JAMES COOK UNIVERSITY AUSTRALIA

CYCLONE TESTING STATION

Tropical Cyclone Debbie
Damage to buildings in the Whitsunday Region

CTS Technical Report No 63

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TECHNICAL REPORT NO. 63

Tropical Cyclone Debbie
Damage to buildings in the Whitsunday Region

By
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Executive Summary

Tropical Cyclone Debbie (TC Debbie) was classified by the Bureau of Meteorology (BoM) as a Category 4 cyclone and crossed the Queensland coast north east of Airlie Beach around midday on Tuesday 28 March 2017.

Before the event, the Cyclone Testing Station (CTS) deployed six mobile anemometers (SWIRLnet) in the area between Ayr and Proserpine. After the event, CTS teams investigated the performance of houses; larger residential structures such as apartments, strata properties and resort accommodation; commercial and public buildings; and sheds. The study area included the communities of Bowen, Proserpine, Airlie Beach, Hamilton Island, Dingo Beach, Wilson's Beach and Conway Beach. A wind field was developed using CTS and BoM anemometer data and showed that buildings within the study area experienced wind speeds lower than their relevant design wind speed.

CTS teams assessed the causes of damage to buildings from wind, wind-driven rainwater and storm surge. Inadequate tie-down details between battens and rafters or trusses, and between the roof structure and walls caused many of the structural failures in buildings constructed before the 1980s. Tie-down connections between roof structure and walls that had been inappropriately detailed also failed on some recently constructed buildings. Connections between verandah beams and posts on some buildings with larger verandahs also failed.

This study confirmed the findings of previous damage investigations concerning the vulnerability of: windows with inadequate fixings, window and door furniture; poorly fixed flashings, gutters and soffit linings; large access doors that had not been strengthened so that they complied with AS/NZS4505; lightweight sheds; and fences.

Many occupants of newer buildings reported significant damage from wind-driven rain entering through windows and doors or under flashings even though there was no structural damage to the building. Many people reported that they mopped up water in front of windward wall windows during periods of maximum winds, which exposed them to risk of injury. Further research is required to improve performance of building elements that leak during high winds.

The storm tide generated during TC Debbie was lower than predicted because the cyclone crossed the coast after high tide. Lower-lying buildings in Wilson Beach were inundated to a height of up to 1.1 m causing damage to wall linings, built-in cupboards, floor coverings and contents. In some cases, wave action broke cladding elements and windows. Wave action and scour undercut footings in some buildings on Hamilton Island and Wilson Beach.

The report provides recommendations to improve the performance of building structure and cladding systems including: adequate detailing for roof to wall connections; improved fixing of flashings, retrofitting options for older buildings; improvements in windows and door furniture under repeated wind loads; and revision of storm surge guidelines.

Acknowledgements

The authors are extremely grateful to the residents of the Bowen, Proserpine, Airlie Beach, Hamilton Island, Dingo Beach, Hydeaway Bay and Wilson Beach who generously assisted with this study by volunteering information, answering questions, providing videos and photos, and inviting the authors into their homes to inspect the house or unit's performance.

The CTS field team acknowledges the invaluable assistance of the 3rd Combat Engineer Regiment (3CER) and the close working relationship developed with them during their deployment in Operation Queensland Assist as JTF 661.2 Emergency Support Force. We especially thank Lieutenant Colonel Jenifer Harris CSC, Major Matthew Dobney, Captain Liam Clarke and Captain Ellysha Gillespie.

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- Oz Cyclone Chasers;
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The CTS field team comprised Geoff Boughton (Leader), David Henderson, Daniel Smith, Korah Parackal, Mitchell Humphreys, Satheeskumar Navaratnam, Geeth Bodhinayake, John Ginger and Debbie Falck from the CTS at James Cook University, and Thomas Kloetske from the University of Queensland.

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Queensland Government   ABCB   bushfire&natural HAZARDS CRC

CTS would like to thank our supporters.

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1. INTRODUCTION

1.1. TC Debbie Overview

Tropical Cyclone Debbie (TC Debbie) was a severe, slow moving tropical cyclone with a relatively large diameter that crossed the Queensland coast south of Bowen around midday on Tuesday 28 March 2017. TC Debbie caused wind and water damage to buildings in the area between Bowen and Mackay, with the most severe damage in and around the communities of Bowen, Proserpine, Airlie Beach and Hamilton Island. Figure 1.1 shows the study area.

Bureau of Meteorology (BoM) models predicted that TC Debbie would generate significant storm surge levels as it approached the coast. Some residents in low-lying areas in the affected region were asked to evacuate. Fortunately the cyclone moved slower than anticipated, and the peak storm tide level did not coincide with high tide. Although some buildings in Wilson Beach and Hamilton Island suffered damage from storm surge, the predicted widespread storm surge effects did not eventuate.

1.2. CTS field investigation

The Cyclone Testing Station (CTS) teams conducted field surveys to investigate the performance of buildings (housing, larger residential structures such as apartments, strata properties and resort accommodation; public buildings and sheds) during TC Debbie. The study area extended between Ayr and Proserpine, and included the communities of Bowen, Proserpine, Airlie Beach, Hamilton Island, Shute Harbour, Hydeaway Bay, Dingo Beach, Wilson Beach and Conway Beach. (Locations are highlighted on Figure 1.1.)

Figure 1.1 Region of investigation

The field studies commenced on Thursday 29 March 2017 with the data collection phase completed on 10 April 2017. The field studies:

- Used The SWIRLnet and BoM data to estimate the peak gust experienced at a number of different locations in the affected area and compared them with the damage to buildings within the study area.
- Examined contemporary buildings constructed using the current regulations 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 structures or structural elements that appear to have systematic weaknesses.
- Assessed the capacity of buildings to withstand wind loading and debris impact loading.
- Assessed the extent of damage to houses and larger buildings from wind-driven rain, focusing on the performance of windows, doors, gutters and flashings.
- Examined older houses and other buildings to determine the need for retrofitting, and assessed the effectiveness of any structural upgrades.
- Determined the extent of structural damage from storm surge in the study area.

1.3. Purpose of the report

The purpose of this report is to present the outcomes of the CTS field investigations into the structural damage to buildings caused by TC Debbie. The report identifies problems in building performance and indicates whether the current regulations are targeting an appropriate level of structural safety and amenity.

Previous investigations following TC Marcia in 2015, TC Yasi (Boughton *et al*, 2011) and TC Larry (Henderson *et al*, 2006) indicated that older houses (built before the changes to Appendix 4 of Queensland's Building By-laws in the early 1980s) do not perform as well as houses constructed in the past 30 years. This was also the case in TC Debbie. As the drivers of damage to older houses have been explored in detail in previous CTS Technical Reports, this investigation focused on:

- Houses built after 1985;
- Commercial buildings and sheds; and
- Strata properties or resort accommodation.

However, the performance of some older buildings that had been structurally upgraded was also assessed. In other cases, options for retrofitting were explored.

2. TC DEBBIE

2.1. BoM Information

First indications of a potential tropical cyclone formation were evident on March 22 2017 when a tropical low developed over the North Coral Sea within a low vertical wind shear environment. Sea surface temperatures around 30°C and an aligned vertical circulation combined to produce conditions favourable for cyclone development. These conditions led to the organisation of convection around the tropical low as it drifted south over the next three days. The low was upgraded to Category 1 TC Debbie at 10 am AEST on 25 March 2017. At this point, TC Debbie was predicted to make landfall as a Category 4 system crossing between Townsville and Proserpine on 28 March 2017 at around 10 am AEST (see Figure 2.1).

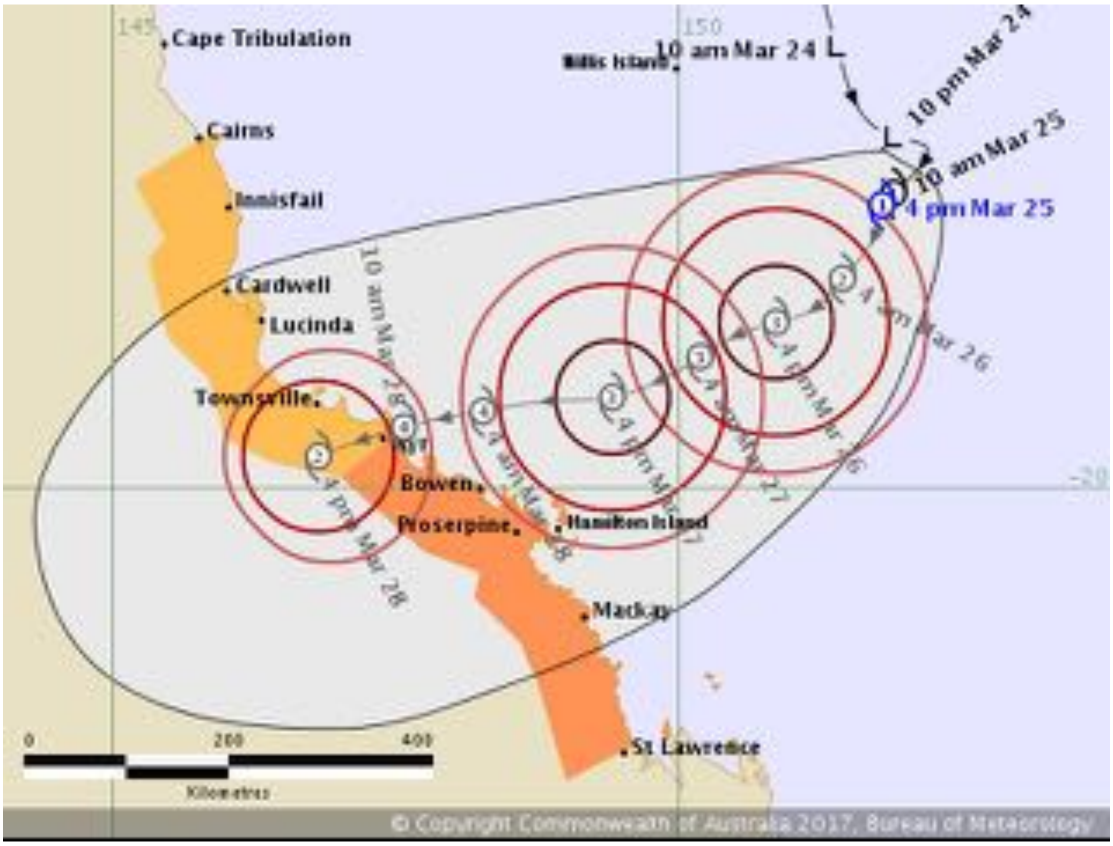


Figure 2.1 25 March 2017 predicted track of TC Debbie
(*Provided by Bureau of Meteorology*)

TC Debbie kept intensifying into a Category 2 cyclone over the following 12 hours and tracked southwest towards the coast. On 26 March, the Category 2 system drifted south. Due to an improvement in the environmental conditions on 27 March, TC Debbie rapidly intensified and reached Category 4 strength within 12 hours. TC Debbie continued moving southwest at a speed of about 9 km/h.

As TC Debbie approached the Whitsundays it began to undergo an eyewall replacement cycle as shown in Figure 2.2. Commencing around 4 am AEST on 27 March, the original inner eyewall began to decay as a concentric secondary outer eyewall began to form. As TC Debbie moved closer to the Queensland coast, the radius of maximum winds expanded. However, the interaction with land interrupted the eyewall replacement cycle and did not allow the inner eyewall to completely decay. Moreover, the outer eyewall never contracted fully, nor did it take the place of the original inner eyewall. The disruption of the eyewall replacement cycle is likely to have impeded further intensification before landfall. The red arrows in Figure 2.2 indicate the inner eye wall and black arrows indicate the outer eyewall.

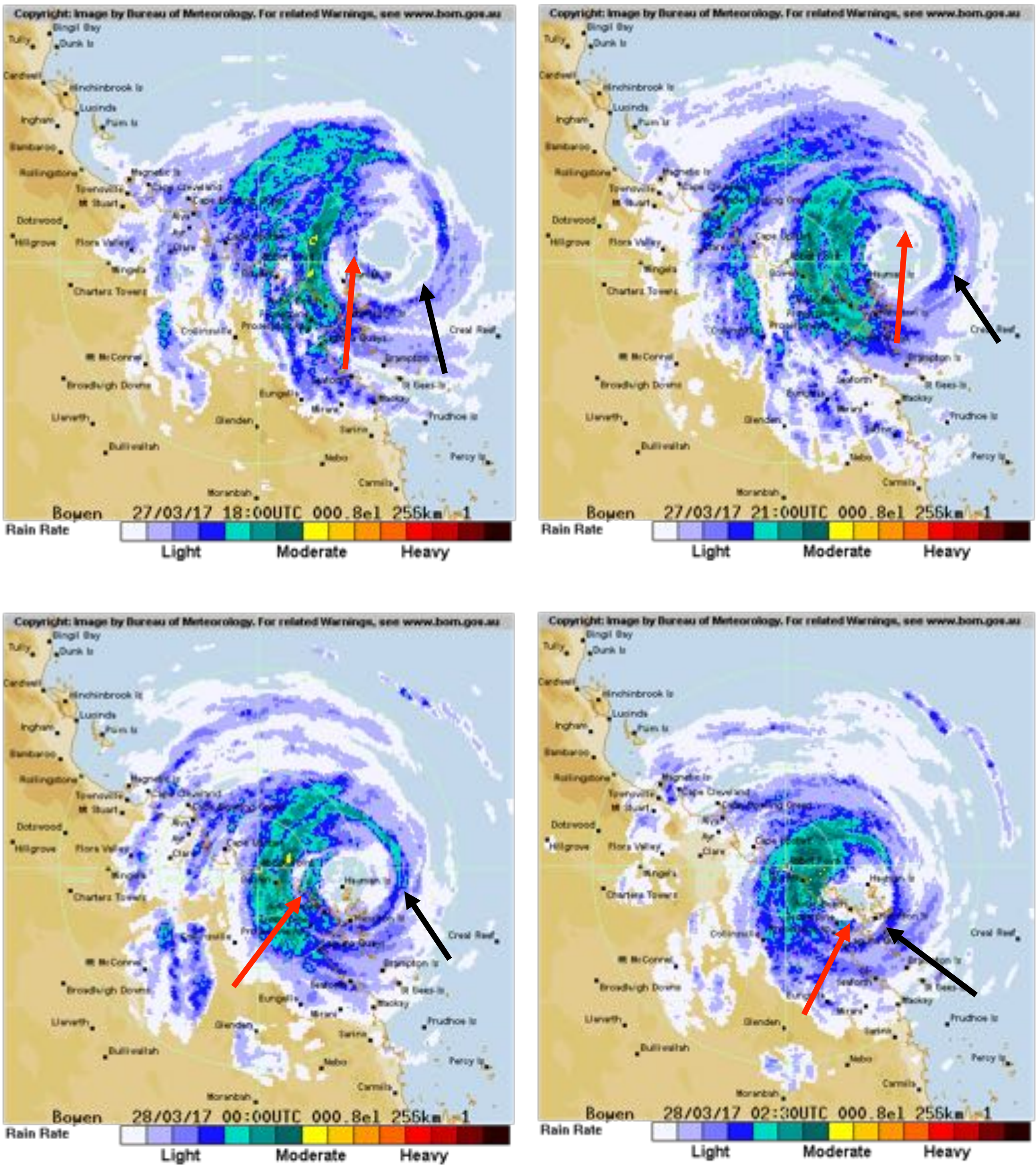


Figure 2.2 Bowen radar 0.8o reflectivity plan position indicator scans during the landfall of TC Debbie. (*Provided by Bureau of Meteorology*)

Note: Times are in UTC (add 10 hours to convert to AEST).

TC Debbie's eye crossed the mainland east of Airlie Beach at around 12:40 pm AEST 28 March 2017 as indicated in Figure 2.3. Near landfall, TC Debbie slowed down to 7 km/h and towns in the affected region (such as Hamilton Island, Airlie Beach and Proserpine) were exposed to strong winds for many hours. As TC Debbie moved further inland, it weakened until it was classified as a tropical low at 3 am AEST on

29 March 2017. The remnants of TC Debbie continued tracking generally south causing extensive rainfall along its path. The greater Mackay area experienced 986 mm in a 24 hour period. The Sunshine Coast, Brisbane and Gold Coast and their hinterland regions experienced up to 600 mm of rain in 24 hours. Heavy rainfall from this event also extended into New South Wales.

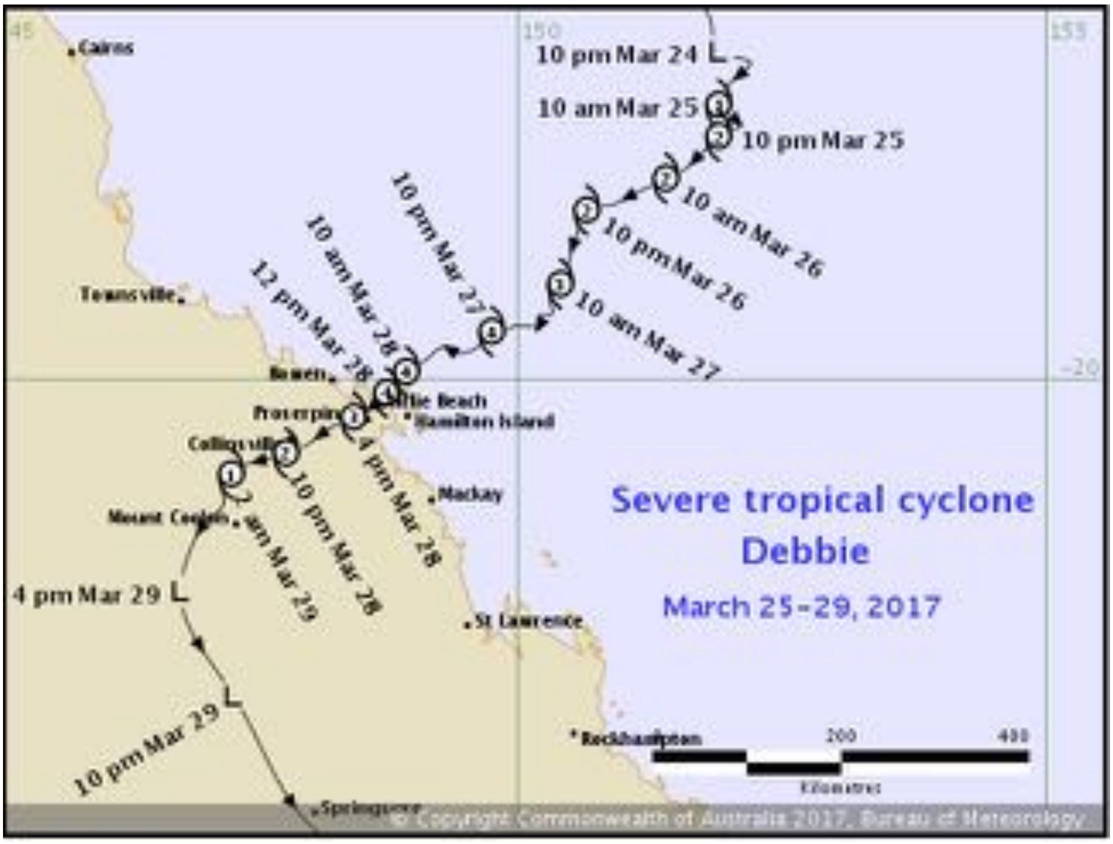


Figure 2.3 Observed track of TC Debbie
(*Provided by Bureau of Meteorology*)

2.2. Anemometer data

A number of Bureau of Meteorology Automated Weather Stations (AWS) recorded wind data during the passage of TC Debbie. These included Hamilton Island, Proserpine, Bowen and Mackay. In addition, the Cyclone Testing Station deployed six of the SWIRLnet portable anemometers to the region (Ayr, Home Hill, Bowen, Proserpine), and the Oz Cyclone Chaser team deployed a portable anemometer at Airlie Beach.

2.2.1. BoM anemometer data

Raw 3-second gust data (i.e. peak 3-second gust observed within the preceding 10-minutes) from the BoM anemometers at Hamilton Island, Proserpine, Bowen, Mackay Airport and Mackay Meteorology Office are shown in Figure 2.4. Table 2.1 summarises the BoM data.

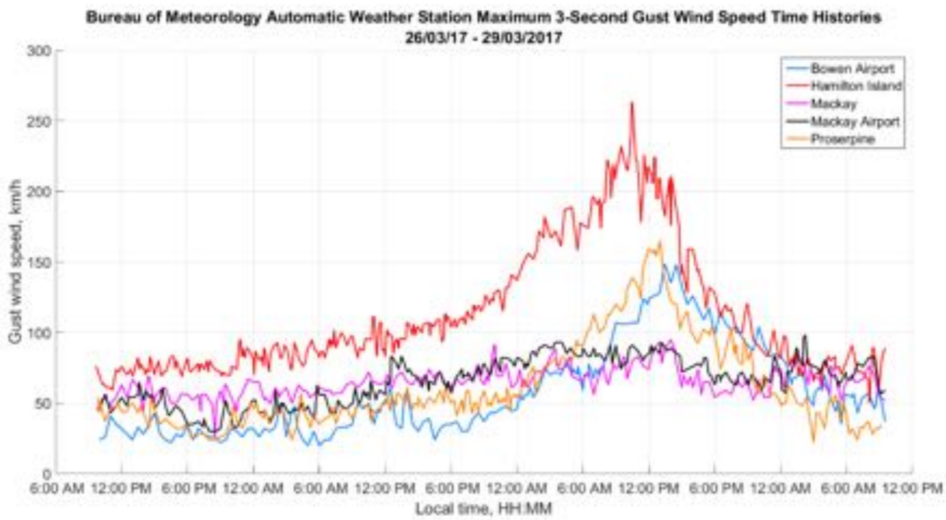


Figure 2.4 BoM AWS 3-second gust wind speed time histories
(*Provided by Bureau of Meteorology*)

A peak wind gust of 263 km/h was recorded by the BoM's AWS on Hamilton Island. The AWS in Proserpine captured a maximum wind gust of 165 km/h. While the wind gust at Hamilton Island AWS is high, it must be noted that the AWS is located on top of a 50 m high hill that increased this peak gust by around 30% compared with measurements on flat ground. The upwind exposures of each AWS site for approach winds at the time of maximum gusts were Terrain Category (TC) 1 at Hamilton Island, and TC 2.5 at Bowen and Proserpine. The latter two anemometers were on flat ground. All BoM AWS anemometers are at an elevation of 10 m.

Figure 2.4 shows the peak gust occurring first at Hamilton Island, then Proserpine and shortly after, at Bowen. Despite heavy rainfall in the area, wind speeds recorded by the AWS at Mackay confirmed that this region was outside the area affected by severe winds. Wind field models discussed in Section 2.3 were calibrated using all the anemometer data after accounting for topography and upwind terrain.

Table 2.1 BoM AWS data

Site	Max 3-s gust [km/h]	Direction (°)	Date/Time	Lowest P [hPa]
Bowen Airport	148	WSW	28/14:30	972.2
Hamilton Island	263	(*ESE*)*	28/10:30	966.3
Proserpine	165	SE	28/13:00	969.0
Mackay	95	E	28/14:00	993.0
Mackay Airport	98	NNE	29/02:15	998.8

* Hamilton Island AWS direction vane was damaged. Direction is estimated from wind over the counterweight.

2.2.2. SWRLnet anemometer data

The CTS deployed six SWIRLnet towers before TC Debbie approached the coast. They were deployed in various terrain conditions ranging from open terrain (e.g. Tower 1 and Tower 4) to terrain with suburban characteristics (e.g. Tower 2 and Tower 6). All anemometers were at an elevation of 3.2 m:

- Tower 1 was located in an open field showground approximately 1 km west of Ayr near an industrial estate.
- Tower 2 was located in a park within the suburb of Queens Park in Bowen. The ocean is approximately 500 m to the NE of the site, with moderately spaced suburban buildings to the NW and SE.
- Tower 3 was located on a sports field at the southern edge of Ayr. A golf course is to the east of the site with variable length fetches of suburban terrain in all other directions.
- Tower 4 was located on a sports field south of Home Hill. The site has suburban exposure from the town for winds from the NW quadrant but is open exposure in all other directions.
- Tower 5 was located in a vacant block of land a few hundred metres from the beach in the southern part of Bowen.
- Tower 6 was installed in a park in the east of Proserpine. Houses and large trees surround the park. Figure 2.5 shows a photo of Tower 6 after installation and during dismantling. The significant difference in foliage on trees around the park is evident.

Figure 2.6 shows the peak 3-second gust wind speed recorded during every 10-minute period for the duration of the cyclone at each SWIRLnet tower. Maximum gusts, their direction, time, and the associated minimum pressure measured by each tower are shown in Table 2.2. Tower 5 in South Bowen recorded the highest gust (126 km/h), with the minimum pressure (962 hPa) recorded at Proserpine. Significantly stronger wind speeds were recorded at Bowen and Proserpine, nearer to the cyclone's landfall, than further north at Ayr and Home Hill.

Wind speed time histories for the Bowen and Proserpine towers are similar up to around 11 am, at which point the North Bowen tower drops below the one deployed in the south of the city. This drop is believed to be due to local upwind site effects, including trees, buildings and possible influence by a 30-40 m high hill 400 to 500 m away. Wind speeds recorded at the Proserpine Tower 6 also drop below South Bowen at this time, despite being deployed closer to TC Debbie's path. The large trees shown in Figure 2.5(a) could initially shield the tower; but as leaves were lost, the shielding would decrease Figure 2.5(b). This time also corresponds to the beginning of a 150° shift in wind direction as the cyclone moved over the region.

Detailed analysis of the SWIRLnet data for turbulence, gust intensity and duration, and changes with different upwind terrain that occurs during the cyclone is continuing in order to better understand cyclonic wind characteristics in the built environment. Of particular interest are the large peaks in the data for the South Bowen tower (i.e. the four spikes in Figure 2.6 beginning with the largest recorded wind gust at 1:30pm), which cannot be explained by turbulence theory.

(a) Tower installed before cyclone

(b) Dismantling tower after cyclone

Figure 2.5 SWIRLnet Tower 6

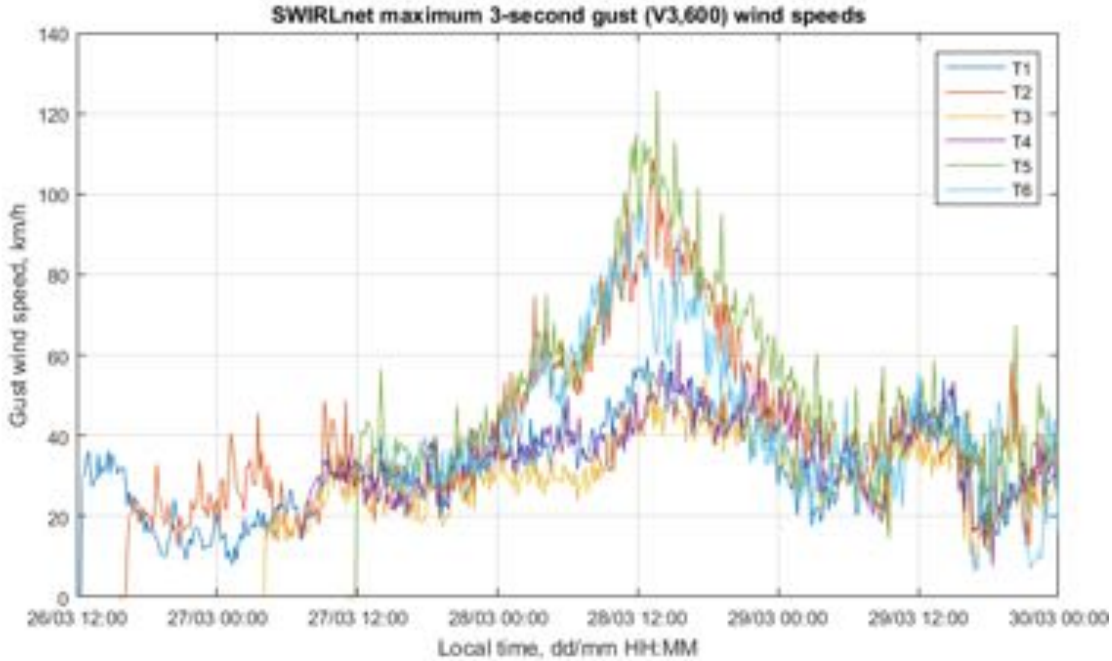


Figure 2.6 CTS SWIRLnet data 3-second gust wind speed time histories

Table 2.2 CTS SWIRLnet data

Site	Max 3s Gust [km/h]	Direction (°)	Date/Time	Lowest P [hPa]
Tower 1 (Ayr)	59.4	245	28/13:00	992
Tower 2 (N. Bowen)	108.9	230	28/13:00	972
Tower 3 (Ayr)	55.5	240	28/13:00	992
Tower 4 (Home Hill)	63.9	240	28/15:00	990
Tower 5 (S. Bowen)	125.7	270	28/13:30	971
Tower 6 (Proserpine)	97.1	150	28/12:00	962

The Oz Cyclone Chasers (OCC) also deployed a portable anemometer (with similar features to the CTS SWIRLnet anemometers, but mounted on a 3 m tower) in a park at Airlie Beach. Data from this anemometer was provided to the CTS and a peak 3-second gust of 181 km/h was recorded. The site was relatively free of adjacent local shielding features, e.g. trees, but winds may have been influenced by the large upwind hotel complex, and the steep topography surrounding the town. Interestingly, large spikes similar to those identified in the South Bowen SWIRLnet tower record were also recorded by the OCC tower and were similarly responsible for the peak gust recorded at that site. The peak values of both these towers should be investigated further as they are based on a single short duration peak (i.e. less than a few seconds, and therefore, highly localised) that is 10-15% greater than the second highest gust.

2.2.3. Wind speeds as a percentage of design wind speed

The Bureau of Meteorology, SWIRLnet and OCC anemometers reported 3-second peak gusts. However, the design gusts presented in AS/NZS 1170.2 (Standards Australia, 2011) are 0.2-second gusts. In order to relate the observed wind speeds with the design wind speeds, the data was converted to the same basis as V_R in AS/NZS 1170.2, i.e.:

- 0.2 second gust;
- flat land;
- open terrain (TC2); and
- no shielding.

Conversions removed topographic influence from measured mean and gust wind speeds using topographic multipliers (M_t) in AS/NZS 1170.2. Gust factors for each instrument were calculated from the mean and gust wind data as well as characteristics of the instrument. These were then converted to equivalent turbulence intensities and subsequently effective roughness lengths (i.e. z_0) for each site/direction. Terrain corrections to the mean wind speed were then made for each record using these effective roughness values and the Log-law equation. Finally, adjusted gusts were estimated using calculated turbulence intensities, measured 3-second peak factors and theoretical peak factor ratios between 0.2-second and 3-second gusts. The converted data is summarised in Table 2.3 where they are also presented as a proportion of design wind speeds (V_R) for a normal structure, i.e. annual probability of exceedance of 1:500 or V_{500}.

While the adjustments detailed above include some assumptions, it appears that all locations in the study area experienced winds less than the design wind speed. Buildings on some parts of Hamilton Island may have experienced winds close to their design wind speed. Buildings in Ayr and Home Hill experienced wind in the order of 35% V_{500}; in Mackay they were less than 50% V_{500}; in Bowen they reached around 70% V_{500} and in Proserpine around 80% V_{500}. Some discrepancy exists between the SWIRLnet and AWS readings in Proserpine, but this is thought to be due to unaccounted for shielding effects of the large trees near the SWIRLnet site shown in Figure 2.5. A shielding factor from AS/NZS1170.2 has been applied to T6.

Estimated wind speeds in the Airlie Beach region are for 80-90% V_{500}, but the wind speeds will be much less for the buildings/suburbs that are directly shielded by the large topography in the area (e.g. units and houses nestled in behind the slopes facing NW-NNE).

Table 2.3 Adjusted anemometer data as a percentage of V_{500}

SWIRLnet Tower (*z* = 3.2 m)	**Location**	$\hat{u}_{3,600,tower}$ **@ 3.2m [m/s]**	$\hat{u}_{3,600,open}$ **@ 10m [m/s]**	$\hat{u}_{0.2,600,open}$ **@ 10m [m/s]**	**% V_{500}**
1	North Ayr	16.5	20.6	22.4	32
2	North Bowen	30.3	37.9	41.9	61
3	South Ayr	15.4	19.5	21.3	31
4	Home Hill	17.7	21.2	23.7	34
5	South Bowen	34.9	42.6	47.6	69
6	Proserpine	27.0	36.4	49.6	72
BoM AWS (*z* = 10 m)					
Bowen Airport		41.1	41.5	47.6	69
Proserpine		45.8	47.2	53.5	77
Hamilton Island		73.1	57.3	67.1	97
Mackay Met. Office		26.4	24.0	26.6	38
Mackay Airport		27.2	27.9	31.5	45

2.3. Wind field study area

The data presented in Table 2.3 were compared with wind speeds calculated using a double Holland model of TC Debbie immediately before and after landfall. Parameters in the model were drawn from BoM data on the cyclone and calibrated against BoM and CTS SWIRLnet anemometer data. Figure 2.7 shows a snapshot of the output from the model just before TC Debbie crossed the coast.

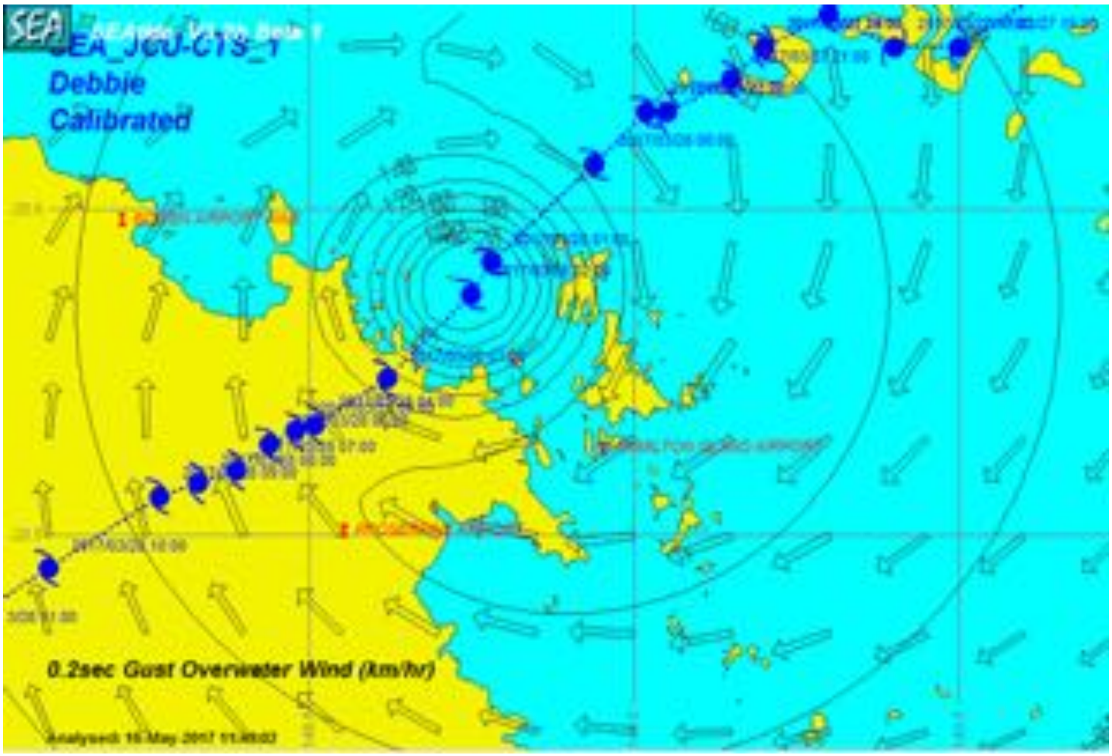


Figure 2.7 3-second Holland model results of wind before landfall
(Diagram provided by Bruce Harper, SEA)

Figure 2.8 shows a comparison between modelled wind velocities and recorded wind speeds at Proserpine AWS.

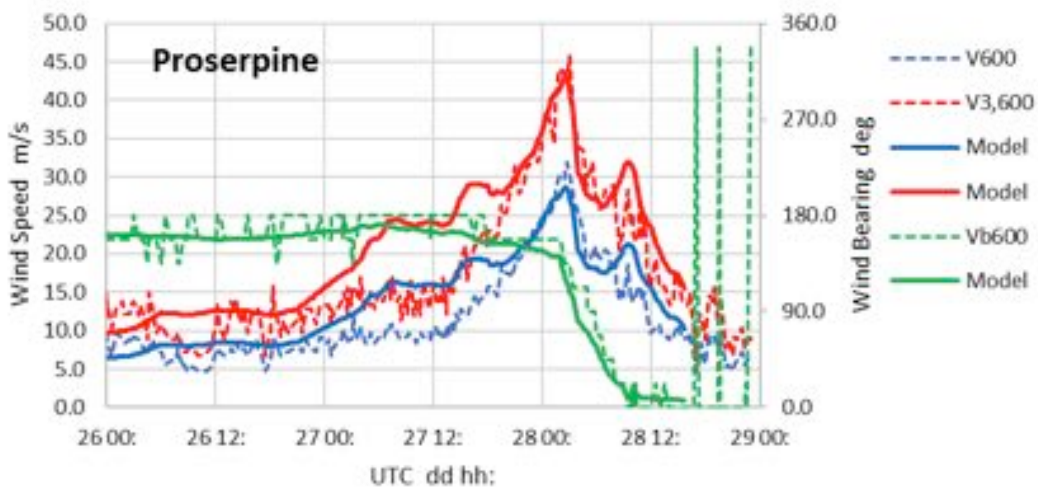


Figure 2.8 3-second Holland model results and AWS data for Proserpine
(Note: Red and blue lines refer to wind speeds, green lines refer to wind bearing.)

The data from the wind field model was also used in the SEA storm surge model (Harper, 2017), which correctly predicted storm surges recorded at Shute Harbour and Laguna Quays.

Figure 2.9 provides an estimate of the percentage of the 0.2-second gusts in relation to the V_{500} design wind speed. The contours were derived from data from anemometers with infill guidance from the Holland wind field model.

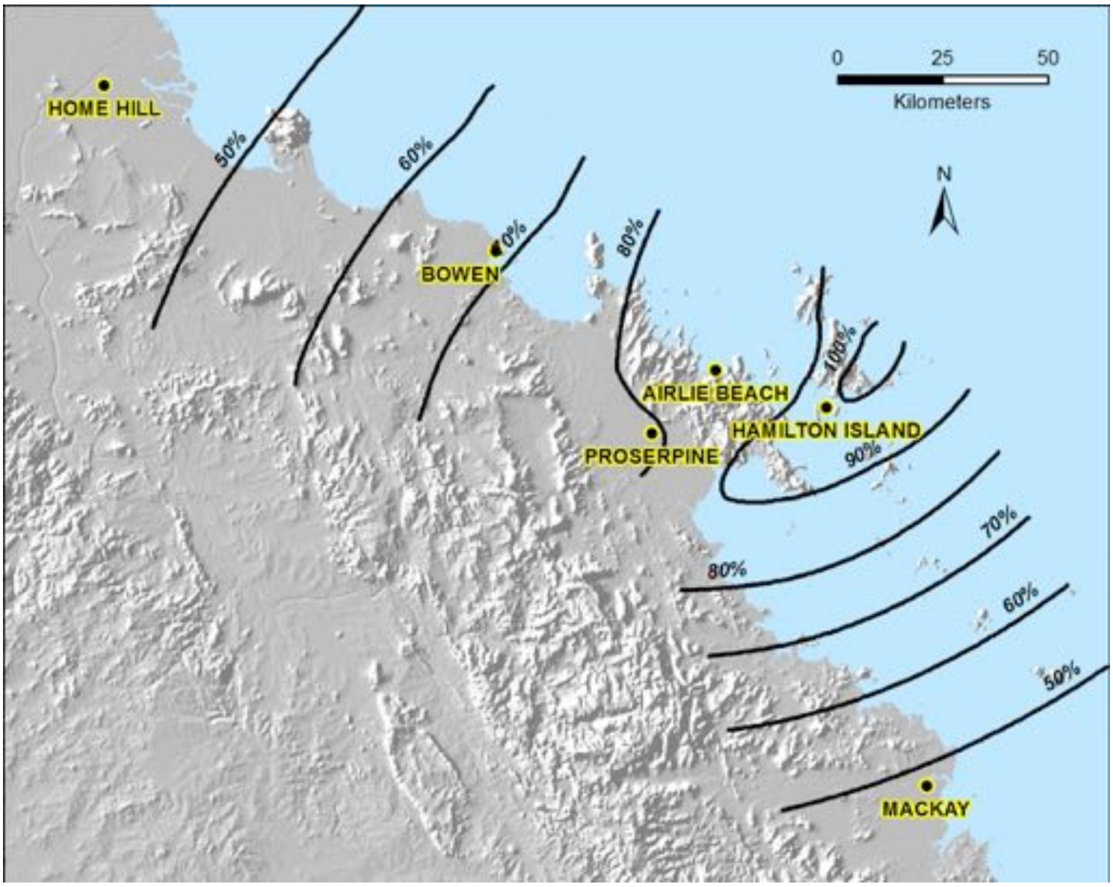


Figure 2.9 Estimate of wind field for 0.2-second gust as a percentage of V_{500}

3. Estimates of Damage from Rapid Damage Assessment

3.1. Rapid Damage Assessment data

Rapid Damage Assessment (RDA) data were provided by both Queensland Fire and Emergency Services (QFES) and the Fire and Rescue New South Wales (FRNSW). It was collected by trained personnel using hand-held electronic devices. The RDA data are collected to enable a more focused and coordinated response and recovery in the immediate aftermath of severe weather events. The survey data are intentionally less detailed than forensic engineering assessments but typically cover a much larger area and include many more data points. It is important to note that the primary objective of damage attribution during the RDA surveys is identifying life safety and recovery issues (i.e. not necessarily reporting all damages relevant to a typical research-based investigation). Therefore, reported information on damage intensity, mode and frequency should be considered as a lower bound for the true extent of damage. It should also be noted that most surveys are conducted from the street and therefore less conspicuous damage is less likely to be reported (e.g. water ingress).

3.2. Distribution of damage

Approximately 11,000 RDA surveys were conducted from Ayr to the Gold Coast (including data for areas affected by the low pressure system as it moved further south). The relevant observations include: location, damage state (undamaged, minor, moderate, severe, total), presence of damaged trees or debris and a brief description of the property damage (e.g., “window damage from tree branch”) in addition to a number of other descriptors used to inform emergency response needs. Photographs of damage were also collected in many instances. The discussion of RDA data in this report mainly focuses on Proserpine. Figure 3.1 shows RDA surveys in the area near TC Debbie landfall.

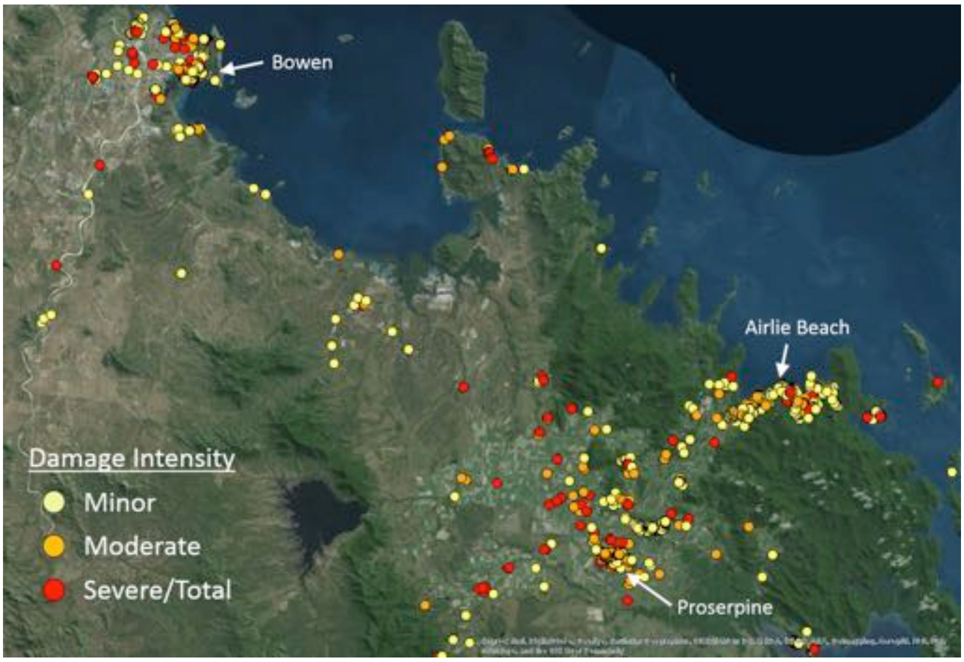


Figure 3.1. Distribution of RDA damage intensity near TC Debbie landfall

Table 3.1 and Figures 3.2 to 3.4 show the distribution of damage intensity in Airlie Beach, Bowen and Proserpine after flood related damage had been excluded. Surveys in Bowen and Airlie Beach were relatively focused on damaged properties (i.e. very few undamaged surveys). In general, the survey of Proserpine was more comprehensive with a significantly higher number of surveys and more detail per survey. It is only possible to estimate percentage of buildings at each damage level for Proserpine.

“Minor” damage typically included broken windows, damaged ancillary items (e.g. fences, gutters, awnings, carports, etc.) and minor roofing or water ingress related failures. “Moderate” and “severe/total” damage generally included more extreme versions of these failures with a high likelihood of water ingress or roofing failures.

Table 3.1. Distribution of damage intensity to all houses by region

Region	# Surveyed	# Damaged	Level of damage in damaged houses		
			Minor	*Moderate*	*Severe/Total*
Airlie Beach	55	38	55%	26%	18%
Bowen	246	201	66%	16%	18%
Proserpine	1283	466	76%	18%	6%

The RDA survey in Proserpine included the entire town and surrounding area – both damaged and undamaged properties. In many cases, RDA crews knocked on doors and discussed damage with property owners. The majority of buildings were single-family homes (81%), commercial (10%) or unit/townhouses (6%).

Of the 1283 houses surveyed in Proserpine, 466 (i.e. 36%) were recorded as having some form of damage. This means that of all surveyed houses in Proserpine:

- 2% had severe or total damage;
- 7% had moderate levels of damage; and
- 27% had minor damage.

It is not possible to calculate the corresponding data for Airlie Beach and Bowen as the surveys did not assess all houses in those towns; only those that were obviously damaged. However, the data in Table 3.1 and estimations of the total number of houses in both Airlie Beach and Bowen from census data indicate that fewer than 5% of houses in both of these towns had any level of damage. The level of damage in both towns is relatively low compared with the damage in Proserpine:

- Bowen experienced lower wind speeds than Proserpine and had a similar percentage of older housing;
- The wind speeds in Airlie Beach were higher but the housing stock was generally of newer construction.

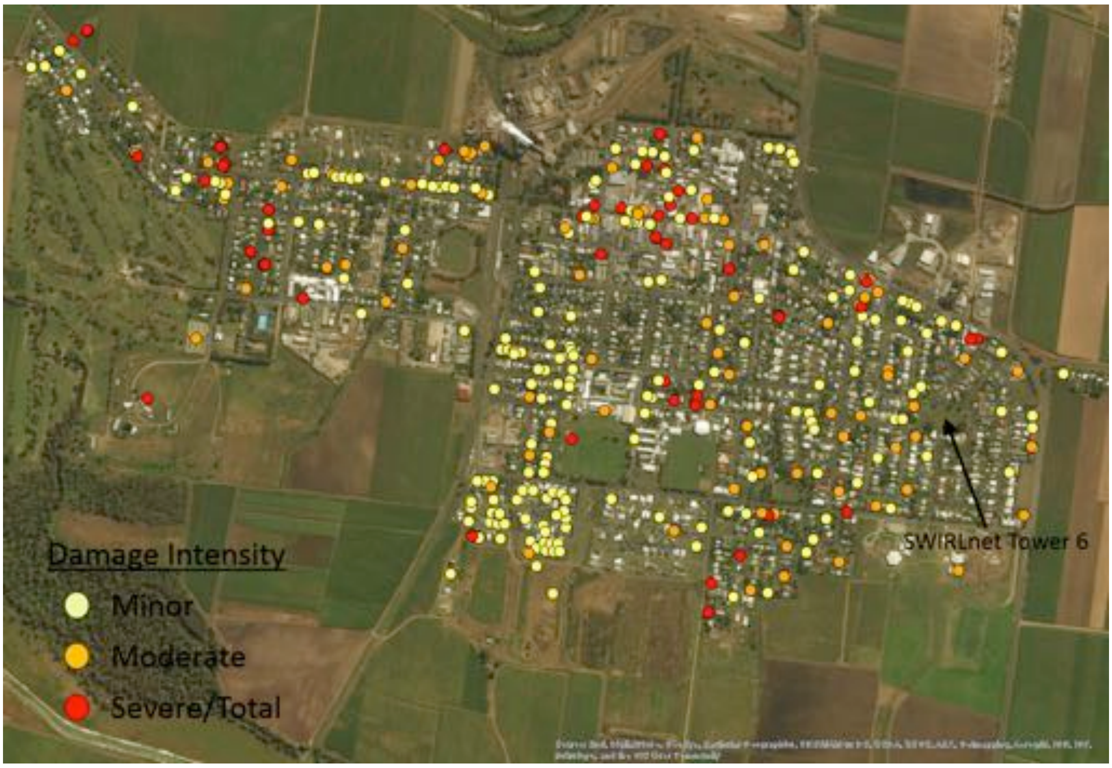


Figure 3.2. RDA damage points in Proserpine from TC Debbie (undamaged buildings are not shown)

The most frequently reported damage in Proserpine was water ingress (41%). In the majority of these cases there was no mention of roof or window damage, indicating that building envelopes were not adequately designed to resist wind-driven rain. This issue has been consistently reported in every post-cyclone damage assessment conducted by the CTS for the last 40 years (e.g. Reardon *et al*, 1999 and Boughton *et al*, 2011) and is the leading contributor to insured losses from cyclones. Recording water ingress can often be difficult when surveys are conducted from the outside of the building, so 41% damage should be considered a lower bound. For comparison, an assessment following TC Larry indicated over 70% of homes had some form of water ingress damage (Henderson and Searle, 2013).

The second most common mode of damage that was noted in the RDA was fencing (24% of all damaged houses). The performance of fences is discussed in Section 7.1. Other frequently observed damage included roofing (14%) and guttering (13%).

The RDA damage surveys did not include information about housing age. To examine differences in performance with respect to age, 106 moderate and severe/total damaged houses in Proserpine were classified, based on CTS interpretation of street view photographs, as pre-1980s or post-1980s construction style. Of the 84 moderate and 22 severe/total houses examined, 53 (63%) and 21 (95%) respectively were pre-1980s. This reinforces findings from previous CTS investigations that indicate older housing is more susceptible to severe/total (e.g. structural) failures but vulnerability is less dependent on age at lower damage states (e.g. gutters, flashings, etc.).

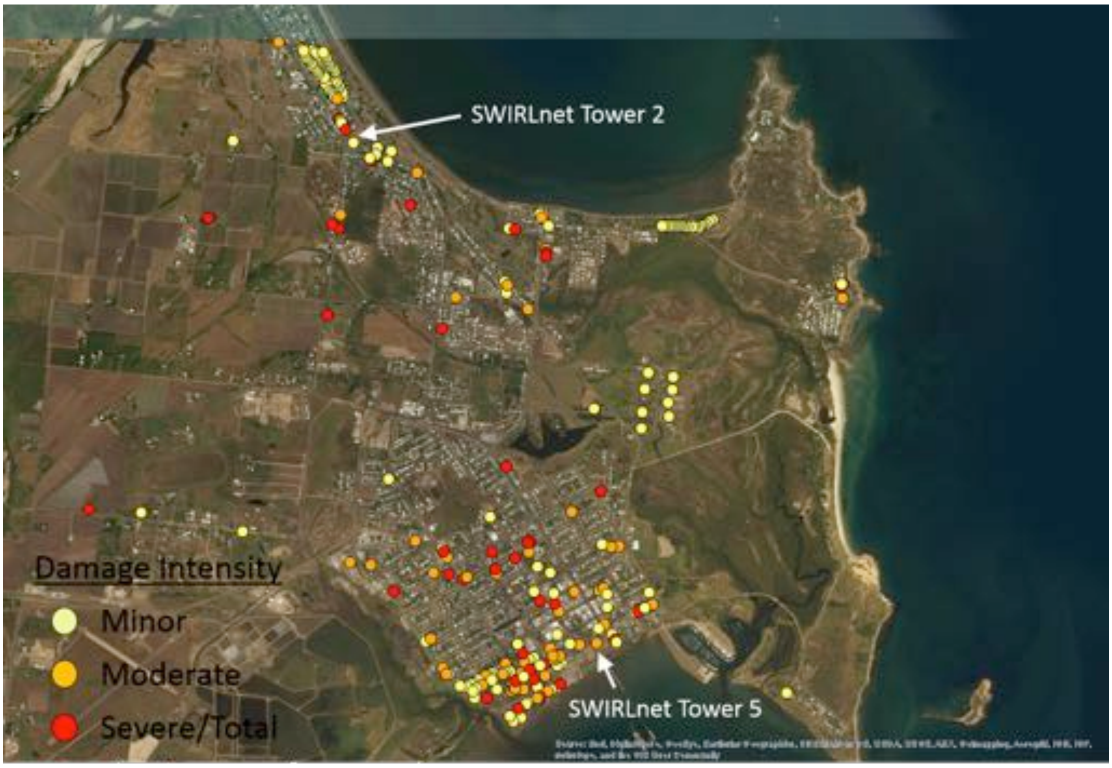


Figure 3.3 RDA damage points in Bowen from TC Debbie (undamaged buildings are not shown)

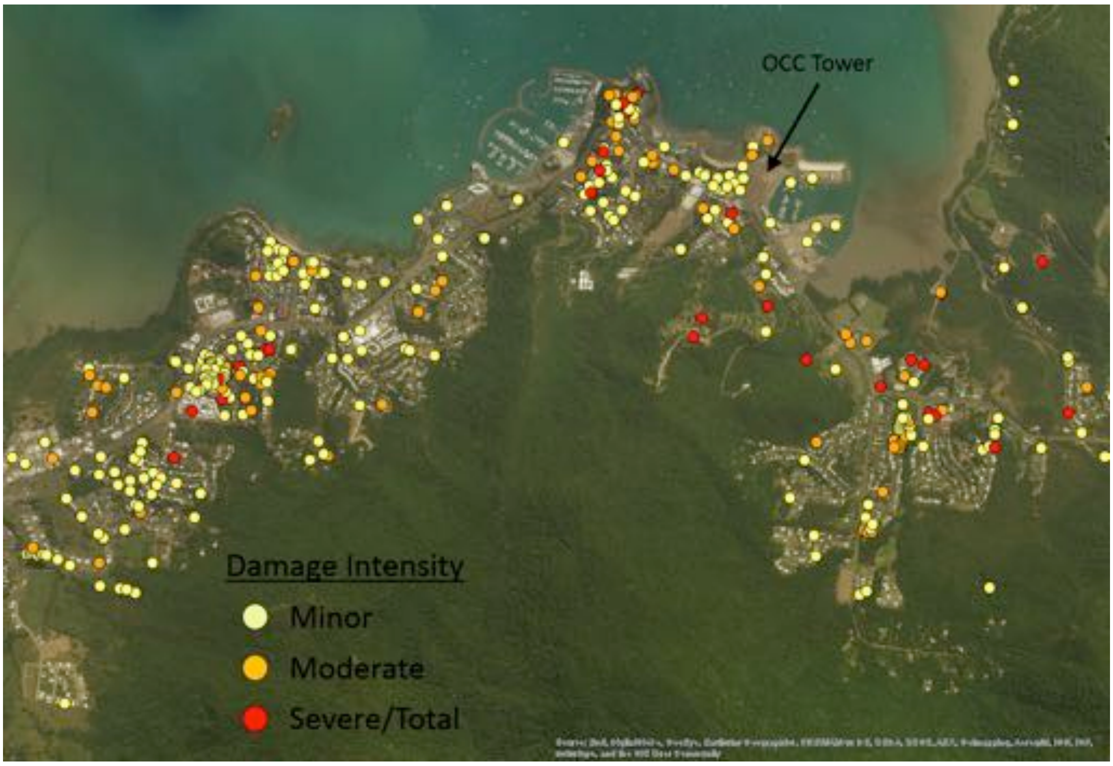


Figure 3.4 RDA damage points in Airlie/Cannonvale from TC Debbie (undamaged buildings are not shown)

4. STRUCTURAL DAMAGE TO LARGE BUILDINGS AND CONTEMPORARY HOUSES

4.1. Design of larger buildings and contemporary houses

Larger buildings such as schools, hospitals, government and commercial buildings, multi-level apartments are all designed using engineers details based on wind loads calculated using AS/NZS 1170.2. Contemporary housing is also designed to resist wind using deemed to-satisfy provisions referenced in Volume 2 of the NCC (Australian Building Codes Board, 2016) that are based on engineered details, and loads calculated from AS 4055 (Standards Australia, 2012) or AS/NZS 1170.2 (Standards Australia, 2011).

Figure 4.1 Damage to larger contemporary buildings

The investigation identified the same failure mechanisms in both larger buildings (Figure 4.1) and contemporary houses. In most cases, the failures were caused by inadequate structural details from either poor design or installation. They are discussed in the following sections.

Conversations with building occupants conveyed the trauma associated with structural damage to buildings in which they were sheltering. Had the wind speeds in the event been higher than the design wind speed, it is expected that many more buildings would have been damaged and larger numbers of people would have been placed at risk. Even under loads higher than the design loads, enhanced protection at the time of the event could be offered by the construction of safe compartments within buildings.

4.2. Cladding

4.2.1. Pierced fixed sheeting

The majority of failures of pierced-fixed metal cladding systems were in older housing where the roofing had come off the house while still attached to the battens. In contemporary construction, where the cladding had separated from purlins or battens, the damage was usually near edges of walls or roofs. The failures observed involved systems that were not installed to appropriate specifications, and in some cases, flashing damage may have contributed to the damage (Figure 4.2).

Figure 4.2 Damage to pierced-fixed cladding

The loss of metal roof tiles illustrated in Figure 4.3 appears to be due to the tiles not being fixed according to current practice. The damage showed that nails had been prised from the back edges but did not appear to have penetrated the tile at nose.

Figure 4.3 Loss of metal roof tiles

4.2.2. Corrosion of fasteners

Failure of cladding systems was initiated by loss of strength from corroded fasteners. This was evident for contemporary structures adjacent to the marine environment.

Figure 4.4 Corrosion of fasteners

4.2.3. Concealed-fixed cladding

Failures of secret-fixed and clip-fixed cladding were observed. An example is shown in Figure 4.5.

Clip-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 few buildings in Proserpine, Airlie Beach and Hamilton Island, but in each case, lack of access to the roof precluded any close inspection of the cladding or clips.

Figure 4.5 Clip-fixed roof cladding failure

4.2.4. Brick cladding

There were two observed cases of damage to larger buildings of an exterior non-structural masonry skin. For both buildings the damaged skin was on the leeward side of the building for the main wind direction. Figure 4.6 shows failure of brick veneer away from the structural masonry wall. Possible reasons for failure include the large spacing between brick ties near the top of the wall, no observed restraint for the top of the brick wall, and a large gap between the masonry wall and the brick veneer.

Figure 4.6 Failure of brick cladding

4.3. Concrete or clay roof tiles

There were significantly less tiled roofs than sheet metal roofs in the study area. However, most tiled roofs had some level of damage; ranging from loss of a few pieces of ridge capping, to damage to more than 30% of the roof.

Figure 4.7 shows tile failure on a building in an exposed location that should have had a high design wind speed. Although there were several other similarly exposed properties with tile roofs in the area, this building was the only one with major tile damage. Tiles on this building may have experienced an increased net wind load on tiles where the eaves were unlined. Clips could not be seen on some rows of tiles. Even where wire clips were observed, some tiles had become dislodged.

Figure 4.7 Tile roofing failure on exposed strata property

Figure 4.8 shows examples where hip and ridge capping tiles were removed from houses due to high local pressures in those areas. Aged or deteriorated pointing material around hip and ridge tiles is well known to have reduced strength and may have contributed to these failures. An amendment to AS 2050, the Australian Standard for installation of roofing tiles, in 2012 (Standards Australia, 2002) requires that hip/ridge tiles on buildings with site classification of C2 or C3 must be installed with screws, nails, etc. in addition to flexible pointing. These houses would probably have been classified as C2 or higher.

Figure 4.8 Failure of tiles and ridge capping

4.4. Batten to rafter or truss connections

While many cases of failure at the batten-to-rafter connection were observed in older housing, there were a few cases of similar failures in larger buildings. None were noted in contemporary housing.

4.4.1. Batten-to-rafter/truss connections using nails

Some older large buildings used exactly the same batten-to-rafter connections as older houses (one or two nails per connection). These low capacity connections together with the large loads from the taller buildings led to failure of these connections as shown in Figure 4.9. The damaged roof was a side roof panel at the windward end of the building. Both battens and rafters were hardwood timbers, which would have been installed green and seasoned in service. The nails had withdrawn from the rafters.

Figure 4.9 Failure of nailed batten-to-rafter connections in older large building

A newer apartment building in an exposed location also lost a significant portion of its roof. Most of the batten-to-truss connections in this building were nailed connections. Figure 4.10 shows the roof failure.

Figure 4.10 Batten-to-truss connection failures in contemporary apartments

4.4.2. Batten-to-rafter connections using screws

An apartment building constructed in the 1980s near the top of a hill also had widespread failures of batten-to-truss connections, shown in Figure 4.11(a). In this case, the connections used one 75 mm plain shank nail and one 75 mm batten screw per connection. There were some signs of mild corrosion on some of the nails and screws, but not enough to affect their capacity. The height of the building and its topography contributed to higher loads on these connections.

The main failure mode was withdrawal of the screws from the trusses as shown in Figure 4.11(b). However, in some cases where the screws held particularly well into the trusses, failure was by pull through in the batten or tear-out of the screws from the truss as shown in Figure 4.11(c).

(a) Batten-to-truss failure

(b) Screw connection

(c) Other failure modes

Figure 4.11 Failure of batten-to-truss screws

4.5. Roof structure

In general, roof structures of most buildings performed well during TC Debbie. There were only a few cases where trusses had failed. In some of these, the truss failure may have been a secondary failure as failure of batten to rafter/truss connection progressed throughout the roof as discussed in Section 4.4 and shown in Figure 4.12.

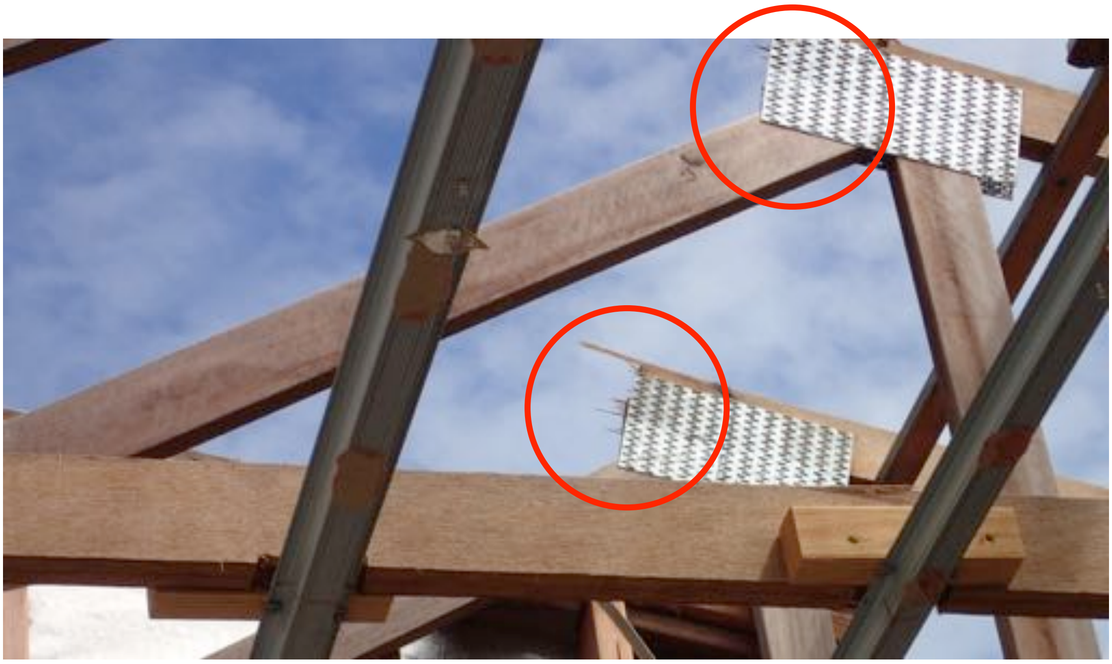


Figure 4.12 Failure of truss top chords following failure of batten-to-rafter connections

Another example is illustrated in Figure 4.10, which shows batten-to-rafter failure in a roof with long cantilevered top chords. Some of these top chords broke as the sheeting was peeled back. The damage to two of the trusses extended beyond the heels of the trusses.

Although no cases of truss failure as the primary cause of roof damage were noted during the investigation, outriggers failed on two buildings with eaves on the gable walls. The outriggers bent upwards on the windward end of the building, which caused loss of roof sheeting over the outriggers, flashing damage at the top of the windward wall and subsequent water damage to the interior of the building:

- Figure 4.13 shows a large building with a skillion roof with 900 mm outriggers that had only a single backspan.
- Figure 4.14 shows two photos of a house with outriggers fixed to the remaining roof structure with metal brackets. The outriggers were true cantilevers with no backspan and the metal brackets did not have the capacity to resist the moment caused by wind pressures on the windward wall.

Figure 4.13 Failure of roof structure caused by excessive roof cantilever

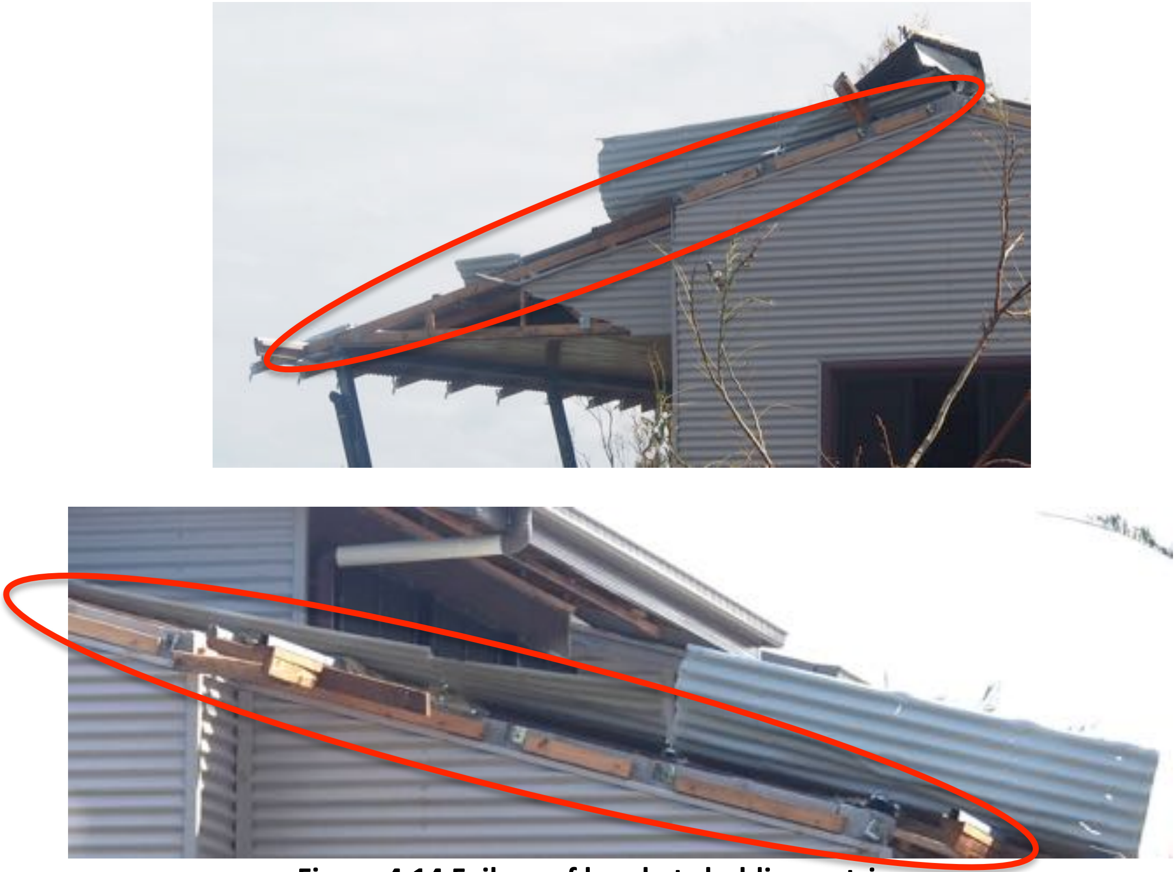


Figure 4.14 Failure of brackets holding outriggers

4.6. Roof structure to wall connections

Failure of connections between roof structures and walls were noted on several buildings inspected as part of the investigation. These failures resulted in significant damage to large sections of roof and allowed substantial volumes of rain to enter the building (refer to Section 5). The detachment of the roof structure also generated large items of wind-borne debris that may have damaged other buildings.

Figure 4.15 shows a three-storey apartment building in which all of the roof trusses were lost. The roof trusses had been fixed to the back wall of the apartments and a steel UB that spanned across the verandahs. The damage occurred when the wind was blowing into the balcony, which created full windward wall pressure on the underside of the verandah roof. The connections between the roof structure and the walls on the balcony side of the apartments included:

- Four framing anchors, each with four nails between each truss and a timber top plate;
- M12 bolts @ 900 mm centres between the top plate and the UB.
- M16 threaded bars at each end of the UBs to concrete cores in the verandah walls.

(a) Photo from leeward side of building
(Photo from 7 News Brisbane Facebook page)

(b) Photo from windward side of building
Figure 4.15 Loss of roof structure on three-storey apartment

Figure 4.16 shows the framing anchors from the windward side of the same building with nails that had pulled out of the trusses. Although this connection may have been adequate for housing in unexposed locations, it did not have the capacity to carry loads from larger span trusses for a larger apartment building in an exposed location. In addition, one of the connections showed that nails had never been driven into the truss through two of the framing anchors.

Figure 4.16 Framing anchors between truss and verandah beam top plate

Figure 4.17 shows LVL verandah beams from which roof trusses had been lost. It is clear that the straps between the trusses and the verandah beam had broken. The strap on the windward edge of the verandah appears to have had only one leg, which may have reduced its effectiveness and triggered the failure. As the verandah roof was connected to the house roof, part of the house roof was also lost. The failure was arrested once it reached a portion of the roof that had two straps per truss heel as the tie down.

Figure 4.17 Failure of roof truss to verandah beam connection

In other cases, damage of the roof to wall connection caused only partial roof loss. Figure 4.18 shows partial roof loss in some identical apartment buildings. The portions of roof that became detached included UB sections, cold rolled steel C purlins, tophat battens, and roofing. The point of detachment was at the connection between the UB sections and the concrete walls.

(a) Apartment buildings with damage to the same elements in all roofs

(b) Loss of part of roof structure at the top of walls

Figure 4.18 Failure of roof structure to wall connections on apartment buildings

Roof structure to wall connections need to be upgraded when roof tiles are replaced with metal sheeting. Metal sheeting is much lighter than tiles, so the net uplift on a roof with metal cladding is much higher than that for a roof with tiles; tie-down connections between the roof structure and the walls need to have higher capacity. Figure 4.19 shows failure of rafter to wall connections that led to loss of a section of roof. The previously used timber tile battens can be seen at close centres still attached to the rafters. The rafters had been skew nailed to the wall top plate whereas a metal clad roof would have required at least straps to carry the net uplift loads.

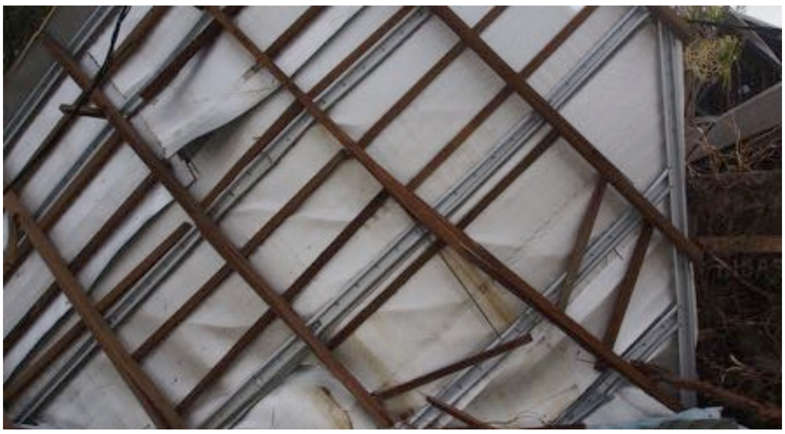


Figure 4.19 Failure of roof structure to wall connections

4.7. Verandah beam tie-down

Many houses and buildings in the coastal areas in the tropics, particularly in exposed locations on hillsides, have large balconies and verandahs to take advantage of the spectacular views. In a number of cases, connections between verandah beams and posts or walls failed. The following factors contributed to loss of the verandah and part of the roof structure:

- Buildings in exposed locations attract higher wind speeds and hence pressures;
- Larger verandahs have larger tributary areas and therefore the verandah beams carry higher loads;

In many of the verandah failures, the connections of the verandah beams to their supports were not able to resist the wind loads, even though Section 2 indicated that the wind speeds in TC Debbie were less than the design value. These failures were observed in a number of different materials – timber, steel and concrete.

For example, Figure 4.20 shows details from a building in an exposed location with large semi-enclosed verandahs where the tie-down of the steel verandah beam to the concrete blockwork failed.

Figure 4.20 Failure of verandah beam to concrete block connection

Figure 4.21 shows a verandah beam to post failure. In this case the SHS verandah beams had been connected to SHS verandah posts with two concealed tek screws. Figure 4.21 also shows that a tack weld had been used on one of the two connections to connect the SHS sections directly. However, the weld was very small, of poor quality and failed.

Figure 4.21 Tek screwed connection between SHS sections

The straps shown in Figure 4.17 were nailed down the full length of the verandah beam and the failure was by tearing of the straps. A similar detail on a different contemporary house had a different failure mode as the straps were nailed to only the upper part of the verandah beam. The bolts to its verandah posts were fixed into the lower part of the verandah beam as shown in Figure 4.22. In this case, the failure was by splitting along the length of the verandah beam as there was a zone down the centre of the verandah beam that had substantial tension perpendicular to the grain.

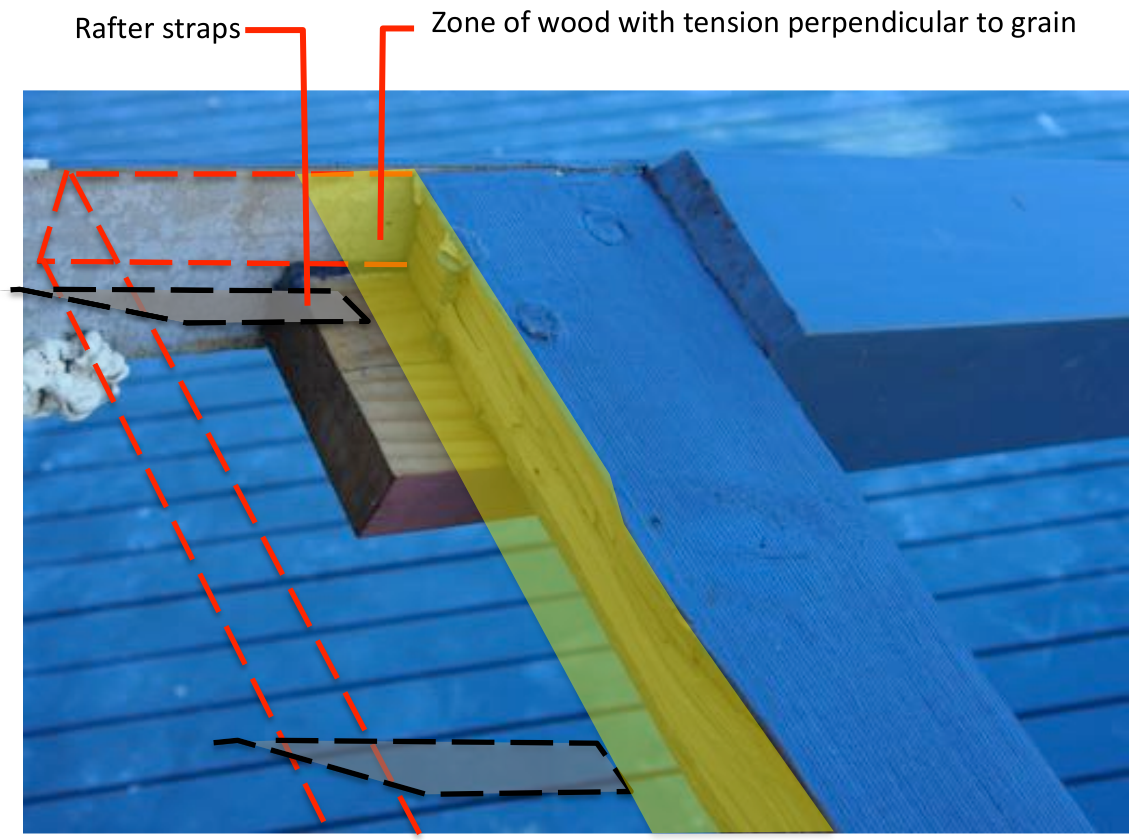


Figure 4.22 Failure due to tension perpendicular to grain in a verandah beam

In Figure 4.22, the outline of the remainder of the verandah beam is shown as a dashed red line, the position of the rafter straps is shown as a dotted black line. There is a zone highlighted in the centre of the beam between the bottom of the straps and the top of the bolts that has to transmit tension forces perpendicular to the grain in the verandah beam. The failure in Figure 4.22 could have been avoided if the straps had been nailed to the full depth of the verandah beam, or if the bolts to the verandah post had extended over the full height of the verandah beam.

Unforunately, the verandah was a continuation of the main roof line, so loss of the verandah led to failure of part of the main house roof as shown in Figure 4.23.

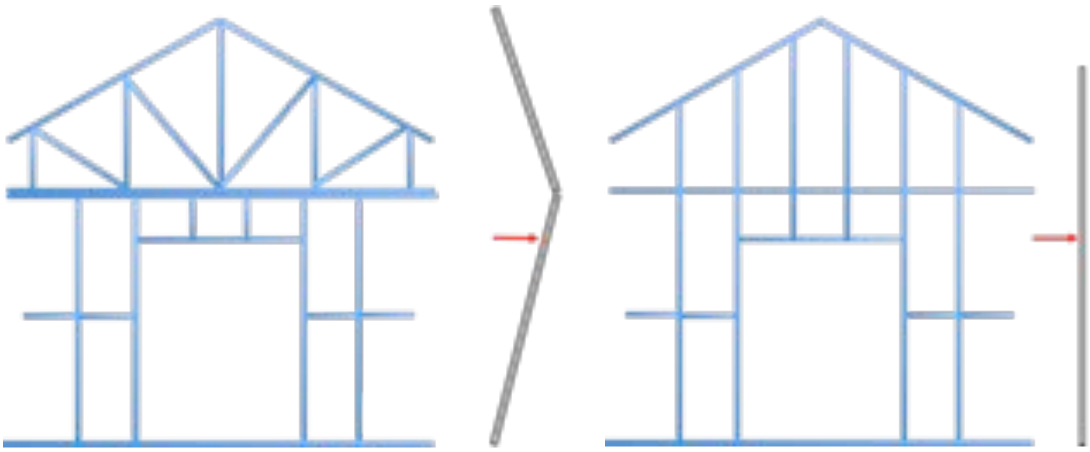
Figure 4.23 Loss of verandah leading to the main roof peeling back

4.8. Light gauge steel framing failures

In three separate buildings, light gauge steel framing had failed out-of- plane above a lintel. Studs usually extend from floor to ceiling height, but in these cases, there was a wall panel above the lintel so that wall was made of two separate panels. The studs were discontinuous, and the wall failed under out-of-plane loads. The walls in Figure 4.24 were windward walls and were pushed into the building.

Figure 4.25(a) is a diagram of the steel gable truss and wall frame system with the grey cross-section highlighting the discontinuity at the truss and wall frame connection under out-of-plane loads. The arrow represents the concentrated load from the window head. Figure 4.25(b) is a diagram showing alternative construction with studs continuous from floor to roofing on the gable end. The grey cross-section shows a continuous bending member that resists out-of-plane loads.

Figure 4.24 Out-of-plane failures in light gauge walls at lintel – windward walls



(a) Separate wall frame and truss **(b) Continuous studs on gable wall**

Figure 4.25 Out-of-plane failure in light gauge walls at lintel

4.9. Windows and doors

Some windows and doors failed under wind pressure, and these issues are detailed in this section of the report. Leakage of wind-driven rain through windows and doors is covered in Section 5.2.

4.9.1. Fixing to wall structure

A few windows and doors failed during TC Debbie because they were not adequately fixed into the building. Figure 4.26 shows a window where the frame had been stapled into the building frame. It is likely that these staples were intended to temporarily locate the window with the intention of fixing it properly later. There was no sign of the final fixing. The loss of the window frame on the windward wall led to high internal pressure and may have contributed to some ceiling damage due to wind pressure alone (see Section 4.10), and the failure of glass in one other window that broke out of the building.

Figure 4.26 Window frame blown from house frame
(right photo by Troy Martin)

Figure 4.27 shows a timber door frame that blew out of a concrete apartment building. There was secure fixing on one side of the frame, but not on the other.

Figure 4.27 Door frame failure

Figure 4.28 shows a window frame in a house in an exposed location that was too light to carry its wind loads. The window frame had been secured to the house frame, but had deformed and allowed glass to break. While the house was an older home, the window appeared to have been relatively recently fitted to the house as part of a renovation.

Figure 4.28 Window frame of low strength

4.9.2. Windows and door sash and furniture failures

Wind pressure caused window frames and sashes in several buildings to fail, allowing wind and water into the building. Figure 4.29(a) shows an aluminium sliding glass door in which the sash had bent allowing it to be pushed into the building without breaking the laminated glass. Figure 4.29(b) shows an aluminium swinging glass door in which the sash had bent and the glass had broken. High internal pressure was also a factor in this failure.

(a) Sliding glass door **(b) Swinging glass door**

Figure 4.29 Sash failures

Figure 4.30 shows a wooden sliding door where the sash had come out of the frame. In this case, deformation of the rail and rollers had allowed the door to be blown in.

Figure 4.30 Timber sliding glass door

There were a number of other cases where poor performance of door furniture led to failure of the door system. Occupants of around 10 buildings surveyed in the investigation indicated that the bolts on aluminium and timber bi-fold and swinging doors shook themselves open during the duration of the cyclone. They had managed to close the doors and wedge the latches closed to prevent them from opening. However, in unoccupied buildings, uncontrolled swinging doors may have destroyed themselves. There were also some reports of winders on awning windows working open.

For example, Figure 4.31 illustrates failure of hinges and latches in timber bi-fold doors. The inset shows plywood over the gap where the doors had been, and similar sets of undamaged doors can be seen on either side of the broken set. The house was not occupied at the time, but it is highly likely that the latches may have worked their way undone due to the shaking of the doors during the cyclone and the uncontrolled swinging of the doors may have destroyed the hinges.

Figure 4.31 Broken hardware on timber bi-fold doors

Figure 4.32 also shows broken hinges on aluminium bi-fold doors. All hinges on one fold had broken as shown in the inset photo. It is likely that the failure of these hinges was caused by bolts working free and allowing the door to repeatedly swing open and closed. Similar doors in a similar exposure also had bolts that worked free, and slammed repeatedly during the rest of the cyclone, but had not failed; the hinges on those doors were more robust and there were twice as many hinges than on the doors shown in Figure 4.32.

Figure 4.32 Failure of hinges on aluminium bi-fold doors

Latches and bolts on entrance doors in some buildings also failed. This was particularly the case for double swinging doors. Figure 4.33 shows bolts that had been prised out of the door by the wind forces on the doors.

Although wind ratings are required for windows and glass doors, they are not required for non-glazed entrance doors. The consequences of failure of entrance doors were similar to those of failure of glass doors.

(a) Bolt at top of door **(b) Recess for bolt at bottom of door**

Figure 4.33 Double entrance door bolt damage

4.9.3. Glass failure

Many newer doors that broke during the cyclone had toughened glass that fractured into small pieces, or laminated glass that remained substantially intact. Figure 4.34(a) shows toughened glass fragments from a bi-fold door that had swung open during the event. Figure 4.34(b) shows float glass failure due to wind pressure. Some fragments of the glass had landed over 6 metres from the window. Persons in front of the window when it broke would be very seriously injured.

(a) Toughened glass fracture

(b) Float glass failure

Figure 4.34 Glass breakage

4.10. Wind damage to ceilings

Creation of openings on the windward wall increased the internal pressure in apartments and houses. In a number of cases, the internal pressure was able to lift suspended ceilings. Figure 4.35 shows two different apartment buildings in which internal pressures forced ceilings upwards.

Figure 4.35 Positive internal pressures caused suspended ceilings to lift

In other cases, positive internal pressures in the ceiling space caused downwards pressures on ceilings. Downward failures of dry ceilings or ceiling panels were observed in a large public building (Figure 4.36) and a number of houses.

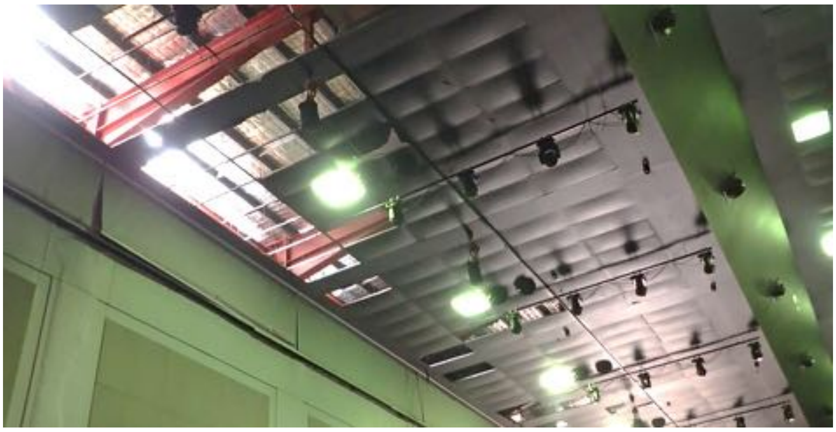
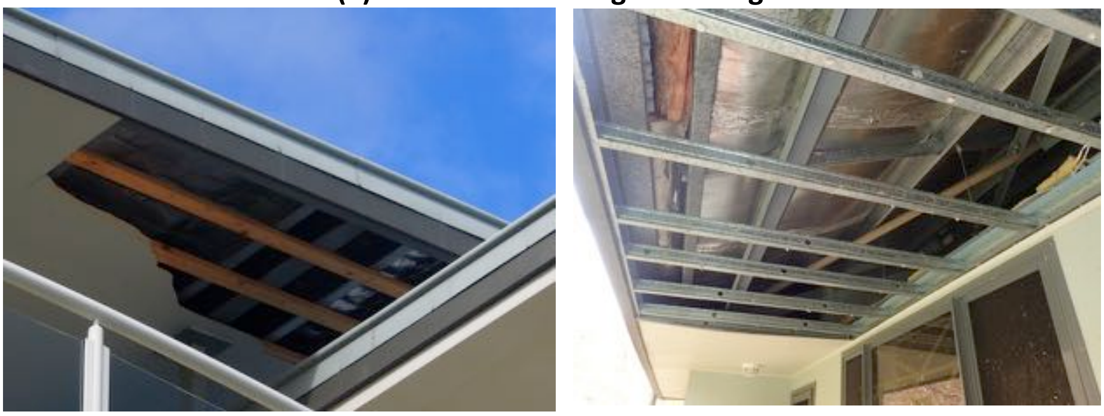


Figure 4.36 Ceiling panels pushed down

4.11. Damage to soffits

Previous CTS reports on damage to buildings following wind events (e.g. Henderson *et al*, 2006 and Boughton *et al*, 2011) have highlighted the high frequency of damage to soffits. Investigations following TC Debbie reinforced those findings. Figure 4.37 shows some examples of damage to soffits in larger buildings.

(a) Loss of soffit and gable linings



(b) Loss of part of the soffit due to wind pressures

(c) Loss of all of the soffit linings

Figure 4.37 Loss of soffits

The soffit systems (lining and connections) In each of the buildings shown in the photos in Figure 4.37 all failed under net wind pressures. Poor performance is due to a combination of connection capacity and spacing and the strength and resilience of the lining itself. Soffit performance can be demonstrated by testing in the same way as other cladding systems.

Soffits made from adequately fastened resilient materials, such as steel sheeting or composite materials (Figure 4.38), were able to successfully resist wind pressures and suffered only local damage under debris impact. Less resilient materials were significantly damaged after relatively minor debris impacts.

(a) Debris damage to brittle soffits

(b) Resilient soffits
Figure 4.38 Soffits

Loss of or damage to soffits on the windward wall of buildings:

- allows large amounts of rainwater into the ceiling space, which can lead to loss of ceilings through much of the building. Where the building has multiple storeys, the water in the building percolates down through the other floors and can damage ceilings on a number of storeys.
- Increases the pressure in the ceiling space, which can lead to increased likelihood of roof or ceiling structural damage.

In these cases, the cost of the subsequent damage is significantly higher than the cost of replacing the damaged soffits.
Loss of soffits on other walls, can lead to small amounts of water ingress and a lowering of internal pressures in the ceiling space. The cost of the damage in these cases is often just the cost of replacing the soffit. However, the cost of replacement of soffit linings includes scaffolding and safe access costs, the cost of lifting part of the roof, as well as normal labour and materials costs. It is much more cost effective to install soffits that can resist the appropriate differential pressures in the first case.

4.12. 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; Boughton *et al*, 2011). The report on TC Yasi (Boughton *et al*, 2011) presented a comprehensive study of the performance of a number of types of large access doors. In response to the reported failures, amendments to AS/NZS 4505 (Standards Australia, 2012) now require that new large access doors must be designed and installed to resist the design wind loads on the structure. This Standard is a NCC referenced document for Wind Regions C and D (Australian Building Codes Board, 2016).

Failure of large access doors during TC Debbie created large openings in the building envelope. In most buildings, this opening became a dominant opening, and dramatically increased the internal pressure. Figure 4.39 shows two buildings where the increase of internal pressure led to other failures of the building envelope after a roller door had failed on the windward side of the building. Figure 4.39(a) shows side wall cladding damage and Figure 4.39(b) shows a roller door that had blown out of the building. The poor performance of pre-2012 roller doors in this event indicates that many buildings are still vulnerable to large internal pressures.

(a) Side wall cladding failure **(b) Leeward wall door failure**

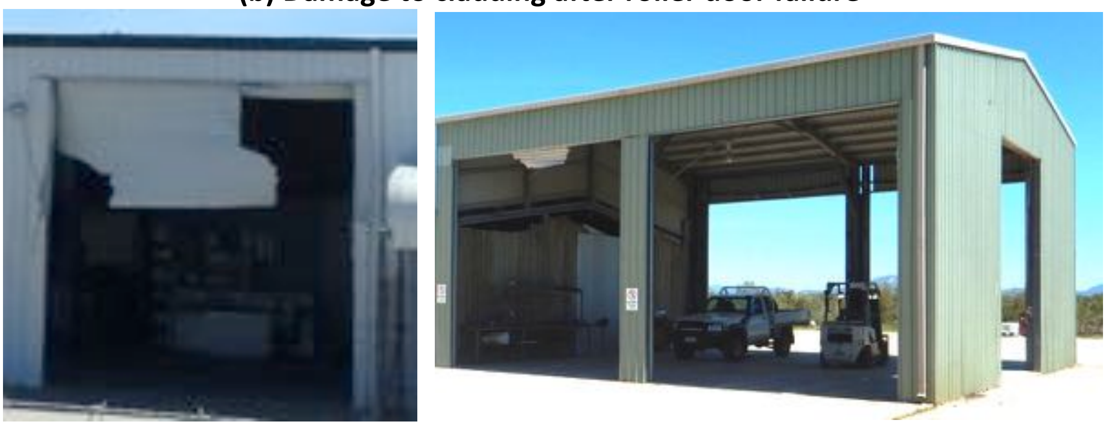
Figure 4.39 Failures caused by windward wall door failures

4.12.1. Roller doors without wind locks

The most common failure mechanism for roller doors installed before 2012 was disengagement of the door from its tracks as shown in Figure 4.40(a). Without wind locks, the flexible door curtain bowed under either positive or negative wind pressures, which allowed it to disengage from its tracks. The door was then free to flap in the opening, and in some cases, caused more damage to interior items and the structure, and in others was ripped from the drum. Figure 4.40(b) shows roller doors that had damaged the building as they flapped against the cladding. In some cases, parts of roller doors became wind-borne debris and where they had separated from the drum, the whole door became wind-borne debris. Figure 4.40(c) shows a door that lost part of the curtain and a building where all of the roller doors separated from the drum.

(a) Curtain out of track

(b) Damage to cladding after roller door failure



(c) Curtain or parts of curtain missing

Figure 4.40 Damage to roller doors

4.12.2. Roller doors fitted with wind locks

To strengthen new roller doors in cyclone regions so that they comply with AS/NZS 4505 (Standards Australia, 2012), manufacturers now anchor the ends of the curtain in the tracks with wind locks, which enable the deflected door to develop significant in-plane tensions in the door curtain. The deflected door uses bending and catenary action (tension) to carry the wind forces to the sides of the opening. The large tension forces from the wind locks must be transmitted from the guides to the building structure, and then 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. For this reason, wind locks should not be retrofitted to existing roller doors unless the guides, supporting structure and walls of the building can carry the additional loads.

No failures of roller door curtains with wind locks were observed in this investigation. Wind locks prevented the main failure mode of roller doors – disengagement from the guides. However, one roller door with wind locks tore the left guide from the building (left photo in Figure 4.41) because the connections to the structure (circled) were inadequate to resist the catenary forces. The right guide is still attached to the frame (right photo in Figure 4.41) and a temporary panel has been placed over the opening as shown in the centre photo in Figure 4.41.

Figure 4.41 Failure of connections between guide and building

4.12.3. Large sliding doors

Large sliding doors, such as those on airport hangers, hang from tracks that traverse the opening, usually with a guide at the base of the doors to prevent the door from swaying laterally. Figure 4.42 shows three views of a sliding door that failed in TC Debbie due to side wall suctions. The doors were located on the tracks and in the guides by the weight of the door, the suction forces on the door were able to shift the doors sideways off the tracks and dragged them away from the building.

(a) Guides at base (b) Sliding door failure (c) Failure of track

Figure 4.42 Damage to large sliding doors

4.12.4. Large hinged doors

Large hinged doors performed well with the exception of several doors shown in Figure 4.43, where the hinges did not have the capacity to resist the loads.

Figure 4.43 Damage to hinges on large swinging doors

4.13. Sheds

Previous investigations (Boughton *et al*, 2011; Henderson *et al*, 2006) have indicated that the performance of sheds is variable, and this investigation was similar.

4.13.1. Garden sheds and garages

Many cases of failed garden sheds were seen. Some older sheds and garages that incorporated frames failed in racking as shown in Figure 4.44.

Figure 4.44 Racking failures of framed sheds and garages

Some more recent sheds that used panel construction failed completely as shown in Figure 4.45. Lack of capacity in the connections between the panels or in the connection with the ground contributed to the failures.

Figure 4.45 Panel failures of garden sheds

4.13.2. Larger engineered sheds

Many larger engineered sheds had little or no damage. No cases were observed where portal frames (either hot-rolled or cold-formed) were damaged.

The main damage observed was to cladding (particularly polycarbonate roof and wall sheeting) or flashing elements, large doors and cold-formed purlins and bridging elements.

Figures 4.46 and 4.47 show damage to cold-formed cladding support elements in relatively new sheds. Figure 4.46 shows buckled top hat battens in the region affected by higher local pressure factors, which allowed deformation of that portion of the roof. The deformation can be seen in the ridgeline and the lintel over the opening. In this case the dominant opening may have influenced the net uplift on the roof, which caused loads that exceeded the lateral torsional buckling capacity of the battens for the large spans used.

(a) External view

(b) Internal view

Figure 4.46 Buckling of battens

Figure 4.47 shows a bridging element that is intended to limit lateral torsional buckling in the purlins. It has buckled itself, but not sufficiently to cause failure of the purlins, so there was minimal structural damage to that shed.

Lateral stability of C purlins can be achieved by ties or by bridging. This building used elements that functioned as ties. However where ties are used, they need to be securely fastened at each end so that tension can stabilise rotation of the purlins in either direction. However, they did not have the necessary connections at the knee to prevent compression in the brace and were not able to resist compression near the apex of the roof.

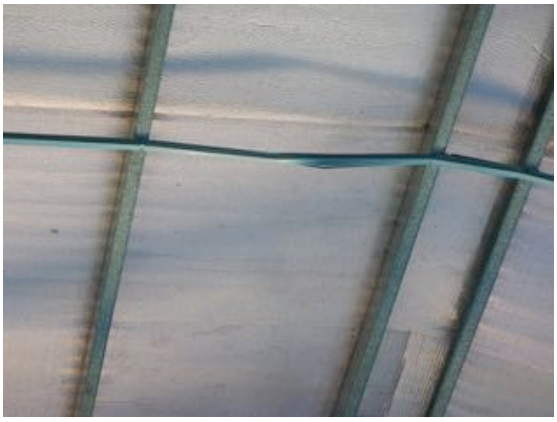


Figure 4.47 Buckling of bridging elements

Figure 4.48 shows a shed with undamaged metal wall cladding, but significant damage to polycarbonate sheeting.


Figure 4.48 Loss of polycarbonate sheeting

In common with other buildings (refer to Section 4.9.2), some personnel doors failed at hinges or latches, as shown in Figure 4.49. An opening of this size will generate high internal pressures, with the potential to overload other structural elements. Although there are requirements for the design of large access doors in cyclone areas in AS/NZS 4505 (Standards Australia, 2012), personnel doors do not need a wind rating in any wind region.


Figure 4.49 Failure of door hinges

Other elements on some engineered sheds failed including:

- roof cladding (Refer to Section 4.2)
- large access doors (Refer to Section 4.12); and
- flashings and gutters (Refer to Sections 5.2, 5.3 and 5.4).

A few large sheds were also damaged by debris during TC Debbie. (Refer to Section 4.14).

4.14. Damage from debris

Some buildings were damaged during TC Debbie by debris such as tree branches or failed elements from adjacent buildings. Debris varied in size from tiles, pieces of timber or gutters to sections of roof structure with rafters and battens attached.

4.14.1. Damage from building elements

Figure 4.50 shows some examples of damage to cladding elements caused by light wind-borne debris from other buildings.

Figure 4.50 Debris damage to cladding elements

Figure 4.51 shows damage from heavy sections of roof structure from adjacent buildings. The larger wind-borne debris items affected larger areas of roofing, gutters, soffits, walls, windows and balconies. The section of roof bounced off the building and came to rest tens of metres away.

Figure 4.51 Damage from larger debris items

4.14.2. Damage by vegetation

Some balconies with glass balustrades were also damaged by wind-borne debris. Figure 4.52 shows a broken handrail that was struck by a wind-borne tree branch. The impact broke both the glass and welds at the base of the balustrade frame. No wind-borne debris damage to tall buildings was observed above 25 m.

Figure 4.52 Damage from wind-borne vegetation

Some buildings were also damaged when trees were blown onto roofs as shown in Figure 4.53.

Figure 4.53 Damage to buildings by fallen trees

5. DAMAGE FROM WIND-DRIVEN RAIN

An important part of this investigation was to identify the extent of damage from wind-driven rain to buildings that had little or no structural damage. During strong winds, differential pressure between the outside and inside of a building can drive rain through any small openings or gaps on the windward side. The survey found that, as in previous events, wind-driven rain had entered some buildings through weepholes or gaps around seals in windows or doors; under missing or damaged flashings and gutters; or through eaves, gable or roof vents. And, as in previous events, it is likely that insurance payouts for damage from wind-driven rain will be a significant percentage of the total cost of damage from TC Debbie.

5.1. Consequences of wind-driven rain entry

Videos taken during TC Debbie and posted on social media showed that considerable volumes of water came through windows and sliding glass doors, under swinging doors, and through light fittings and ceilings. In many cases, the water entered buildings that had no damage to the building envelope. The rain caused damage to vulnerable elements such as plasterboard wall linings and ceilings; floor coverings; and personal belongings. In multistorey buildings, the rain percolated down through the building for a number of storeys below the original point of entry.

5.1.1. Risk to life while mopping up water in front of windward wall windows

Many of the people interviewed during the study indicated that they had tried to control the amount of water entering their homes through windows and glass doors by placing towels in front of windows or doors, and regularly wringing them out and replacing them. This meant that people were mopping up water in front of windward wall windows and glass doors during the cyclone when debris from damaged trees or other buildings were flying around. They risked serious injury if the windows or doors had been broken by debris, or if they had slipped on the wet floors. Figure 5.1 shows towels that occupants had placed in front of glass sliding doors in their apartment during TC Debbie.

Figure 5.1 Towels placed in front of large windward wall windows to control large amounts of water *(still photos from video by Shane Howden)*

Where small volumes of water had entered through windows, occupants who had placed towels in front of the windows before the cyclone did not need to replace them and therefore were not at risk of injury.

5.1.2. Damage to building components and contents

In addition to the risk of injury, the uncontrolled volumes of water entering buildings through windows, doors, flashings, gutters or vents caused significant damage to:

- Ceilings;
- Walls;
- Floor coverings;
- Internal fittings;
- Electrical wiring and electrical appliances; and
- Building contents.

Ceilings

Wind-driven rain entered upper storey ceiling spaces under inadequately secured flashings, or through roof vents. Lower storey ceilings were affected by any water that had entered the floor above. Plasterboard ceilings exposed to rain initially sagged under the weight of pooled water and saturated insulation, softened, broke, and collapsed as illustrated in Figures 5.2 and 5.3. The photos in these figures are typical of the damage to tens of buildings assessed during the investigation.

Figure 5.2 Examples of damage to plasterboard ceiling caused by rain being driven under inadequately secured flashings

Figure 5.3 Collapsed lower storey ceilings

Timber-lined ceilings are also vulnerable to damage from water ingress. Water that ponds on timber elements causes it to swell and cup, as shown in Figure 5.4.

Figure 5.4 Examples of damage to timber-lined ceilings

Walls

The investigation noted many examples of houses where plasterboard wall linings had been affected by water ingress. The plasterboard softened, swelled, and in some cases detached from the wall frames, as illustrated in Figure 5.5.

Figure 5.5 Water damaged plasterboard wall partially detached from frame

Figure 5.6 shows examples of staining, paint blistering and swelling, which are early signs of water damage to plasterboard. This type of damage often progresses to mould growth or detachment of the plasterboard.

Figure 5.6 Early signs of damage to plasterboard wall linings

Plasterboard walls with even minor water damage may need to be replaced.

Floor coverings

Carpet and timber flooring saturated by water entering buildings through failed ceilings, windows or glass sliding doors needed to be replaced if it couldn't be dried quickly. Figure 5.7 shows examples the consequences of rainwater entering buildings during TC Debbie.

Figure 5.7 Damage to carpet and timber floors

Internal fittings
Water-saturated fixtures such as kitchen cupboards and wardrobes made from timber, melamine or particleboard swelled and were no longer serviceable, as shown in Figure 5.8.

Figure 5.8 Water damage to cupboards

Electrical wiring and electrical appliances
Electrical wiring in water-affected ceilings and walls needed to be checked by an electrician, and replaced if necessary. Figure 5.9(a) shows damage to electrical fittings caused by ceiling loss. Where ceilings are lost, there was damage to light fittings, smoke detectors and ceiling fans. Figure 5.9(b) highlights water dripping through a light fitting during the event.

(a) Damage from ceiling loss **(b) Water dripping through light fitting**
Figure 5.9 Electrical wiring and light fittings affected by water ingress
(Photo (b) from video by Shane Howden)

Building contents
Damage to personal belongings such as furniture, clothing, books, toys, etc. is a consequence of water entering homes and buildings that affects the amenity and functionality of the building. This affects individuals and the community emotionally and financially. Figure 5.10(a) shows the inside of one of the many homes and

apartments where people's personal belongings were saturated by large volumes of water, and Figure 5.10(b) shows an office affected by water ingress and ceiling collapse that can no longer be used.


(a) Contents in an apartment (b) Contents in an office

Figure 5.10 Water damaged building contents

Mould develops very quickly in the humid environment that accompanies cyclones. Within a few days after TC Debbie passed through the affected region, plasterboard linings, floor coverings, furniture, clothes and other items in water-damaged buildings began to go mouldy and smell. The mould could have been a health risk to some people. Figure 5.11 shows two of the many examples of mould that had developed in ceilings within less than a week following TC Debbie.


Figure 5.11 Mould in ceilings affected by water entering under failed flashings

5.2. Flashings that were damaged or lost

Significant volumes of water entered buildings through flashings that were lost during TC Debbie and caused extensive damage as discussed in Section 5.1. As flashings are often located on the corner and edge regions of buildings, they are subject to higher uplift loads than elements in other parts of the roof. In some cases, failure of the flashing also allowed partial loss of roof sheeting.

Figure 5.12 shows a selection of relatively recently constructed larger buildings that had lost sections of barge flashing. Some commercial areas suffered this type of damage to more than 20% of the buildings.

Figure 5.12 Examples of failure of flashings on larger industrial buildings

Similar extent and type of flashing damage was also noted on houses and apartments. Where the flashing was removed from the windward end of the building, differential pressure drove water well into the building. In some cases, water was driven throughout the ceiling space causing water damage more than 10 m from the damaged flashing.

5.2.1. Inadequate fixing of flashings

Some barge flashings were lost during TC Debbie as they had no fixings to the barge. Figure 5.13 shows two examples.

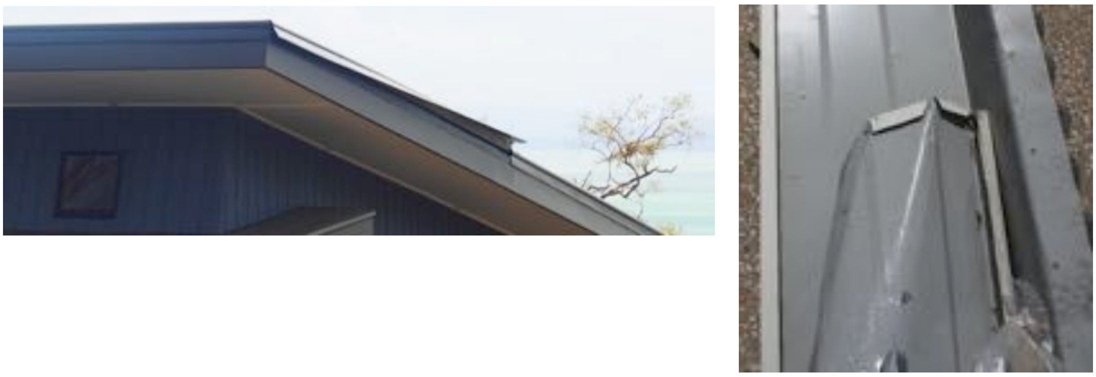


Figure 5.13 Examples of barge flashings with no fastenings to walls

Previous investigations following severe wind events (Henderson *et al*, 2006; Leitch *et al*, 2009; Boughton *et al*, 2011; Boughton *et al*, 2015) have found that flashings fastened with pop rivets have often detached from buildings. Throughout the study, we observed flashings fastened to at least one surface with pop-rivets. Many of the examples shown in Figure 5.12 included barge flashings that had been fastened with pop rivets.

Figure 5.14 shows some other flashings that had been fastened with pop rivets and failed during TC Debbie.

Figure 5.14 Examples of flashings that had been fixed with pop rivets

5.2.2. Minimum requirements for flashing fixing

Flashings that were fastened with screws on all unsupported sides performed well as shown in Figure 5.15. As indicated in previous CTS Technical Reports (e.g. Boughton *et al*, 2011; Boughton *et al*, 2015), flashing fasteners should have at least the same capacity as fasteners used in the roof sheeting; minimum fixing requirements for flashings have been included in the current Public Comment Draft of AS 1562.1. These requirements are consistent with HB 39 (Standards Australia, 2015).

Figure 5.15 Flashing fastened with screws on buildings in exposed locations that performed well during TC Debbie

It is cost effective to ensure that flashings are appropriately fastened. While flashing damage appears relatively minor from the outside of a building, there is disproportionate damage to linings and contents on the inside.

5.2.3. Gaps in flashings

In another house, a gap at the end of the apron flashing, highlighted in Figure 5.16(b), had allowed water to pool around the timber window frame. The timber had rotted over many years, and therefore did not have the capacity to resist the wind forces during TC Debbie. The frame failed and the entire window blew into the house, producing high internal pressures that blew out the window on the opposite wall.

(a) Apron flashing on verandah **(b) Gap in apron flashing**

Figure 5.16 Gap in apron flashing

5.2.4. Sealing the building envelope

Figure 5.17 shows an example of a house that suffered damage to ceilings (shown in Figure 5.2) because there was no flashing installed at the junction of the balcony deck and the external wall of the building. This allowed rain to be driven through the deck into the house and onto the ground floor ceiling.

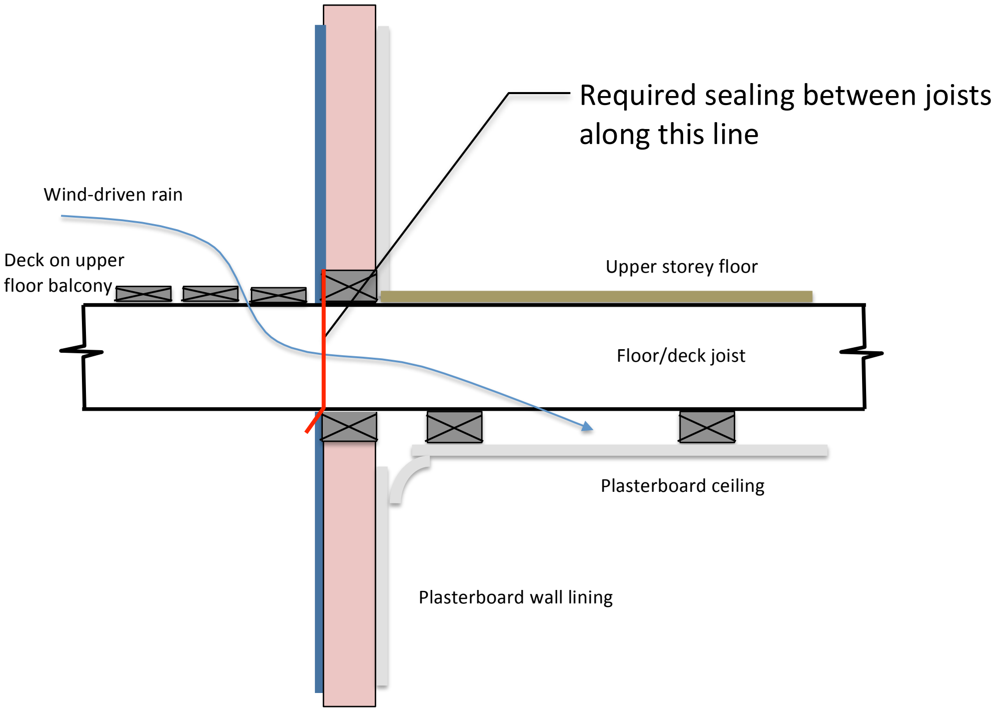


Figure 5.17 Diagram of seal required at junction of deck and external wall

5.2.5. Flashings causing partial loss of roof sheeting

In a few buildings assessed during the investigation, loss of flashings contributed to partial loss of the adjacent roof sheeting. An example is shown in Figure 5.18. In this case, flashing around a penetration and barge flashing were lost and roofing started to lift. This failure may have been prevented if the penetration had been installed in the wall rather than the roof.

Figure 5.18 Loss of flashing contributed to loss of roof sheeting

5.3. Water under undamaged flashings

Flashings play an important role in preventing rainwater entering buildings. During a cyclone, extremely fast moving air drags rainwater in an upward direction over the building envelope. Flashings designed to channel usually downward-moving water away from the building may require extra details to prevent upward moving water entrained in the fast-moving air from entering the building during high wind events.

The study found many examples where water entrained in upward moving air was driven under flashings and into buildings causing damage to or collapse of ceilings. This was particularly the case for buildings with skillion roofs that require apron flashings, or roofs with complex designs that require additional flashings on many roof edges. Figure 5.19 shows a roof that had problems with water ingress before TC Debbie, as indicated by the silicon sealant around the flashings. The flashings and sealant were ineffective during TC Debbie at preventing water from entering the building.

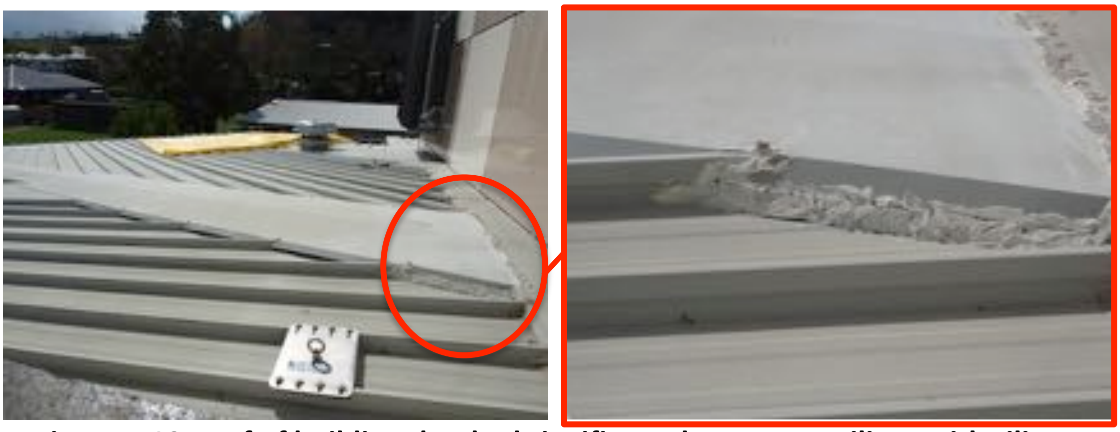


Figure 5.19 Roof of building that had significant damage to ceilings with silicon sealant near apron flashing

Figure 5.20 shows a different section of the same roof where leaves entrained in the wind had been driven under the flashing. It is likely that water was also driven up the roof and under the flashing.

Figure 5.20 Leaves driven under roof flashing

There were a number of houses where rainwater had been driven under the apron flashings on skillion roofs and saturated the ceilings underneath. An example is shown in Figure 5.21.

Figure 5.21 Apron flashing on skillion roof

5.4. Gutters

5.4.1. Missing or damaged gutters

Rainwater entered buildings when gutters were damaged or lost. Many gutters were attached to fascia with clips or fixings that did not have the capacity to resist the wind forces during TC Debbie. Figure 5.22 shows an example of damage to linings following the loss of a gutter. Where the gutter had been lost, water was driven under the roof sheeting and into the ceiling space. For many buildings, relatively minor damage to gutters caused disproportionate damage to building linings and contents.

Figure 5.22 Damage to ceiling in a building with missing gutters

5.4.2. Blocked gutters

Gutters that are usually effective in moving rainwater off roofs and into drains often become blocked by the large amount of broken tree and plant debris that becomes part of the airstream during cyclones. Blockages cause rainwater to overflow into buildings and damage ceilings and wall linings.

Figure 5.23 shows a box gutter that became blocked during TC Debbie causing water to overflow into the ceiling space and extensively damage the ceiling underneath. The photo was taken after it had been partially cleaned out. The detritus can block both the gutter and its outflow pipe. Overflow pipes can also become blocked.

Figure 5.23 Box gutter that had been blocked by tree debris

Figure 5.24(a) shows a blocked eaves gutter (that also overflowed during TC Debbie) and Figure 24(b) a blocked downpipe on the same building.

(a) Blocked eaves gutter **(b) Blocked downpipe**

Figure 5.24 Blocked eaves gutter

In previous damage investigations, the CTS found that box and eaves gutters often performed poorly during high wind events:

- Box gutters usually only have a drain at one end. Strong winds can drive water pooled in the gutter to the opposite end to the drain where it piles up and overflows into the ceiling space. Therefore, box gutters should have the overflow at the opposite end to the normal outflow into the downpipe. This will provide drainage at both ends of the box gutter. Each end should have a spillway overflow so the overflows can't be blocked by detritus.
- The back edge of eaves gutters should be higher than the front so that they overflow to the outside of the building rather than into the eaves and ceiling space.

5.5. Water ingress through windows and sliding doors

Previous CTS investigations (Boughton *et al*, 2015) have found that water entered buildings through undamaged windows and doors, and caused significant distress to occupants and damage to floor coverings, and ceilings of lower floors if water comes through windows or door in upper storeys.

There is a large range of window sill designs in the marketplace; some window sealing and drainage systems are simple, while others are very complex. All windows must satisfy performance criteria in AS 2047 (Standards Australia, 2014), which includes a test to ensure only acceptable levels of water penetration at the test pressure (around one-third of the serviceability test pressure).

The volumes of water entering buildings that had no structural damage were difficult to accurately quantify. Nor was it possible to clearly differentiate the types of windows that performed well and those that allowed large amounts of water into buildings. For example, similar sliding glass windows and doors on windward walls performed well in one building, but poorly in another building that was in a similar location (terrain, topography, and shielding).

5.5.1. Water ingress through weep holes

Weep holes in windows or glass sliding doors (Figure 5.25) are designed to allow condensation and minor leakage around seals to pass from the inside to the outside of the building. However, in high winds, differential pressure forces horizontally driven rain on windward walls through weep holes (i.e. in the opposite direction intended in design) and through other gaps in the building envelope. The mechanism of water ingress through weepholes is explained in more detail in CTS Technical Report 61 (Boughton *et al*, 2015).

Figure 5.25 Weephole in glass sliding door frame

As in previous investigations, many people interviewed as part of the investigation after TC Debbie reported that water entered their homes and buildings through windows and glass sliding doors or under swinging doors or bi-fold doors. Some said they were able to manage the small amounts of rainwater that came in with a few towels placed in front of windward windows. Others reported that they were unable to keep up with positioning and then wringing out saturated towels that produced up to 8 buckets full per hour during the cyclone. The long period of high intensity wind and rain during TC Debbie meant that occupants had to manage water ingress for many hours.

Figure 5.26(a) is a still photo from a video taken during TC Debbie. This photo shows water bubbling through the weepholes at the bottom of the glass sliding door. In this case, water ingress could be managed satisfactorily. However, Figure 5.1 shows larger volumes of water coming through a similar door that could not be managed. Figure 5.26(b) shows the consequence of water entering through sliding windows.

(a) Rainwater bubbling and spurting through glass sliding door frame
(still photo from video taken by Michelle Boyd)

(b) Damage to plasterboard under sliding windows
Figure 5.26 Rainwater through sliding windows and glass sliding door frame

Some people interviewed during the investigation reported that they had no water or only a small amount of water enter through their sliding windows during TC Debbie. Of seven new adjacent houses surveyed following TC Debbie in Proserpine where the wind speeds were less than the strength design wind speeds but above the serviceability design, six houses experienced significant water ingress through windows and one did not. The windows without significant water ingress had weep holes that were covered by external rubber strips. Figure 5.27(a) shows a window from that house and another in a larger apartment building with rubber seals over the weepholes that performed well. The windows and glass sliding doors in another apartment building (Figure 5.27(b) had an external baffle that concealed the weepholes; only a small amount of water leaked through them. This door also had a step that would have prevented any water that pooled on the balcony near the bottom of the door from being driven inside.

(a) Sliding windows with rubber flaps over weepholes

(b) Sliding glass doors with baffle that concealed the weepholes

Figure 5.27 Windows and glass sliding doors that prevented wind-driven rain entering the building

5.5.2. Water ingress through sashes and seals

Wind pressure can also cause glass and sashes to flex inwards and open gaps between sashes and frames in windows or sliding glass doors. Water is pushed through these gaps by the same differential pressure that forces rainwater through weepholes. A few people interviewed as part of the investigation after TC Debbie said that water had entered their homes through window sashes, saturating carpets several meters into the room. Windows that satisfy the serviceability requirements in AS 2047 (Standards Australia, 2014) should not allow water into buildings in this way.

In other cases, worn or damaged window seals were ineffective in preventing water penetration into buildings. As indicated in CTS Technical Report 61 (Boughton *et al*, 2015), mohair seals on sliding windows were less effective than flap-type seals.

5.5.3. Water ingress through louvres

The performance of louvres was also variable; some louvres leaked while others didn't let any water into the building at all. One homeowner said that he had taped the louvres in his house as part of cyclone preparations (Figure 5.28(a)), and no water came through his windows during the TC Debbie. No water entered through any of the louvre windows on windward walls in another building assessed during the investigation (Figure 28(b).

(a) Louvres taped before cyclone **(b) Louvres on a public building**

Figure 5.28 Louvres on windward walls that allowed no water into the building

Louvres are a popular choice of window for larger buildings and contemporary houses in the tropics. More research is needed on the difference between windows that do and don’t leak to prevent water damage to buildings in future events.

5.6. Water entry through bi-fold and swinging doors

During TC Debbie, significant amounts of rainwater were driven under some swinging and bi-fold doors. A large number of contemporary houses and apartments used bi-fold doors in entertainment and living spaces.

5.6.1. Bi-fold doors

Rainwater was forced under bi-fold doors that had gaps between the bottom of the door and the floor or window ledge. Figure 5.29 shows a bi-fold kitchen window installed directly over a bench without a sill where occupants reported that significant volumes of water had entered the building.

Figure 5.29 Bi-fold windows over a kitchen bench

The bi-fold doors shown in Figure 5.30 with a gap underneath and no sill also allowed rainwater ingress.

(a) Photo of bottom of bi-fold doors taken from inside the building

(a) Photo of bottom of same bi-fold doors taken from outside the building

Figure 5.30 Gap under bi-fold doors with no sill

There were several examples where outward opening bi-fold doors with a sill performed well. Windward wall pressure pushed the doors back against the sill and seal to prevent rainwater being driven into the building. Figure 5.31 shows an example of this type of bi-fold door with the same exposure as the doors illustrated in Figure 5.30.

Figure 5.31 Bi-fold doors

As discussed in Section 4.9.2, the bolts on some bi-fold doors and windows shook loose and opened. Even if there was no damage to the door, this allowed uncontrolled rainwater ingress.

5.6.2. Swinging doors

In the majority of cases where water entered through swinging doors on windward walls, there was no sill and water was driven through the gap under the door, even if there was a flap-type weather seal. Figure 5.32 shows a timber floor that had been damaged by water that was driven metres into the building under the entrance door.

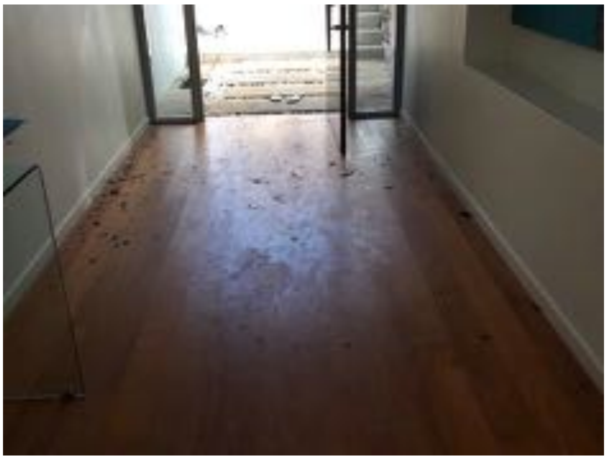


Figure 5.32 Water ingress under swinging door

5.7. Eaves and gable vents

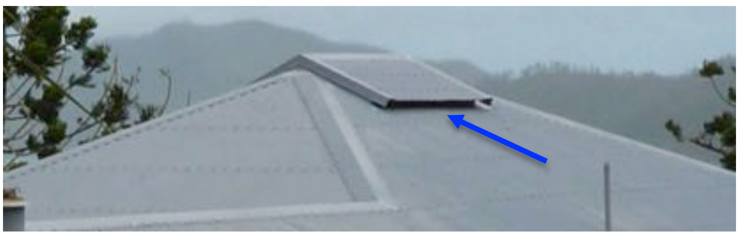
Water that entered the roof space caused significant damage to the ceilings as indicated in Section 5.1. In some buildings, vents in the roof space had allowed water to enter the roof space without damaging any envelope components. Figure 5.33 shows water entry points that contributed to ceiling damage:

- Gable vent (Figure 5.33(a));
- Eaves vent (Figure 5.33(b));
- Ridge vent (Figure 5.33(c)).

Vents provide an effective way of cooling roof spaces in normal circumstances. However, to minimise damage from wind-driven rain, there needs to be a method of closing them as part of preparation of the building for an approaching cyclone.

(a) gable vent

(b) eaves vent



(c) ridge vent

Figure 5.33 vents that allowed water into the roof space

6. DAMAGE FROM STORM TIDE

Storm tide refers to the combination of storm surge on top of normal (astronomical) tide. Storm surge consists of:

- increased seawater level caused by a decrease in atmospheric pressure under the cyclone;
- water pushed towards the land by surface friction of the wind over the open ocean;
- wave set-up – increase in mean sea level caused by shoaling waves (waves getting larger as they approach the shore); and
- wave run-up – forward momentum of breaking waves.

All cyclones generate a storm surge, but the height of the storm surge is affected by:

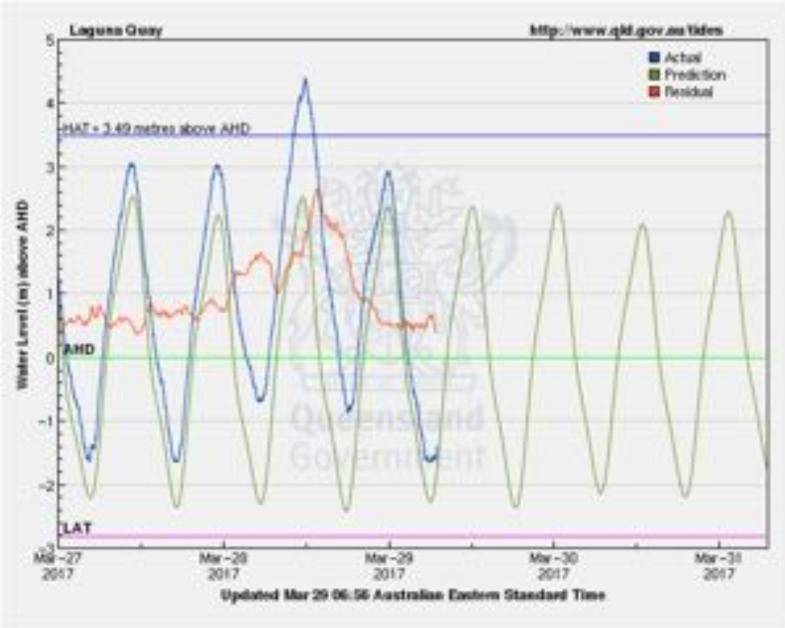
- The intensity of the cyclone – as the wind speed increases, seawater is piled higher and the breaking waves on top of the surge are taller i.e. the higher the wind speed, the higher the storm surge.
- The forward speed of the cyclone – the faster the cyclone crosses the coast, the more quickly the surge builds up and the more powerful the wave action.
- The angle at which the cyclone crosses the coast – in general, if the cyclone crosses perpendicular to the coast, the higher the surge. However, storm surge can also be higher in narrow inlets and bays.
- The shape of the sea floor – shallow sea beds near the coast generally create stronger surges than steeply sloping sea beds or along coasts protected by reefs.
- Local topography - bays, headlands and offshore islands can funnel and increase the intensity of the storm surge.

6.1. Storm tide in TC Debbie

Where the highest level of storm surge corresponds to a high tide, the storm tide level is the sum of the height of high tide plus the height of the storm surge. However, the height of the highest storm surge that accompanied TC Debbie was measured at Laguna Quays as 2.5 m and occurred as the tide was ebbing. This meant that the storm tide recorded at Laguna Quays was approximately 1 m higher than the highest astronomical tide (HAT).

A significantly higher storm surge of around 5 m had been predicted as TC Debbie was expected to make landfall at high tide.

Figure 6.1 shows tide gauge records from Laguna Quays and Shute Harbour – the two gauges that showed highest storm surges during TC Debbie.



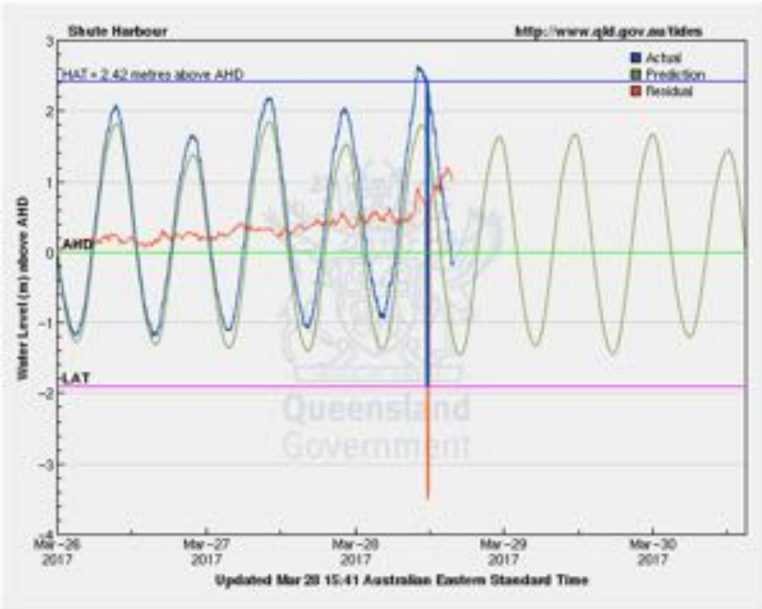


Figure 6.1 Tide gauge data

Figure 6.2 shows that the maximum storm surge height recorded for four tide gauges, and the resulting mean seawater surface height above HAT. Bowen and places north of Bowen were not affected by storm tide. Storm tide was effectively zero at Mackay, but wave action may have caused problems for coastal developments. The largest storm tides occurred between Shute Harbour and Midge Point (including Conway Beach, Wilson Beach and Laguna Quays). Buildings at Wilson Beach, Conway Beach, Shute Harbour and Hamilton Island were assessed as part of the investigation into damage to buildings from storm surge.

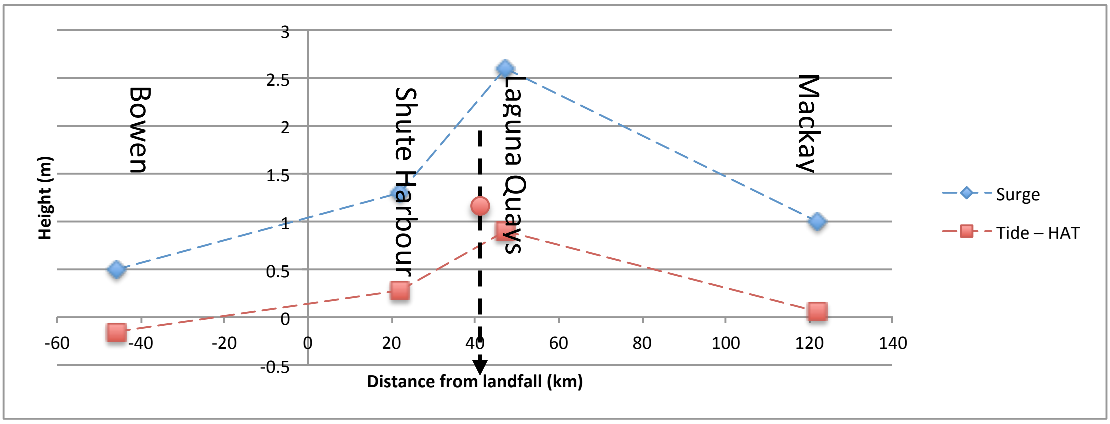


Figure 6.2 Storm surge heights

There was little damage by storm surge to buildings at Shute Harbour and Hamilton Island, but there was inundation of buildings at Wilson and Conway beaches (dotted arrow in Figure 6.2 indicates their location between Shute Harbour and Laguna Quays). The circle shows the expected storm surge (1.2 m above HAT) at Wilson Beach from storm surge modelling (Harper, 2017).

Figure 6.3 shows that Wilson Beach is located on a shallow inlet at the mouth of the Proserpine River and the gently sloping seabed and narrow inlet may have contributed to the higher surge at that location compared with the surge at Shute Harbour. While the narrow inlet and its bar may have increased the mean sea level due to surge, it also reduced the wave height experienced at those locations.

Figure 6.3 Mouth of the Proserpine River

Residents at Wilson Beach indicated that storm tide water entered their community from two directions as shown in Figure 6.4:

- The wave action from the surge that approached buildings in Wilson Beach from the South (blue arrows in Figure 6.4) caused the aggressive erosion shown in Figure 6.5(a) and scour at footings shown in Figure 6.9.
- Water from the surge that approached buildings from the north via a tidal creek and mangrove flats (yellow arrow in Figure 6.4) did not have wave action, and rose in the same way as riverine flooding. Figure 6.5(b) is a photo of the rising water from the tidal creek above fence height.

Figure 6.4 Directions of storm tide inundation at Wilson Beach

(a) storm surge damage to foreshore **(b) inundation from tidal creek**
(Photo from Rob and Rosie Stevenson)

Figure 6.5 Effect of storm tide at Wilson Beach

Water inundated properties up to a depth of around 0.7 metres on the south (seaward) side of the main street and up to 1.1 m on the north (creek side of the street. The houses on the south side of the town were built on a slight rise (remnant dune) behind the beach, while the houses on the north side had lower floor elevations.

The depth of inundation was measured by marks on internal walls of buildings that reflected the average water depth. For houses on the north side of town, this depth reflected the maximum depth of the water impacts, but those on the south side of town had wave action that contributed to extra loads on building components. Wave action contributes significantly to the structural impact of storm surge damage.

6.2. Wave action on building elements

Storm tide water approaching directly from the sea has the combined effects of inundation and wave action. Some media photos captured the impact of waves on a building on Hamilton Island that faced the north east and are reproduced in Figure 6.6.

(a) before the cyclone (ABC news photo) (b) during the cyclone (ABC news photo)

(c) Luke Young social media photo

Figure 6.6 Wave action on a building

This building was inspected after the event and detritus had been left well inside the upper storey of the building (Figure 6.7(a)). Heavy steel shutters offered protection to openings on the lower storey (Figure 6.7(b)), but scouring under the footings was noted (Figure 6.7(c)).

The most significant remedial action for the building due to the storm surge damage will be the underpinning and repair of the undercut footings. It is likely that the storm tide level in this location was between half a metre and a metre above Highest Astronomical Tide, with most of the damage to the footings of the building from the wave action that was impacting the building directly with the elevated water level. Other damage to the roof of the building was probably caused by wind actions.

(a) Detritus on upper storey

b) Protected doors on lower storey

(c) Undercut footings (building subsided on right)

Figure 6.7 Affect of wave action on a building

In buildings on the south-facing beach front at Wilson Beach, waves impacted directly on the face of some of the buildings. Because the beach was protected by Cape Conway, and was within the inlet rather than the open sea, the waves were likely to have been less than those illustrated in Figure 6.6. Figure 6.8 is a photo captured by a building occupant as waves that had broken a glass door were entering a building.

Figure 6.8 Waves entering a building at Wilson Beach

(Photo provided by Wilson Beach resident)

Wave action on buildings at Wilson beach during TC Debbie caused damage to the following structural elements:

- foundations and subfloor structure
- windows and doors
- external wall linings
- internal wall linings
- roller doors
- floors

6.3. Storm tide effects on subfloor structure

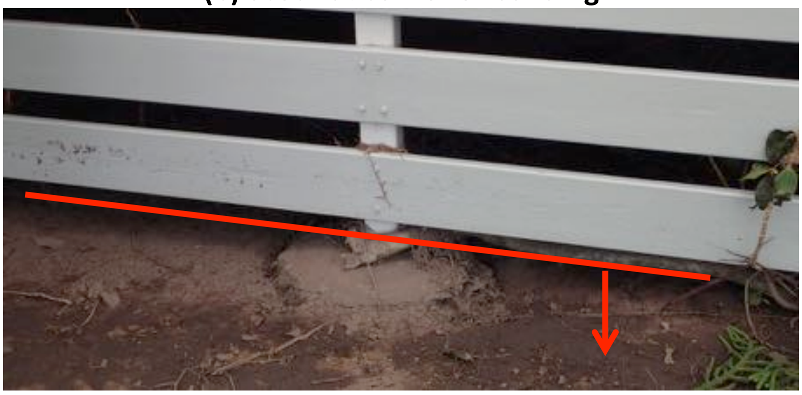
Waves that impact buildings over a few hours can cause extensive damage to building structure and contents. Only massive structural elements are capable of withstanding breaking wave forces generated during a storm surge. Waves washing over the land around a building have two main effects: they cause water movement above the soil next to the building; and they put lateral forces on the parts of the building in contact with the ground.

6.3.1. Scour around footings and piles

Fast flowing water associated with waves can cause localized scour around a building and its foundation. This scour washes soil from beside the footings as shown in Figure 6.9.

(a) Soil washed out beside building

(b) Scour at corner of building



(c) Ebb flow scour against pier footing

Figure 6.9 Scour around footings and piles

Figures 6.9 (a) and (b) were taken near buildings on the south side of the town that were affected by wave action as the waves overtopped the low frontal dune. Water accumulated in the whole town, but as the storm surged dropped, the ebb flow was mainly directed through the lowest point – in reverse along the yellow line in Figure 6.4. Ebb channels have been known to develop in high flow areas as the sea water recedes, and where the flow is very fast, can create deep and wide canals across the affected area. If a fast flowing channel develops near a house with standard footings, scouring has been known to wash the building into the channel. In TC Debbie, the ebb flow was not powerful enough to develop channels, but did cause some minor scouring of footings as shown in Figure 6.9(c).

Where the scouring continues once the bottom of a footing or slab has been reached, the erosion can undercut the structure and cause the loss of bearing capacity or anchoring resistance of the foundation elements. Figure 6.10 shows examples of undercutting that occurred around buildings during TC Debbie. Undercutting can present problems for reconstruction. However, in storm surge-prone areas, scouring against footings and slabs is a real possibility and both the initial design and any reconstruction should include deeper footings to reduce the risk of scouring from undercutting the concrete.

(a) Undercut footings

(b) Undercut floor slab

(c) Undercut footpath

Figure 6.10 Undercut footings and slabs

6.3.2. Lateral forces on subfloor

Waves can exert drag on the substructure of buildings that incorporate suspended floors. Where the building is on an upward sloping block or where the back of the subfloor is enclosed, the waves being forced up under the building can put upward forces on the underside of floors. Upward wind action on the roof and upward wave actions on the underside of the floor can reduce the effects of friction from the weight of the building on the subfloor structure. Unless the building is tied securely to the subfloor structure and the subfloor structure itself can resist the lateral loads from the wave action, the building may be washed off its stumps.

This was the case for the beach-front house illustrated in Figure 6.11. The steel post with the tape wrapped around it in the photo foreground is a floor stump and the house has been washed backward off it and is now resting with the bearers on the ground. The house had been pushed backwards by the waves around 2 m.

Figure 6.11 House pushed off stumps by storm surge

6.4. Effects on external envelope

Windows and some external cladding were damaged by wave action that affected the houses on the south side of Wilson Beach only.

6.4.1. Windows and doors

A number of windows of houses in the wave-affected area were broken. Figure 6.8 showed small waves coming through glass sliding doors that had been pushed out of their track by wave action. Figure 6.12 shows glass that was broken by wave action. The window shown in Figure 6.12(a) was above the inundation line visible on the inside of the building, so it can only have been broken by waves impacting the outside of the building.

(a) Broken window **(b) Broken laminated glass from sliding door**

Figure 6.12 Window damage due to storm surge

6.4.2. Cladding materials

Most cladding materials were undamaged by the waves in TC Debbie. However, thin fibre cement sheeting was damaged on every building in affected by wave action. Figure 6.13 shows examples of damage to houses near the foreshore at Wilson Beach.

Figure 6.13 Damage to thin fibre cement sheeting

6.5. Effects of inundation

Sections 6.3 and 6.4 discussed damage that was caused by wave action, but like riverine flooding, all houses that experienced inundation due to storm surge had damage to the following building elements: internal fittings such as cupboards; internal linings; electrical outlets – power points; and floor coverings and building contents. Examples of the effects of inundation are shown in Figure 6.14.

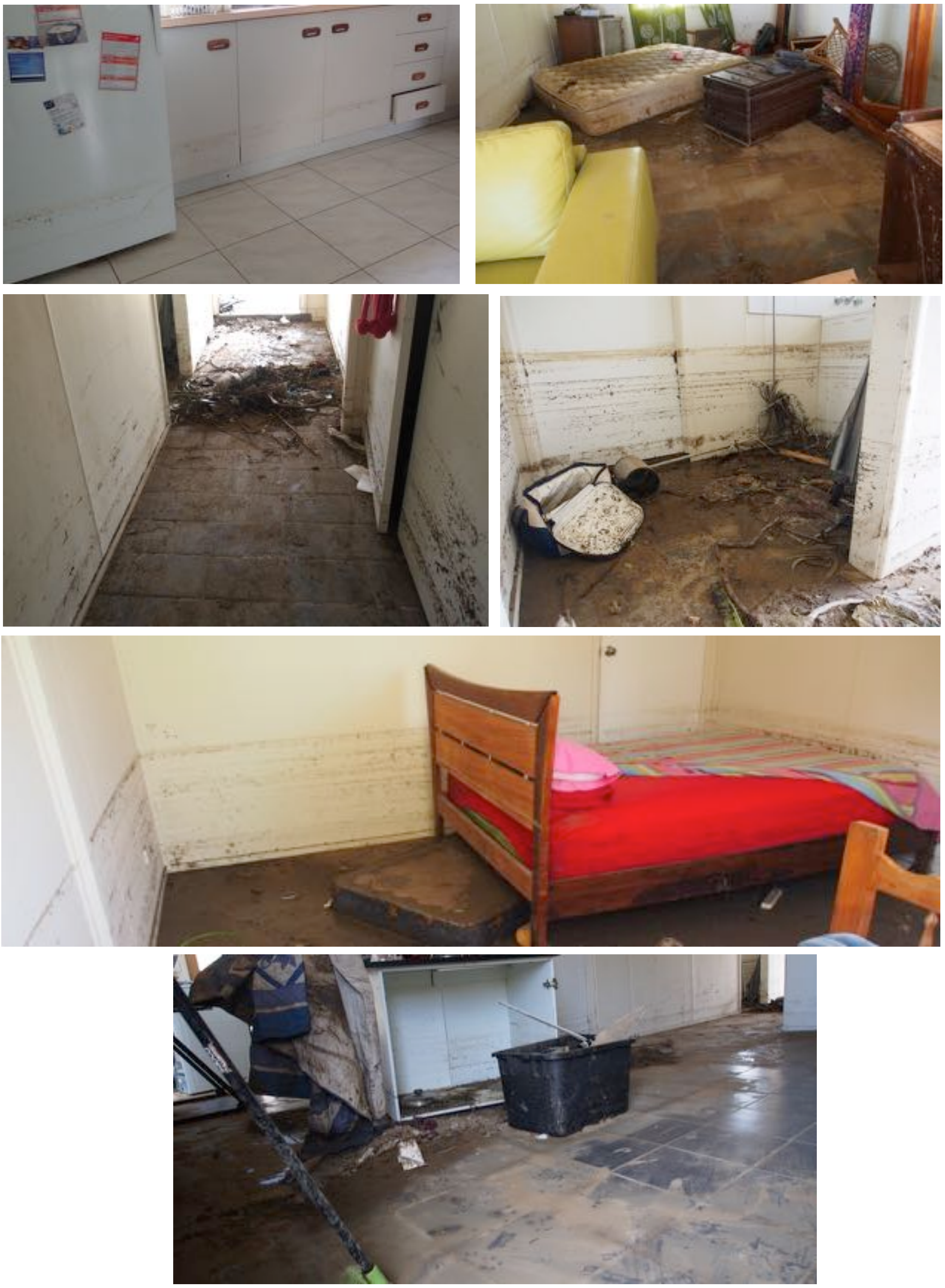


Figure 6.14 Damage to internal building elements and contents

Because the inundation was by salt water, the potential for corrosion of metal objects such as electrical wiring and contacts, nails and screws was much higher than if the flooding had been from fresh water. The receding water left a layer of mud on floors and marked walls.

The water level rose and fell quite quickly. However, there was sufficient time to allow vulnerable building elements such as plasterboard and particleboard to take on enough water to swell and weaken. In some cases, occupants reported that the rapid fall in water level meant that the water that was still held within wall cavities forced linings off the wall frame.

Floor coverings such as carpet, soft furnishings and furniture were particularly affected by the water and mud and will need to be replaced.

6.6. Comparison with storm surge in TC Yasi and safety issues

The reported storm surge in TC Yasi (Boughton *et al*, 2011) had a combined water and wave height of around 2 m in some houses, which was enough to break unreinforced masonry walls and flatten some lightweight cladding material. In that event, all windows within the wave zone were broken. A comparison of the damage to similar building types between the two events showed significantly less structural damage in the storm surge in TC Debbie.

If the storm surge had occurred at the same time as high tide, the depth of inundation in the Wilson Beach area would have been at least 0.9 m higher than that experienced. The higher water depth would have led to higher waves and more damage to houses. It is highly likely that the predicted storm surge could have had similar effects on buildings to that in TC Yasi in Hull Heads and Tully Heads (Boughton *et al*, 2011). In that scenario, people could have been seriously injured or killed if they hadn’t evacuated from vulnerable buildings.

The relatively low storm tide in TC Debbie closed the only access road into Wilson Beach, which underlines the importance of early evacuation of vulnerable communities ahead of difficult to predict storm tides.

7. DAMAGE TO ANCILLARY ITEMS

This section covers items that are attached to a building or covered by building insurance policies.

7.1. Boundary fences

Fences regularly fail during high wind events in all regions of Australia, contributing to insurance claims for the events. In cyclone regions, broken fences can become part of air-borne debris that pose a risk to people and other buildings.

During TC Debbie, high winds, falling trees and air-borne debris damaged a large number of boundary fences in suburban properties within the study area.

Four types of boundary fences were assessed; examples are shown in Figure 7.1.

- Timber picket fences;
- Sheet metal fences;
- Steel mesh fencing; and
- Composite fences.

(a) Timber picket fence

(b) Steel mesh fence

(c) Sheet metal fence

(d) Composite fence

Figure 7.1 Typical types of fences

7.1.1. Timber picket fences

Timber fences are the most prevalent type of boundary fence within the suburban communities in the investigation area, and were the most common type of boundary fence that failed during TC Debbie. Most timber picket fences studied had round treated pine poles, but some had SHS poles. All had small gaps between the pickets compared with the width of the picket and were effectively non-porous.

Most failures were due to insufficient footings; either the treated pine posts were placed in post-holes without concrete, or there was insufficient concrete. Some timber posts failed in bending, and other fences failed when connections between the posts and cross members on the fencing were ineffective. Figure 7.2 shows some examples of timber fences that had problems during TC Debbie.

(a) Posts in ground without footing **(b) Posts without concrete in post-holes**

(a) Connection failure **(b) Steel posts bending failure**

Figure 7.2 Typical timber fence failures

7.1.2. Sheet metal fences

There were two main modes of failure: failure of the steel posts (Figure 7.3(a)), and detachment of sheet panels from the frame (Figure 7.3(b)). Sheet metal fences are also non-porous and are more likely to become wind born debris due to their light weight and shape.

(a) Post failure of steel fence

(b) Sheet metal fence panel failure

Figure 7.3 Sheet metal fence failures

7.1.3. Steel mesh fences

Steel mesh fencing was also common throughout the study area and generally performed well during TC Debbie (Figure 7.4). The wind loads on steel mesh or grid fences are generally lower than the wind loads on other types of fences as they are very porous. The investigation did not find any steel mesh fences that failed under wind loads.

Due to its porosity, this fencing is the only type that has the potential to effectively resist wind forces. Composite fences with metal mesh infill also performed well under wind loads.

Figure 7.4 Porous steel mesh fences

7.1.4. Composite fences

Composite fences are built using a range of materials; usually masonry columns with timber, metal sheeting or steel mesh between them. Although these types of fences weren't common in the affected area, there were some cases where footings or columns failed as shown in Figure 7.5.

(a) Concrete footing over turning failure

(b) Masonry column failure

Figure 7.5 Composite fence failures

7.2. Glass panels on balconies

Many apartment buildings utilised glass panels on balcony balustrades and pool fences to minimise impact on the occupants' view. A number of glass panels failed under wind actions or by debris.

7.2.1. Framed glass panels

Figure 7.6 shows some framed glass panels that had failed under wind-borne debris actions.

Figure 7.6 Failure of framed glass balcony balustrades

Even though the glass panels failed, the partially damaged frame was still able to mark the position of the barrier. However, in some cases, deflection of the handrail from impact from debris may have broken the glass panels either side of the debris impact.

7.2.2. Frameless glass panels

Frameless glass panels function as vertical cantilevers and are vulnerable to damage from both wind loads and debris. Figure 7.7 shows an example of a frameless glass pool fence that failed under wind pressure.

Figure 7.7 Failure of unframed glass pool fence

7.3. Swimming pools

Almost every swimming pool seen during the investigation was discoloured due to vegetation or other debris that had been blown in during the cyclone as shown in Figure 7.8. The volume of vegetation and the loss of power for many days after the event, which prevented occupants from running filters, meant that it was difficult to clean up the water remaining in the pool.

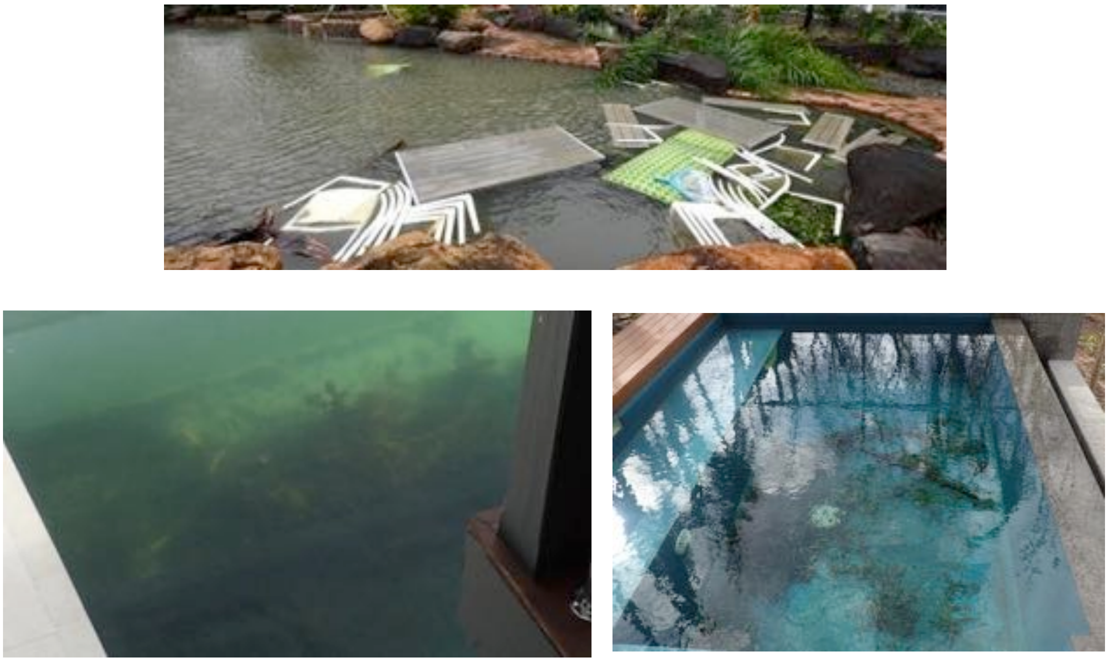


Figure 7.8 Vegetation in swimming pools

Many occupants had to drain, manually clean and refill the pools, particularly if broken glass had been blown into the pool. Figure 7.9 shows a pool that contained broken glass from damaged glass pool fences and Figure 10 a pool that had been drained before cleaning and refilling.

Figure 7.9 Broken glass in swimming pool

Figure 7.10 Swimming pool drained for cleaning and restoration

7.4. Roof-mounted items

7.4.1. Solar hot water and photovoltaic panels

There were many buildings that had either solar hot water systems or solar photovoltaic systems installed on roofs that had no wind damage to either the solar panels or the roof. Figure 7.11(a) shows a roof in an exposed location with no damage to either the roof or the solar panels.

A few houses lost part of their roof and solar panels remained attached as shown in Figure 7.11(b).

(a) Undamaged roof and solar panels

(b) Roof loss

Figure 7.11 Solar panels usually remained attached to the roof structure

There were only a few examples (Figure 7.12) where the mounting brackets between roofs and solar hot water or photovoltaic panels failed. In both cases, it was difficult to determine whether the panels had been fixed to the roofing itself or to the roof structure. The panels became wind-borne debris, damaged other buildings, and contributed to the amount of broken glass the community had to clean up.

(a) Solar hot water panels

(b) Photovoltaic panels

Figure 7.12 Loss of solar and photovoltaic panels

7.4.2. Aerials and vents

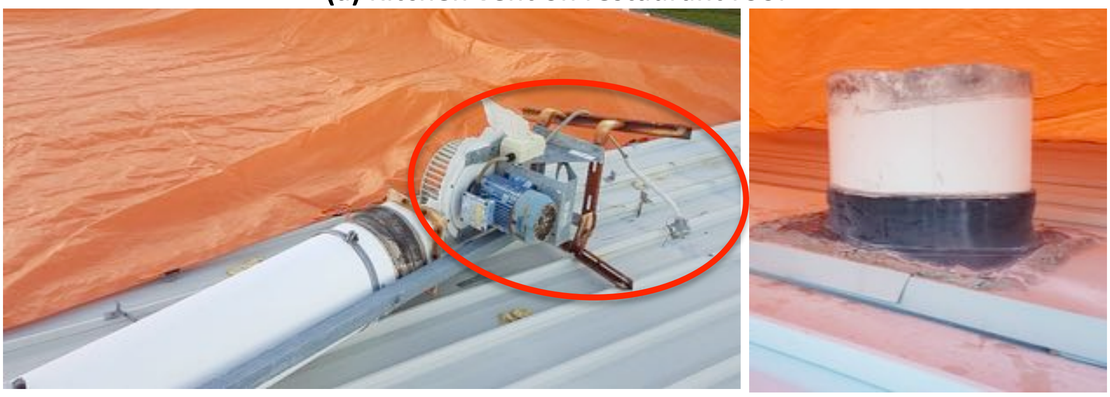
Most aerials remained attached to roofs, and were usually only lost if they had been hit by debris. However, Figure 7.13(a) shows an aerial that had inadequate fixing to the roof structure.

(a) Aerial lost due to inadequate roof fixing **(b) Aerial struck by debris**

Figure 7.13 Loss and damage to aerials

Figure 7.14 shows some large vents in roofs on commercial buildings that had failed. Each failure contributed to water damage to the ceilings below. The two tall vents highlighted in Figure 7.14(b) were next to some roofing damage and may have contributed to the loss of roof sheeting. The highlighted frame appeared to have been fixed only to the roof sheeting. The guy wires in the left photo in Figure 7.14(c) were attached to the roof sheeting, which lifted when the vent was blown over.

(a) Kitchen vent on restaurant roof



(b) Tall stacks

(c) Large industrial vents

Figure 7.14 Detachment of vents from roofs

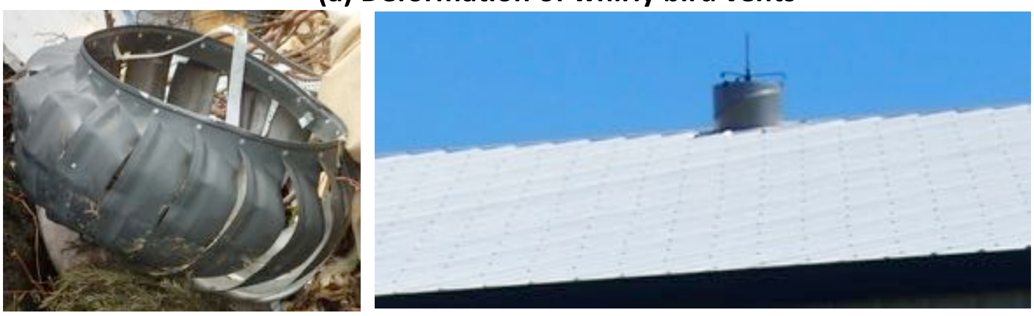
There were many reports of water ingress through small vent pipes that were sealed with rubber boots. Figure 7.15 shows an example where the boot and the sealant had deteriorated and allowed water to enter the ceiling space.

Sewer vent pipes are often located above an external wall, but if installed around the edge of the roof instead they would not be a roof penetration that may contribute to water ingress in high wind events.

Figure 7.15 Seals on vent pipes

As observed in previous investigations (Henderson *et al*, 2006 and Boughton *et al*, 2011), whirly birds vents flattened (Figure 7.16(a)) during TC Debbie due to centrifugal forces generated at cyclonic wind speeds. In some cases, the rotor separated from the vent (Figure 7.16(b)) and contributed to water ingress.

(a) Deformation of whirly bird vents



(b) Damaged whirly bird vents

Figure 7.16 Loss or damage to whirly bird vents

7.4.3. Skylights

Translucent skylights were damaged by both wind pressure and wind-borne debris as shown in Figure 7.17.

(a) Skylights broken by wind pressure **(b) Skylights damaged by debris**

Figure 7.17 Damage to skylights

7.5. Cloth shade structures and carports

There were instances of tension membrane, draped shade-cloth and netting structure failures observed in some carparks, entertainment areas, homes and farms (Figure 7.18). It is unlikely that any of these fabric structures would have been designed for severe wind loads. Typically the designs are predicated on the fabric being taken down during preparations for approaching cyclone (during the watch/warning stages). Once the fabric is ripped or the cables/connections broken, the flailing fabric/cables can damage the neighbouring structures.

Figure 7.18 Examples of damage to sail and shade cloth structures

7.6. Free-standing shelters

There were a many free-standing shelters at beaches, parks and recreation facilities in the study area. A number of these were undamaged.

Captain Liam Clarke of JTF661.2 completed a detailed assessment of two free-standing shelters beside a sports oval were damaged when the connections between the support posts and the footings failed. The shelters were blown more than 50 m from their original position. The shelters appeared to have been removed a single unit and suffered some damage on impact with the ground and trees as shown in Figure 7.19.

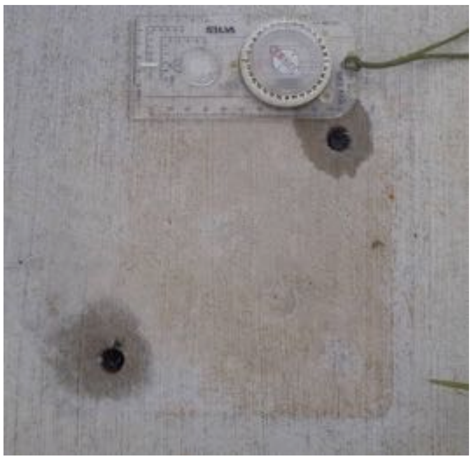
(a) Original position

(b) Resting place

Figure 7.19 Loss of free-standing shelter (*Photos Captain L. Clarke*)

An assessment of the anchorage system indicated that the expanding masonry anchors withdrew from the concrete. Figure 7.20(a) shows that the anchors had not been tensioned to activate the sheath i.e. forced over the bell at the base of the shank. Figure 7.20(b) shows that the bolts had withdrawn cleanly from the holes, whereas if they had been tensioned, concrete would have spalled away from the edges. In addition, only 8 of 20 possible bolting points were used in these two shelters.

(a) Expanding masonry anchors



(b) Holes in footings

Figure 7.20 Footings of free-standing shelter (*Photos Captain L. Clarke*)

A third shelter in the same area lost its roof because the detail that connected the roof to the masonry walls allowed a tension perpendicular to the grain failure in the roof beam as shown in Figure 7.21. The rafters had been connected to the top of the roof beam with framing anchors and the beam bolted to the walls at the bottom. The centre part of the beam would have been in tension, similar to the beam illustrated in Figure 4.22.

Figure 7.21 Failure of roof beam in tension perpendicular to grain (*Photos Captain L. Clarke*)

The roof of a beach shelter failed at the purlin to rafter connections. Figure 7.22(a) shows that the windward edge of the roof folded back with most of the purlins still attached. In two cases, a tension perpendicular to grain failure could be seen in the purlins. One is illustrated in Figure 7.22(b).

(a) Purlin to rafter failure

(b) Tension perpendicular to grain in purlin

Figure 7.22 Failure of roof beam in tension perpendicular to grain

8. IMPROVING WIND PERFORMANCE OF OLDER BUILDINGS

The investigation of damage to buildings after TC Debbie confirmed the findings of previous damage surveys (Boughton *et al*, 2011; Henderson *et al*, 2006; Henderson *et al*, 2010); older buildings are damaged more frequently and severely than newer ones unless they have been adequately upgraded or retrofitted.

Uplift forces act on the roof cladding, and can only be resisted by transferring the uplift forces through the complete structure to the ground. A secure chain of structural elements and connections is required to transmit the forces from the upper surface of the roof to the ground. This is illustrated in Figure 8.1.

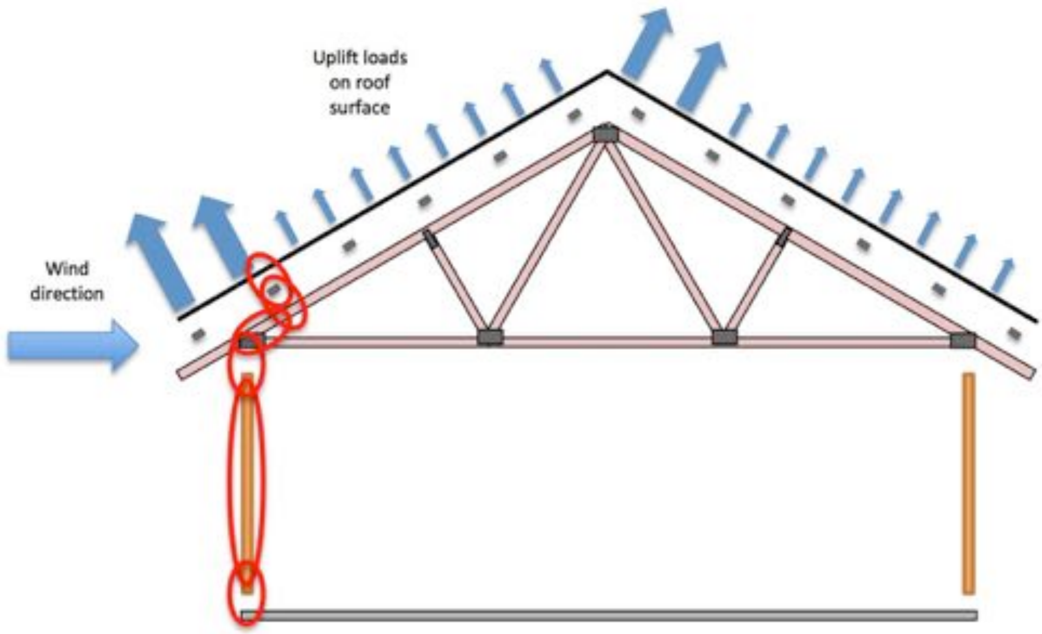


Figure 8.1 Tie-down chain

The elements that may form part of this chain include:

- roof sheeting – spanning between battens;
- sheeting fasteners – carrying loads from the sheeting to the battens;
- battens – spanning between rafters or roof trusses;
- batten fasteners – carrying loads from battens to the rafters;
- roof structure or roof trusses – carrying loads from the batten fasteners to the tops of the walls;
- roof structure tie-down to the top of walls;
- uplift load transfer within the wall from the top plate to the base of the wall;
- uplift load transfer from the bottom of the wall to the floor system; and
- uplift load transfer through the floor and sub-floor systems to the ground.

As the loads pass further down the vertical load path, the weight of all elements above is engaged, which reduces the net uplift that has to be carried by elements lower in the chain.

8.1. Wind damage to older buildings

8.1.1. Batten to rafter/truss connections

Batten to rafter or truss connections were the most commonly observed failure in the roofs of older buildings as illustrated in Figure 8.2.

Timber battens and timber rafters were both typically spaced at 900 mm centres. In buildings where batten to rafter connections failed, battens were a range of sizes with widths typically 70 to 90 mm and thicknesses typically 35 to 45 mm. We observed both softwood and hardwood battens, which were most commonly nailed to the rafters with two 75 mm long x 3.15 mm diameter plain shank bullet head nails. These failures often led to large panels of the cladding with battens attached separating from the rest of the roof structure.

Figure 8.2 Batten-to-rafter failures in buildings built before 1985

8.1.2. Rafter/truss to wall connections

There were some buildings where roofs with upgraded batten to rafter connections failed at the rafter to wall connections because they were only skew nailed and had not been strengthened as part of the roof upgrade. Figure 8.3(a) shows a roof that had been built as a tiled roof and had been replaced with steel sheet cladding. The connections between the roof and the wall were insufficient to resist the higher net uplift forces.

(a) Failure of roof where tiles had been replaced by sheeting

(b) Failure of roof panel

Figure 8.3 Rafter to wall connection failure in buildings built before 1985

Roof panels with rafters attached were more rigid and seemed to travel further in the airstream.

8.1.3. Other failures

Some other buildings failed due to:

- Use of nails instead of screws to secure roof cladding. Figure 8.4(a) shows roof cladding that had been fixed with lead head nails. Nails through roof sheeting have consistently led to premature failure either by tearing the sheeting or withdrawing from the battens. All pierced-fixed cladding manufacturers recommend screw fixing of sheeting.;
- Corrosion of sheeting or fasteners. Figure 8.4(b) shows a roof where corrosion along a lap line caused loss of roofing thickness at connections.

- Failure of rafters in tension perpendicular to grain. Figure 8.4(c) shows a roof in which new metal battens had been screwed to existing rafters next to recesses cut for deep purlins. The penetration of the screw into the rafter was less than the depth of the notch and led to tension splits perpendicular to the grain in the rafters that started at each notch. This mode of failure is also discussed in Section 4.7.

(a) Nails used to secure roof cladding

(b) Corrosion of roof sheeting

(c) Failure of rafters in tension perpendicular to grain

Figure 8.4 Other roof failures

8.2. Retrofitting older buildings

Section 8.1 highlighted systematic problems with the tie-down chain in older buildings. The purpose of retrofitting is to upgrade all links in the tie-down chain so they have sufficient capacity to resist the wind loads during future tropical cyclones.

8.2.1. Repair of wind damage to roofs

In buildings where one link in the tie-down chain has failed, the loss of roof above the failure prevented connections lower in the building from being loaded. For example, if batten to rafter connections have failed, weak rafter to wall connections may not have failed because once the battens had gone, there was no longer any load on the rafter to wall connection. Once the roof is repaired with new and compliant batten to rafter connections, a future event may cause failure at the rafter to wall connections as they become the weakest link in the tie-down chain. These connections should also be upgraded as part of the repair to the roof.

Where only part of the roof has failed, the remainder of the roof should also be checked and upgraded. Figure 8.5 shows a roof that had failed in TC Ului (Henderson *et al*, 2010), been repaired, and then failed in TC Debbie because the verandah posts had corroded and were not upgraded at the same time. This highlights the need to assess the condition of all elements in the tie-down chain and repair or upgrade as necessary .

Figure 8.5 Failure of a previously repaired roof

The Cyclone Testing Station (Cyclone Testing Station, 2017), the QRA (Queensland Reconstruction Authority, 2017) and the QBCC (Queensland Building and Construction Commission, 2017) provide guidance on the repair of roofs.

8.2.2. Strengthening roofs in older buildings

This investigation and others after previous tropical cyclones have demonstrated that older buildings are generally at higher risk of damage in tropical cyclones than contemporary buildings. In order to mitigate these risks, building owners should engage an engineer or builder to assess the entire roof structure and upgrade connections and members if required.

Upgrades that may be needed include:

- Battens if the current battens have deteriorated,
- Batten to rafter or truss connections if nails are currently used – upgrade may include screws or straps; and
- Rafter to wall connection if these are currently skew nails – upgrade may include straps or bolts.

These upgrades are easiest to perform when the roof cladding has been removed, and should be done whenever the roofing is replaced. Where tiles are replaced by sheeting, upgrades to underlying roof structure and connections are vital; sheet metal roofs are lighter than tile roofs, so the net uplift is greater and stronger tie-downs are required for sheet roofs. The websites referred to in Section 8.2.1 also provide information strengthening roofs in older buildings.

8.3. Maintenance

In some cases, the failures in older buildings reported in this investigation were due to deterioration of:

- Connections due to corrosion (Figure 8.6);
- Timber members due to rot or termite activity (Figure 8.7); or
- Metal members due to corrosion.

Figure 8.6 Failure of roof due to corrosion of screws

Figure 8.7 Failure of walls due to termite activity

Regular inspection and maintenance of all older houses is recommended to help prevent damage in future wind events.

9. COMMENTS ON CHANGES TO STANDARDS

9.1. Large access doors

AS 4505 (Standards Australia, 2012) was revised as a result of recommendations in TR57 (Boughton *et al*, 2011) and adopted in the NCC 2013. While failures in some garage doors were observed in the investigation after TC Debbie, these were all doors that would have pre-dated the revised standard. The observations of the damage to doors supported the revision of the Standard.

Wind locks require extra forces to be transmitted from guides to the building structure. These forces are noted in the revised Standard, and failures of connections that were too weak to transmit these forces during TC Debbie confirmed the changes to the Standard were required.

9.2. AS 4055 – Topographic effects and wind classification

AS 4055 (Standards Australia, 2012) was revised in 2012 to include new definitions of Terrain Categories and the calculation of topographic effects based on the maximum hill slope rather than the average hill slope. The revision means that some exposed locations would now have higher C classifications than they would have had in the previous version of the Standard.

The investigation identified a number of damaged houses in exposed locations that were designed and built before the revision to the Standard, which confirmed the need for the revision. However, there were few new houses within the scope of AS 4055 (Standards Australia, 2012) in exposed locations and designed and built since 2012. Therefore, it is not yet possible to assess whether the revision has been effective in reducing damage to contemporary housing.

9.3. Roof Tiles

Loss of roof tiles during TC Debbie reinforces the importance for all tiles in cyclonic areas to be securely mechanically fastened, especially at leading edges and other discontinuities (e.g. hips and ridges). Observed damage of tile roof systems with clips highlights the need for tile systems for cyclonic regions to be evaluated for wind load resistance using a standardised cyclic test method.

9.4. Flashings

Investigation of damage following TC Olwyn (Boughton *et al*, 2015) drew attention to the consequences of inadequate flashing connections. (The Late) Graeme Stark submitted a proposal to amend AS 1562.1 (Standards Australia, 1992), which was approved in 2016. The amendment will include requirements for fastening of flashings. The investigation following TC Debbie confirmed the prevalence and consequences of inadequate flashing connections (See Section 5.2 of this report).

9.5. Roof vents

The repeated failure of roof vents (e.g. whirly birds) indicates either non-compliance of the vents or that the test standard is not appropriate and needs to be examined and revised if required.

10. RECOMMENDATIONS

Based on the findings in this investigation, the following recommendations aim to improve the performance of buildings in future tropical cyclones.

10.1. Structural performance of buildings

Section 4 of this report outlined structural failures that occurred in buildings where the wind speeds were less than the design wind speed for most buildings. These recommendations address the structural deficiencies identified in the report.

Observed failures of roof structures on buildings in cyclone regions highlight the need for designs to account for the possibility of high positive internal pressures.

Further education within the building industry is required to ensure all structural details are correctly designed and installed in order to avoid damage under wind loads.

10.1.1. Roof tiles

The percentage of tile roofs that were undamaged in the study area was significantly lower than the percentage of sheet metal roofs that were undamaged.

All tiles, part tiles and ridge/hip tiles must be secured (mechanical fixing) to the battens/structure (Section 4.3). The fixings should be robust enough so that any damage from debris to an individual tile would not dislodge neighbouring tiles. As the tile cladding system uses metal fixings, it should be able to demonstrate its ability to resist the wind load cyclic test regime as detailed in the NCC (Australian Building Codes Board, 2016).

10.1.2. Batten to rafter/truss connections

The failure of batten to rafter/truss connections is the most commonly observed cause of structural damage in all investigations following high wind events (Section 4.4).

Capacity of connections – Nailed batten to rafter/truss connections do not have sufficient capacity to resist uplift loads in cyclonic regions. The capacity of the selected batten to rafter/truss connections should match the high uplift loads in cyclonic areas. For houses in cyclone areas, AS 1684 indicates that screws, straps or framing anchors are required for all timber roof structures.

Detailing connections – For timber rafters and trusses, connections should be detailed to minimise tension perpendicular to grain in the rafters/trusses. This generally involves extending the batten to rafter/truss connection to the bottom of the rafter or truss.

10.1.3. Roof structure to wall connections

Previous investigations have stressed the importance of upgrading batten-to-rafter connections, but if batten to rafter/truss connections are upgraded to comply with current requirements, fewer of these connections will fail in future events and all uplift loads will be transmitted to the roof structure to wall connections. The roof structure to wall connections may then become the next weakest link in the tie-down chain.

Detailing connections – The roof structure to wall connections on a number of contemporary buildings failed during TC Debbie (Section 4.6). Particular attention needs to be given to the details required to transmit significant forces between dissimilar materials as connection details are not presented in a single Standard. For example, adequate depth of embedment of rods and bolts through timber or steel into masonry or concrete, and the compaction of concrete around the embedded bars is important to keep the roof attached to the walls.

10.1.4. Verandah beam tie-down

Wind load design – Calculation of wind design pressures needs to observe the geometric limitations of AS 4055 (Standards Australia, 2012) and where houses do not fit within the limitations. AS/NZS 1170.2 (Standards Australia, 2011) should be used to determine wind actions. Even on houses within these limitations, very large verandahs may incorporate larger Roof Load Widths and spans than those included for timber verandah beams in AS 1684 (Standards Australia, 2010) and must be designed to AS 1720.1 (Standards Australia, 2010). Connections for steel verandah beams should be designed in accordance with the relevant steel standard.

Capacity of connections – Verandah beams, particularly those on the large verandahs and balconies in the study area, are vulnerable to damage from wind forces because they transmit large loads through the connections at each end (Section 4.7). The large forces require high capacity structural connections, which usually include large fasteners such as bolts rather than screws.

Tension perpendicular to grain in timber verandah beams – Connections for timber verandah beams should be detailed to minimise tension perpendicular to grain. This generally involves ensuring that the connection (usually bolts) between the verandah beam and the post is evenly distributed over the full depth of the beam and not concentrated near the bottom of the beam.

10.1.5. Light gauge steel framing

Section 4.8 indicated that studs in light gauge steel framing need to be continuous from the roofline to the floor in order to resist out-of-plane forces generated by wind pressure. It is particularly important that studs are continuous either side of lintels where window heads are part way up the wall, such as at gable ends of buildings (Refer to Figure 4.25).

10.1.6. Windows and doors

In general, there were significantly fewer structural failures of windows and doors (refer Section 4.9) compared with the water-ingress through windows (refer Section 5.5).

Fixing to wall structure – Section 4.9 discussed the need to use the recommendations provided in the AWA Guide (Australian Window Association Industry, 2010) to ensure that windows are securely held in the building structure.

Wind rating – use appropriately rated windows and glass doors to ensure they are strong enough to resist wind loads and stiff enough to minimise water ingress.

Window and door furniture – install resilient door and window furniture such as locks, hinges and latches on all doors and windows including non-glazed external doors. This furniture should be designed to resist loads appropriate to the wind rating of the house. Manufacturers should ensure that locking mechanisms (such as latches and drop bolts) are prevented from vibrating open under repeated wind loading.

10.1.7. Soffits

Broken and missing soffits caused significant damage to building linings from water ingress (Section 4.11).

Fastening soffits – soffits should be designed and fastened to resist the wind pressures given in AS 4055 (Standards Australia, 2012) or AS/NZS 1170.2 (Standards Australia, 2011). Soffit fastening systems can be tested using the same procedures as other cladding materials.

Resilience of soffit materials – use linings such as steel sheet cladding or composite materials to improve the resilience of soffits to water saturation and debris impact. Alternatively, the spaces between the top of walls and roof cladding can be sealed with bird boards to protect the inside of the building from water ingress if the soffit fails. Plasterboard should not be used as an exterior cladding material in cyclone regions – even for soffits.

10.1.8. Large access doors

While many recently constructed large doors were able to withstand the wind forces in TC Debbie, older large access doors would not have had to comply with AS/NZS 4505 (Standards Australia, 2012) and in many cases did not perform well (Section 4.12). The Cyclone Testing Station is currently undertaking research to determine appropriate guidelines for upgrading existing roller doors to meet the current Standard.

Where wind locks are installed on roller doors, the structure and connections to the structure must be designed to resist the catenary forces developed by the wind locks.

10.1.9. Sheds

Many garden sheds failed during TC Debbie and contributed to wind-borne debris (Section 4.13). Because their failure has consequences for other buildings, they should be designed and built to resist the site wind speed (refer to the Shed Safe industry guidelines).

Larger engineered sheds, particularly those in cyclone areas, should have purlin and cladding systems that have been designed for high positive internal pressures.

10.1.10. Maintenance of all buildings

Building materials deteriorate with time, with the rate of deterioration depending on factors such as proximity to salt spray, moisture, coating protection, etc. Inspection and maintenance of structural elements within the roof space should be undertaken for all buildings:

- after any event in areas where the applied loads were near the design ultimate wind loads; or
- whenever the roofing is removed (e.g. for replacement of roof sheeting); or
- at seven to ten yearly intervals (considered to be a reasonable interval for general inspections, as other inspections to detect progressive deterioration of building structure, such as pest inspections, are usually undertaken at one or two yearly intervals).

10.1.11. Strong compartments

Strong compartments within buildings and houses can provide more secure shelter for occupants during extreme events, even if the remainder of the building is damaged. Development of guidelines on the design of strong compartments within residential buildings will enable the planning of better protection for communities affected by events that are higher than the design wind speed, or for buildings that experience accidental damage by large items of debris during tropical cyclones.

10.2. Wind-driven rainwater ingress

Reports of wind-driven rain entering buildings were widespread (Section 5.1). These recommendations address the structural deficiencies identified in the report.

Research should focus on developing strategies to reduce the volumes of water that enter otherwise undamaged buildings. This will help prevent damage to internal linings and contents and potential risk of injury to occupants mopping up water in front of windward wall windows during the storm.

Where possible, roof designs should be simple with few valley gutters and flashings. This will reduce the risk of rainwater ingress. Minimising roof penetrations such as vent pipes also decreases opportunities for wind-driven rain to enter buildings under or through flashings.

10.2.1. Flashings

AS 1562.1 (Standards Australia, 1992) should specify minimum requirements for flashings and their fixings to resist applied wind loads. HB39 currently recommends:

- appropriate screws (not pop rivets) at a maximum of 600 mm centres; and
- on horizontal and vertical faces of barge flashing. (Section 5.2)

10.2.2. Gutters

The performance of gutters (Section 5.4) can be improved by:

- Increasing the number and stiffness of gutter brackets used to prevent loss of perimeter gutters;

- Including spillway overflows on both ends of box gutters to allow wind to disperse box gutter overflow before they are full and water flows back into the building; and
- Detailing roof drainage to minimise gutters being blocked by the large volumes of wind-borne leaf matter often present during tropical cyclones.

10.2.3. Windows and doors

CTS suggests research to develop water penetration ratings for windows and doors (refer Section 5.5). The rating could indicate the volume of water leakage that is likely to occur at wind speeds above the serviceability test requirements, and would be useful for building owners and insurers in providing guidance on relative benefits and risk of interior damage. The better windows and doors would have lower leakage flow rates and a higher rating.

10.2.4. Vents

Instances of water ingress and resulting damage occurred from wind driven rain entering via eaves and gable vents (Section 5.7). Research should be undertaken to develop an appropriate retrofit (e.g. screwing on a cover for large vents and taping for small vents) on existing homes. The design of new vents, particularly for cyclone regions, should take into account the potential for wind-driven rainwater ingress.

10.3. Storm surge

Section 6 of this report outlined damage to buildings from storm tide. These recommendations address the issues identified in the report.

Ideally, buildings should be built with a floor height above the surge height level shown on Local Council maps. Structural damage can be minimised by selecting resilient materials for walls and floors below potential storm surge levels and ensuring that there is unimpeded flow of water through, around and under the building. Openings In some buildings may be protected from wave action by robust steel covers.

Appendix A in 'Planning for a stronger, more resilient Queensland, Part 1' (Queensland Reconstruction Authority, 2011) should be amended to also account for wave action on elements.

10.4. Ancillary items

Section 7 of this report outlined failures of ancillary items. These recommendations address the issues identified.

Roof mounted ancillary items such as vents, flues, aerials, and air conditioning equipment should always be securely fastened to the roof structure rather than the roof cladding. In many cases, the roof structure will need to be strengthened to resist the additional wind loads.

10.4.1. Fences

The high percentage of failures of paling and sheet fences (Section 7.1) suggests the need for minimum standards in design and construction if these products are to be used in cyclonic wind regions.

10.4.2. Vents

Domestic (e.g. small diameter) “Whirly birds” (Section 7.4.2) should be assessed for common failure modes under wind loads to reduce avenues for water ingress and subsequent damage to linings.

10.5. Pre-1980s buildings

Section 8 of this report outlined structural failures that occurred in older (pre 1980s) buildings. These recommendations address the structural deficiencies identified.

Inspection and maintenance of structural elements such as those within the roof space, verandah posts, house stumps and associated steel bolts, should be undertaken every seven to ten years. Any deterioration identified in these inspections should be remedied. Where sub-standard building elements are identified, retrofitting should be undertaken to improve wind resistance in future events.

Partially damaged elements inside of the roof structure, may not be noticed in external inspections. The CTS recommends roof structure inspections on pre-1980s buildings in the TC Debbie, study area that have not had recent structural upgrades. These inspections should be undertaken by qualified builders, building surveyors or structural engineers.

The CTS has a series of mini-videos for both homeowners and builders to provide some information on repairing damaged roofs from cyclones. These videos can be found at:
https://www.jcu.edu.au/cyclone-testing-station/videos-And-resources

The Queensland Building and Construction Commission also has important links to information on rebuilding after cyclones (such as the ‘Repair Checklist’ and ‘Tie-down designs’ PDFs):
http://www.qbcc.qld.gov.au/home-maintenance/rebuilding-after-natural-disaster

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Appendix A: Windicators

Windicators are simple structures that have well defined aerodynamic and structural properties such that the wind pressure to cause a structural failure can be robustly calculated (Boughton et al 2011).

Typical cantilevered road signs make good windicators, provided the failure is by yielding of the steel posts and the surrounding terrain is flat and reasonably free of shielding. The wind loads acting on these plates can be estimated to give upper (U) and lower (L) bounds for wind speeds. Figure A1 shows a standing sign (upper bound) and a failed sign (lower bound).

Figure A1 Upper bound sign and Lower bound sign types

Table A1 Windicator estimates of wind speed at 10 m height in open terrain

Sign location	Latitude	longitude	Vr (km/hr)	Vr (m/s)	Type
Near Bowen airport	-20° 1'19"	148°13'5"	128	35	L
Close to Proserpine airport	-20.48	148.59	176	49	L
			229	64	U
			183	51	U
Proserpine-Shute harbour road	-20°22'48"	148°35'16"	140	39	L
			246	68	U
			185	52	L

For previous CTS damage investigations, windicator estimates were used to estimate the wind field and inform the wind field model. For this investigation, and with the anemometer data available, the windicator estimates were not provided to the team calculating the wind field, as a somewhat independent check on both the wind field model and the windicator method.

Appendix B: Damage to properties from landslide and erosion

An overview of damage and recommendations by;
Karen Messer BEng MIEAust RPEQ (Director, Northern Consulting Engineers).
http://www.nceng.com.au/

Within the Whitsunday region, there is steeply sloping terrain bordering towns and semi-rural communities. Several hillside residences and properties in the Airlie Beach, Shute Harbour and surrounding areas have been damaged from landslide/erosion following the heavy rainfall associated with Cyclone Debbie. Predominantly the damage is a result of the volume of uncontrolled movement of overland flow. The damage types range from damage to driveways and landscaping (Figure B1), erosion of embankments, through to the extreme with movement of building foundations and/or landslide debris impacting and into the building (Figure B2). There was a significant landslide adjacent to properties in Cannonvale (Figure B3). The debris/sediment from the landside blocked nearby gully which may have contributed to flash flooding of properties downstream.

Figure B1 Erosion of landscaping over significant portion of property down slope

Figure B2 Landslide debris impacting house with material entering into house

Figure B3 Landslide in Cannonvale

In undertaking inspections of the damage, several factors have been identified that have contributed to the initiation of the landslides:

- Lack of landscaping and general construction in accordance with Geoguide LR8 "Good Hillside Practice".
- Lack of Landslide Hazard Assessment by geotechnical engineers with sites classified with S/M/H etc instead of a P class site in accordance AS2870. It should be noted however that there would appear that there is no mandatory requirement as there is no landslide hazard criteria within the local government planning scheme.
- In some cases there was a general lack of compliance with geo-technical recommendations provided in the design phase where a potential issue was identified.
- Poor planning and design in the discharge of storm-water.
- Minimal to no maintenance of discharge drains
- Lack of guidance provided to the homeowner resulting in limited awareness from the homeowner as to importance of site design and maintenance.
- Instances of limited inspection of retaining walls.

Recommendations:

- Implementation of a landslide hazard overlay within the regions' planning schemes and the associated planning approvals put in place to provide broader implementation of landslide mitigation strategies for developments and promote importance of the issue to the property owners.
- Construction and landscaping to reference and follow Geoguide LR8, with particular focus on storm-water control and drainage.
- Building owners to be informed of the best practice to maintain their properties.