Tropical Cyclone Damien

Damage to buildings in the Pilbara Region of WA

CTS Technical Report No 65

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TECHNICAL REPORT NO. 65

Tropical Cyclone Damien Damage to buildings in the Pilbara Region of Western Australia

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Executive Summary

Tropical Cyclone Damien (TC Damien) was classified by the Bureau of Meteorology (BoM) as a Category 3 tropical cyclone and crossed the Pilbara coast of Western Australia near Dampier and Karratha around 3:30 pm on Saturday 8 February 2020.

The Cyclone Testing Station (CTS), Department of Mines, Industry, Regulation and Safety (DMIRS) and the Department of Fire and Emergency Services (DFES) collaborated to investigate damage. The study focused on the performance of houses; apartments and strata properties; and commercial and public buildings. The study area included the communities of Karratha, Dampier, Roebourne, Wickham and Point Samson. Buildings within the study area experienced wind speeds less than 70% of their design wind speed – close to the serviceability wind speed. The storm tide generated during TC Damien was lower than the Highest Astronomical Tide because the cyclone crossed the coast at low tide.

The roof structures of most contemporary houses performed well during TC Damien. Contemporary houses were those built recently – roughly in the last 10 years. However, it is concerning that approximately 30 contemporary roofs (around 3%) sustained some wind damage at around the serviceability wind speed; this indicates that there are problems with the design and/or construction of some new houses that need to be addressed by the industry. Most contemporary houses in the Pilbara are constructed of light metal frames and in a number of cases, local failures of the framing at the connections highlighted the need to test key assemblies using cyclonic load sequences as detailed in AS/NZS 4040.3.

As in previous investigations, reports of wind-driven rain entering buildings were widespread. Research should be undertaken to develop strategies to reduce the volumes of water that enter otherwise undamaged buildings. Research should focus on flashings, doors, and windows.

Some flashings failed during TC Damien even though the fastener spacings were only marginally more than the current maximum spacings specified in AS 1562.1. Research could indicate the appropriate maximum spacing of flashing fasteners for cyclonic regions. Many undamaged flashings allowed water into buildings, so, it is also recommended that guidance documents detailing suitable flashings for buildings in cyclone regions are developed.

Inward opening doors allowed wind-driven rainwater to enter buildings past ineffective seals. Flexing of doors under wind pressure also allowed water to bypass the seals at the top and bottom. It is recommended that door systems are required to pass the same tests for wind rating as windows.

Most building owners that investigators spoke with reported that rainwater entered through weepholes in windows, including fixed windows, and glass sliding doors. It is recommended that weep holes are designed to minimise water entry at serviceability wind pressures, and that water penetration tests report the leakage rates at the serviceability limit state. (Currently AS 2047 only requires a window to resist water penetration to around one-third of the serviceability design pressure.)

As part of the preparation for an approaching cyclone, building owners should be able to remove shade sails and shade cloth, and blades from outdoor ceiling fans. These elements need to be designed so they can be easily removed and replaced later.

This study reinforced many of the findings from previous damage investigations concerning: the vulnerability of some types of concealed-fixed roof cladding, the need to strengthen the tie-down chain in older buildings, and the need to inspect and maintain all buildings regardless of age.

Acknowledgements

The authors are extremely grateful to the residents of the Karratha, Dampier, Point Samson, Roebourne, and Wickham communities who generously assisted with this study by volunteering information, answering questions, and inviting the authors into their homes, apartments and commercial properties to inspect damage.

The CTS team worked closely with the Department of Fire and Emergency Services (DFES) Western Australia, and the Department of Mines, Industry, Regulation and Safety (DMIRS) during this investigation. The collaboration between the three organisations enabled a coordinated, efficient and effective approach to the investigation, which increased the amount of data and information that was able to be gathered in a short period of time. The outcomes of the investigation will ultimately contribute to improved community resilience to future tropical cyclones in all parts of Australia.

The authors particularly acknowledge the support given by;

- Greg Flowers – field investigator representing the Building Compliance Directorate, Department of Mines, Industry, Regulation and Safety;
- Stephen Gray, Peter McCarthy, Mark Casotti, Paul Rogers (all from DFES) – co-ordinating DFES involvement, arranging travel, providing information on the location of damaged properties, and providing access to affected areas;
- Sean de Prazer and Allan Shiell – co-ordinating Building and Energy Division DMIRS involvement;
- Bruce Harper, Systems Engineering Australia;
- Joe Courtney from Bureau of Meteorology; and
- Pilbara Ports Authority.

Geoff Boughton represented CTS and led the investigation.

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CTS would also like to thank our supporters.

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1. INTRODUCTION

1.1. TC Damien Overview

Tropical Cyclone Damien (TC Damien) crossed the Pilbara coast just west of Karratha during the afternoon of Saturday 8 February 2020. TC Damien caused wind and water damage to buildings in the towns of Karratha, Dampier, Roebourne, Point Samson and Wickham, with the most severe damage in and around Karratha.

Bureau of Meteorology (BoM) models predicted that TC Damien would generate a storm surge that might cause coastal flooding. However, the peak storm tide level did not exceed normal high tide levels. No buildings were damaged by storm surge.

1.2. Damage investigation

The field study commenced on Monday 10 February 2020 and the data collection phase was completed on Wednesday 12 February 2020. Figure 1.1 shows the study area. The field study:

- Determined that the highest recorded wind gust in the study area was 70% of the Wind Region D design wind speed.
- 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 enough 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 ability 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 maintenance and retrofitting and assess the effectiveness of any structural upgrades.

Figure 1.1 Region of investigation –
Inset – map of WA indicating region investigated

1.3. Purpose of the report

The purpose of this report is to present the outcomes of the joint CTS/DMIRS/DFES field investigation into the damage to buildings caused by Tropical Cyclone Damien. The report identifies problems in building performance and indicates whether there needs to be any changes to current codes and standards and building practices.

Previous investigations following TC Vance in 1999, TC George in 2007, and TC Olwyn in 2015 indicated that older houses in WA (built before the early 1980s) do not perform as well as houses constructed in the past 30 years. This was also the case in TC Damien. 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;
- Apartments and strata properties.

The performance of some older buildings was also assessed.

2. TC DAMIEN

2.1. BoM Information

On 1 February 2020 a tropical low developed in the Indian Ocean off the Kimberley coast. The low moved westwards and intensified; it was upgraded to Category 1 TC Damien on Thursday 6 February. TC Damien turned south towards the Pilbara coast on the morning of Friday 7 February. At that time, TC Damien was predicted to make landfall as a Category 4 system crossing between Port Hedland and Exmouth on 8 February 2020. The communities between Dampier and the Pardoo Roadhouse were warned of the possibility of dangerous waves and flooding. Figure 2.1 shows the path of TC Damien.

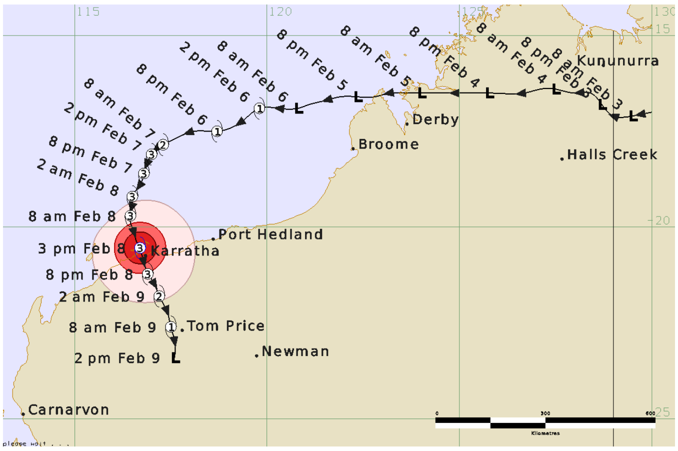


Figure 2.1 Track of TC Damien
(*Provided by Bureau of Meteorology*)

TC Damien crossed the coast near Karratha at 15:00 pm WST on 8 February 2020 as indicated in Figure 2.1. The radar images in figure 2.2 showed that Karratha and Dampier both experienced the eye of the cyclone.

As TC Damien moved further inland, it weakened until it was classified as a tropical low on 9 February 2020. The remnants of TC Damien continued tracking generally south causing extensive rainfall along its path.

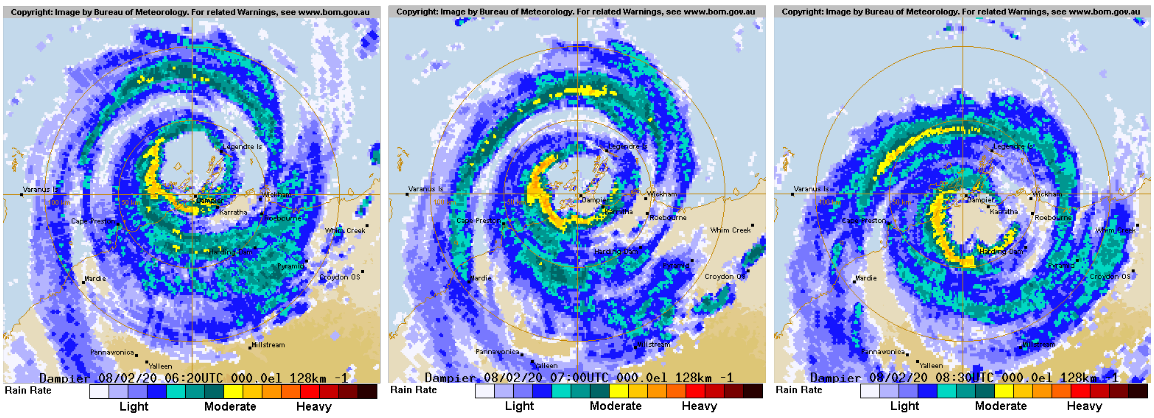
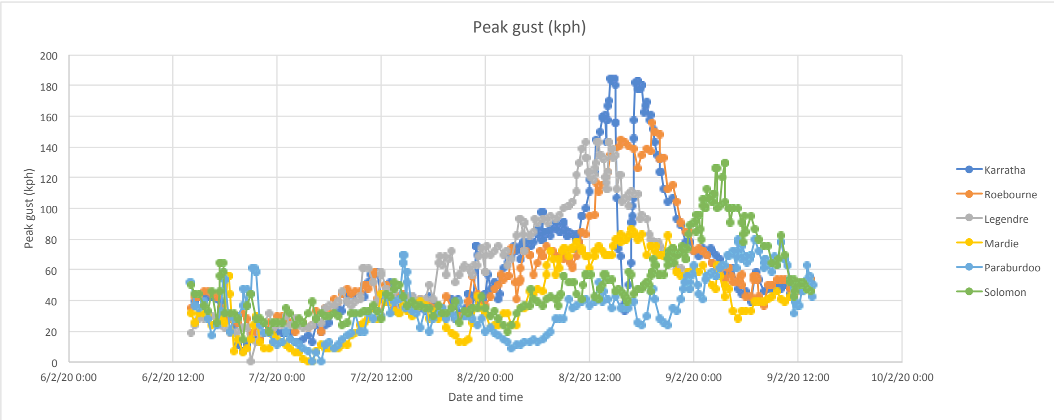


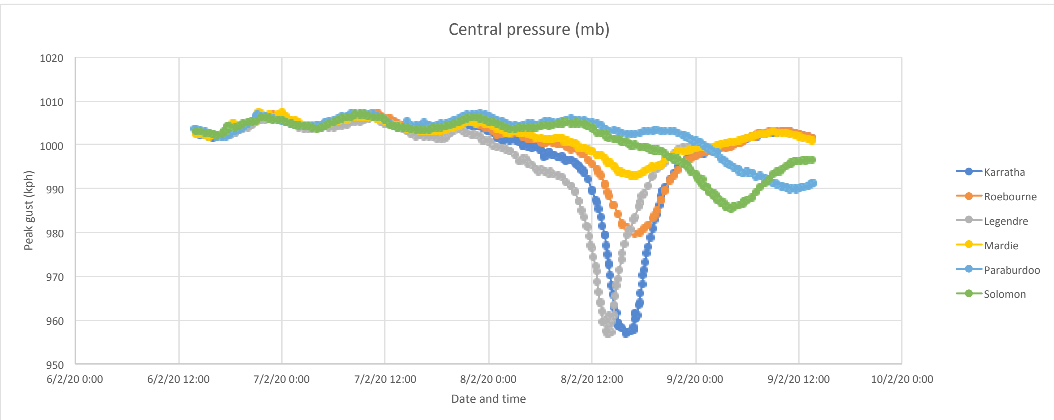
Figure 2.2 Rain radar scans during the landfall of TC Damien.
(*Provided by Bureau of Meteorology*)
Note: Times are in UTC (add 8 hours to convert to WST).

2.2. BoM Anemometer data

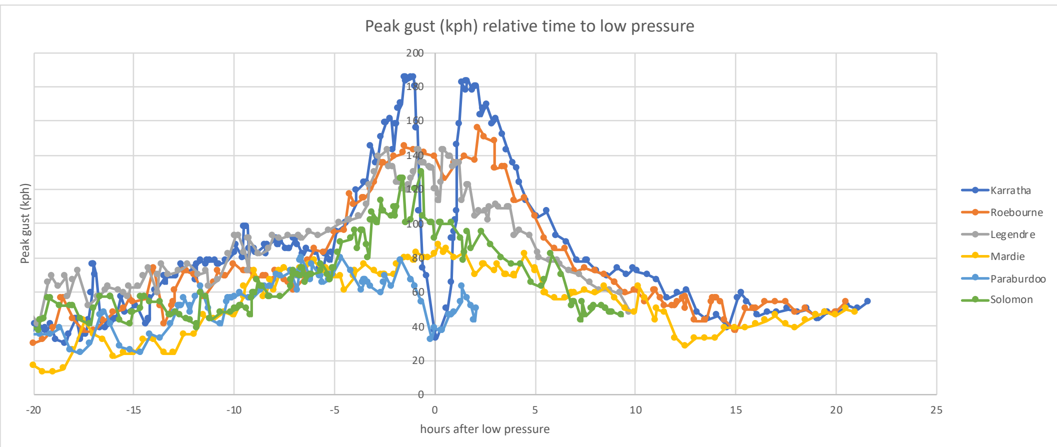
A number of Bureau of Meteorology Automated Weather Stations (AWS) recorded wind data during the passage of TC Damien. The raw 3 second data from the BoM anemometers at Karratha, Roebourne, Legendre Island, Mardie, Paraburdoo and Solomon are shown in Figure 2.3. Figure 2.3(a) shows the data in real time, Figure 2.3(b) shows the mean sea level (MSL) pressure and Figure 2.3(c) shows the anemometers aligned so that the x-axis is hours before or after the lowest MSL pressure



(a) Anemographs showing 3 second gusts



(b) Barograph showing MSL pressure



(c) Anemographs aligned to lowest pressure at time 0

Figure 2.3 BoM AWS 3-second gust wind speed time histories
(*Provided by Bureau of Meteorology*)

A peak wind gust of 194 km/h was recorded by the BoM's AWS at Karratha Airport, which is located on flat land with winds approaching over TC 2.

Wind field models discussed in Section 2.3 were calibrated using the anemometer data from Karratha.

Table 2.1 BoM AWS data

Site	Max 3s Gust [km/h]	Direction	Date/Time	Lowest P [hPa]
Karratha Airport	194	E	8/2/20 14:31	957
Roebourne	161	NNW	8/2/20 19:19	980
Legendre Is	143	NE	8/2/20 12:51	956
Mardie	90	SSW	8/2/20 17:07	993
Paraburdoo	83	ESE	9/2/20 07:08	990
Solomon	130	ENE	9/2/20 03:24	988

2.2.1. Wind speeds as a percentage of design wind speed

The Bureau of Meteorology anemometers reported 3 second peak gusts. However, the design gusts presented in AS/NZS 1170-2 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; and
- no shielding.

Conversions removed topographic influence from measured mean and gust wind speeds. Gust factors for each instrument were calculated from the mean and gust wind data and the characteristics of the instrument. Terrain corrections to the gusts were made based on estimations of the terrain roughness of each site in the direction of the measured wind speed. Finally, the gusts were converted from 0.3 sec gusts to 0.2 sec equivalents.

The converted data is summarised in Table 2.2. It was compared with the design wind velocity (V_R) for Importance Level 2 i.e. appropriate for housing and smaller commercial and public buildings – an annual probability of exceedance of 1:500 or V_{500}.

Table 2.2 BoM Anemometer data as a percentage of V_{500}

Location	$\hat{u}_{3,600,open}$ @ 10m [m/s]	$\hat{u}_{0.2,600,open}$ @ 10m [m/s]	% V_{500}
Karratha Airport	54.0	62	70%
Roebourne	44.8	52	59%
Legendre Island	39.7	46	52%
Mardie	25.0	29	33%
Paraburdoo	23.1	27	30%
Solomon	36.0	41	47%

Table 2.2 shows that all locations in the study area experienced winds significantly less than the design wind speed. The peak wind speed estimated in the study area was 70% of the design wind speed for Importance Level 2 buildings. This would produce pressures that were 49% of the design wind pressure for the same buildings.

A number of buildings in Karratha that were classified as Importance level 4 buildings were investigated. For these buildings the target annual probability of exceedance is 1:2000 and the ultimate design regional wind speed is 99m/s. This means that the TC Damien wind speeds were around 63% of the design wind speed for these buildings and the wind pressure was around 39% of the design wind pressure.

The serviceability wind speed is independent of Importance Level. The wind speed recorded at Karratha airport is very close to the serviceability design wind speed for buildings in Wind Region D. Therefore, it is possible to conclude that all buildings in the study area experienced winds at or just below their serviceability design wind speed.

2.3. Wind field study area

The data presented in Table 2.2 were compared with wind speeds calculated using a double Holland model of TC Damien immediately before and after landfall. Parameters in the model were drawn from BoM data on the cyclone and calibrated against BoM anemometer data. Figure 2.4 shows a snapshot from the model just before TC Damien crossed the coast.

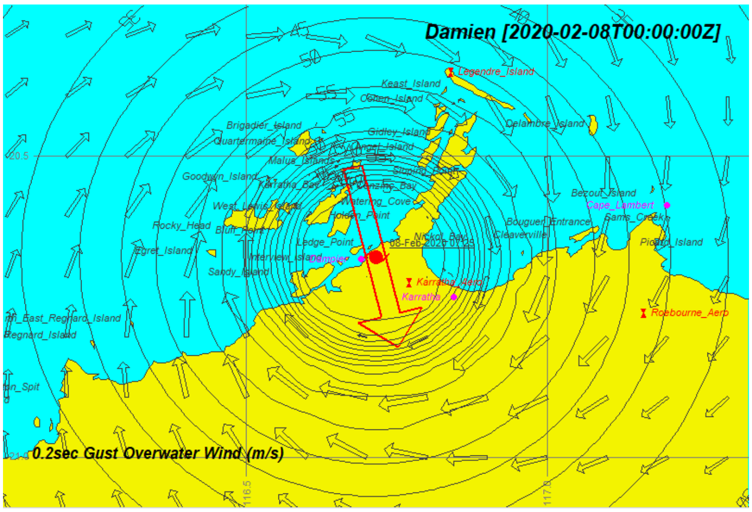


Figure 2.4 3-second Holland model results of wind at landfall
(Model output and diagram provided by Bruce Harper, SEA)

The data from the SEA wind field model was used for a number of different positions of the eye to generate the wind field envelope shown in Figure 2.5. The model was also used in the SEA storm surge model (Harper, 2020), which correctly predicted the regional storm surge.

Figure 2.5 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. The region between the two 68% contours was consistently about that level, with the Karratha Airport wind speed at 70%. The wind speed at each location was used to provide context for the damage described in the report.

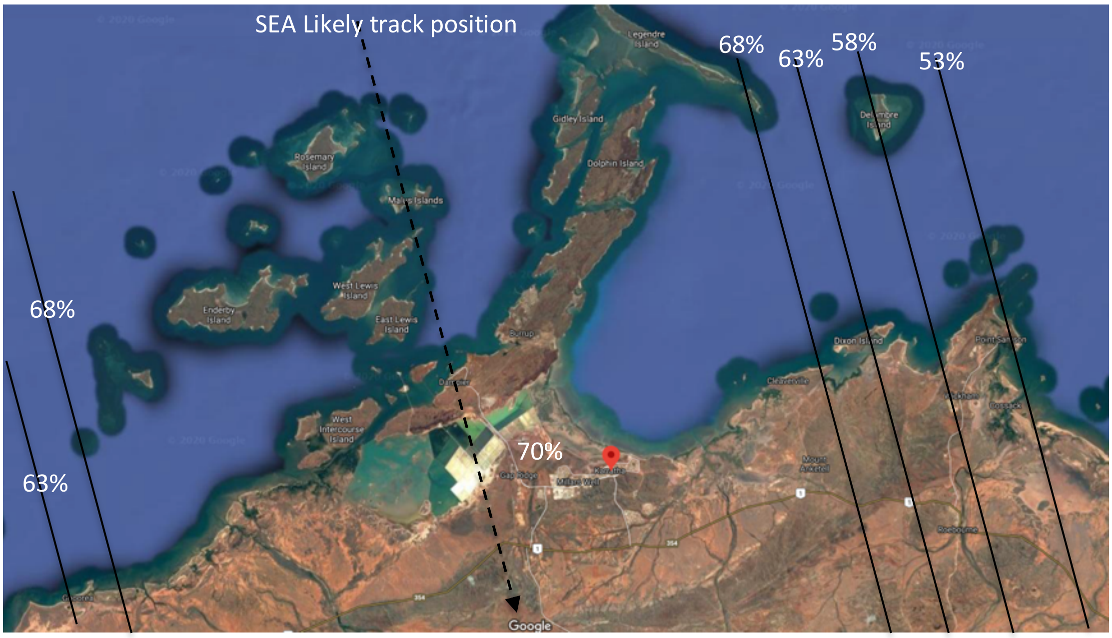


Figure 2.5 Estimate of wind field for 0.2-second gust as a percentage of V_{500}
(Information provided by Bruce Harper, SEA)

3. Estimates of Damage from Rapid Damage Assessment

3.1. Rapid Damage Assessment data

Rapid Damage Assessment (RDA) data were provided by the WA Department of Fire and Emergency Services (DFES). They were collected by trained personnel using hand-held electronic devices. The RDA data are collected to complement the data from Requests for Assistance (RFA) received by the SES to form a more focused and coordinated response and recovery in the immediate aftermath of severe weather events. The RDA is performed as a street assessment and may miss internal damage or roof or structural damage not visible from the street. Therefore, reported information on damage intensity, mode and frequency should be considered as a lower bound for the true extent of damage.

Table 3.1 presents a summary of the information on damage from both RDAs and RFAs.

Table 3.1 Summary of SES reports of Damage

Locality	Wind damage	Tree damage	Water ingress	Rough % houses with wind damage
Older areas of Karratha	102	28	30	3.9%
Contemporary Karratha	52	32	68	3.4%
Dampier	6	4	4	1.5%
Roebourne	8	2	2	5.5%
Point Samson	2	0	2	1.7%
Wickham	10	2	10	1.5%

The percentages represent the number of houses categorised with wind damage divided by the total number of houses in each locality.

Where the damage indicated both wind damage and water damage, it was counted as both. It is highly likely that the number of properties with water damage only was significantly underestimated as it was not possible to observe the extent of the damage from the outside.

Table 3.1 showed that the percentages of wind damage in older areas of Karratha were similar to those in contemporary areas of Karratha. It also showed that in spite of the generally higher age of houses in Wickham and Dampier that these houses suffered lower levels of damage compared with those in Karratha and Roebourne.

3.2. Distribution of damage

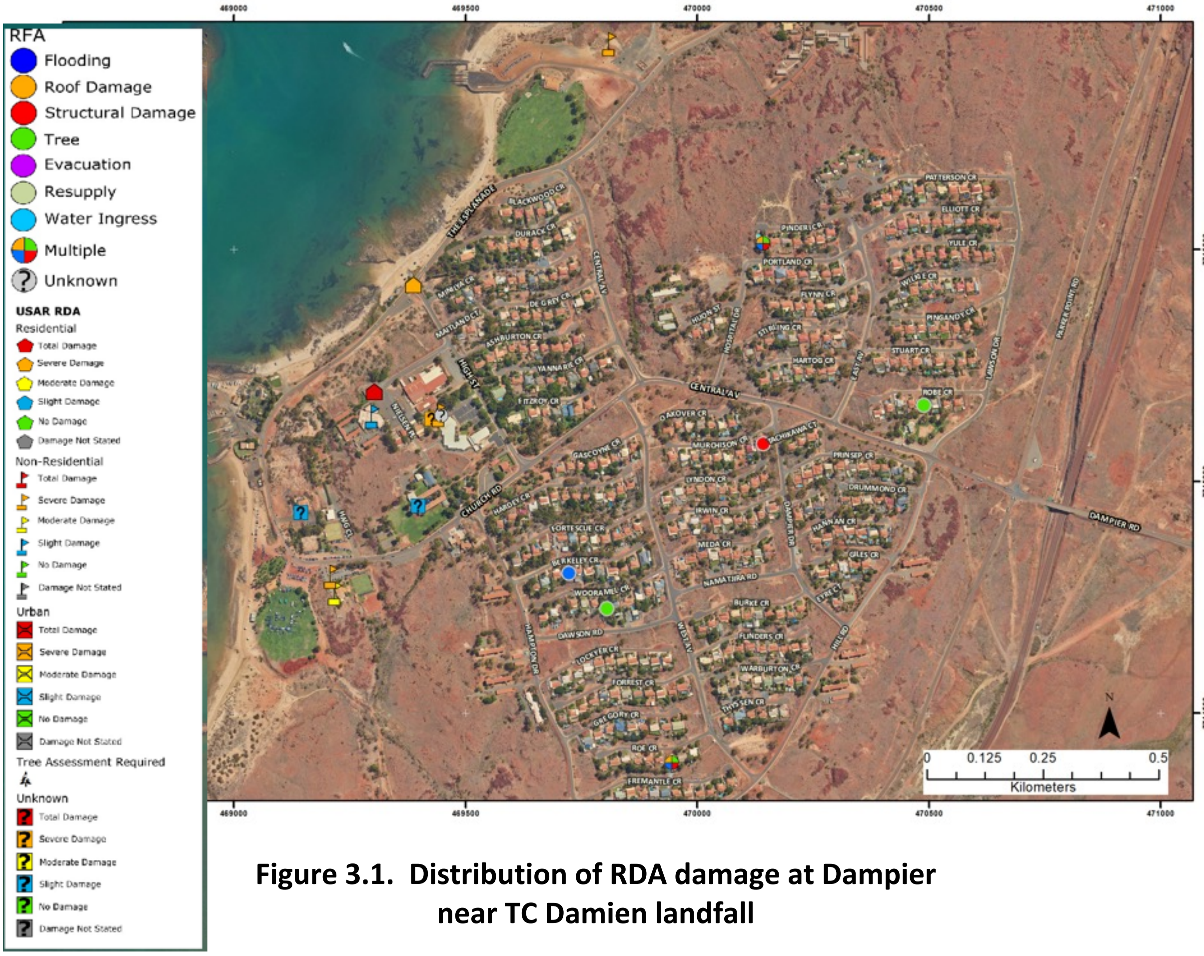


Figure 3.1. Distribution of RDA damage at Dampier near TC Damien landfall

TC Damien made landfall over Dampier and the results of the RDA is illustrated in Figure 3.1. The legend is the same for all damage plots. Most of the damage survey focused on Karratha which is shown in Figures 3.2 and 3.3. The contemporary housing was in the regions shown within the blue lines in Figure 3.3. These Figures show 13 buildings with structural damage in the contemporary housing area. Some of these houses were in streets that the investigation team did not visit in the limited time available, and others had been covered by the time we arrived (most of the cleanup had finished by the third day of our site investigation), so only two of the houses identified in the RDA were common to the damage investigation list of damaged houses in this area. Many more contemporary houses had Requests for Assistance as a result of wind damage. The SES data shows that more than 50 houses in the contemporary house region in Karratha had wind damage, of which it was estimated more than 30 involved damage to roofs.

Other RDAs for Roebourne, Point Samson and Wickham are shown in Figure 3.4

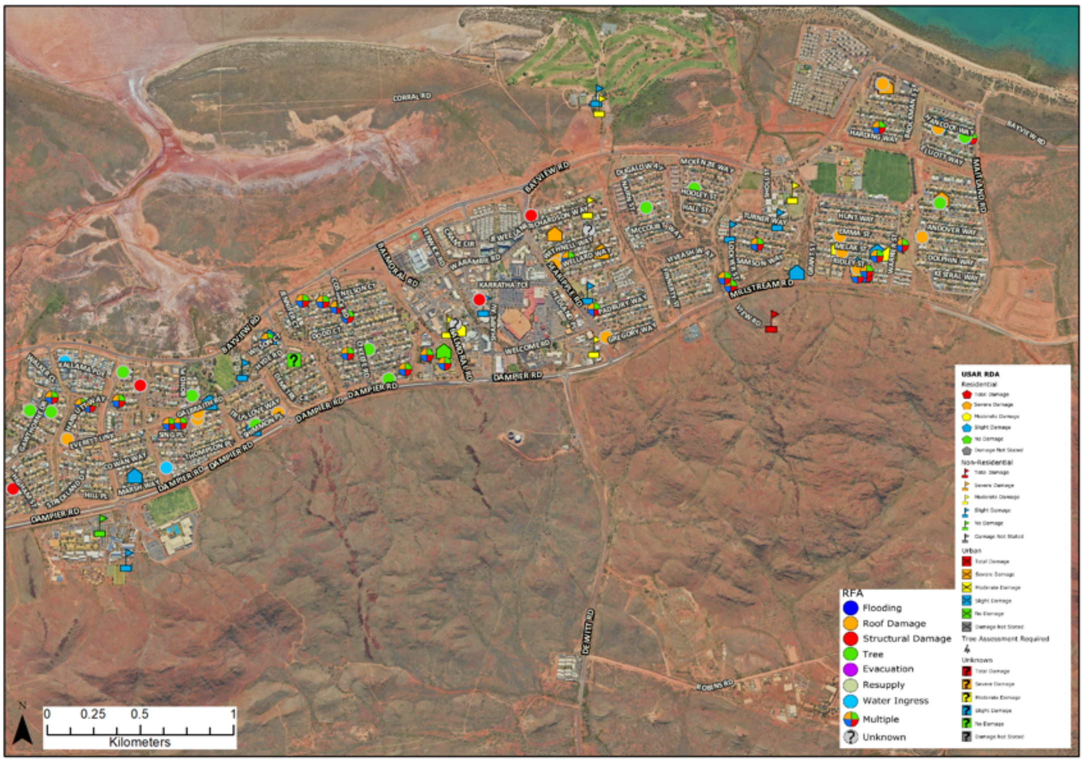


Figure 3.2. RDA damage points in Karratha (East end) from TC Damien (undamaged buildings are not shown)

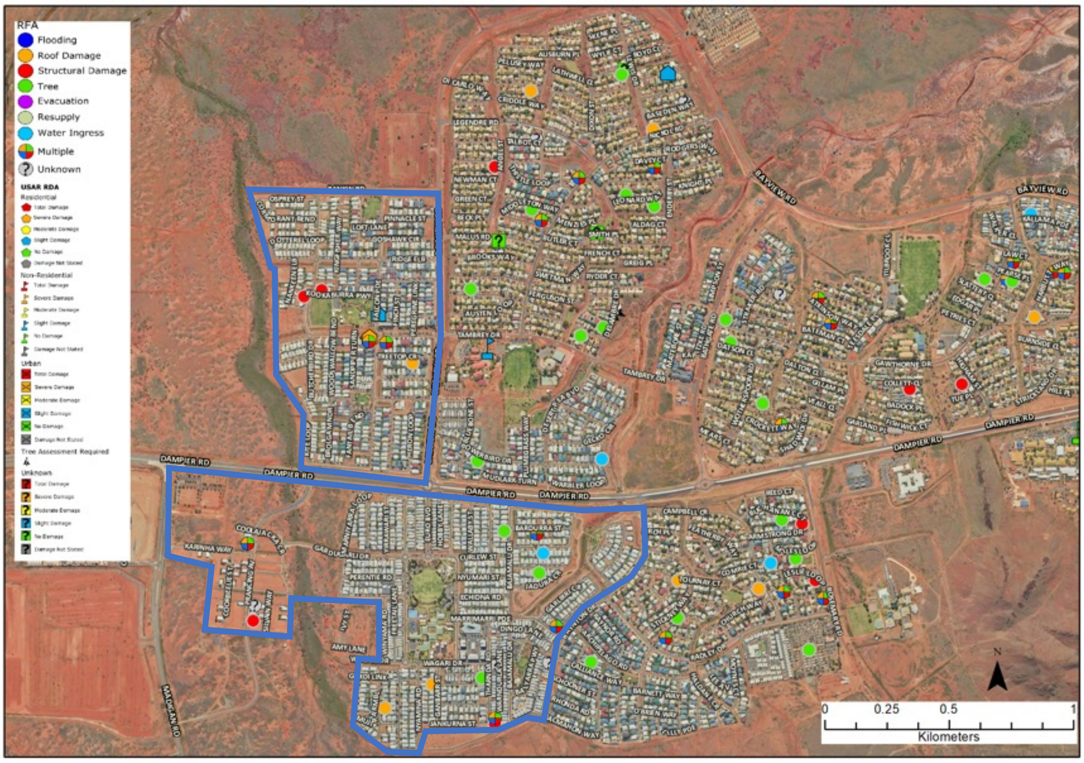
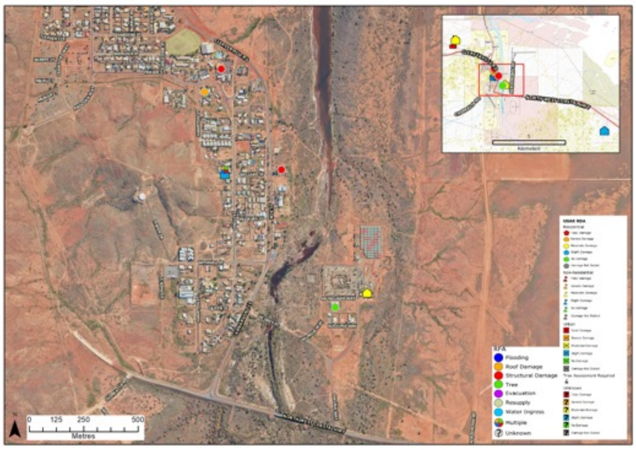


Figure 3.3 RDA damage points in Karratha (East end) from TC Damien (undamaged buildings are not shown)



(a) Roebourne

(b) Wickham

(c) Point Samson

Figure 3.4 RDA damage points in other centres from TC Damien (undamaged buildings are not shown)

4. WIND DAMAGE TO CONTEMPORARY BUILDINGS

For the purpose of this report, contemporary buildings are considered to be those constructed in the past 10 years i.e. since 2010.

Larger buildings such as schools, hospitals, government and commercial buildings, multi-level apartments are all designed using engineer's details based on wind loads calculated using AS/NZS 1170.2. Contemporary housing can be designed using the wind loads calculated from either AS 4055 (Standards Australia, 2012) or AS/NZS 1170.2 (Standards Australia, 2011). Most of the contemporary housing in the investigation area was constructed during the last part of the recent mining boom i.e. between 2010 and 2015. Few houses were built within the study area in the period 2015 to 2020.

Wind around 70% of the design ultimate wind speed (producing 49% of the design wind load for houses) caused structural failures in some contemporary houses in Karratha. An example is shown in Figure 4.1. In most cases, the failures were caused by inadequate structural details; either poor design or installation. They are discussed in the following sections.

Figure 4.1 Example of damage to a recently constructed house

If the wind speeds in TC Damien had been higher, but still less than the design wind speed, it is likely that more contemporary buildings would have been damaged and larger numbers of people would have been placed at risk.

4.1. Summary of performance

Most contemporary homes in the Pilbara region have the following features:

- Walls of either light steel frames with a thin metal or fibre cement cladding; or brick veneer.
- Roof structures of light gauge metal trusses or heavier rolled steel sections for cathedral ceilings.
- Roof shape is predominantly hip, with a number of valley gutters; or skillion (monoslope).

Larger contemporary buildings in the Pilbara use similar construction techniques to contemporary houses, or are of tilt-up concrete construction. Figure 4.2 shows some examples of contemporary larger buildings and houses.

Figure 4.2 – Examples of contemporary houses and buildings in the Pilbara

4.1.1. Roofs

There were few structural failures of roofs on large buildings. The only wind-related failures observed on large buildings were associated with flashings (Section 4.5) and Roof-mounted items (Section 7.6).

The investigation team inspected seven contemporary houses with wind damage to the structure, two with damage to soffits, and a few with flashing damage. Also, there was wind damage to two recently re-roofed house-sized buildings. Not all contemporary buildings in the affected areas could be assessed, so these figures are conservative.

The roof structures of most (more than 95%) contemporary houses performed well during TC Damien. However, it is concerning that approximately 30 roofs sustained damage at around the serviceability wind speed; this indicates that there are problems with the design and/or construction of some new houses that need to be addressed by the industry.

4.1.2. Walls, windows and doors

In general, walls, windows and doors on contemporary buildings and houses were not damaged by wind during TC Damien, which is expected, as the wind speeds during TC Damien were only around 65% of the ultimate design wind speeds. (The investigators noted one broken window on a house, which could have been broken by gravel picked up by the wind.) However, a significant number of buildings were damaged by wind-driven rain entering through doors and windows. This is discussed further in Section 5.

There were only a few houses with garage doors, and no damage was observed. (However, the investigation team was did not inspect any garage doors on industrial buildings.)

4.1.3. Load paths

Wind uplift forces are applied to the roof cladding. A secure chain of structural elements and connections is required to transmit the forces from the roof cladding to the ground. This is illustrated in Figure 4.3.

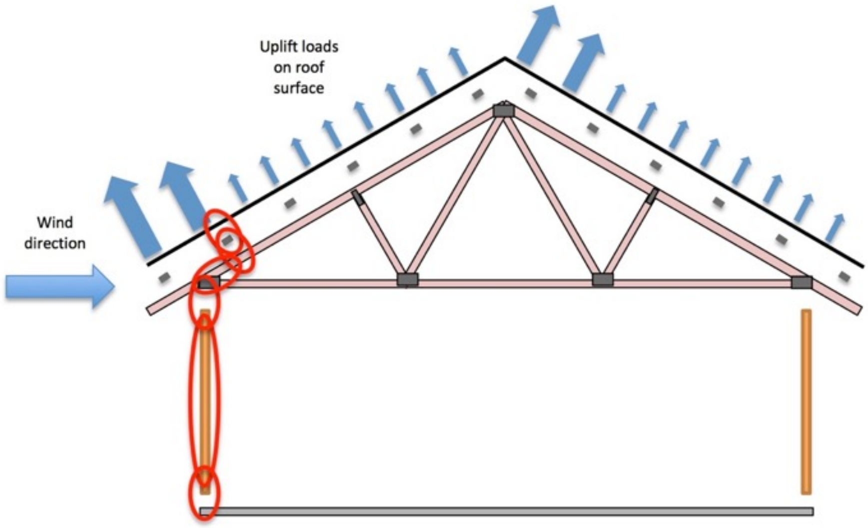


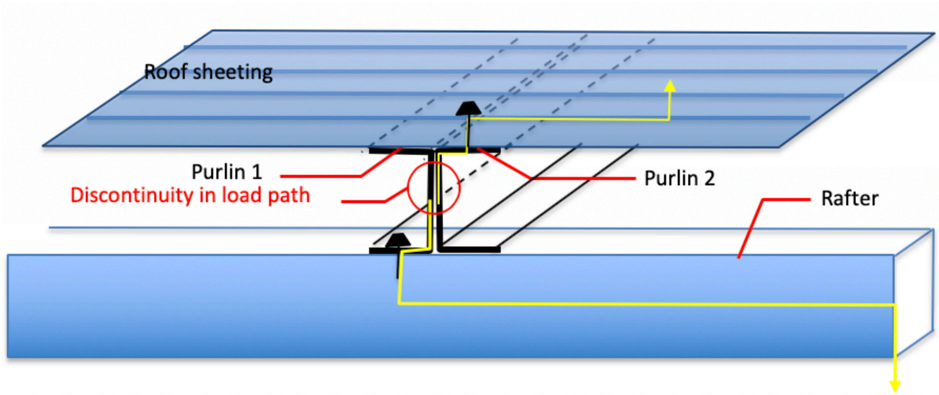
Figure 4.3 Tie-down chain

The elements that form part of this chain include:

- roof sheeting and fasteners – carrying loads from the sheeting to the battens/purlins;
- battens/purlins and fasteners– carrying loads from battens/purlins to the rafters/trusses;
- roof structure including rafters or trusses and tie-down to the top of walls – carrying loads from the batten/purlin fasteners to the tops of the 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.

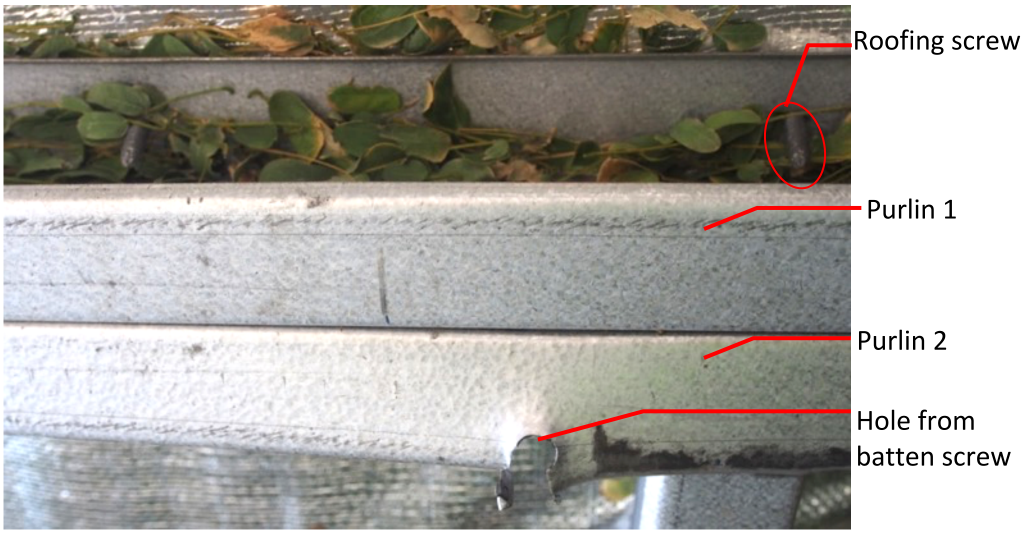
One of the inspected buildings that failed during TC Damien included non-standard structural system and a discontinuity was noted in the tie-down chain. Figure 4.4 shows the disconnected purlins after failure, and Figure 4.5 includes photos and a diagram of the back-to-back purlins used in a part of a roof that failed.

Figure 4.4 Disconnected purlins in neighbour's property



(a) Diagram of back-to-back purlins

(b) Roof section showing back-to-back purlins



(c) Detail of back-to-back purlins`

Figure 4.5 Load path through back-to-back purlins

In the part of the roof that detached, the roof sheeting was screwed to only one of the purlins and the other purlin was fastened to the rafter. The system included bridging members that were connected to the purlins with pop rivets. There was very little connection (one or two tek screws in 4 m) between the two back-to-back purlins and therefore effectively no load path from the roof sheeting to the rafter. It is imperative that engineers, detailers, builders, supervisors and trades know the importance of the tie-down load path. Further education in the industry is required to avoid discontinuities in the load path.

4.2. Roof cladding

In general, the roof cladding on almost all buildings was undamaged, which should be expected for measured wind speeds less than 70% of the design wind speeds.

However, loss of some concealed-fixed cladding was observed in a recently constructed community building, shown in Figure 4.6. There was no evidence that the sheets had been fixed at the crests. There was no marking on the sheeting to identify the specific profile and it was not possible to access the roof to inspect the clip system.

Figure 4.6 Failure of concealed-fixed roof cladding

Concealed-fixed cladding relies on a good fit between the clip and the profile shape to resist uplift forces on the sheeting. This requires precision rolling, transport without deformation and rigorous attention to detail during installation. It is imperative that the cladding system is checked after installation to ensure that the cladding has properly engaged with the clips. This is often difficult to do for some concealed-fixed sheeting systems, which means that some concealed-fixed roofing systems may not be suitable for use in cyclonic areas.

4.3. Batten/purlin-to-rafter/truss connections

The investigators found one house where the purlins had separated from the rafters. The failure mode involved tearing of the purlins from around the screws, as highlighted in Figure 4.7.

Figure 4.7 Failure of batten-to-rafter connections in a contemporary house

Tear-out failures of thin purlin sections around the purlin or batten fixings have been observed in previous cyclones in the Pilbara (Boughton and Falck, 2007). The purlins from the roof shown in Figure 4.7 had a wall thickness of around 0.75 mm and did not have a washer that could spread the load under the head of the fastener. Each purlin screw was loaded by at least 6 roofing screws (that used large cyclone washers to spread the load from the roof sheeting). It is unlikely that this purlin connection detail would have passed the requirements of the Wind Region D pressures for uplift tests in AS 4040.3 (Standards Australia, 2018).

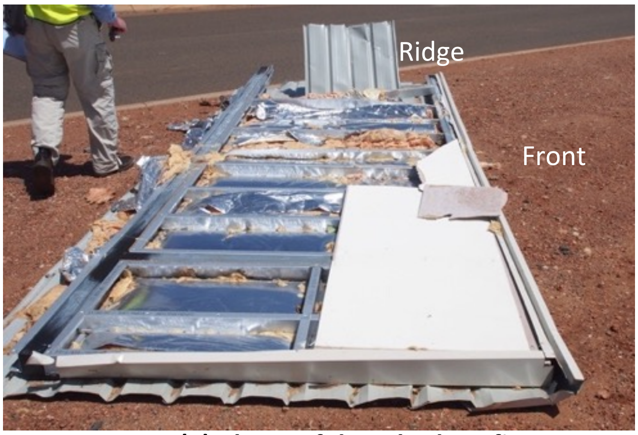
4.4. Roof structure to wall connections

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 sections of roof and allowed substantial volumes of rain to enter the building. In some cases, the detachment of the roof structure also generated large items of wind-borne debris that damaged other buildings. In other cases, for example the left side of the roof shown in Figure 4.8, the detached portion did not cause damage to other property.

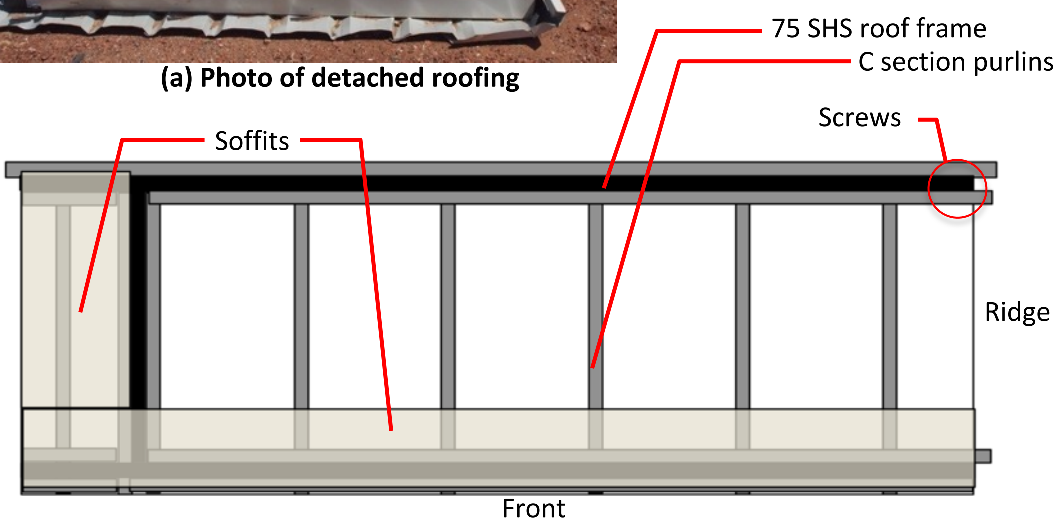
In other cases, for example the right side of the roof shown in Figure 4.8, the damaged section of roofing remained attached to the building. Figure 4.8 also shows the ends of the roof failing for each major wind direction of the cyclone (i.e. before and after the eye crossing).

Figure 4.8 Failure of roof to wall connections in a steel framed contemporary house

Four houses with the same type of skillion roof lost about 2 m width of the main roof associated with the two-way overhang. Figure 4.9(a) shows the detached portion of roofing with the SHS frame around the edge. The purlins were securely fixed to the SHS frame, but there was little evidence of tie-down between the SHS frame and the walls. Screw holes to connect the frame to another roof member were only found in one corner of the SHS frame as shown in Figure 4.9(b).



(a) Photo of detached roofing

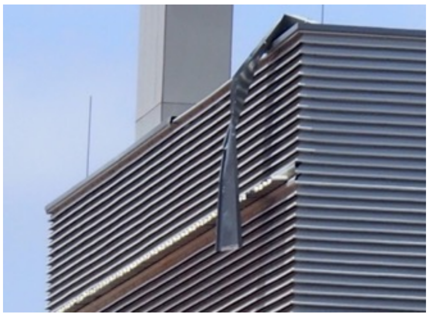


(b) Diagram of fixings noted in detached roofing

Figure 4.9 Failure of skillion roof

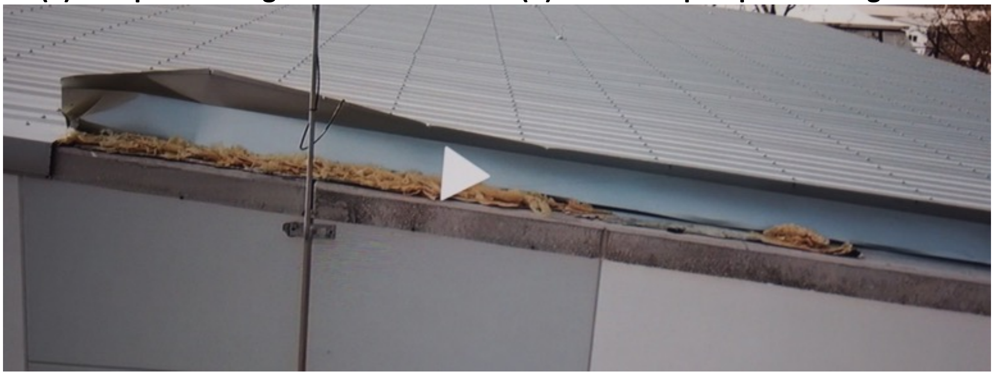
4.5. Flashings

A significant number of buildings, including contemporary buildings had damage to flashings. Some lifted flashings are shown in Figure 4.10. In each case, the lifted flashing allowed significant water entry into the roof space causing water damage, as discussed in Section 5.



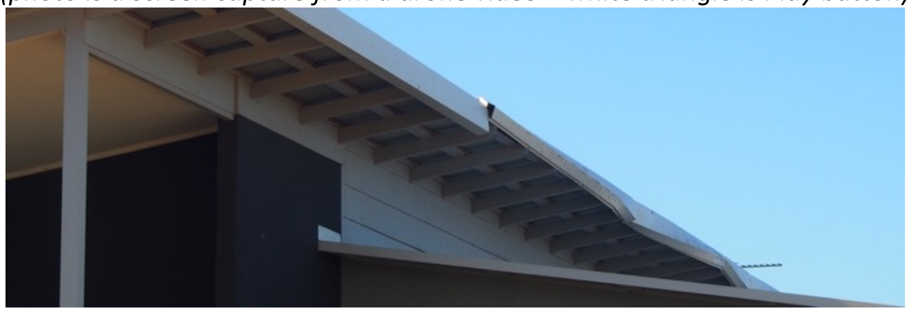
(a) Parapet flashing

(b) Detached parapet flashing

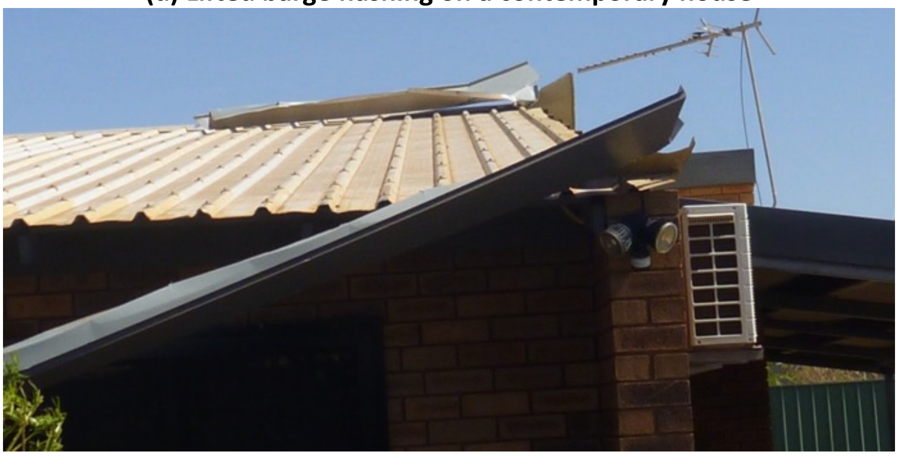


(c) Lifted barge flashing on a commercial building

(photo is a screen capture from a drone video – white triangle is Play button)



(d) Lifted barge flashing on a contemporary house



(e) Lifted barge flashing on an older house

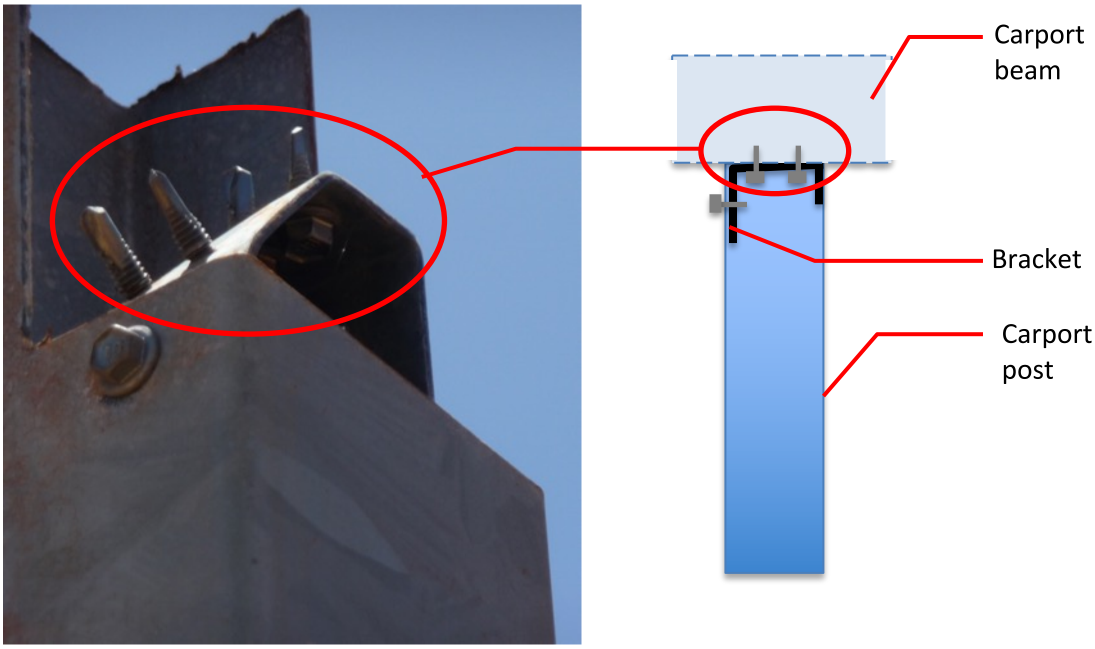
Figure 4.10 Failures of flashings

The flashings shown in Figure 4.10 had all been fastened with screws, with spacings varying from 650 to 1200 mm. This is more than the maximum spacing specified in recent amendments to AS/NZS 1562.1. However, failures occurred at around 49% of the Wind Region D design wind load (around 70% of the design wind speed) in flashings where the spacing in some cases was only marginally more than the maximum required spacing. This suggests that the maximum spacing requirements for cyclonic regions may need to be reviewed. It is recommended that some research be undertaken to determine appropriate maximum spacings for flashing fasteners for Wind Regions C and D. However, until that research is completed, it is vital that no spacings be greater than the maximum spacings published in AS/NZS 1562.1 (Standards Australia, 2018).

4.6. Carports

Some carports lost their roofs completely as shown in Figure 4.11. The structural connection from the roof to the columns had been via a bracket screwed into the SHS column and into the underside of the carport beams as shown in Figure 4.11(b).

(a) Loss of carport roof in uplift



(b) Tek screws in tension on carport structure

Figure 4.11 Failures of carport roofs in uplift

The screws in the posts were in shear under uplift, but the screws into the beams were in tension and had pulled out of the carport beams. The carport roofs were not found by us in spite of some effort in looking. It would have been interesting to see how thick the steel was in the beams that the screws had withdrawn from.

Tie-down details in which the screws or bolts are in shear are much more effective than those in which the fasteners are in tension.

In the example shown in Figure 4.11, the carport roof was a continuation of the main house roof and the failure had not propagated into the house, though the loss of the carport roof gave a pathway for water ingress into the main house. Figure 4.12 shows a house from a similar construction period with similar construction details in the carport.

Figure 4.12 Undamaged carport with similar construction details

Figure 4.13 shows a missing carport where the carport roof line was completely separate from the house roof where the edge of the carport roof had been screwed into the house wall. However, a number of the screws did not align with the studs (shown as dashed lines in Figure 4.13) in the house wall, resulting in reduced tie-down capacity. The details at the top of the posts were the same as those illustrated in Figure 4.11.

Figure 4.13 Damaged carport with connections not aligned with wall studs

4.7. Soffits and gable linings

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 Damien reinforced those findings. Figure 4.14 shows an example of damage to soffits in both contemporary and older houses. In both these cases, the failures originated in the connections of the brittle material to the frame above. In addition, the end joints were not supported by framing, which is not in accordance with manufacturers' recommendations.

(a) Older house ***(b) Loss of soffit on a contemporary house***

Figure 4.14 Loss of soffits

While in general soffit systems (lining and connections) performed quite well, it is concerning that some are failing at wind speeds close to the serviceability limit state. Soffit performance can be demonstrated by testing in the same way as other cladding systems and for the high design wind speeds in Wind Region D, may require closer connection spacings than those used in other Wind Regions.

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 more cost-effective to install soffits that can resist the appropriate differential pressures in the first place.

4.8. Damage from debris

Only a small number of buildings were damaged by debris such as tree branches, unsecured items or failed elements from adjacent buildings.

4.8.1. Damage from building elements

Figure 4.15 shows damage to roof cladding caused by a large section of roof structure detaching from another house.

Figure 4.15 Debris damage to cladding elements

The failed section of the roof caused damage to several houses and cars before landing over 300 metres away in a neighbour's outdoor area (Figure 4.16).

Figure 4.16 Failed roof structure in neighbouring property

4.8.2. Damage from broken vegetation

Figure 4.17 shows examples buildings that were struck by fallen trees.

Figure 4.17 Damage from fallen trees

4.8.3. Damage from other debris

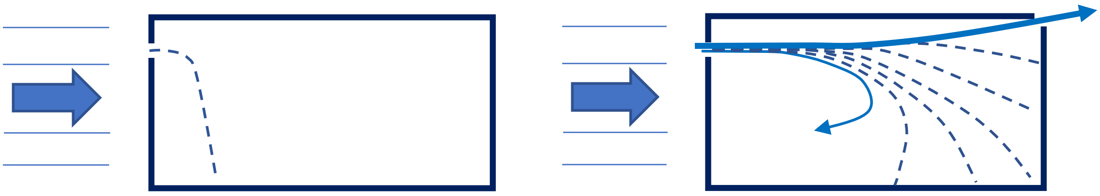
Figure 4.18 shows an unsecured trampoline and a section of roof that became airborne during TC Damien. The loose trampoline illustrates the need to clean up properties and secure items as part of the preparation for a cyclone, and the risk to life and safety created by wind-borne debris.

Figure 4.18 Wind-borne debris *(Photos – Channel 9 Perth)*

5. DAMAGE FROM WIND-DRIVEN RAIN

An important part of this investigation was to continue the study of the effects of wind-driven rain on buildings that had little or no structural damage. Previous investigations (Reardon *et al,* 1999, Boughton and Falck 2015) found that wind-driven rain had entered some buildings through weepholes or gaps around seals in windows or doors; under doors with inadequate or missing seals; or under missing or damaged flashings and gutters. This was also the case for TC Damien, 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.

A new observation from this investigation was that significantly more water entered buildings where there was a path for air through the roof space caused by two openings, (compared with the volume of water entering if there was only a single opening). A single opening into an otherwise sealed space would not allow much air to enter as it could not escape; so less entrained water would enter the space. However, when openings on opposite sides of the building created a large differential pressure, it made an air path through the roof space. Air could pass right through and bring rainwater a considerable distance into the roof space. Figure 5.1 illustrates the principle.



(a) Single opening to closed space **(b) Two openings giving air flow through space**

Figure 5.1 Air and water movement through internal spaces

5.1. Consequences of wind-driven rain entry

A street survey of 20 houses in a single street showed that rainwater came through windows and doors in all of the houses visited. Some videos taken during TC Damien also showed that rainwater came through windows and sliding glass doors, and under swinging doors. In many cases, water entered buildings that had no damage to the building envelope.

5.1.1. Damage to building components and contents

The significant volumes of water that entered many buildings caused significant damage to:

- **Ceilings** – plasterboard and suspended ceilings exposed to rainwater ingress initially sagged under the weight of pooled water and saturated insulation, softened, broke, and collapsed. Lower storey suspended ceilings were affected by any water that had entered the floor above.
- **Walls** – plasterboard wall linings were vulnerable to water damage. MDF skirting boards were used extensively and were damaged by ponded water on floors.
- **Floor coverings and flooring** – carpet saturated by water needed to be replaced if it couldn't be dried quickly. Particle board flooring under carpets or vinyl had started to swell within days of the cyclone.
- **Electrical wiring and electrical appliances** – power was off due to concerns about water in junction boxes in a number of buildings. This would delay any repairs to the building.
- **Building contents –** furniture, electronic appliances, personal belongs, etc. were affected by rainwater.

Figure 5.2 shows examples of damage caused by wind-driven rain entering buildings.

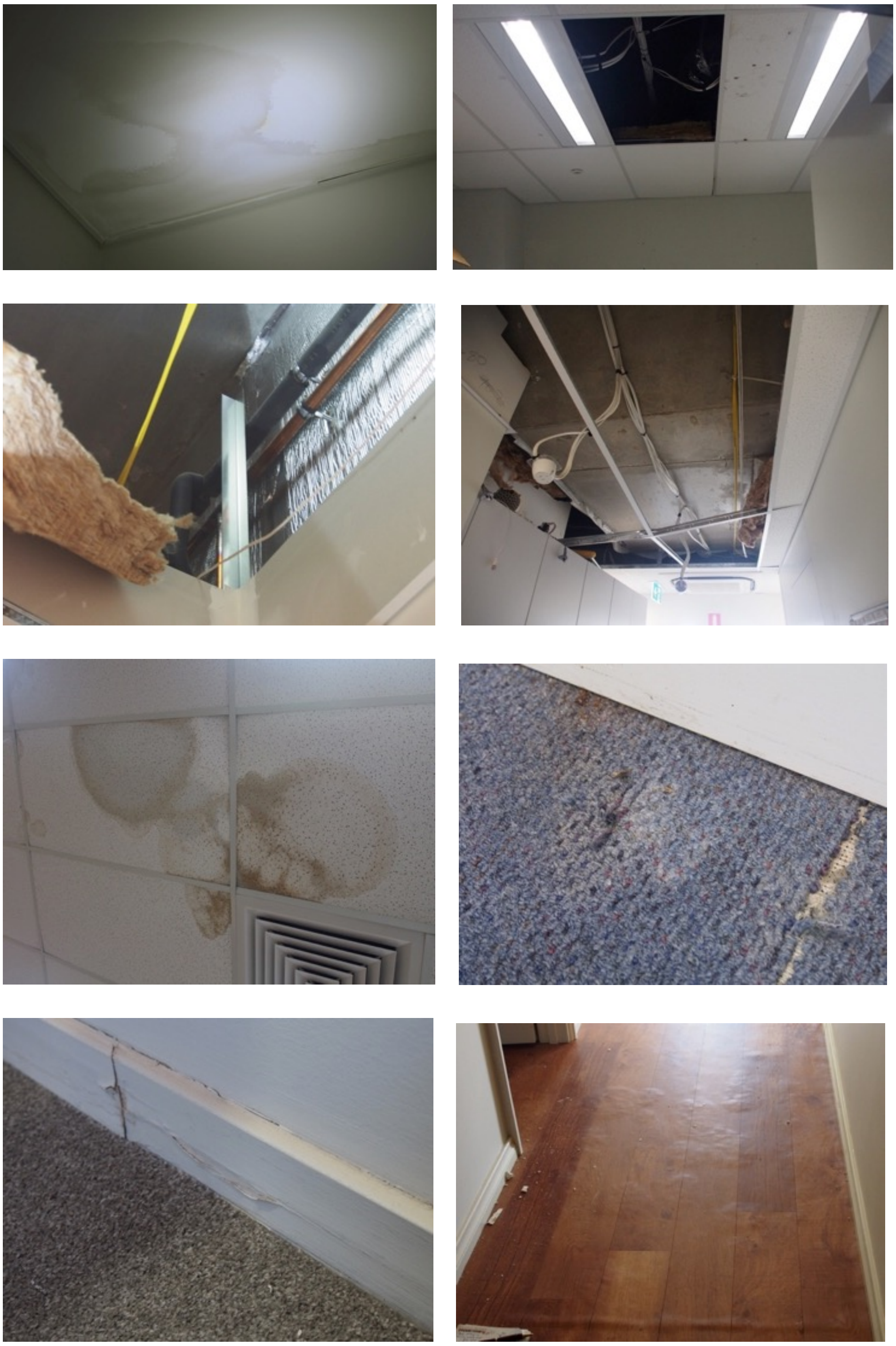


Figure 5.2 Damage from wind driven rain entering buildings

Mould can develop quickly in the humid environment that accompanies cyclones. Within a few days after TC Damien 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 be a health risk to some people.

5.1.2. Risk to life

As noted in previous reports (Boughton *et al*, 2017), people stood in front of windward windows and glass doors to take videos of the cyclone or mop up rainwater. They risked serious injury if the windows or doors had been broken by debris, or if they had slipped on the wet floors. In fact, one person was filming as a window on the front of their building broke, sending shattered glass, broken bits of blind and large volumes of rainwater into the room (Figure 5.3).

Figure 5.3 The moment a windward wall window broke
(Still photo from video on Channel 9 news website)

5.2. Wind-driven rain around flashings

Significant volumes of water entered buildings through flashings that were lifted or lost during TC Damien and caused extensive water entry with the types of damage noted in Section 5.1. The cost of the damage caused to floors, wall and ceiling linings by rain entering through poorly secured flashings is disproportionately high compared with the cost of installing screws at the appropriate spacings as detailed in AS 1562.1 (Standards Australia, 2018). Detailing flashings correctly can minimise damage to buildings from wind-driven rain.

5.2.1. Damage to flashings

Figures 5.4 and 5.5 show a selection of relatively recently constructed buildings that had lost sections of flashing.

Figure 5.4 Examples of failure of flashings on a commercial building

Figure 5.5 Examples of failure of flashings on houses

5.2.2. Water entry under flashings

Flashings are designed to channel downward-moving rainwater away from buildings. However, during a cyclone, fast moving air can move rainwater upwards and water can enter buildings under flashings

Flashings that don't fit properly can allow rainwater to be driven up the external wall, behind the flashing and into the roof space, causing damage to or collapse of ceilings. Figure 5.6 shows an example of a flashing that was poorly installed.

Figure 5.6 Example of a poorly installed flashing

A relatively complex roof shape on a public building (involving a number of apron flashings) led to water being forced up the roof sheeting and under the apron flashing, as shown in Figure 5.7. This caused extensive damage to ceilings and carpets. Complex roof configurations can be difficult to seal against wind-driven rain.

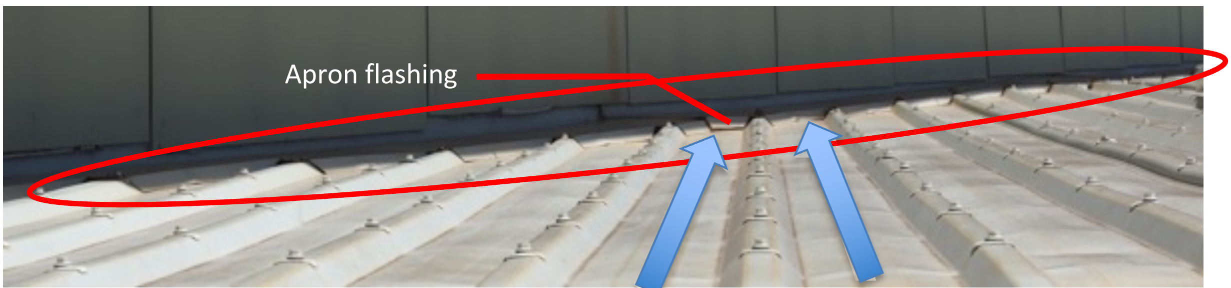


Figure 5.7 Point of entry of wind-driven rain

5.2.3. Sealing the building envelope

Figure 5.8 shows an example of a building where roof sheeting laps had lifted. There were no fasteners along a significant length of the ribs that had lifted.

Figure 5.8 Roof with ribs without fasteners (highlighted)

Figure 5.9 shows a building in which the roof sheeting had been sealed to a rigid structural system using a flexible sealant. During TC Damien when the wall shown was on the windward side, the roof sheeting flexed enough to break the sealant and allow significant volumes of wind-driven rain to be channelled into the building through the crack. Sealant shouldn't be the primary flashing element.

Figure 5.9 Inadequate waterproofing at junction of the roof and walls

5.3. Gutters

5.3.1. Missing or damaged gutters

Many buildings in Karratha did not have gutters. On some buildings with gutters, rainwater entered when gutters were damaged or lost. Some gutters were attached to fascia with clips or fixings that did not have the capacity to resist the wind forces during TC Damien, as shown in Figure 5.10.

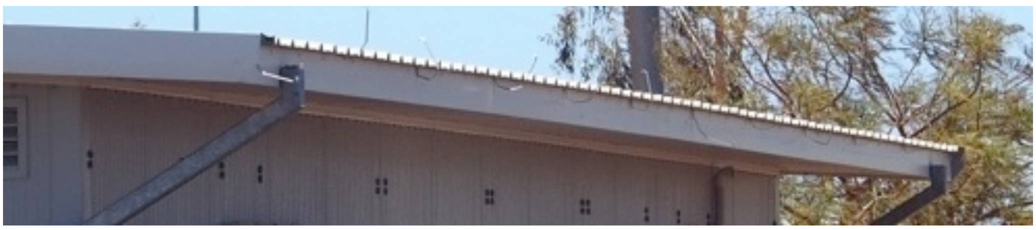


Figure 5.10 Loss of gutters

5.3.2. 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 5.11 shows a valley gutter that became blocked during TC Damien causing water to overflow into the ceiling space and damage the ceiling underneath.

Figure 5.11 Example of a blocked valley gutter

In previous damage investigations (Boughton *et al*, 2017, Boughton *et al*, 2011), the CTS team found that rainwater was driven over the edge of box gutters 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. However, Figure 5.12 shows a box gutter completely open at both ends. Rainwater was still blown over the right edge of the box gutter and into the roof space. Therefore, most configurations of box gutters are likely to allow water into a building during high wind events.

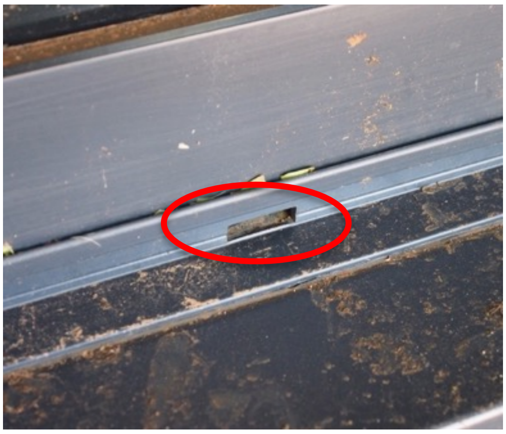
Figure 5.12 Box gutter open at both ends

5.4. Windows and glass sliding doors

Wind driven rainwater entered buildings through undamaged windows and doors, and caused significant damage to floor coverings, skirtings and cabinetry. The conclusions about wind driven rain entering buildings through windows and doors during TC Debbie (Boughton *et al*, 2017) were reinforced by this investigation following TC Damien and are summarised below:

- Rainwater is driven by differential pressure between the outside and inside of buildings through weep holes in the sills of windows and glass sliding doors. Rainwater bubbled up through weep holes, and in some cases, spurted into rooms.
- Weep holes covered by rubber flaps on the outside generally let in less water than unprotected weep holes. (Only a few windows had these flaps in Karratha.)
- Wind pressure can also cause glass and sashes to flex inwards and open gaps between sashes and frames. Water is pushed through these gaps by the same differential pressure that forces rainwater through weep holes.
- Worn or damaged window seals were ineffective in preventing water penetration into buildings.
- Significant volumes of water can come through windows and doors. (Some people said they were unable to keep up with positioning dry towels to contain water ingress through windows and doors during the cyclone.)

In addition, many windows in commercial buildings and apartments investigated after TC Damien are non-opening (fixed). Even these windows leaked around the window frame, as shown in Figure 5.13.



(a) Uncovered weep hole in a fixed window on the outside of a building

(b) Staining on inside of window sill from leakage

Figure 5.13 Examples of water penetration through a fixed window

A number of windows also showed signs of leakage around the window head. (Figure 5.14). the highlighted area indicates where the plaster has started to soften as a result of water through the gap at the window head.

Figure 5.14 Example of leakage around a window head

5.5. Swinging doors

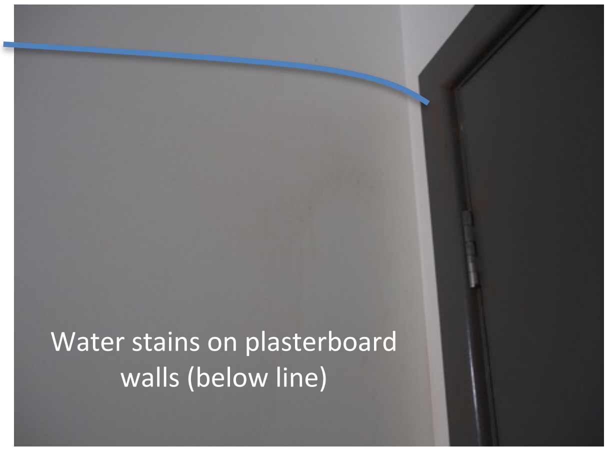
During TC Damien, significant amounts of rainwater were driven under some swinging doors. In the majority of cases where water entered through swinging doors on windward walls, there was no sill and water was driven through the gap under the door, even though there was a weather seal. Figure 5.15 shows some examples of gaps under doors where wind driven rain entered buildings.

Figure 5.15 Gaps under swinging doors with weather seals

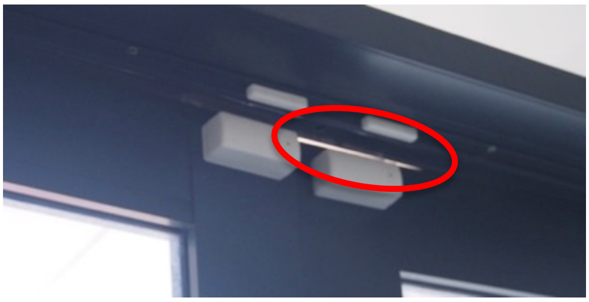
Many doors flexed under wind loads. The latch in the middle of the door prevented movement away from the jamb at that location, but the door flexed at the top and bottom. This allowed water to be driven around the top and bottom of inward opening doors on a windward wall. Figure 5.16(a) shows water stains on the wall adjacent to a door; rainwater was driven around the edge of the door when it flexed inwards under wind pressure.

Figure 5.16(b) shows an outward opening double door that was on a side wall during TC Damien. It flexed enough to allow a path for air to exit the building, which allowed increased volumes of air and water into the building through a lifted flashing on the windward side of the building. (The mechanism is described in the introduction to Section 5.)

Figure 5.16(c) shows that even outward opening doors on the windward wall will let some water in around the edge of the door where there are no seals.



(a) Door on windward wall



(b) Doors on a side wall **(c) outward opening door on windward wall**

Figure 5.16 Examples of doors that flexed under wind loads

Figure 5.17 shows some examples of how far rain and leaf litter were driven into buildings under or around doors. Many commercial buildings had carpets on the floors and these sustained quite a lot of water damage.

Figure 5.17 Examples of rainwater entry under or around swinging doors

5.6. HVAC and Air conditioners

Wind driven rainwater can enter buildings through any openings in the building envelope including vents and machinery rooms. During TC Damien, rainwater was driven through the air intake for the HVAC of a large building in Karratha and entered rooms in the centre of the building through the air conditioning ducts. Figure 5.18 shows the single stage louvres on the machinery room for the building, and the ground floor corridor that was flooded.

Figure 5.18 Large building in Karratha – Machinery room louvres and ground floor corridor in the centre of the building

In one of the buildings inspected, wind-driven rainwater had blown in through the split system air conditioners; probably through the drainage pipe.

6. STORM TIDE IN TC DAMIEN

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

Fortuitously, the peak storm surge that accompanied TC Damien occurred near a predicted low tide. This meant that the peak storm tide recorded at South Reef was approximately 0.3 m lower than the Highest Astronomical Tide (HAT) and almost identical to the next predicted high tide. Figure 6.1 shows tide gauge records from South Reef.

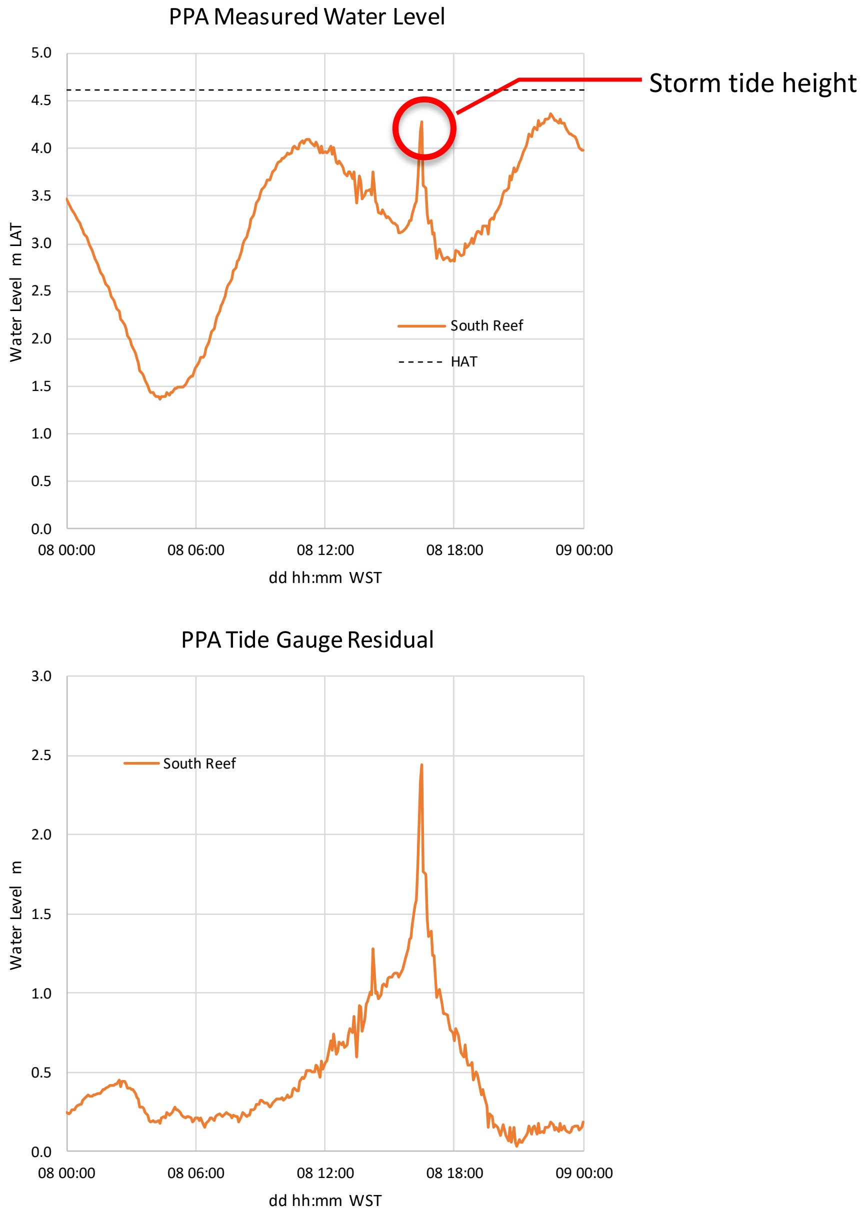


Figure 6.1 South Reef Tide gauge data
(supplied courtesy of the Pilbara Ports Authority)

There are three tide gauges near Dampier operated by the Pilbara Ports Authority. South Reef continued transmitting throughout the passage of TC Damien. The other two gauges (King Bay and Fairway Beacon) experienced some communications issues at varying times through the event. The peak storm surge height was measured at South Reef (approximately 6 km NW of Dampier) as 2.4 m. reaching 4.28 m LAT on the tide gauge (1.72 m MSL).

Figure 6.2 shows a photo of the foreshore at Searipple lookout at Karratha in Nickol Bay. The dashed line shows the approximate position of the Highest Astronomical Tide (HAT) and the blue line shows the inferred storm tide position, which includes the effect of wave run-up. The two campfire mounds near the HAT line were not affected by sea water, but the one in the foreground had been washed by moving sea water. The highest storm tide corresponded with winds from the east at this location.

As the highest storm tide was lower than the Highest Astronomical Tide, there was no damage to buildings.

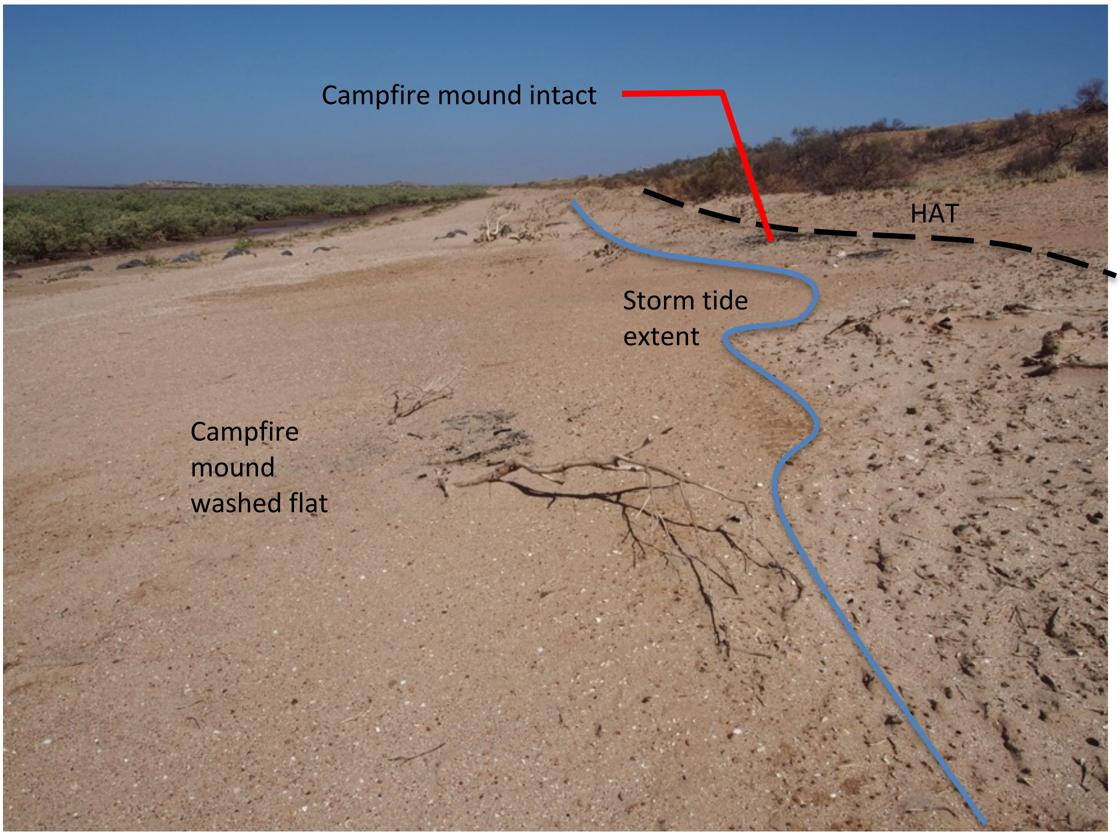


Figure 6.2 Foreshore at Searipple lookout, Karratha

7. DAMAGE TO ANCILLARY ITEMS

This section discusses items that are attached to buildings or in the grounds of properties.

7.1. 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.

In Karratha, a building permit is required for fences; they need to be constructed to meet local council requirements as Importance Level 2 structures (the same design criteria as houses). Although the wind speeds during TC Damien were at or lower than 70% of the design wind speed, there was damage to many fences in the area.

During TC Damien, high winds and falling trees damaged some boundary fences. Figure 7.1 shows two examples where fence posts failed under wind loads.

(a) The moment of failure *(Photo – Channel 9)* **(b) Corroded posts**

Figure 7.1 Fence post failures

In some cases, the ground around the posts failed and allowed the fence to lean as shown in Figure 7.2.

Figure 7.2 Failure of ground around posts

In other cases, the loss of a fence created a safety issue around pools. Figure 7.3 shows an example (a temporary fence needed to be erected quickly after the event).

Figure 7.3 Temporary fence around pool

7.2. Cloth shade structures

There were instances of tension membrane, draped shade-cloth and netting structure failures (Figure 7.4). It is unlikely that any of these fabric structures would have been designed for severe wind loads. The designs are usually predicated on the fabric being taken down during preparations for approaching cyclone (during the watch or warning stages). Once the fabric is ripped or the cables or connections are broken, the flailing fabric and/or cables can damage neighbouring structures.

Figure 7.4 Examples of damage to sail and shade cloth structures

7.3. TV and lighting towers

The lighting towers shown in Figure 7.5 failed by local buckling. The towers were designed to be lowered for maintenance and may have escaped damage if they had been lowered in preparation for TC Damien.

Figure 7.5 Damage to lighting towers

Figure 7.6 shows a stayed TV tower that collapsed. It is likely that the corroded stays first failed in tension and then the now un-stayed tower failed by buckling.

(a) Broken stays near top of the tower (inset – broken stay)

(b) Buckling of compression leg at the base of the tower

Figure 7.6 Damage to Karratha TV tower

7.4. Balustrades on balconies

Some apartment buildings and houses have glass panels on balcony balustrades. Figure 7.7 shows framed glass panels that failed when they were struck by wind-borne debris.

Figure 7.7 Failure of framed glass balcony balustrades

Figure 7.8 shows a screen capture from a Channel 9 video of a balcony panel failing under wind loads.

Figure 7.8 Failure of balcony panel *(Photo – Channel 9)*

7.5. Outdoor ceiling fans

Outdoor ceiling fans are often damaged during tropical cyclones. During TC Damien, wind drag on the fans swung them against the ceiling and damaged their blades. In many cases, they were spinning at the same time, so all blades and a number of ceiling panels were damaged. Figure 7.9 shows a selection of damaged fans. All of these fans will need to be replaced, and in one case, repair work to the ceiling will be required.

Figure 7.9 Examples of damage to outdoor ceiling fans

The owner of one of the houses inspected by the team, had removed the fan blades from an outdoor ceiling fan during preparation for the cyclone. This fan is shown after the event in Figure 7.10. It remained undamaged throughout and can be returned to service by reattaching the fan blades.

Figure 7.10 Blades removed from ceiling fan in preparation for TC Damien

7.6. Roof-mounted items

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 shows roofs in an exposed location with no damage to either the roof or the solar panels. The investigators found no examples where the mounting brackets between roofs and solar hot water or photovoltaic panels failed.

Figure 7.11 Securely attached roof top solar panels

However, a polyethylene pipe pool heating system on one house was ripped from its attachment to the roof as shown in Figure 7.12.

Figure 7.12 Damaged pool heating system

Communication aerials are also vulnerable to damage from wind forces and wind-borne debris. However, most satellite dishes and TV aerials remained attached to roofs during TC Damien, and were usually only lost if they had been hit by debris. Figure 7.13 shows an example of aerials that were damaged during TC Damien.

Figure 7.13 Damaged roof-top satellite dish and aerial

Some externally mounted split-system air conditioners were damaged by wind forces. Figure 7.14 shows a roof-mounted system that was inadequately fastened, and a number of systems that failed due to over-speeding of the fans. In both buildings, external units needed to be replaced, but as these are not marketed as independent components, the complete split systems were replaced.

(a) Failure of attachment on the A/C external unit

(b) Damage to fans in external units

Figure 7.14 Damaged roof-top air conditioning units

8. Older buildings

The investigation of damage to buildings after TC Damien confirmed the findings of previous damage surveys (Boughton *et al*, 2017, Boughton and Falck, 2015, Boughton *et al*, 2011; Boughton and Falck 2007, Henderson *et al*, 2006); older buildings are damaged more frequently and severely than newer ones unless they have been adequately upgraded or retrofitted.

8.1. Damage due to deterioration

A significant proportion of the older buildings that failed during TC Damien showed signs of deterioration in several structural elements. Many of them remained undamaged in previous more severe tropical cyclones, but had now deteriorated so they failed during Category 3 TC Damien.

8.1.1. Corrosion

The coastal Pilbara region in WA is exposed to high air humidity and temperature, dust particles, and to prevailing onshore winds that are salt-laden. This combination of factors accelerates atmospheric corrosion of steel elements.

Several buildings in Karratha had tie-down rods that extended from the roof into concrete footings. A number of these had corroded severely at the connection with the concrete. Unfortunately, these details were completely hidden within masonry columns or walls and could not have been inspected during normal building maintenance. Other parts of the rods appeared to be in good condition.

Figure 8.1 shows the extent of the loss of section in the tie-down rod near the concrete footing in which it had been embedded. The rod was concealed within the brick walls and failure of the rod just above the footings led to loss of the whole roof structure.

Figure 8.1 Corrosion in tie-down rod that led to loss of steel framed roof

The same type of failure also occurred on the building shown in Figure 8.2. However, in this case, the rods were concealed within the brick columns.

Figure 8.2 Corrosion in tie-down rod that led to loss of timber framed roof

Figure 8.3 shows square hollow section (SHS) posts that had corroded severely at the interface with the concrete footings. The posts in photos 8.3(b) and (c) support a house that is only six years old. These posts were able to resist loads during TC Damien, but may fail in future events.

(a) (b) (c)

Figure 8.3 Corrosion in SHS posts

Figure 8.4 shows the stay from the TV tower discussed in Section 7.3 that failed at low wind speeds. It is clear that all of the outer strands had corroded.

Figure 8.4 Corrosion in TV tower stay

8.1.2. Termites

The predominant species of termite north of the Tropic of Capricorn (*mastotermes darwinensii*) is particularly voracious. Some failures in older buildings in the study area exposed timber elements that had signs of significant termite activity. Figure 8.5 shows trusses on two separate houses where most of the top and bottom chords of one truss had been removed by termites. The failure in both houses started at the affected truss.

Figure 8.5 Failures due to termite activity

The timber in the trusses appeared to be jarrah (which is classified as termite resistant). *Mastotermes darwinensii* has been known to consume even termite resistant species.

Most of the perimeter of the two houses in which termite activity was noted, had been treated. However, the portions of the perimeters under the affected trusses had been omitted from the treatment. In one case, a dripping tap at the same location provided optimal conditions for termite attack.

8.2. Damage due to poor detailing

Some older buildings were damaged because tie-down details were ineffective.

8.2.1. Metal roof tiles

Many older buildings in Karratha have metal tile roofs. Most roofs were undamaged, but a few lost tiles off parts of the roof.

The loss of metal roof tiles illustrated in Figure 8.6 was caused by the tiles not being fixed according to recommended practice. The damage showed that nails had been driven through the top of the tiles that failed rather than through the nose.

As these particular tile profiles are no longer sold, it will be difficult to replace portions of damaged roof and in many cases, a complete re-roof may be required. (Refer to Section 8.4.)

Figure 8.6 Loss and damage to metal roof tiles

8.2.2. Inadequate tie-down system

In other investigations after tropical cyclones, batten-to-rafter or truss connections were the most commonly observed failure in the roofs of older buildings. However, in TC Damien, there were relatively few. An example is given in Figure 8.7; a building that was probably not in use at the time of TC Damien.

Figure 8.7 Loss of roof sheeting and battens at batten-to-truss nailed connections

This building had nailed batten-to-truss connections and used pipe overbattens for the roof system tie-down, but the J-bolts that anchored them to the walls straightened under wind uplift forces, as shown in the inset to Figure 8.7.

Other older buildings had used overbatten systems for global tie-downs. In many cases, these systems worked well at the loads in TC Damien. In a couple of heritage buildings, the overbattens had been timber, but had deteriorated to the point that they no longer existed. While there was wind damage to these buildings, it was much less severe than it could have been. Figure 8.8 shows a heritage building with deteriorated overbattens.

Figure 8.8 Deterioration of overbattens on a heritage building

One of the buildings inspected had originally been constructed with overbattens as the primary tie-down system for the roof. The roof sheeting had been replaced and the bolts securing the tie-down battens cut, but no alternative tie-down method had been installed. Figure 8.9 shows the building, the parts of the roof on a road, the cut tiedown bolts and empty holes in the battens for the tie-down rods. The roof cladding is continuous over these holes indicating that the tie-down rods had not been put through the battens or the new roof cladding following the re-roofing in 2011.

Figure 8.9 Building where overbattens were removed during re-roofing

8.3. Asbestos

Many older buildings were constructed using fibre-cement building products that contain asbestos. There were a number of damaged buildings, including two primary schools that we did not have access to. They were fenced-off as a precaution because responders had identified material that may have contained asbestos.

The presence of asbestos has the following consequences:

- The site may be isolated until an expert confirms the presence or absence of asbestos.
- Material containing asbestos may need to be professionally removed from the damaged part of the building, and in some cases from the undamaged part, prior to any repair.
- During repair, the work may be stopped and the above steps repeated if more material containing asbestos is discovered.

These steps all have the potential to both delay the repairs and make them more expensive.

8.4. Maintaining, upgrading and retrofitting older buildings

It is likely that the older buildings that were damaged during TC Damien would have been even more significantly damaged during a design wind event. Also, many older buildings in the affected area that were undamaged during TC Damien, could have been damaged if the wind speeds had been higher.

As discussed in the introduction to Section 8, 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 building, especially the roof structure, and upgrade connections and members if required. Section 9 provides more information.

9. Maintenance, upgrading and retrofitting

All buildings, regardless of age, need to be regularly inspected and maintained. This is particularly important for buildings that have recently experienced a strong wind event.

Inspection involves examining existing details to determine whether they have the capacity to resist the wind loads and are in good condition. These details include roof cladding, roof structure, garage doors, flashings, windows and doors.

- If the details have deteriorated but would have sufficient capacity if they were in good condition, they can be **maintained** by painting, cleaning and repairing.
- If the details would not have sufficient capacity, even if they were in good condition, they can be **upgraded** by replacing them with similar elements with the required capacity.
- An alternative strategy is to bypass the existing details by fitting a new system – **retrofitting** – the older details are not removed, but the loads are transmitted through a new parallel system.

The following sections summarise strategies to maintain, upgrade or retrofit older buildings.

9.1. Maintenance

Regular inspection and maintenance of all buildings is recommended to help prevent damage to buildings in future wind events:

- Engage a builder to inspect structural elements in the tie-down chain (refer to Figure 4.3)
- Replace timber elements that have deteriorated due to rot or termite activity;
- Replace any metal elements that have deteriorated due to corrosion;
- Check for signs of leaks in plumbing, flashings, gutters and downpipes and repair or replace if required.

9.2. Upgrading

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 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.

Many upgrades are easiest to perform when the roof cladding has been removed. Whenever roofing is replaced, the roof structure should be checked to see if an upgrade is required. 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 CTS has a series of mini-videos for both homeowners and builders to provide some information on repairing damaged roofs from cyclones. These videos are available at:
https://www.jcu.edu.au/cyclone-testing-station/education

Upgrades could include:

- Adding extra fasteners (screws) to flashings so the fixings comply with AS/NZS 1562.1 (Standards Australia, 2018).
- Replacing nails in batten-to-rafter or truss connections with screws or straps.
- Fitting straps or bolts in rafter to wall connections if these are currently skew nailed.
- Replacing windows where glass thickness or seals are inadequate.
- Installing bolts into the frames of external doors.
- Replacing garage doors with doors that comply with AS/NZS 4505 (Standards Australia, 2012), and upgrading the wall structure near the track supports if necessary.

9.3. Retrofitting

The purpose of retrofitting is to bypass inadequate links in the existing tie-down chain so they have sufficient capacity to resist the wind loads during future tropical cyclones. In general, the retrofitting systems need to be designed by an engineer and installed by a builder.

Retrofitting to improve roof anchorage could include:

- An external tie-down system that uses overbattens and tie-down cables outside the walls as shown in Figure 9.1;
- Tie-down cables outside the walls that are connected into trusses within the roof system; or
- Additional tie-down elements within the wall framing.

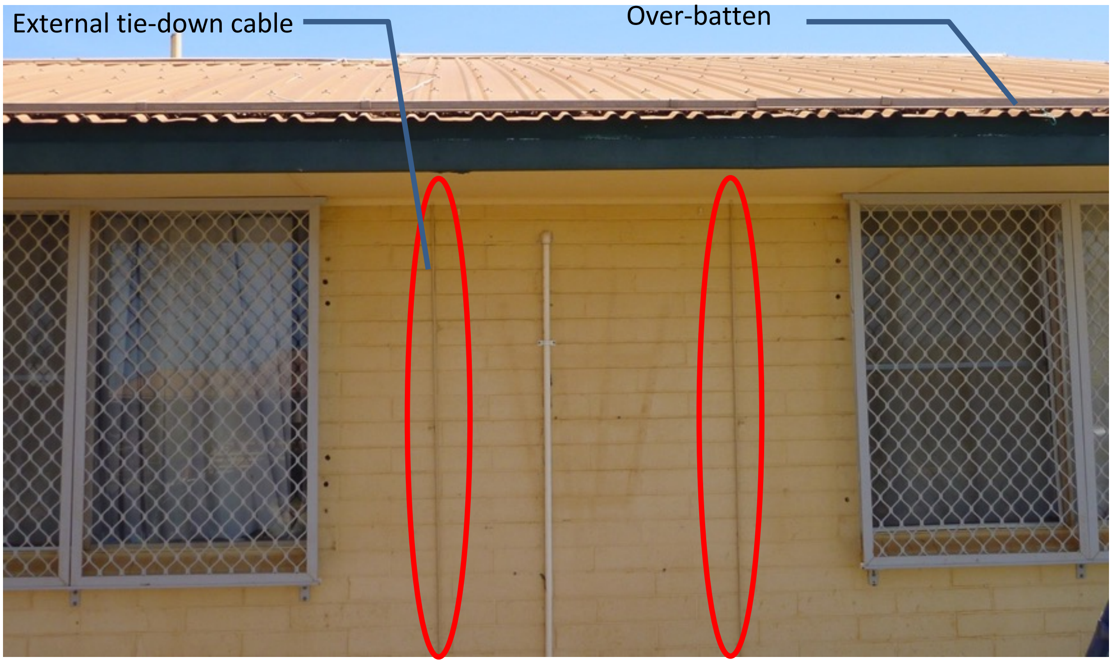


Figure 9.1 House with external tie-down cables and over-battens

Extra protection to windows can be offered by tested debris screens or by fitting temporary shutters.

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. Performance of contemporary buildings

TC Damien applied wind loads that were around or less than 49% of the design wind load for all houses in the study area. More than 20 contemporary houses that had wind damage to the structure, envelope or flashings were identified by either the CTS investigation or the RDA assessments. In addition, these and many other contemporary buildings were damaged by wind-driven rainwater.

10.1.1. Load paths

Some damage to buildings was caused by discontinuities in the tie-down load path. It is not clear whether the discontinuities were because of design or construction errors. However, all people involved in the design and construction of houses for the cyclone region need to be acutely aware of the need for a robust load path between the roof and the ground. If anyone notices a discontinuity in this path, they should immediately bring it to the attention of the builder and seek a resolution to the problem.

It is recommended that further education and training within the building industry is undertaken to ensure that all designers, builders, supervisors and trades can identify tie-down load paths through houses, and ensure that there are no missing or weak links in the load path.

10.1.2. Inspections

The large number of buildings with wind damage at relatively low loads compared with the design wind load suggests that there are design and/or construction errors in some of the contemporary houses in Karratha.

It is recommended that the number of failures in recently constructed buildings at wind speeds around 70% of the design wind speed be considered in discussions about whether inspections during construction should be mandatory for the higher risk areas in WA – Wind Regions C and D. (See Recommendation No. 1, Fogliani 2015)

10.2. Maintenance

Building materials deteriorate over time; the rate of deterioration depending on factors such as proximity to salt spray, moisture, coating protection, etc. Steel posts, cables, rods and wires embedded into concrete appeared to have higher levels of corrosion just above the concrete. This area should be regularly inspected and maintained.

It is recommended that inspection and maintenance of structural elements within the roof space, and where any steel elements contact concrete should be undertaken for all buildings, regardless of age:

- *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).*

10.3. Light gauge metal framing

Most contemporary housing in the Pilbara uses light gauge metal framing. Screwed connections have high stresses around the rims of the screw heads. In TC Damien, roofs were lost because of failure of the connections within the framing. Tests of these systems to AS/NZS 4040.3 will determine whether the system will be able to resist the expected loads. Where the stress concentrations compromise the capacity of the system, washers or brackets can be detailed to improve the capacity. Small variations in the geometry of members or connections can make significant differences in the response of the system. Note that the deemed to satisfy solutions in NASH (2011) are valid up to C2 wind classifications, and many of the houses in Karratha are C3 or C4.

The NCC requires that light metal cladding support systems are tested to demonstrate that the connection details can resist repeated cyclonic loading, as detailed in AS/NZS 4040.3. It is recommended that certificates presenting the results of these tests are attached to all design documentation.

10.4. Roof cladding

10.4.1. Concealed-fixed roofing

Manufacturers' guidelines for the design and installation of concealed-fix roofing highlight significant limitations on the use of concealed-fixed roofing in cyclonic regions. In general, systems that have been appropriately tested and indicate that they are suitable for cyclonic regions use some pierced-fixing or have clips that deform the sheeting so that it is possible to check that the roofing is properly fixed.

10.4.2. Pierce-fixed roofing

Likewise, the performance of pierce-fixed roofing must be demonstrated by testing of a complete system that includes the roofing, the roofing fasteners and the purlins. Manufacturers' recommendations need to be specific about all of the components in the system and need to be based on testing to the appropriate Australian Standards. Using components that are not specified in the manufacturers' recommendations may mean that the performance of the complete system is unknown.

10.4.3. Metal tiles

Some older buildings in Karratha lost metal tiles from parts of the roof; caused by the tiles not being fixed according to recommended practice. The damage showed that nails had been driven through the top of the tiles that failed rather than through the nose.

It is recommended that designers, builders and certifiers check the validity of roof cladding manufacturers' literature and test data. Roof cladding installers should follow manufacturers' recommendations for the appropriate Wind Region when installing roofing materials.

10.5. Minimising wind-driven rain entering buildings

Reports of wind-driven rain entering buildings were widespread (Section 5.1). Research should be undertaken to develop 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.

10.5.1. Flashings

Some flashings failed during TC Damien even though the fastener spacings were only marginally more than the current maximum spacing specified in AS 1562.1 (Standards Australia, 2018).

It is recommended that research be undertaken to determine the appropriate maximum spacing of fasteners for cyclonic regions. If necessary, AS 1562.1 should be revised to specify minimum requirements for flashings and their fixings to resist cyclonic wind loads.

Until that information is published, it is recommended that in Wind Region D, the maximum spacing should be around half that indicated in AS 1562.1.

A number of buildings that had no structural damage were severely affected by water ingress through flashings in complex roof designs. Simple roof shapes and appropriately fastened conventional flashings are generally more effective at keeping water out of buildings.

It is recommended that where innovative or complex roof designs and flashing details are to be used on buildings, designers consider horizontally driven rain and significant differential pressure from the outside to the inside when designing the flashings and seals.

It is also recommended that guidance documents detailing suitable flashings for all buildings in cyclone regions are developed.

A flexible sealant was used to seal the roof sheeting to a rigid structure on one of the buildings investigated during the study. During TC Damien, the roof sheeting flexed enough to break the sealant and allow significant volumes of wind-driven rain to be channeled into the building through the crack.

It is recommended that sealant is not used as the only 'flashing' on sheet metal roofs.

10.5.2. Windows

Windows with flaps over the weep holes seemed to let in less water than those with open weep holes during TC Damien (where the wind speed was close to the serviceability design event).

It is recommended that weep holes in windows are designed (e.g. using rubber flaps or ball valves) to minimise water entry at serviceability wind pressures.

10.5.3. Doors

Inward opening doors allowed wind-driven rainwater to enter buildings under ineffective seals. Many doors with only a mid-height latch flexed and allowed water to bypass the seals at the top and bottom of the door.

It is recommended that door systems are required to pass the same tests for wind rating as windows – ultimate, serviceability and water penetration. (Their function is similar to windows, so similar performance is required.)

10.5.4. HVAC intakes

Investigators identified a building in Karratha where a considerable volume of rain entered through the single stage louvres in a HVAC system. Rain entered rooms in the centre of the building through the air conditioning ducts.

It is recommended that HVAC intakes have at least double stage louvres and well-drained plenums. For some buildings, it might be possible to fit a temporary shutter over the air intakes as part of the preparation for an approaching cyclone.

10.6. Soffits

Soffits are cladding systems that form part of the building envelope. Where soffits fail, it is possible for wind-driven water to enter the roof space. However, soffits and their framing can be tested as a cladding system in order demonstrate performance under cyclonic wind actions.

It is recommended that soffits, fixings, and their supporting framework are tested in the same way as other cladding systems to the wind pressures specified in AS 4055 or AS/NZS 1170.2. Fastener spacings for soffits installed in buildings in Wind Region D may need to be closer than those used in other Wind Regions.

10.7. Ancillary structures and items

Damage to ancillary elements such as shade or cloth structures, aerials, satellite dishes and ceiling fans can compromise the functionality of the building or cause extra damage to cladding when they detach. Where these items had been removed or lowered as part of the preparation for TC Damien, the recovery of the building was much faster.

10.7.1. Shade sail structures

There were instances of tension membrane, draped shade-cloth and netting structure failures (Figure 7.4). It is unlikely that any of these fabric structures would have been designed for severe wind loads. The designs are usually predicated on the fabric being taken down during preparations for approaching cyclone (during the watch or warning stages). Once the fabric is ripped or the cables or connections are broken, the flailing fabric and/or cables can damage neighbouring structures.

It is recommended that shade sails are removed as part of the preparation for an approaching cyclone.
(In order for this recommendation to be implemented, shade sails should be designed so they can be easily taken down in preparation for an approaching cyclone, then easily put back up once the cyclone has passed.)

10.7.2. Outdoor ceiling fans

During TC Damien, wind drag on ceiling fans swung them against the ceiling and damaged their blades. In many cases, they were spinning at the same time, so all blades and a number of ceiling panels were damaged. In one case, the blades were removed, and both the fan and the ceiling suffered no damage. The fan could be quickly returned to service by reattaching the blades.

It is recommended that, where possible, the blades of outdoor ceiling fans are removed as part of the preparation for an approaching cyclone.

10.8. Retrofitting older buildings

Older buildings are generally at higher risk of damage in tropical cyclones than contemporary buildings. In particular nailed batten-to-truss connections, skew nailed rafter or truss to wall connections do not have sufficient capacity for any buildings in the cyclone Wind Regions. Also, some light gauge metal connections may not have the resilience to withstand load concentrations under significant uplift loads. A few examples of each were noted in the investigation of damage during TC Damien. Retrofitting of fit-for-purpose connections significantly improve the resilience of older buildings. Because these connections are difficult to inspect and assess, a building professional should be engaged to determine suitability of existing details and to design improvements.

It is recommended that building owners engage an engineer or builder to assess the entire building, especially the roof structure, and upgrade connections and members if required.

10.9. Changes to Codes and Standards

The wind loads in this event were not sufficient to indicate that elements that had survived TC Damien without damage performed adequately. Hence the evidence of success could not be used to justify a change. In each case, where failures occurred, the cause of the failure lay with unsatisfactory design, detailing or installation.

It is recommended that

- *wind rating tests are included in the AS/NZS 4420 series for swinging doors;*
- *water penetration tests for windows and doors include a requirement to declare the leakage rate at the serviceability wind pressure.*

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