substructure is designed to allow the water to flow largely unimpeded beneath – although the possibility of scour needs to be taken into account.
- 800 mm inundation above floor level by storm surge can cause structural damage although 200 mm does not appear to, indicating that if the cyclone had crossed on high tide there would have been extreme structural damage at Tully Heads with possibly 2.8 m above floor level, and major damage along the beach front strip from Bingil Bay to South Mission Beach, and in the Cardwell – Port Hinchinbrook area with possibly 2.7 above floor level.

4.5 Consequences of structural storm surge damage

The relative height of floor level to storm surge is vital to determining the consequences. This can be seen by comparing the stumped house in Figure 4.9 where the floor height was greater than the surge height with the stumps remaining on the right hand side in Figure 4.7 (red ellipse) where the surge height was greater than the floor level of that house. It is also important to detail the house for storm surge with the same care as is used for wind loads. For example the house in Figure 4.9 had the appropriate floor height for this event, but it also had enough lateral load resistance and anchorage in the subfloor to be able to cope with water lapping at the floor without floating or falling off its stumps.

Ebb channels develop as the water recedes after the storm surge falls in the ocean. These were observed at Tully Heads, but fortunately not adjacent to houses. Figure 4.13 shows that the depth of one ebb channel was near 2 m. Had such a channel developed near a house with standard footings, scouring may have washed the building into the channel.

Figure 4.13 Ebb channel cut by receding storm surge

4.6 Options for improvement

In considering options for storm surge resistant construction, successful mitigating measures can be found overseas. For example, construction in the US is permitted in areas at risk from storm surge provided the ground floor is at a specified level above HAT, the substructure under the floor must be designed to allow the surge to flow through it relatively unimpeded and to take possible scour into account. For houses, detailed guidelines are given in the 'Design and Construction Manual for Residential Buildings in Coastal High Hazard Areas' published jointly by the US Department of Housing and Urban Development and the US Federal Emergency Management Agency. In this document the design criteria differentiates between the area at significant risk from wave action in addition to the surge flow known as V-Zone and areas behind the V-Zone which is at risk from the surge flow only which is known as the A-Zone.

A similar approach can be adopted in storm surge risk areas in Australia to reduce damage to buildings. In view of the structural consequences, the required floor level could be set at the same level of risk as adopted for ultimate limit state wind design – i.e. the water level arising from combined storm surge, tide and wave set up which has an average frequency of exceedence of less than once on 500 years.

The insurance industry could be encouraged to insure buildings designed and constructed to the Australian requirements for construction in the storm surge zone.

5. Conclusions

Tropical Cyclone Yasi (TC Yasi) made landfall in the early hours of Thursday 3rd February 2011 with the eye passing over the Mission Beach region. There was no official anemometer in the path of the core of the cyclone to measure wind speeds. The estimated wind field for the study area was mapped using the Holland (1981) model for winds in tropical cyclones. The model was calibrated on meteorological information sourced from the Bureau of Meteorology and other sources including pressure and available anemometer data. Anemometer data was augmented with estimates of wind speeds at other locations based on the wind load required to form a plastic hinge in the post holding up a road sign. The study highlighted the dearth of recording anemometers along the tropical coast. A robust anemometer chain is proposed.

Estimated maximum wind gusts

Based on the wind field model and available data, the wind field's estimated maximum gusts experienced by structures in the highest wind areas of the study area were around 225 km/h (standardized to 10 m height over Terrain Category 2, as defined in AS/NZS 1170.2). The estimation error was +/-10%. The significance of this speed is that it is around 90% of the regional wind speed for Importance Level 2 (BCA) buildings in the region. That is, a very severe event, but below the wind speeds that would be expected to cause structural damage to current construction.

House structure performance

It was found that less than 3% of houses built post-1980s (i.e. housing built to current standards) and located in the area of highest estimated wind speeds, suffered significant roof damage. However, more than 12% of Pre-80s housing in the same area suffered significant roof damage. This level of damage indicates that this group has a lower structural reliability than the Post-80s housing. Where possible, roof space inspections should be performed on all houses that experienced winds near the design wind speed to look for structural damage that cannot be seen from outside the building.

The report found that the main reasons for the poorer performance of Pre-80s housing were deterioration of the structure with time, and the fact that the specified tie-down methods used at the time of construction do not meet the current requirements. Both of these problems can be addressed by inspection of the structural elements in the roof space and maintenance and/or upgrading of any elements that do not satisfy current requirements.

Roller door failures

Roller door failures were over-represented in the damage with a frequency of occurrence in Post-80s housing of about ten times the frequency of serious roof damage in the same housing. Sectional doors had a damage frequency in Post-80s housing of about twice that of serious roof damage in the same housing. Both types of doors were vulnerable to debris damage with small impacts causing major damage to the door. However, the roller doors had a significant number of failures under wind pressures. Improvements in door performance are urgently required, but also solutions for retrofitting existing doors to give them additional support to resist ultimate wind events also need to be developed.

Tiled roof damage

Tiled roofs also had a higher frequency of damage compared with sheet roofs. Failures of tile anchorage systems were most noticeable in ridge capping but also extended into the main body of the roof particularly from the ridges that ran along hips. Many of the ridges that had failed used flexible pointing as the only fastening method, and more resilient systems for anchoring ridges need to be developed. Failures in Post-80s tiled roofs were particularly frequent in exposed locations with more than half of the tiled roofs in C3 locations and all of the tiled roofs in C4 locations suffering some damage.

Structural damage to sheds

Wind damaged sheds were observed in rural, suburban and commercial settings. In very few of these settings could a shed have been classed as an Importance Level 1 building either due to the proximity of other habitable structures or because the shed was being used as a dwelling. Some failures had been initiated by prior roller door failures and in other cases, the sheds were open on one or more sides. Design and construction to resist pressures derived from dominant openings would have reduced the level of damage considerably.

Non compliance with codes, standards and industry information

Failures of most structures could be tracked to detailing that was not in compliance with current Codes, Standards and industry information. Some of the areas in which improvement is needed were found to be:

- Determining the wind classification of sites.
- Selection of the right connections for use with the given wind classification.
- Selection of sufficiently durable materials for use in near coastal environment.
- Installation of sheeting and tiles fasteners in accordance with the manufacturer's recommendations.
- Connection of window frames to the supporting members to transmit wind forces to the rest of the structure.
- Detailing windows to resist the wind pressures.
- Selecting appropriate door and window furniture to transmit wind loads without allowing the door or window to open.
- Care in installation of connections to ensure that the correct size of fastener and the correct number of fasteners is used for the Wind Classification. In a number of connections, care is also needed to ensure that the fastener is driven into the innermost member (particularly with roofing fasteners where the installer cannot see the batten or purlin into which they are fixed).

A study of the effectiveness of repairs after TC Larry showed that many repaired structures were able to safely resist the loads from similar wind speeds in the Kurrimine Beach area. However, from the limited survey sample, the results indicated that the performance of repaired buildings had a lower success rate than newly constructed buildings.

Damage and topographic exposure

There was a positive correlation between damage to buildings and the topographic exposure. For Post-80s houses, higher topographic class sites generally had more damage. Unconservative modeling of topography for ridges and escarpments in AS 4055 was one reason for this trend, and recommendations to address this have been made.

Wind-borne debris hazard

The study observed a range of different sizes of materials that had become wind-borne debris:

- Detached roof tiles had become wind-borne debris that had impacted other part of the roof from which they had been removed and nearby buildings. Tiles were observed to have broken windows and penetrated steel roofing and wall cladding.
- Some pieces of timber close to the size of the standard test piece were observed. Some of these had penetrated the outer cladding of buildings but few had made it into the inside other than through windows. One piece was observed to have come through a roof.
- Very large pieces of buildings had become wind-borne debris. These items included large assemblies of roofing and battens, significant portions of the roof structure, whole sheds and a complete shipping container.

The larger sized items of debris caused significant damage to buildings that they struck. Where these buildings had been able to resist the effects of dominant opening internal pressure, the damage was contained to the impact site. Where the building was not able to resist the higher internal pressures that came from damage to the building envelope, then the damage of the struck building escalated.

As a result of this conclusion, the Street Survey data was used to show that between 20% and 40% of the large pieces of debris released from Post-80s houses caused further damage to down-wind buildings. This will help in assessment of the costs and benefits of mandating the requirement that all low-rise buildings in Regions C and D should be designed to resist internal pressures arising from dominant openings.

Strengthened compartment in houses

The presence of large wind-borne debris and/or the risk of wind speeds exceeding design in an extreme event raised the issue of life safety of occupants of buildings and led to the consideration of “strong compartments” within residential buildings. A “strong compartment” within the building would give protection to the occupants even if large sized wind-borne debris was to penetrate the building envelope.

Guttering and solar hot water systems

Conclusions were also drawn on a range of other specific issues:

- Guttering and flashing had higher frequency of damage than most roof structures. While these items are generally thought of as non-structural, their repair has the potential to prolong the recovery process. Flashing damage also contributed to water entry.
- Solar hot water systems and solar photovoltaic panels were observed with no damage, with debris damage, and cases were observed where panels had become detached from the roof. Due to the mixed performance of these items and the variations in manufacturer further work on the wind loading and tie down of these elements is required.

Water penetration

Water penetration of the building envelope was observed in a large number of both Pre-80s buildings and Post-80s buildings. In the Post-80s buildings the common use of plasterboard linings and carpet floor coverings meant that many buildings that sustained no structural damage still had significant damage to linings and contents from water ingress. Some options for minimizing the impact of this water ingress on the community and its recovery from the event were proposed.

Inspections of large apartment and resort buildings showed that all had issues with water ingress, wind driven debris damage, and flashing and soffit damage, but there was no observed damage to major structural elements.

Storm tide damage

Studies of the structural damage in storm tide showed that the buildings that performed best had their ground floor level above the storm tide crest and were sufficiently open underneath to allow the water to move past the building unimpeded. The study found that while most structural components of houses could resist 200 mm above the floor level with minimal impact on the structure, at depths above floor level of approximately one metre, structural damage resulted. Requirements for the construction of buildings within the storm tide zone need to be developed for Australia.

6. Recommendations

In general, buildings constructed since the 1980s performed well in TC Yasi, but this investigation has highlighted some potential problems in buildings of all ages and the following recommendations aim to improve future performance of buildings in tropical cyclones.

6.1 Buildings in storm surge zone

Addressing the risk to the building stock through either avoiding or resisting the loads induced by storm surge will require both planning and building design considerations. Requirements have been written for other jurisdictions and these need to be examined to see if they can be modified to suit the Australian built environment.

Observations on the performance of buildings in the storm surge zone in TC Yasi indicated that only those buildings with a floor level above the surge height and with open areas that allowed the unimpeded flow of water and debris around, under or through the building fared well in the storm surge experienced. However requirements should recognize that in events where the design storm surge level is exceeded, the damage can be catastrophic for the affected communities.

6.2 Recommended changes to Standards

6.2.1 AS/NZS 1170.2 Structural design actions – wind actions

At present, Clause 5.3.2 allows the ultimate limit states design internal pressures to be calculated assuming that all openings that can be protected against wind-borne debris, are closed and unbroken, provided it can be demonstrated by a test that the protection is adequate. This study has shown that the size of many items of observed wind-borne debris is significantly larger than the test pieces of debris and the larger items would have significantly more energy and momentum than the current and revised debris tests in AS/NZS 1170.2.

A detailed study should be undertaken to examine the costs and benefits of revising AS/NZS 1170.2 so that low-rise buildings in wind regions C and D should only be designed for wind pressures obtained using potential dominant openings. Such a requirement is compatible with the robustness provisions of AS/NZS 1170.0 which require that the repair of a structure be a function of the extent of damage to it. In other words, if a window is broken by any means, the owner should only have to repair the window rather than replace the whole roof.

6.2.2 AS 4055 Wind loads on housing

At present AS 4055 underestimates the topographic class of sites on ridges and escarpments. It is recommended that the Standard be amended so that the maximum slope is considered rather than the average of the maximum and minimum slope.

AS 4055 does not give net pressure coefficients for soffits (eaves lining). These items can have significant differential pressure and the investigation showed that they experienced high levels of damage in TC Yasi leading to other failures in the structure (often ceiling panels). Design pressures for soffits and supporting structures should be included in AS 4055 to permit them to be designed to resist these differential pressures.

6.2.3 Strong compartment within residential buildings

As indicated in Section 6.2.1, large debris has the potential to breach the building envelope at winds near the ultimate limits state design wind speed. To protect occupants from the harm that this debris may cause, residential buildings should have a strong compartment. Such a compartment can be a purpose built room, or strengthened small rooms that are a normal part of the building.

Some requirements for the construction of small rooms with strength to resist debris impact have been developed in the past.

The implementation of this recommendation does not lessen the need to design the whole envelope of buildings to resist expected wind pressures. It offers a means of protecting the life and safety of occupants in the event of large debris impact.

6.2.4 AS/NZS 4505 Domestic garage doors

At present, AS/NZS 4505 presents wind pressures that do not align with those calculated for garage doors using AS/NZS 1170.2. AS/NZS 4505 should be amended to make design wind pressures compatible with those presented in AS/NZS 1170.2.

The scope of AS/NZS 4505 should also be expanded to include commercial and industrial doors or, a separate part developed for commercial and industrial doors, as there is currently no Standard for these larger doors. (The current Standard is limited to domestic garage doors.)

6.2.5 AS 2050 Installation of roof tiles

The failures of tile anchorage systems particularly at ridge tiles, indicates that the means of fastening ridge tiles and part tiles near ridges and hips should be reviewed.

The current practice of downgrading wind classifications for tiled roofs where the roof is sarked may need to be revaluated in the light of the particularly high levels of tile damage in high wind classification areas.

6.3 Reconstruction

As part of the reconstruction effort after TC Yasi and other major wind events that cause significant damage, there is an urgent need for all builders and owner repairers to have access to relevant information and training to ensure that they are aware of the requirements for construction in cyclonic areas.

Trades that have minimal or no experience in building in cyclonic regions should also be made aware of the requirements of the relevant Standards and industry information to ensure that their work is appropriate for the wind loads of the cyclone region.

Roof space inspections should be undertaken to look for partial or hidden failures of structural connections within the roof. If these are not repaired at this stage, the strength of the structure will have been compromised with the potential for reduced performance in the next cyclonic event.

Where part of the roof has been damaged, the whole roof should be upgraded to the required standard or in accordance with Standards Australia Handbook HB 132.2. The investigation showed that where the undamaged portion was left unimproved, it could initiate failure of the whole roof in the next event.

6.4 Improving performance of Pre-80s houses

The investigation found that Pre-80s houses had significantly more damage than Post-80s houses. The strength of these houses should be assessed, and where necessary, upgraded to comply with the current Standards. For timber structures, the current requirements can be found in AS 1684.3:2010 and supporting industry documentation. General information on upgrading structural performance in existing houses can be found in Standards Australia Handbook HB 132.2.

This recommendation applies to all Pre-80s buildings in Wind regions C and D whether they have been affected by TC Yasi or not. The assessment and upgrading is easiest when the roofing has been removed for other maintenance.

6.5 Issues requiring education

6.5.1 New construction

The correct use of most structural elements in a building is supported by documents – either Codes and Standards or manufacturer’s design and installation guides. The latest versions of this information should be used to assist in the appropriate use of building elements to resist cyclonic wind loads.

The study has highlighted the need for continuing education in the following areas of new building construction:

Connections are the key element in wind resistance of all types of construction. They must be detailed correctly and maintained if they are to continue to provide their intended function for the life of the structure. In particular:

- Trades need to have training that all connections should be installed to provide their correct edge distances and depth of embedment. This includes all timber connectors and masonry anchors.
- Building specifiers need to understand that materials used for connectors should be carefully considered in near coastal environments. High exposure sites also often have high salt loading, so the connectors need to be especially durable.

Because the external cladding, including doors and windows is the building envelope, each element is important for separating internal and external pressures in buildings. Designers and certifiers should receive training on the need for all doors (including large access doors) and windows to be designed in accordance with the current Codes and Standards to resist the differential pressures at the design wind speed. This includes not only the glazing, but also the frame, connections to the structure and any furniture that secures opening panels.

Care is required that metal sheet roofs are installed in accordance with recommendations. Failures of incorrectly installed sheet roofing systems, indicates that there is a continuing need for education of installers and certifiers. Installers must be sure that all fasteners penetrate the purlin or batten properly so that they can be relied on for their full capacity.

For both tiled roofs and secret fixed steel roofs, particular care is required in following installation guidelines as it is practically impossible to inspect the anchorage systems for compliance once the roof construction is completed.

6.5.2 Maintenance

All building materials deteriorate with time. Investigators observed signs of deterioration in some buildings that had been classified as Post-80s buildings. It is particularly important that builders be trained to inspect structural elements for deterioration, tighten bolts and reapply any protective coatings when the elements are visible. Inspection and maintenance of structural elements within the roof space should be undertaken for all buildings:

- after any event in areas where the applies loads were near the design ultimate wind loads, or
- whenever the roofing is removed (eg for replacement of roof sheeting), or
- at a maximum of ten yearly intervals.

These recommendations will need to be understood and in some cases, implemented by building owners, and they must be informed of the need to undertake this work.

6.5.3 Curriculum changes

It is particularly important for all practicing trades that are involved in constructing the building structure to be aware of the importance of connections in the structural system, and the need to match capacity to wind load requirements. These topics should also be included in trade training programs and syllabuses.

Training in the correct determination of site wind classification should be included in courses for designers, certifiers and builders. Basic training and continuing education for trades should deliver an understanding of the construction needs of different wind classifications.

6.5.4 Community education

A program for educating the public at large with respect to maintenance of buildings should be undertaken.

Section 3.2.10 highlighted the dangers of wind driven debris. Public education programs should continue to stress the importance of minimizing potential debris in the lead up to the cyclone season and then during cyclone warnings.

Home owners need to be informed of the expected damage to contents from water ingress through wind driven rain in severe events.

6.6 Measuring wind speeds

Anemometer records are vital to reassess the design wind speeds used in Australia, and the peak gusts in the zone of maximum winds were not measured by anemometers in TC Yasi. Systems should be implemented to take more anemometer readings in tropical cyclone events. This can be achieved by:

- Establishing additional robust AWS stations in populated parts of the cyclone affected area with the maximum spacing between stations of around 50 km.
- Setting up a number of portable anemometers and providing resources to use them so that they can be deployed just before an event makes land-fall, and the wind speeds recorded at a number of strategic locations for the duration of the event.

Anemometers should be positioned in flat open terrain far from major obstructions such as large buildings, and be located in regions unlikely to experience debris attack with wind in any direction.

A study should be undertaken to select the options for anemometers that will give best possible information on gust wind speeds in tropical cyclones in Australia.

6.7 Tiled roofs

Post-80s tiled roofs did not perform as well as other Post-80s roofs. Tile anchorage systems utilize elements that may be sensitive to fatigue, so manufacturer's recommendations should be based on demonstration of performance when tested to a cyclic test regime such as those in AS 4040.3 or the BCA.

The manufacturer's recommendations require reassessment in order to deliver the same reliability as other components of the building envelope. In particular:

- Methods for securing ridge capping and cut tiles in high winds need to be improved.
- A close examination of tile anchorage in exposed sites (C3 and C4 as defined in AS 4055) is necessary.
- Fastening systems should not allow complete detachment of tiles to prevent them from causing further damage to the same roof or to nearby structures.

6.8 Large access doors

The level of damage to roller doors was significantly greater than any other component of Post-80s housing. These doors should satisfy the BCA requirement that all elements of the building envelope are able to resist the design wind pressure for the building site.

Sectional doors had a lower failure rate than roller doors, but it was still higher than other structural components in contemporary housing, so improvement of their performance is also required.

The following actions are recommended:

- All large access doors should be manufactured to resist the directly applied wind loads. Their anchorages must also be designed and constructed to take those loads to the ground.
- Where the door itself generates secondary loads in resisting the wind forces (e.g. where wind locking devices have been fitted to doors and generate in-plane tensions), the interaction with the remainder of the structure must be able to safely transmit the

secondary loads to the structure and the structure must be designed and constructed to carry these loads to the ground.

- Where doors have demonstrated that they are unable to resist wind loads in TC Yasi, like-for-like replacement should not be specified. In all cases where the damage to the door was not caused by wind-borne debris, stronger doors must be fitted to ensure that the building envelope is capable of resisting the design wind pressures.
- Building designers must include wind design information in the specification of large access doors. All large access doors should have a wind rating fixed to the door so that it can be independently checked against the specific building design requirements.

Consideration should also be given to retrofitting devices to existing doors to ensure that they have an appropriate level of performance in future events. The recommendation for upgrading existing doors is not restricted to those doors that have been affected by TC Yasi, but for all doors in Wind regions C and D.

6.9 Sheds

Sheds have to be designed for the same conditions as other buildings with respect to wind loads. This includes the provision of a complete load path to the ground for all elements (including roller doors) that attract wind loads:

- Damaged sheds present a significant debris hazard. Sheds should be designed and constructed using Importance Level 2 or above, unless the shed is to be at least 200 m from any habitable building.
- Shed design should allow for dominant opening internal pressure, while checking that all parts of the building envelope including doors, windows, roller doors, skylights and cladding can resist the stated design wind pressures.
- Evidence should also be provided that the shed itself can resist all loads applied by all structural elements, windows, doors, roller doors and associated connections.
- Where purlins are used as compression bracing members, they should be designed to resist the combined effects of out-of-plane wind loads as well as axial compression loading.

Existing sheds should also be reviewed against the above recommendations.

6.10 Wind-driven rain

Using current practices, the water-tightness criteria of most buildings will have been exceeded at wind speeds approaching the ultimate limit states. As a result, significant ingress of water must be expected using current building technologies and this was observed during the investigation. Both structural and non-structural elements appear to have been selected without allowing for the possibility and consequences of water entry.

Water ingress has demonstrated that it can ruin linings and furnishings to the extent that structurally undamaged houses are no longer habitable. It therefore contributes to homelessness after tropical cyclones, and lengthens recovery times for communities. Consideration must be given to options for minimizing the impact of water ingress on the strength and amenity of buildings:

Either

- A standard testing procedure should be drafted to ensure that all elements of the building envelope, including their connections to adjacent elements are weather-tight at the ultimate limit states wind,

Or,

- Structural and other elements should be selected on the understanding that there will be significant water entry to the building when the wind speeds are approaching the ultimate limit states.

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Appendix A

A.1 Holland wind field model

In order to provide a more complete picture of the wind field generated by Cyclone Yasi at landfall, the well-known Holland model (Holland, 1980) was employed, primarily as an interpolation tool for the anemometers and 'windicators'.

The Holland model requires a number of parameters to be provided:

- The central pressure of the cyclone, p_c. In this case, it was taken as 930 hPa, based on the measurement at Clump Point, close to the point of landfall of Cyclone Yasi.
- The ambient pressure, far from the centre of the cyclone, p_0. In this case an average value of barometric well before the cyclone made landfall was used. Thus at 3 a.m. on February 2, the barometric pressures at Cairns, Townsville, Lucinda Point and South Johnstone were respectively: 1006 hPa, 1008 hPa, 1007 hPa and 1007 hPa. An average value of 1007 hPa was used for p_0.
- The radius of maximum winds, r_{max}. This is somewhat greater than half the diameter of the eye as visible from radar (estimated as 30 nautical miles, or 50 kilometres) and a value of 62.5 kilometres was used for r_{max}.
- Holland 'B' parameter. This is a non-dimensional exponent that depends weakly on the central pressure. It is an adjustable parameter that can be used to 'best-fit' the available measurements of wind speed. An empirical formula was recommended for B by Holland:

  $$B \cong B_0 - (p_c/160) \qquad \text{(A.1)}$$

  A value of 7.625 was originally proposed by Holland for B_0, giving B equal to 1.81 for a central pressure, p_c, equal to 930 hPa. McConochie, Hardy and Mason (2004) surveyed 64 historical tropical cyclones in the Coral Sea and found values of B_0 between 6.8 and 8.5, corresponding to values of B between 1.0 and 2.7 for a central pressure of 930 hPa. A best fit of a lognormal distribution to B_0 give a modal value of 7.3, corresponding to a value of B of 1.49.

  A value of B of 1.7 was used in the present modeling of Cyclone Yasi winds – this value is quite compatible with the above estimates.

The Holland model is an equation for the gradient wind, and requires factors to convert this to a 10-minute mean wind speed at 10 metres height, and a gust factor to convert the latter to a 3-second gust. In the present case, the ratio of 10-minute mean winds to gradient wind was taken as 0.7, and the gust factor was taken as 1.4 for overland winds and 1.3 for overwater winds.

Once a cyclone makes landfall, there is an immediate weakening in strength as the eye collapses. This continues progressively as the storm moves further inland. In the case of the modelling of Cyclone Yasi, the following weakening factors were applied to the wind speeds, as a function of the distance of the centre of the storm from landfall.

Table A.1. Weakening factors after landfall

Distance from landfall (km)	Weakening factor
0	1.0
10	0.90
20	0.875
30	0.85
40	0.83

The factors in Table A.1 are based on data from land falling U.S. hurricanes analyzed by Kaplan and de Maria (1995 and 2001).

The sensitivity of the predictions from the Holland model to the assumed 'best-estimate' parameters is discussed in a following section.

Outside the radius of maximum winds, the vortex gradient winds produced by the Holland model were summed vectorially with a forward motion component, taken as 10 m/s (36 km/h) in a direction 24 degrees south of west, based on observations of radar and satellite images.

A.1.1 Calibration of the wind field model

Figure 2.4 shows a cross plot of the peak gusts from the model wind field against the 'measured' values, with the latter consisting of a combination of anemometer readings (i.e. values in Table 2.1 plus two readings from reef anemometers close to the approach track) and averages of upper and lower limits from the 'windicators' (Table 2.2).

Generally good correlation is seen, with a correlation coefficient of 0.85, and a slope very close to 1.0, indicating no systematic bias in the model. The model overestimates the anemometer reading for South Johnstone. In the former case, topographic and terrain effects may not have been fully corrected.

The model also showed a slight underestimation of the maximum gusts at Tully, and a small overestimation at Cardwell. Both of these are probably a result of topographic effects with channeling between Mount Tyson and Mount Mackay producing an increase at Tully for north and south winds, and shielding from Hinchinbrook Island reducing gusts from easterly winds at Cardwell.

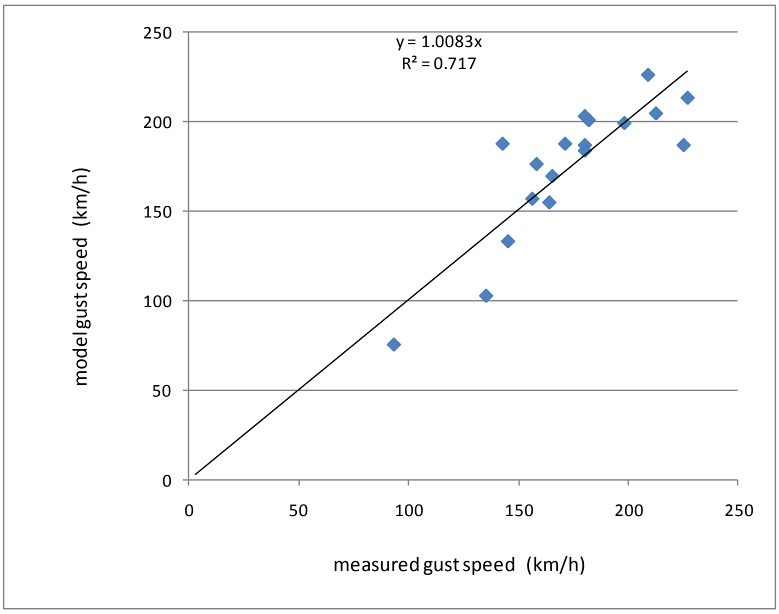


Figure A.1 Cross plot of model and measured maximum gust values

Time histories of wind gusts and directions were obtained by locating the centre of the cyclone at 10 kilometre intervals along its track, and evaluating the vectorial sum of the vortex speed and the forward speed of the storm. Nine positions of the storm were used spanning 40 kilometres before and after the landfall, and a total time of more than two hours.

The resulting histories of speed and direction as a function of position of the storm are shown for ten locations in Appendix A. These show that Tully, Tully Heads, Kurrimine, Bingil Bay, Mission Beach and South Mission Beach all experienced the eye of the cyclone with a clear fall in wind speed, and a direction change approaching 180 degrees. However, Cardwell, Innisfail, and Lucinda did not experience the eye, but suffered high winds for several hours.

The maximum 'best-estimate' winds are about 10% below the design wind speeds (V_{500}) for most buildings (i.e. Level 2 in the BCA). The estimates indicated that wind gusts equivalent to V_{150} occurred at Cardwell and Tully Heads (and possibly at Tully if channeling occurred). At Bingil Bay, El Arish and Mourilyan, the maximum wind gusts are estimated to be equivalent to about V_{50} in AS/NZS1170.2, and at Innisfail wind gusts to V_{20} are estimated to have occurred. At Ingham, Halifax, and Lucinda the maximum wind gusts were equivalent to about V_{10} in AS/NZS1170.2.

A.1.2 Sensitivity of the model to varying parameters, and errors

The maximum gradient wind speed produced by the Holland model is solely dependent on the parameter B, and the pressure difference between ambient pressure and central pressure; $\Delta p = p_0 - p_c$,

i.e.

$$U_{grad,max} = \sqrt{\frac{B.\Delta p}{\rho_a . e}} \quad \text{(Holland, 1981)} \qquad \text{(A.2)}$$

where ρ_a is the density of air, and e is the mathematical constant, 2.71828.

Thus given that Δp is accurately known for Cyclone Yasi, Eqn. (A.2) can be used to determine the effect of varying B on the estimates of maximum wind speed. A 10% change in B results in about a 5% change in maximum wind speeds.

Thus the assumed value of B of 1.7 gives a value of $U_{grad,\,max}$ of 63.3 m/s from Eqn. (A.2). Applying the surface-to-gradient factor of 0.7, and a gust factor of 1.3, this corresponds to maximum gust over water of about 240 km/h (including a maximum forward motion component of 10 m/s). Increasing the value of B to 1.87 results in a maximum gust speed over water of 250 km/h; reducing B by 10% to 1.53 gives a maximum gust of 230 km/hour. However, changing the value of B in the model results in a departure from 1.0 of the slope of the best-fit line in Figure A.1 – increasing B by 10% increases the slope to 1.04, and reducing it by 10% reduces the slope to 0.97.

It is interesting to note that values of B of 2.7 to 2.8 would be required for the model to generate maximum gusts in the range of 295 to 300 kilometres per hour, as reported by some media outlets before and after the event.

Table A.2 following shows the sensitivity of the slope and correlation coefficient R to variations in the assumed parameters, B, r_{max}, forward speed, ambient pressure p_0, and the ratio of mean wind at 10 metres height to gradient wind. It can be seen that the assumed parameters give good correlation, with a slope close to 1.0, compared with the alternative assumptions. The correlation coefficient, R, is insensitive to the assumptions, but the slope is fairly sensitive.

Table A.2 Sensitivity of model-measured correlation to varying model parameters

Parameter	Slope	R
assumed*	**1.01**	**0.85**
B –10% (1.53)	0.97	0.84
B +10% (1.87)	1.04	0.84
r_{max} –20% (25 km)	0.91	0.89
r_{max} +23% (40 km)	1.00	0.62
p_0 –4% (1003 hPa)	0.98	0.85
p_0 +3% (1010 hPa)	1.03	0.85
forward speed: 6m/s	0.99	0.81
forward speed: 12m/s	1.02	0.85
$\bar{V}_{10}/V_g = 0.65$	0.94	0.85
$\bar{V}_{10}/V_g = 0.75$	1.08	0.85

* assumed parameters are: B = 1.7; r_{max} = 32.5km; p_0 = 1007 hPa; forward speed = 10 m/s; $\bar{V}_{10}/V_g = 0.70$

There is a more advanced form of the Holland wind field model, known as the 'double' Holland model. It aims to match the radial distribution of barometric pressure, as well as wind speed, and incorporates an outer vortex, as well as the inner vortex used in the standard model (e.g. McConochie *et al.* (2004)). This model involves more adjustable parameters than does the standard model, and aims to better model the outer part of the cyclonic wind field. It is more important to model the outer wind field for storm surge prediction (personal communications: B.A. Harper, J.D. McConochie), and no attempt was made in the present work to incorporate the additional terms of the advanced model. As shown in Figure A.1, reasonable agreement between model and measured data was achieved using the standard Holland model of cyclone wind field, with the assumed parameters.

It should also be noted that both the standard and 'double' versions of Holland model are based on the assumption of axisymmetric vortices. Real-world tropical cyclones may not necessarily be of this form, especially after landfall, due to factors like topography and surrounding meteorological constraints.

A.2 Use of road signs as "windicators"

The analysis of different road-signs was used to derive upper and lower bounds as shown in Figure A.2:

- Signs that had a plastic hinge in the posts indicated that the maximum bending moment had exceeded the plastic moment capacity. A sign in this condition could be used to estimate a lower bound on the wind speed providing the sign was free of evidence of impact damage, and the direction of fall was normal to the axis of the sign.
- The upwind terrain and topography was simple and unambiguous.
- The cross section and steel grade of the posts could be used to establish the plastic moment capacity.
- Undamaged posts give an upper bound to the wind speed while bent posts give a lower bound.
- The dimensions of the sign could be used to infer the load that would have been required to exceed the plastic moment capacity.
- The load could be used with the height of the sign and the upwind terrain and topography to deduce the wind speed that was exceeded to cause failure of the posts.

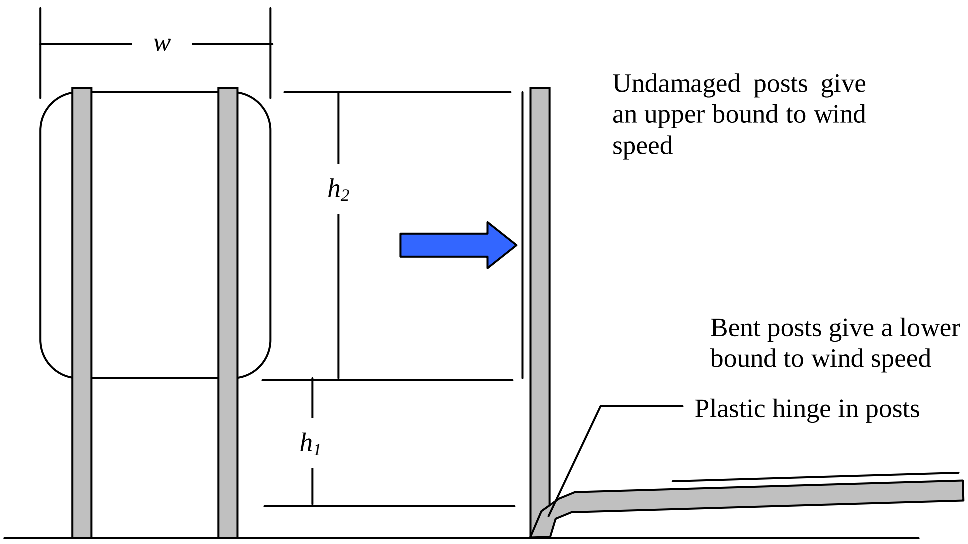


Figure A.1 Road sign analysis – upper and lower bounds to wind speed

A.2.1 Relating wind speed to sign measurements

The peak net wind load (F_n) across the sign can be given by Equation A.3.

$$F_n = \tfrac{1}{2}\rho \hat{V}_h^{\,2}.C_{F,n}.A \tag{A.3}$$

Here: $C_{F,n}$ is the net drag force coefficient, equivalent to C_{fig} in AS/NZS1170.2. [2]

A is the area of the plate (i.e. road-sign)

ρ is the density of air = 1.2 kg/m^3

$\hat{V}_h$ is the 3s gust velocity at the centroid (ie. $l = h_1 + 0.5h_2$) of the sign where the plastic hinge is at ground level.

The resulting maximum (i.e. base) bending moment M_{max} on the post(s) is given by Equation A.4, where the lever-arm l is the distance between the base and centroid.

$$M_{\max} = F_n.l = (\tfrac{1}{2}\rho \hat{V}_h^{\,2}.C_{F,n}.A).l \tag{A.4}$$

l is the distance from the hinge in the posts to the centroid of the sign

The plastic moment capacity of the posts M_p is given by Equation A.5 where f_y is the yield strength of the material and s is the plastic section modulus.

$$f_y = M_p / s \;\; ; \;\; M_p = f_y.s \tag{A.5}$$

A plastic hinge in the post(s) is created when the bending moment generated by the wind load exceeds the plastic moment capacity M_p of the post(s), as shown in Equation A.6. The failure wind speed at centroid height is then determined from Equation A.7.

$$M_{\max} \geq M_p \;\; ; \;\; (\tfrac{1}{2}\rho \hat{V}_h^{\,2}.C_{F,n}.A)l \geq f_y s \tag{A.6}$$

$$\hat{V}_h^{\,2} \geq f_y s / [(\tfrac{1}{2}\rho.C_{F,n}.A).l] \;\; ; \;\; \hat{V}_h \geq \sqrt{f_y s / [(\tfrac{1}{2}\rho.C_{F,n}.A).l]} \tag{A.7}$$

This wind speed is then factored by accounting for the approach terrain and topography to obtain the post failure wind speed in Terrain Category 2 at 10m height, V_r.

Importantly, wind tunnel measurements on a flat plate indicate that for a plate of near square planform, the normal force coefficient, $C_{F,n}$ is almost constant for winds approaching within a range of directions within ±45^o from the normal to the plate. This means that these road signs can be used as robust indicator of wind speeds for winds approaching from two 90^o sectors on opposite sides of the plate.

The calculated values of V_r are dependent on the dimensions of the sign and posts, the strength of the post material, and the values of $C_{F,n}$ and Terrain Roughness ($M_{z,cat}$). Posts from five failed signs were supplied to the CTS by the Main Roads Qld. Sample lengths of these posts were subjected to 4 point bending tests at the CTS to determine their plastic moment capacities M_p. Following an analysis of these parameters, failure wind speeds are estimated as V_r.

This process was used to determine upper and lower bounds to wind speed for a number of signs in the investigation area as detailed in Table A.3.

Table A.3 Signs used to Estimate Wind Speeds

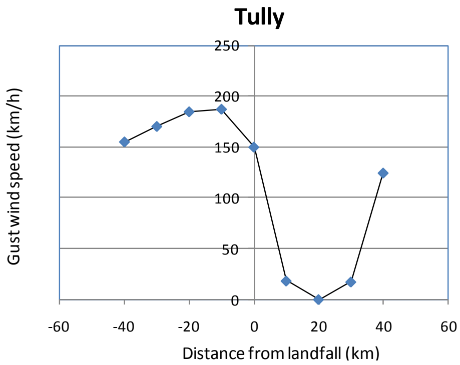
ID	*V*r	V_r	U/L	Location	TC	Sign Area	Leg properties No.	OD	h_1
	(kph)	(m/s)				(m^2)		(mm)	(mm)
A	140	39	L	Mourilyan	2	7.17	2	75	970
A	202	56	U	Mourilyan	2	3.45	2	75	1620
B	194	54	L	Cowley Beach	2	3.6	3	76.1	2000
C	173	48	L	Silkwood	2	0.94	1	60.3	1700
C	187	52	U	Silkwood	2	3.12	2	88.9	2300
D	198	55	U	Japoon	2	0.94	1	60.3	1100
E	173	48	L	El Arish	2	.94	1	60.3	1700
E	187	52	U	El Arish	2	3.12	2	88.9	2300
F	133	37	L	Kurrimine Beach	2	6.00	2	75	1980
F	230	64	U	Kurrimine Beach	2	0.48	1	60.3	2100
G	194	54	L	Bingil Bay	2.5	0.80	1	60.3	1800
G	202	56	U	Bingil Bay	2.5	0.94	1	60.3	1250
H	187	52	L	Mission Beach	2.5	0.80	1	60.3	1440
I	209	58	L	South Mission Bch	2	1.12	2	60.3	2000
I	245	68	U	South Mission Bch	2.5	2.25	2	88.9	2100
J	216	60	L	Tully	2	0.72	1	60.3	1400
J	234	65	U	Tully	2	0.72	1	60.3	1100
K	198	55	U	Jarra Ck	2	0.94	1	60.3	1100
L	176	49	U	Euramo	2	1.19	1	60.3	1000
M	187	52	L	Munro Plains	2	1.13	1	60.3	955
N	166	46	L	Dullachy-Bilyana	2	1.22	1	60.3	1500
N	194	54	U	Dullachy-Bilyana	2	2.88	2	76	1680
O	180	50	L	Kennedy	2	1.08	1	60.3	1500
O	245	68	U	Kennedy	2	0.56	1	60.3	1855
P	198	55	L	Cardwell	2	0.94	1	60.3	1300
P	220	61	U	Cardwell	2	2.56	2	88.9	1900
Q	144	40	L	Halifax - Macknade	2	4.96	2	76.1	1600
Q	184	51	U	Halifax - Macknade	2	1.81	2	60.3	1600

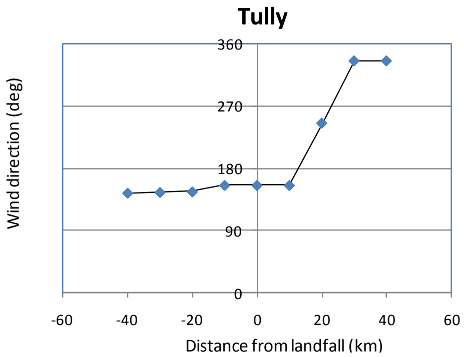
V_r = estimated wind speed for 10 m height in open terrain
U/L = Upper or Lower Bound sign
TC = Terrain Category
OD = measured outside diameter of pipe
h_1 = Height (mm) from hinge or potential hinge to underside of sign

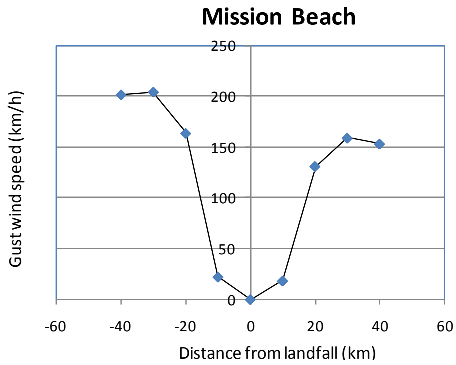
Appendix B

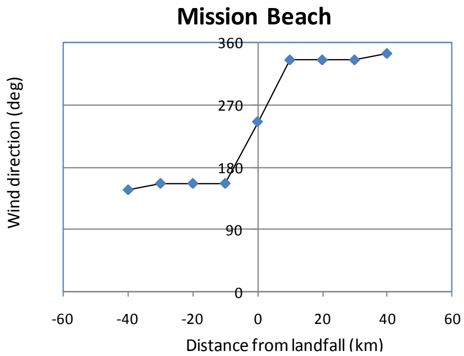
B.1 Plots of wind speed and direction

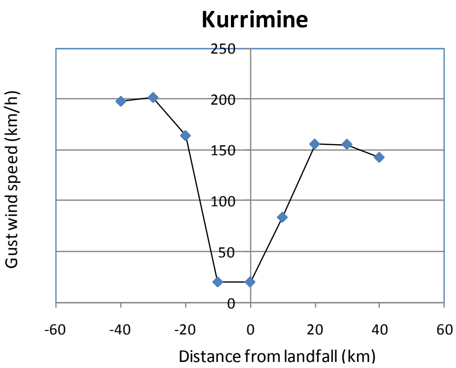
The following graphs show the variation in maximum gust wind speed and direction as a function of the position of the centre of Cyclone Yasi with respect to its position at landfall. Graphs are given for ten different locations in the event. The data was produced by the standard Holland model with factors for terrain and weakening after landfall, calibrated against anemometer readings and 'windicators' as discussed in the main text. However, no account of possible topographic effects, or local effects such as downdrafts, has been made in developing these plots.

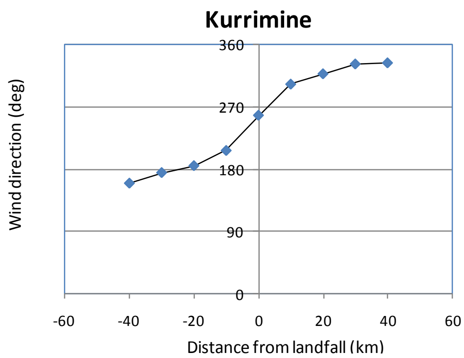


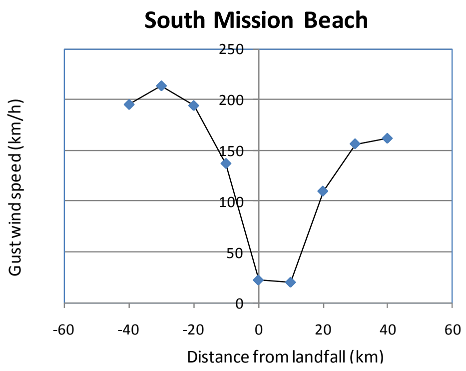


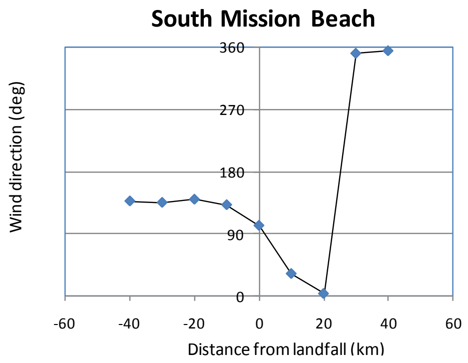


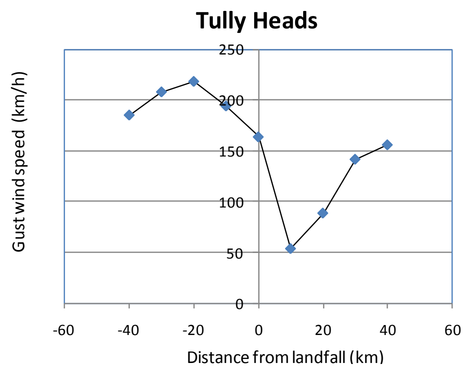


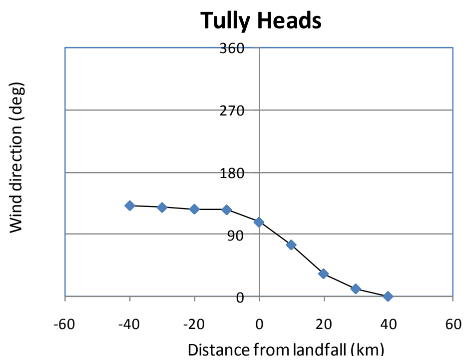


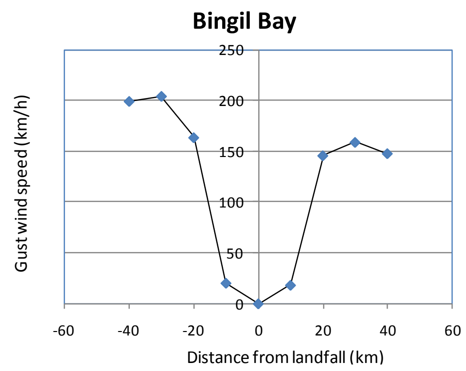


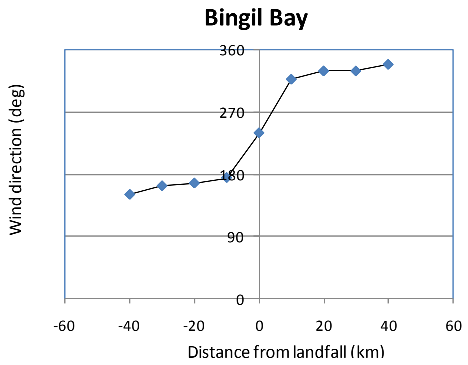

South Mission Beach
Gust wind speed (km/h)
250
200
150
100
50
0
-60 -40 -20 0 20 40 60
Distance from landfall (km)

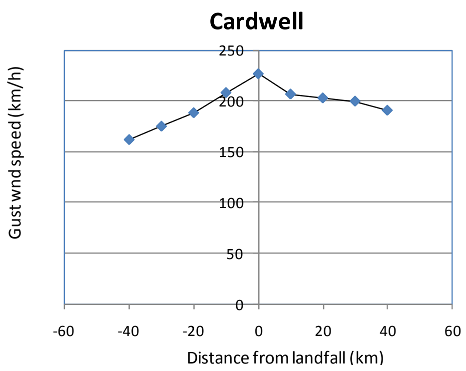

South Mission Beach
Wind direction (deg)
360
270
180
90
0
-60 -40 -20 0 20 40 60
Distance from landfall (km)

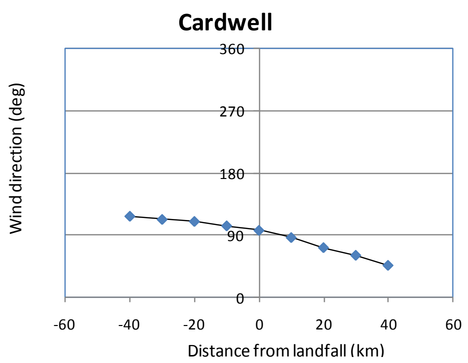

Tully Heads
Gust wind speed (km/h)
250
200
150
100
50
0
-60 -40 -20 0 20 40 60
Distance from landfall (km)

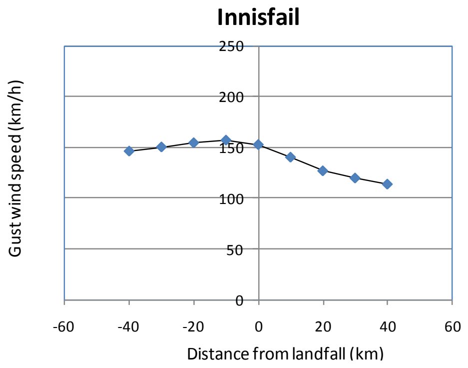

Tully Heads
Wind direction (deg)
360
270
180
90
0
-60 -40 -20 0 20 40 60
Distance from landfall (km)

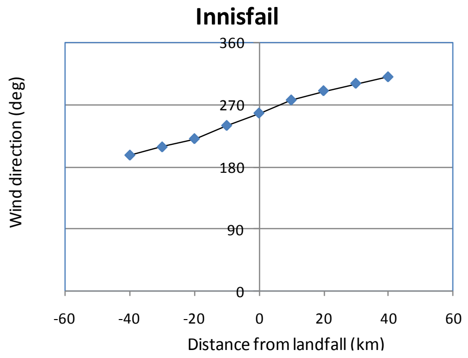

Bingil Bay
Gust wind speed (km/h)
250
200
150
100
50
0
-60 -40 -20 0 20 40 60
Distance from landfall (km)

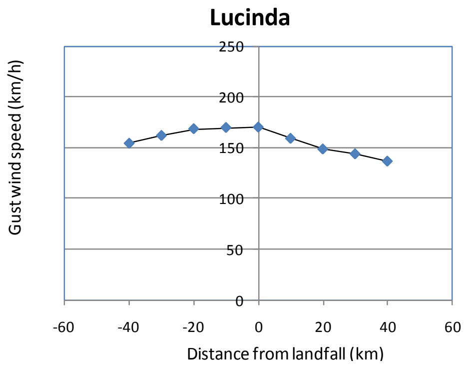

Bingil Bay
Wind direction (deg)
360
270
180
90
0
-60 -40 -20 0 20 40 60
Distance from landfall (km)

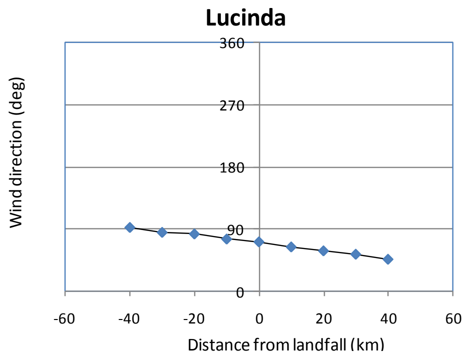

Cardwell
Gust wnd speed (km/h)
250
200
150
100
50
0
-60 -40 -20 0 20 40 60
Distance from landfall (km)

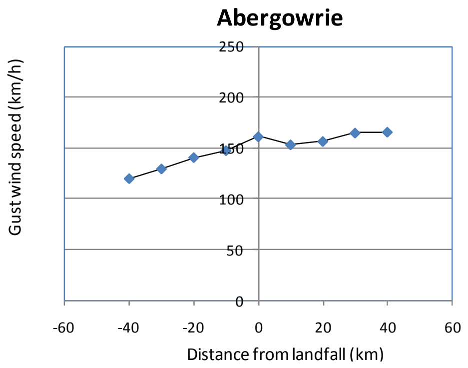

Cardwell
Wind direction (deg)
360
270
180
90
0
-60 -40 -20 0 20 40 60
Distance from landfall (km)

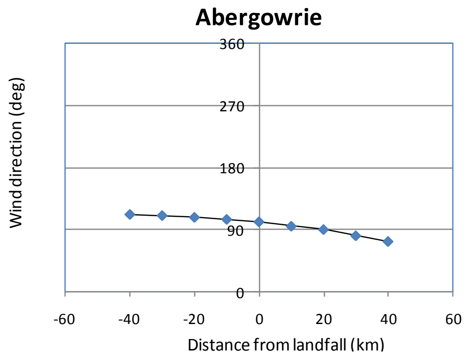

Innisfail
Gust wind speed (km/h)
Distance from landfall (km)


Innisfail
Wind direction (deg)
Distance from landfall (km)


Lucinda
Gust wind speed (km/h)
Distance from landfall (km)


Lucinda
Wind direction (deg)
Distance from landfall (km)


Abergowrie
Gust wind speed (km/h)
Distance from landfall (km)


Abergowrie
Wind direction (deg)
Distance from landfall (km)

Appendix C Street survey information

C.1 Summary of street survey data

The building and damage characteristics of each of the towns have been presented in Table C.1. The table shows:

1. Number of Pre-80s houses is the number of buildings judged to have been built or had the last substantial renovation prior to 1980.
2. Number of Post-80s houses is the number of buildings judged to have been built or substantially redeveloped since 1980.
3. Average Damage Index for Roofing, Openings, or Walls was obtained by averaging the digit representing that Damage Index category for all the houses within the groups. (See detail below on use of averaged Damage Index and Averaged topographic class).
4. Average topographic class was obtained by averaging the topographic class for all buildings within the group.

Table C.1 Damage classification for each town

	Pre-80s					Post-80s				
Locality	**No**	**avg R**	**avg O**	**avg W**	**avg Topo**	**No**	**avg R**	**avg O**	**avg W**	**avg Topo**
Bingil Bay	69	0.96	0.77	0.23	1.13	129	0.49	0.16	0.05	1.32
Mission Beach	22	2.36	0.18	0.00	1.00	217	0.53	0.06	0.05	1.12
Wongaling Beach	62	0.73	0.15	0.00	1.00	356	0.51	0.10	0.06	1.06
South Mission Beach	26	1.12	0.42	0.42	1.23	277	0.45	0.15	0.10	1.58
Hull Heads	32	0.59	0.19	0.00	1.00	14	0.07	0.00	0.00	1.00
Tully Heads	73	1.70	3.71	1.78	1.00	129	0.71	1.28	0.61	1.00
Cardwell	162	1.70	0.49	0.07	1.00	176	0.51	0.10	0.02	1.00
Tully	146	1.08	0.38	0.14	1.27	44	0.43	0.09	0.00	1.73
Total	592	1.30	0.82	0.32	1.09	1371	0.51	0.22	0.11	1.21

Table C.2 shows the comparison between the damage observed in the Post-80s and Pre-80s housing.

1. Difference between the Post-80s and Pre-80s performance was found by subtracting the average Damage Index of the Pre-80s buildings in the town from the average Damage Index of the Post-80s houses in the town. A negative number means that there is reduced damage in the newer houses compared with the older houses.
2. ‘sig avg’ means the statistical significance of the difference between for example the ‘avg R’ as found using the student-t test. The smaller the number in this column, the more confidence we have that the difference is significant. Normally if this number is less than 0.05, statisticians say that the difference is significant.

Table C.2 Damage classification for each town

	Difference between Post-80s and Pre-80s					
Locality	**avg R**	**sig avg R**	**avg O**	**sig avg O**	**avg W**	**sig avg W**
Bingil Bay	-0.45	0.03	-0.61	0.01	-0.19	0.02
Mission Beach	-1.84	0.00	-0.13	0.00	0.05	0.92
Wongaling Beach	-0.21	0.02	-0.04	0.19	0.06	0.99
South Mission Beach	-0.66	0.01	-0.28	0.01	-0.32	0.00
Hull Heads	-0.52	0.00	-0.19	0.06	0.00	
Tully Heads	-0.99	0.04	-2.43	0.02	-1.17	0.04
Cardwell	-1.19	0.01	-0.39	0.00	-0.05	0.00
Tully	-0.64	0.10	-0.29	0.03	-0.14	0.01
Total	-0.79	0.000	-0.61	0.00	-0.21	0.00

C.1.1 Use of average Damage Index

As shown in Table 3.1, there are three digits in the damage index, each of them represents the scale of damage to one aspect of the building (Roof, Openings and Walls). While each is a classification only and cannot be regarded as a linear progression, the damage is worse for the higher numbers than the lower numbers. In other words, as the Damage Index increases, the damage is more severe and more costly to repair for all three of the digits.

Thus in averaging the Damage Indices across a group, if the damage is generally low, the average index will be a low number and if it is generally high, then the average will be a higher number. For example, in Mission Beach, the average R index was 2.36 for Pre-80s houses and 0.53 for Post-80s houses. This does not mean that all of the pre-80s houses had debris damage to the roof and all of the Post-80s houses had gutter damage. However, it is possible to say that on average, the level of damage in the Pre-80s houses was greater than that in the Post-80s houses. The importance of these two Indices is that the Pre-80s Index was higher than the Post-80s Index indicating, on average, the Pre-80s housing suffered greater damage than the Post-80s housing.

C.1.2 Use of average topographic class

The topographic class is a parameter used in AS 4055 to represent topographic accelerations of wind. Compared with the representation of topography in AS/NZS 1170.2, this representation has a number of simplifications. It is basically a function of the average slope of the top half of the hill or ridge and the position of the site with respect to the top of the hill or ridge. The topographic class can have 5 values: T1 is the lowest Class and corresponds to nearly flat land or the bottom of hills and the classes range to T5 which is the very top of very steep hills.

In this study, as the recommendations include a change to the assignment of the topographic class, the Class was allocated based only on the highest slope that the maximum winds would have approached. This gave for every house in the Street Survey a topographic class from T1 to T5, calculated in line with the recommendations of this report.

To facilitate statistical analysis of the topographic effects, the "T" was dropped so that the topographic class ranged from 1 to 5. In a similar way to the Damage Index, while the relationship between the classes is not necessarily linear (but it is close to linear), 2 represents higher velocities than 1. Therefore the higher the multiplier, the higher the topographic effects and the higher the design wind speed.

Thus in averaging the topographic class across a group, if the topography is generally flat, the average will be a low number and if it is generally steep, then the average will be a higher number. The average topographic class cannot and should not be related to AS 4055, but it does give a general indication of the effect of topography on the design wind velocity across the class.

For example in Tully Heads, all houses had a 1, so the average was 1.000. This indicates that the topography across the whole group was flat. In South Mission Beach there were quite a number of T2s and even some T3s. The average was a number between 1 and 2 1.581 for Post-80s houses and 1.231 for Pre-80s houses. Comparing the three items of data shows that generally South Mission Beach had more houses on hills and ridges than Tully Heads. It also indicates that the older houses (Pre-80s) were generally built on flatter land, and the new developments have had more houses on hills or ridges. In general the Post-80s houses will have experienced higher wind speeds than the Pre-80s houses in TC Yasi, because of the generally higher topographic effects.

The averaging of topographic class gives an indication of the effect of topography on a group of houses.

C.2 Relationships between parameters

Sections C.1.1 and C.1.2 showed how the parameters could be used to determine the differences between parameters for different groups of houses. Other statistical operations could be performed on these parameters.

C.2.1 Statistical significance of the differences

In C.1.1 the example showed how there was a difference between the average R for Pre-80s houses (2.36) and Post-80s houses (0.53) for Mission Beach. The difference of Post-80s – Pre80s was – 1.83. The significance of this result can be tested using the student t-test.

Each data set gives a mean value and a standard deviation of the Damage Index. This can be used together with the number in each group to evaluate *t* using equation (C.1).

$$t = \frac{\left(\overline{R_1} - \overline{R_2}\right)}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad \text{with } S_p = \sqrt{\frac{(n_1 - 1)S_1^{\,2} + (n_2 - 1)S_2^{\,2}}{n_1 + n_2 - 2}} \qquad \text{equation (C.1)}$$

with $\overline{R_1}$, S_1, n_1 the mean, standard deviation and number in group 1 respectively
$\overline{R_2}$, S_2, n_2 the mean, standard deviation and number in group 1 respectively
S_p the estimate of the population standard deviation

The t value calculated using equation (C.1) can then be used to evaluate the confidence that the difference between the means is other than zero. The number returned as sig avg R in Table C.1 is effectively the probability that the difference is equal to zero. For the example of Mission Beach quoted above, the difference was -1.83 and this has a probability of being equal to zero of 1×10^{-8} which is very low. This is saying that the probability that the difference is actually zero is miniscule, and the difference we have found is therefore very significant. Statistically, it can be said that the difference is significant if the probability is less than 0.05.

C2.2 Correlations between parameters

Because each house in the Street Survey data has a number of parameters attached to it, correlations between some of these parameters can be investigated.

For example with both Damage Index and topographic class being numbers with larger numbers having higher damage or more adverse topography, a correlation can be investigated between them. A positive correlation shows that more adverse topography can be linked with higher levels of damage. This was the case with the investigation.

Firstly only those communities that had a variation in topography were selected for correlations. As indicated above, Tully Heads did not have any houses with topography more adverse than T1. There was no point using Tully Heads or other communities with no variation in topography to ascertain relationships involving topography.

In consideration of communities with variations in topography, a positive correlation was found between topography and damage index. The body of the report presents this information as comparative column charts.

Appendix D on Storm Surge

D.1 Background information on storm surge

Well away from the coast the surge is predominantly a mound of water which mirrors the pressure drop, the increase in sea-level being approximately 1 cm for every drop in surface pressure of 1 hPa (Stark, 1980). As this mound of water approaches the coast it is amplified due to frictional effects associated with the shallowing of the water and high wind stresses on the sea surface which push water towards or away from the coast. The storm surge tends to be highest on the edge of the eye where the winds are strongest falling away either side of this. Along the eastern Queensland coastline this would typically result in a profile of storm surge north and south of the eye as shown in Figure D.1

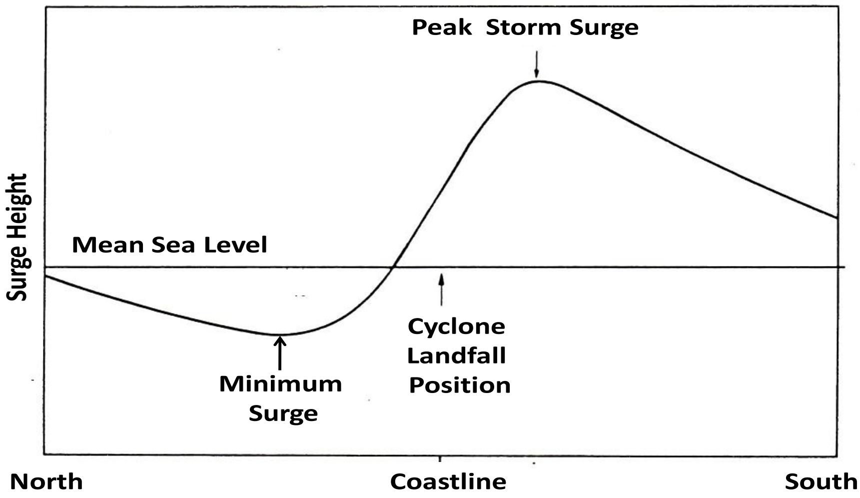


Figure D.1 Schematic of variation in height of storm surges along the east coast of Queensland

The actual storm surge height at the shoreline depends on the characteristics of the tropical cyclone such as central pressure, size, track and history over the ocean, forward speed, and wind field, as well as the bathymetry of the ocean adjacent to the coast, the shape of the coast, and islands and reefs over which the cyclone passes. As a result for a given central pressure at landfall the peak storm surge can vary greatly, and the variation along a coastline can also vary greatly from the smooth curve shown in Figure D.1. However mathematical modelling of storm surge development taking these factors into account is a relatively well established technique, and has become the basis of most forecasting of storm surge heights.

Time wise a storm surge resembles a tide rising and falling over a period of hours not minutes, with the peak roughly corresponding to when the centre of the tropical cyclone crosses the coast. In this respect it is quite different from a tsunami with which it is often compared, and more like major riverine flooding with steadily rising water accompanied by a reasonably strong current but not the extremely strong currents associated with a tsunami. What makes it different from riverine flooding is the accompanying wave action which produces additional forces on structures adjacent to the shoreline.

The level of impact of the storm surge on coastal buildings and other structures depends on the combination of storm surge height, the normal astronomical tide levels on which it is superimposed, and the associated wave action, which increases the actual water level at the coastline due to wave set up. This combination is depicted schematically in Figure D.2.

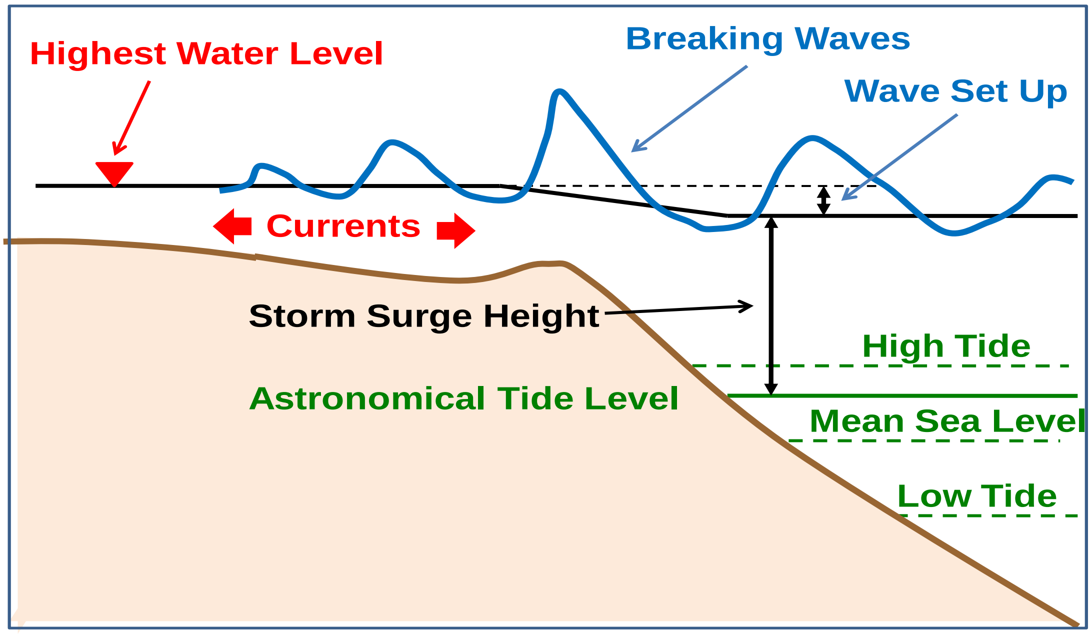


Figure D.2 Schematic of Combination of Storm Surge, Tide and Waves at Coastline

In regions where the tidal range is small such as the Gulf coast of the southern US the timing of the crossing of the tropical cyclone is not very critical, but in regions like the east coast of Queensland where the tidal range is of the order of metres the timing of the landfall of the centre of the cyclone can make a big difference. Major storm surge losses occur in this region when tropical cyclones with relative large storm surges landfall at close to high tide, which is relatively rare.

D.2 Previous Storm Surge in Australia

Historically the worst storm surge in terms of impact to hit the east coast of Queensland was that from Cyclone Mahina in 1899 in Princess Charlotte Bay on Cape York Peninsula, with an estimated highest water level including wave run up reported to be of the order of 14 m above mean sea level and penetration inland of the order of 5 km, sinking over 100 vessels in a Pearling fleet and drowning over 400 persons. The most serious storm surges to hit the Queensland coast in the last 100 years were about 7 weeks apart in 1918 and both appear to have peaked around high tide. The first hit Mackay in January producing a storm surge variously reported as between 3.5 m and 5.5 m in height at roughly high tide, which in combination with the flooded Pioneer River inundated much of the town, and in combination with the severe winds destroyed much of it. A few weeks later the Innisfail area was hit by an even more powerful cyclone which at Mission Beach produced a storm surge which in combination with the tide resulted in a depth of water up to about 3.5 m deep sweeping hundreds of meters inland. These three cyclones appear to have not only produced the most severe storm surge damage, but have been the most severe to hit the east coast of Queensland since European settlement.

Since 1918 and prior to Cyclone Yasi there have been a number of severe cyclones cross the coast with peak storm surge heights between 2m and 3m which could have produced major damage had they crossed near high tide but they didn't. Cyclone Althea produced a storm surge of the order of 2.8m which if it had occurred at high tide would probably have resulted in the loss of several hundred lives because of the lack of recognition of the threat at that time. One consequence of this long period with no significant losses due to storm surge has been a tendency to ignore the threat in relation to buildings, although it is well recognised in terms of warnings when cyclones are threatening.