Tropical Cyclone Seroja – Damage to buildings in the Mid-West Coastal Region of WA

CTS Technical Report No 66

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TECHNICAL REPORT NO. 66

Tropical Cyclone Seroja Damage to buildings in the Mid-West Coastal Region of Western Australia

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Executive Summary

Severe Tropical Cyclone Seroja (TC Seroja) was classified by the Bureau of Meteorology (BoM) as a Category 3 severe tropical cyclone and crossed the Mid-West coast of Western Australia near Port Gregory (between Kalbarri and Geraldton) around 8:15 pm on Sunday 11 April 2021. TC Seroja caused extensive wind damage to buildings in coastal and inland towns. The storm tide generated during TC Seroja was higher than the Highest Astronomical Tide but did not damage any buildings.

This report presents the findings from the joint Cyclone Testing Station (CTS); Department of Mines, Industry, Regulation and Safety, Building and Energy Division (Building and Energy); and the Department of Fire and Emergency Services (DFES) investigation of damage to buildings caused by TC Seroja. The study focused on the performance of houses built since the late 1990s in Kalbarri, Northampton, and Port Gregory but included other buildings such as apartments, strata properties and commercial buildings. The report describes the impact of a tropical cyclone on communities in Wind Region B and highlights the need to review Australian codes, standards and building practices for this region.

Analysis of Bureau of Meteorology (BoM) and other data indicated that the maximum 0.2-sec gust wind speed over land was between 46 and 51 m/second (166 to 184 km/h) at Kalbarri, around 80 to 90% of the design wind speed for Importance Level 2 buildings in Wind Region B. The 0.2-sec gust wind speed over Morawa, the town along TC Seroja's track in Wind Region A that experienced the highest wind speed, was estimated to have been 37 m/s (134 km/h) which is also between 80% and 90% of the Wind Region A design wind speed for houses.

Data from DFES Rapid Damage Assessments and information obtained during the CTS and Building and Energy damage investigation were combined to determine the extent and causes of damage to buildings in the affected areas. Around 10 % of buildings in Kalbarri and Northampton had damage classified as 'severe' or 'total'. The performance of roofs significantly influenced the level of overall damage to buildings. Many newer houses in Kalbarri had structural damage.

The main cause of severe structural damage to houses in Kalbarri was the combination of large suction forces on the roof and a rapid increase in internal pressure created by an opening in the building envelope (usually from wind-borne debris breaking a door or window in a windward wall). Designers that use AS/NZS 1170.2 can choose between using low internal pressures from a table applicable to sealed buildings, or higher internal pressures from a table for buildings with openings. Houses in Wind Regions A and B that are designed using AS 4055 have N wind classifications that are based on low internal pressures. Because the tie-down connections in the roofs of many of the buildings were designed assuming low internal pressure, they were not strong enough to cope with the higher loads that were applied when a door or window broke.

The CTS recommends that Wind Region B is classified as cyclonic in the wind loading standards, AS/NZS 1170.2 and AS 4055. The design wind speeds would remain the same, but designers would use higher internal pressures applicable for buildings with openings. These changes will enable buildings to comply with the robustness requirements in the National Construction Code – breaking a window or door should not lead to major damage to structural systems. If this is successful, some parts of other Australian Standards, including those for wind ratings for garage doors, roof tile fastenings, tests on sheet metal roof cladding, and tie-down straps into brickwork, may also need to be reviewed.

A significant number of buildings in the affected areas will need to be extensively repaired or rebuilt. If the tie-downs in the new roofs are not designed and installed correctly, they will likely fail in future cyclones. CTS suggests that guidelines for homeowners, builders and trades are developed and distributed as soon as possible.

Some buildings were damaged because structural elements had deteriorated. Regular maintenance on buildings of all ages is recommended, and components and systems upgraded as necessary.

TC Seroja also highlighted the need to research the feasibility of providing a 'strong room' in new and existing houses in cyclone-prone areas, including those in Wind Region B. The development of appropriate design criteria and construction methods to strengthen the walls and ceiling of a small room or hallway will offer protection to occupants if the rest of the house is significantly damaged during a cyclone.

TC Seroja has reminded the community that severe tropical cyclones affect towns and cities in Wind Region B. To protect these communities, buildings must be designed and built to resist all of the characteristics and impacts of tropical cyclones including, high winds, wind-borne debris, wind-driven rain and storm surge.

Acknowledgements

The authors thank the residents of the Kalbarri, Northampton, Port Gregory and Geraldton communities who generously assisted with this study by volunteering information and inviting the authors into their homes to inspect and photograph the damage.

During this investigation, the CTS team worked closely with DFES WA and Building and Energy. The collaboration between the three organisations enabled a coordinated, efficient, and effective approach to the investigation that increased the amount of data and information gathered in a short period of time. The outcomes of the study will ultimately contribute to improved community resilience to future tropical cyclones in all parts of Australia.

The authors particularly acknowledge the support given by

- Sean de Prazer, senior engineer and Justin McAullay, building inspector – representing Building and Energy;
- DFES – arranged accommodation and provided information and data on the location of damaged properties. The team particularly appreciated the assistance of Damien Pumphrey, Stephen Gray, Catherine Timms, Brett McGregor, and Sarah Morrison.
- DFES Urban Search and Rescue, Geraldton SES and support volunteers;
- IAG – Dr Joanna Aldridge and Dr Bruce Buckley for assistance with estimating the wind field.
- Dr Bruce Harper of SEA for assistance with storm-tide evaluation, Dr Matt Mason from the University of Queensland for help with correction of anemometer data used to estimate the wind field, and Joe Courtney of the Bureau of Meteorology for assistance in interpreting meteorological data.

The CTS appreciates the financial support provided by DFES, Building and Energy, and the CTS Sponsors and Benefactors.

FOR A SAFER STATE

CTS would also like to thank our supporters.

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1. INTRODUCTION

1.1. Severe Tropical Cyclone Seroja Overview

Severe Tropical Cyclone Seroja (TC Seroja) crossed the coast at Port Gregory, Western Australia, a small town between Kalbarri and Geraldton, around 8:15 pm on Sunday 11 April 2021. TC Seroja caused wind damage to buildings in Kalbarri, Northampton, Port Gregory, Morawa, Mingenew, Perenjori, Carnamah, Geraldton and other towns in the area. No buildings in the area surveyed were damaged by the storm tide.

1.2. Damage investigation

The field study commenced on Monday, 12 April 2021 and concluded on Wednesday, 14 April 2021. The investigation team included two representatives from the Cyclone Testing Station (CTS) and two from Department of Mines, Industry, Regulation and Safety, Building and Energy Division (Building and Energy). The WA Department of Fire and Emergency Services (DFES) provided data on damaged buildings and invaluable logistical support.

Figure 1-1 shows the study area. The affected towns are near the coast of a region of WA called the Mid-West. The investigation team focused on structural damage to houses (residential buildings) in Kalbarri but also assessed some houses in the Greater Geraldton area and visited Northampton and Port Gregory to check the extent of damage in those towns. Section 3 includes DFES Rapid Damage Assessment data that illustrates the extent of damage in the affected areas.

The field study:

- Examined contemporary buildings constructed using the Building Code of Australia (BCA) to determine whether their performance was appropriate for the estimated wind speeds during the event. The team documented structural failures in enough detail to determine recommendations to improve future construction.
- Examined patterns of damage to determine whether any structural elements had systematic weaknesses.
- Checked simple structures such as signs to use as ‘windicators’ and identified features used to adjust anemometer readings for terrain and topography.

1.3. Purpose of the report

The purpose of this report is to present the outcomes of the joint CTS, Building and Energy, and DFES field investigation into the damage to buildings caused by TC Seroja. The report identifies problems in building performance and highlights issues that need to be considered for changes to Codes and Standards, building practices, and ongoing maintenance.

This investigation focused on structural damage to residential buildings built after the late 1990s so the results could be used to comment on current building practices and, if necessary, recommend changes to Codes and Standards. The performance of some older residential buildings and commercial buildings was also assessed.

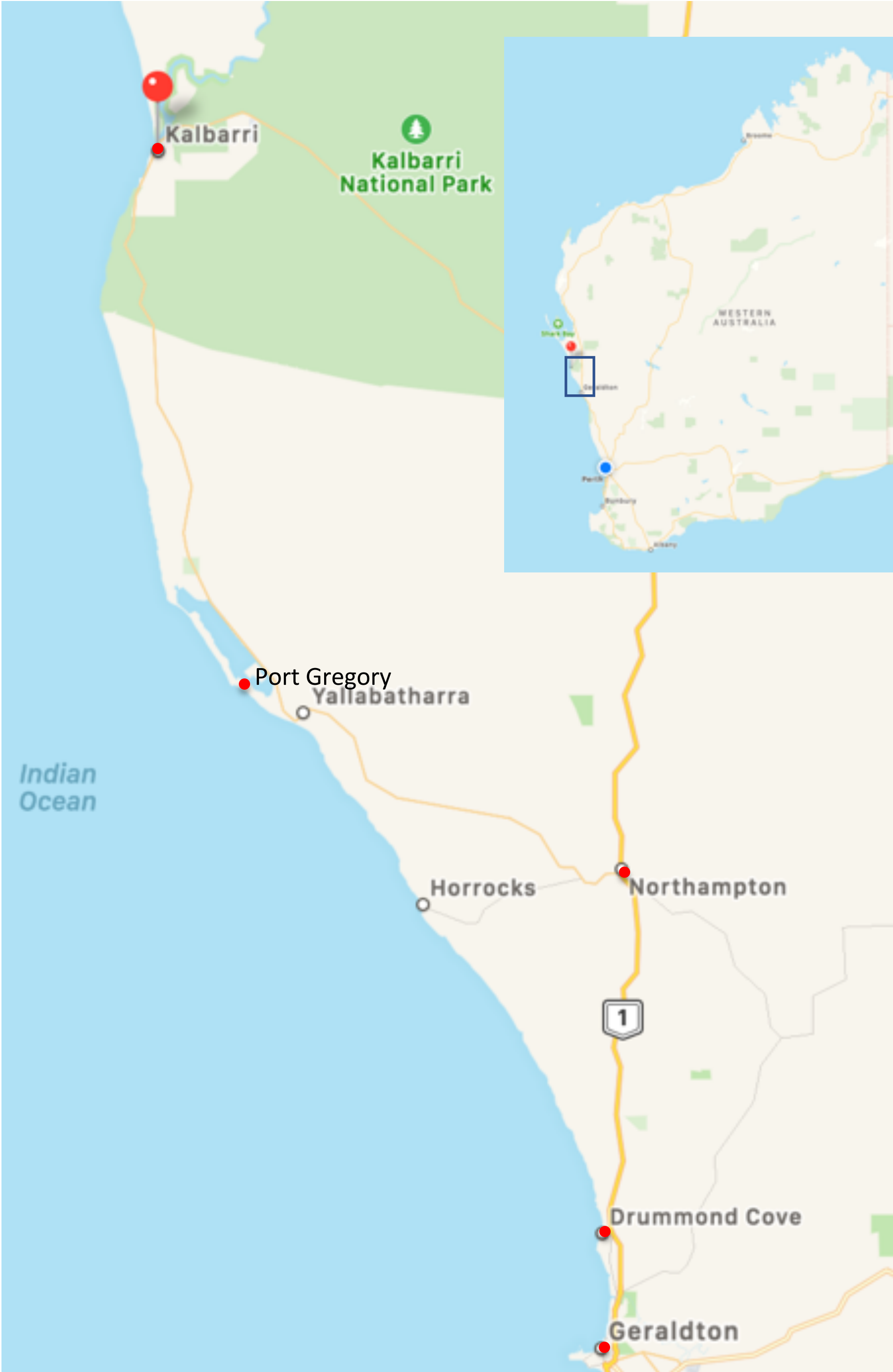


Figure 1-1 Area of damage investigation (Google maps)
Inset – Map of WA indicating region investigated

1.4. Wind Region B

The wind loading Standards, AS/NZS 1170.2 (Standards Australia, 2011) and AS 4055 (Standards Australia, 2012), divide Australia into Wind Regions, as shown in Figure 1-2.

Figure 1-2 Wind Regions in Australia (from AS/NZS 1170.2:2011, Standards Australia)

Kalbarri, Northampton, Port Gregory and Geraldton, which were the focus of this report, are in Wind Region B and are located within the red rectangle shown in Figure 1-2. Some other towns that experienced damage, such as Mingenew, Three Springs, Carnamah and Mullewa were also in Wind Region B. Other towns in which damage was also reported, Morawa, and Perenjori, Dalwallinu and Mukinbudin, are in Wind Region A. (These towns are shown in Figure 2-1.)

2. Severe Tropical Cyclone Seroja

2.1. BoM Information

A slow-moving tropical low developed near the southwestern end of the island of Timor on 3 April. Due to the low-pressure system remaining slow moving for several days, sustained and heavy rainfall caused extensive flooding and landslides on Timor and neighbouring islands. Widespread and devastating damage was reported including more than 150 fatalities.

The low-pressure system intensified and on 5 April it was named Seroja by Jakarta TCWC. It started moving initially west and then southwest, quickly intensifying into a category 2 tropical cyclone. As it continued moving southwest during 6 and 7 April the system weakened back to a category 1 system. During 8 and 9 April it began to interact with another tropical low, that briefly intensified into Tropical Cyclone Odette. Over a period of approximately 36-48 hours the two systems interacted via the Fujiwara effect, a phenomenon rarely observed in the Australian region.

The interaction with Odette is likely to have been a factor in maintaining Seroja's track towards the southwest, rather than recurving into the west Pilbara coast. As Odette circled around to the north and then the east of Seroja, it also made conditions more favourable for intensification by replacing the dry air that had been limiting Seroja's intensity with moist air that could fuel its intensification. The increased moisture combined with lower vertical wind shear resulted in Seroja re-intensifying into a category 2 while Odette weakened and eventually dissipated.

During 10 April, Seroja took a sharp turn towards the southeast and began to accelerate towards the Western Australian coast. The system further intensified into a severe (category 3) tropical cyclone on 11 April and maintained this intensity through to its coastal crossing just south of Kalbarri around 8pm AWST. It is very unusual for severe tropical cyclones to maintain their intensity this far south. Impacts at Kalbarri and the nearby town of Northampton were severe with around 70% of buildings sustaining significant damage, mostly consisting of lost roofs but with many structures destroyed. Many locations recorded maximum wind gusts more than 125km/h with the highest being 170km/h from Meanarra Tower near Kalbarri. Seroja weakened as it moved further inland, though due to its rapid motion destructive winds extended a long way inland before it eventually weakened below tropical cyclone intensity early in the morning of 12 April near the town of Merredin.

Widespread power outages were experienced through Western Australia's Mid-West region due to fallen trees and power lines.

Tropical Cyclone Seroja was the eighth tropical cyclone and the second severe tropical cyclone in the Australian region for the 2020/21 season.

All information relating to intensity and track is preliminary information based on operational estimates and subject to change following post analysis.

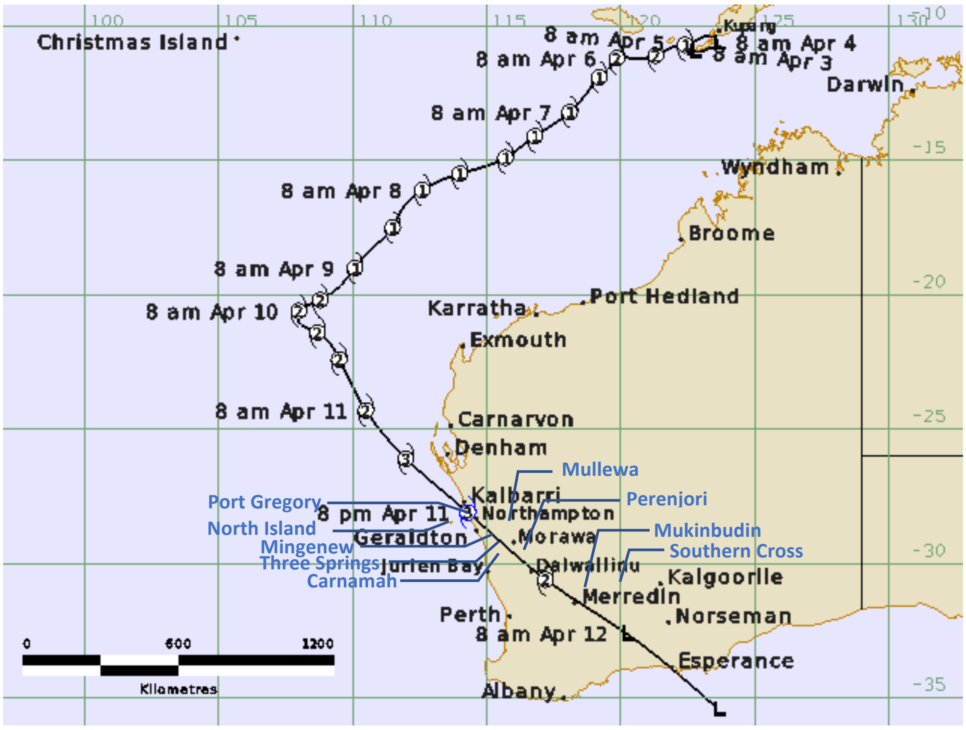
Extreme values during cyclone event (estimated)

Note that these values may be changed on the receipt of later information

Maximum Category:	*3*
Maximum sustained wind speed:	*120 km/h*
Maximum wind gust:	*170 km/h*
Lowest central pressure:	*971 hPa*

Source: http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/history/past-tropical-cyclones/

Figure 2-1 shows the path of TC Seroja.



All times shown are in Australian Western Standard Time (AWST), that is UTC +8 hours.

Figure 2-1 Track of TC Seroja (*Bureau of Meteorology*)

TC Seroja crossed the coast near Port Gregory at 8:15 pm WST on 11 April 2021, as indicated in Figure 2-1. The radar image in Figure 2-2 shows that the eye was just north of Port Gregory. When TC Seroja moved further inland, it weakened until it was classified as a tropical low on 12 April 2021. The remnants of TC Seroja continued tracking south-east causing rainfall and high winds. The strongest winds were mainly to the north east of its path.

Figure 2-2 Rain radar scans during the landfall of TC Seroja

(*Provided by Bureau of Meteorology*)
Note: Times are in UTC (add 8 hours to convert to WST).

2.2. TC Seroja – a severe tropical cyclone in Wind Region B of WA

It is not unusual for tropical cyclones to travel into and even south of Wind Region B. Figure 2-3 shows tracks of tropical cyclones that have passed south of Kalbarri over the past 50 years. The BoM classified at least three of those shown in Figure 2-3 as severe cyclones, so they may have had similar intensities to TC Seroja. The last time the SES was deployed to address tropical cyclone damage to buildings in the area was after TC Wally in 1976.

Although the wind speed estimated on land for TC Seroja was the highest for a tropical cyclone in 50 years in this region, wind speeds in some other cyclones at around the same latitude while they were over the ocean were similar to TC Seroja. The design wind event for Importance Level 2 buildings has a probability of 1/500. The estimated annual probability of the peak gust over land in TC Seroja was between 1/70 and 1/180 based on Table 3.1A in AS/NZS 1170.2:2011. The wind speeds in all towns in Wind Region B within the affected area were less than the design wind speed.

Tropical cyclones are expected in Wind Region B and are part of the design criteria. Wind Region B wraps around the tropical cyclone Wind Regions C and D and is a transition to Wind Region A, where the design wind events are often associated with severe thunderstorms.

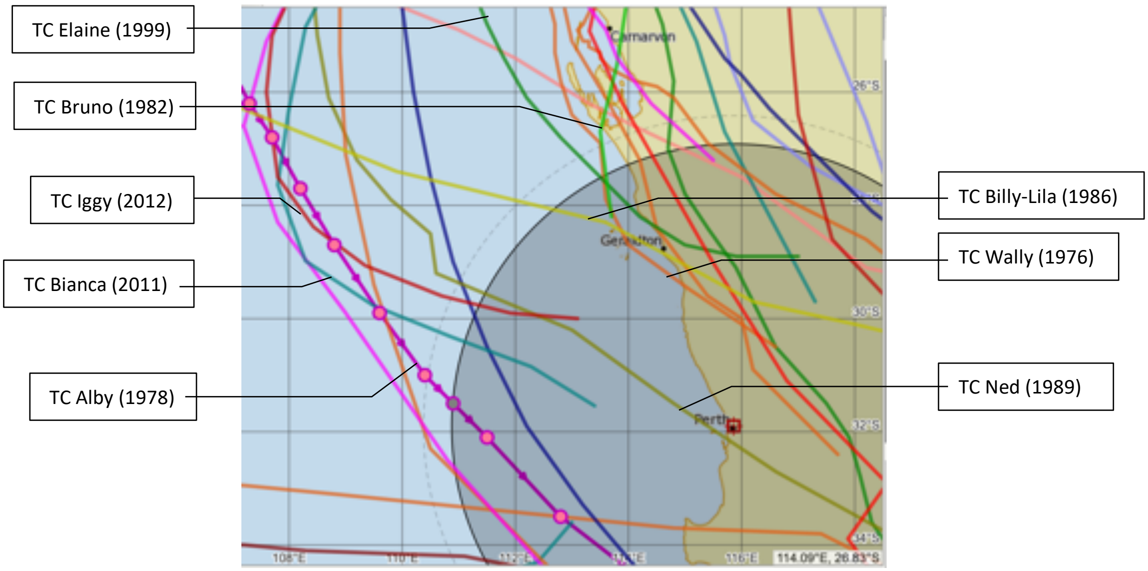
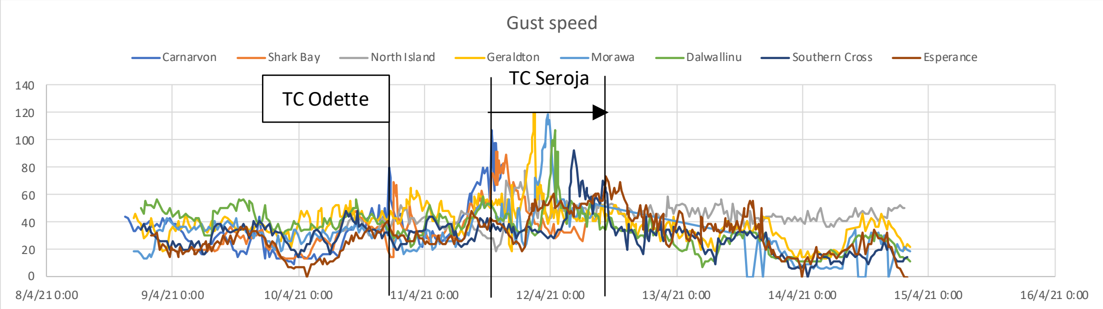


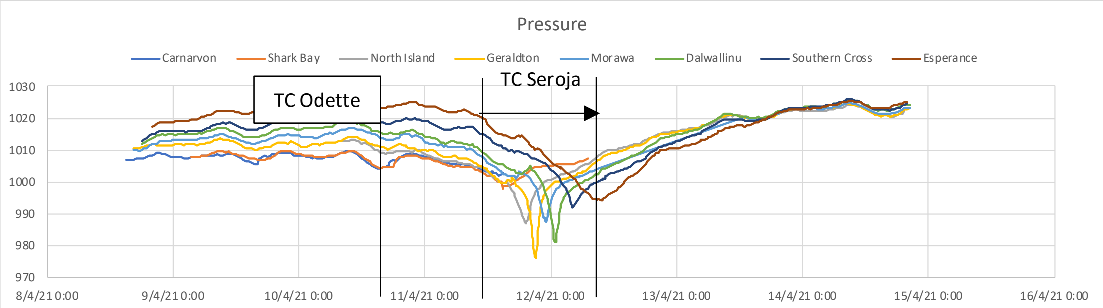
Figure 2-3 Cyclone tracks in the south of WA 1971 to 2018
(available Bureau of Meteorology website)

2.3. BoM Anemometer data

Several BoM Automated Weather Stations (AWS) recorded wind data during the passage of TC Seroja. Figure 2-4(a) shows the raw 3-second data from the BoM anemometers at Carnarvon, Shark Bay, North Island (Abrolhos Islands), Geraldton, Morawa, Dalwallinu, and Southern Cross. Figure 2-4(a) shows the data in real-time, and Figure 2-4(b) shows the mean sea level (MSL) pressure.



(a) Anemographs showing 3-second gusts



(b) Barograph showing MSL pressure

Figure 2-4 BoM AWS time histories of 3-second gust wind speed and MSL pressure

The BoM's AWS recorded a peak wind gust of 120 km/h at Geraldton Airport, which is located on flat land with winds approaching over Terrain Category 2, as defined in AS/NZS 1170.2 (Standards Australia, 2011). Table 2-1 presents the data for the AWS in the vicinity of TC Seroja's path.

Table 2-1 BoM AWS data

Site	Max 3s Gust [km/h]	Direction	Time/Date	Lowest MSL pressure [hPa]	Position relative to the path
Carnarvon	107	N	12:47 11/4/21	1002	230 km NE of path
Shark Bay	91	NNE	13:47 11/4/21	998	150 km NE of path
North Island	78	ESE	19:10 11/4/21	987	70 km SW of path
Geraldton	120	E	21:00 11/4/21	976	20 km SW of path
Morawa	119	NNW	23:26 11/4/21	987	35 km NE of path
Dalwallinu	107	NNE	00:50 12/4/21	981	15 km SW of path
Southern Cross	93	N	04:30 12/4/21	992	80 km NE of path

2.3.1. Wind speeds as a percentage of design wind speed

The BoM anemometers reported 3-second peak gusts. However, the design gusts (V_R) presented in AS/NZS 1170-2 are 0.2-second gusts. To compare 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 instrument's characteristics. 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 using the factors in AS/NZS 1170.2. Finally, the gusts were converted from 3-sec gusts to 0.2-sec equivalents.

The converted data is summarised in Table 2-2. They were 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	Wind Region	V_R (1:500) [m/s] design	3 s gust @ 10m [m/s]	0.2 s gust @ 10m [m/s]	% V_{500}
Carnarvon	D	88	29.7	33.3	38%
Shark Bay	C	69	25.3	28.3	41%
North Island	B	57	21.7	24.2	42%
Geraldton	B	57	33.3	37.5	66%
Morawa	A	45	33.1	37.1	83%
Dalwallinu	A	45	29.7	33.3	74%
Southern Cross	A	45	25.8	28.9	64%

Table 2-2 shows that all BoM anemometer locations near the track of TC Seroja experienced winds less than the design wind speed. Two of these, Morawa and Southern Cross, were quite close to the band of maximum wind speeds associated with TC Seroja. Morawa was quite close to the point at which the band of maximum winds passed from Wind Region B into Wind Region A and recorded a peak gust (corrected to 0.2 s) of around 83% of the design wind speed for Wind Region A. No towns in Wind Region A would have experienced wind speeds above the design wind speeds.

In addition to the data from the BoM AWS, information was also available from a sonic anemometer on Meanarra Hill. Correcting the data from this station to the same basis as V_R presented in AS/NZS 1170.2 gave an estimation of the peak gust of between 46 and 51 m/s (166 and 184 km/h). This wind speed is between 80% and 90% of the design wind speed for Importance Level two buildings (e.g., houses) in Kalbarri.

2.4. Wind field study area

The wind field models discussed in Section 2.4 were calibrated using the anemometer data from Geraldton and Morawa (presented in Table 2-2), the sonic anemometer on Meanarra Hill near Kalbarri, and the 'windicator' (damage to road signs) data. ('Windicator' data are presented in Appendix 1.)

A Holland model was used to generate the wind field in the study area using the meteorological attributes of TC Seroja, taking into account its high forward speed and the asymmetry of the convection in the system. The wind field showed that the weakening of the cyclone as it progressed over land was less pronounced than expected.

The output of the model was converted to 0.2-second gust wind speeds and combined with the anemometer data from the BoM automatic weather stations shown in Table 2-2 to derive contours of the wind speed across the study area. These contours were compatible with the 'windicator' analyses (refer to Appendix 1) and were used to generate the contours of the percentage of design wind speed shown in Figure 2-5.

The peak gust wind speed at Kalbarri was estimated by analysis of sonic anemometer data at nearby Meanarra Hill. It was around 80% to 90% of the design wind speed for Importance Level 2 buildings in Wind Region B. The peak gust wind speed would have produced 65% to 80% of the design wind pressure for those buildings.

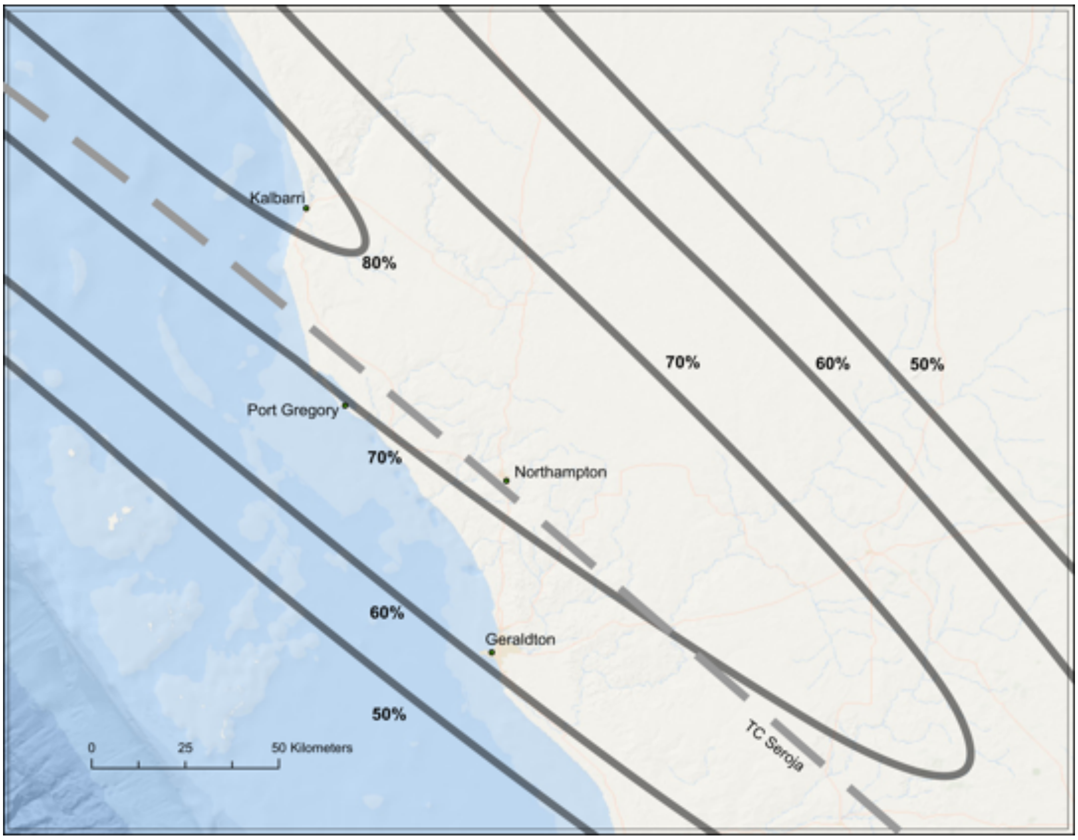


Figure 2-5 TC Seroja Wind speeds in the investigation area as a percentage of the design wind speed for Importance Level 2 buildings in Wind Region B

The wind field is compatible with the data in Table 2-1. It shows that Kalbarri experienced the highest gust wind speeds over land in the region, which accounts for the higher levels of damage in Kalbarri and Northampton compared with Geraldton and Port Gregory.

The band of maximum wind speeds shown in Figure 2-5 indicate that the maximum wind gusts passed over Kalbarri and then within 20 km of Northampton. The band of maximum wind gusts entered Wind Region A over Morawa (just off the lower-left corner of the map). It then continued over Perenjori, Mukinbudin and Westonia. DFES reported damage at all of these locations. The wind field and anemometer data over the cyclone's track over the Wheatbelt areas of WA showed that the peak wind gusts decreased by around 4 m/s for each 100 km of travel.

2.5. Buildings of other Importance Levels

The National Construction Code (NCC) links different Annual Exceedance Probabilities (AEPs) to buildings with different Importance Levels. The Importance Levels relate to the number of people that could be expected in the building, or its function during and immediately after a severe loading event.

Figure 2-6 shows that Importance Level 4 buildings can include hospitals, police stations, ambulance depots and buildings used by emergency services such as DFES. Several Importance Level 4 buildings were damaged during TC Seroja. It is important that design briefs for these buildings make it clear that their function requires a higher design level corresponding to a 1:2000 AEP.

Table B1.2a Importance Levels of buildings and structures

Importance Level	Building Types
1	Buildings or structures presenting a low degree of hazard to life and *other property* in the case of failure.
2	Buildings or structures not included in Importance Levels 1, 3 and 4.
3	Buildings or structures that are designed to contain a large number of people.
4	Buildings or structures that are essential to post-disaster recovery or associated with hazardous facilities.

Table B1.2b Design events for safety

Importance Level	Annual probability of exceedance for non-cyclonic wind	Annual probability of exceedance for cy-clonic wind	Annual probability of exceedance for snow	Annual probability of exceedance for earthquake
1	1:100	1:200	1:100	1:250
2	1:500	1:500	1:150	1:500
3	1:1000	1:1000	1:200	1:1000
4	1:2000	1:2000	1:250	1:1500

Figure 2-6 Design criteria for buildings with different Importance Levels (NCC)

3. Estimates of Damage from Rapid Damage Assessment

3.1. Rapid Damage Assessment data

The WA Department of Fire and Emergency Services (DFES) provided Rapid Damage Assessment (RDA) data. Trained personnel collected the data using hand-held electronic devices. The RDA data are collected to complement the data from Requests for Assistance (RFA) received by DFES to form a more focused and coordinated response and recovery in the immediate aftermath of severe weather events. The RDA assigns a level of damage to each building. RDAs are conducted from the street and may miss internal damage and wall, roof or structural damage not visible from the road. Therefore, reported information on damage intensity, mode and frequency underestimates the actual damage.

The damage levels assigned in the RDAs were compared with the damage to buildings observed by the CTS team and with photos taken during the RDAs. These comparisons led to the following interpretations of the RDA damage levels:

- Slight damage – largely non-structural damage, e.g. dented roofing, damage to gutters and finishes, fences;
- Moderate damage – damage to small areas of the building, e.g. broken windows or doors, loss of or a relatively small part of the roof;
- Severe damage – damage to large areas of the building and houses are probably uninhabitable, e.g. most of the roof missing, many windows broken
- Total damage – building destroyed and uninhabitable, e.g. loss of all of the roof, missing walls

3.2. Distribution of damage

RDAs for Kalbarri are shown in Figure 3-1 and Figure 3-2. For this investigation, Kalbarri was divided into three areas based on the estimated year of construction of most houses in each area:

- Kalbarri A – town centre; some commercial buildings and generally older houses constructed before 2000; few vacant blocks.
- Kalbarri B – the area adjacent to and just south of the main town centre; no commercial buildings; generally, houses built since around 1990; more developed blocks than vacant blocks.
- Kalbarri C – new subdivisions around 5 km south of the Kalbarri town centre and east of George Grey Road; no commercial buildings; houses constructed since 2000; more vacant blocks than developed blocks.

Figure 3-3 and Figure 3-4 shows RDAs for Northampton and Port Gregory.

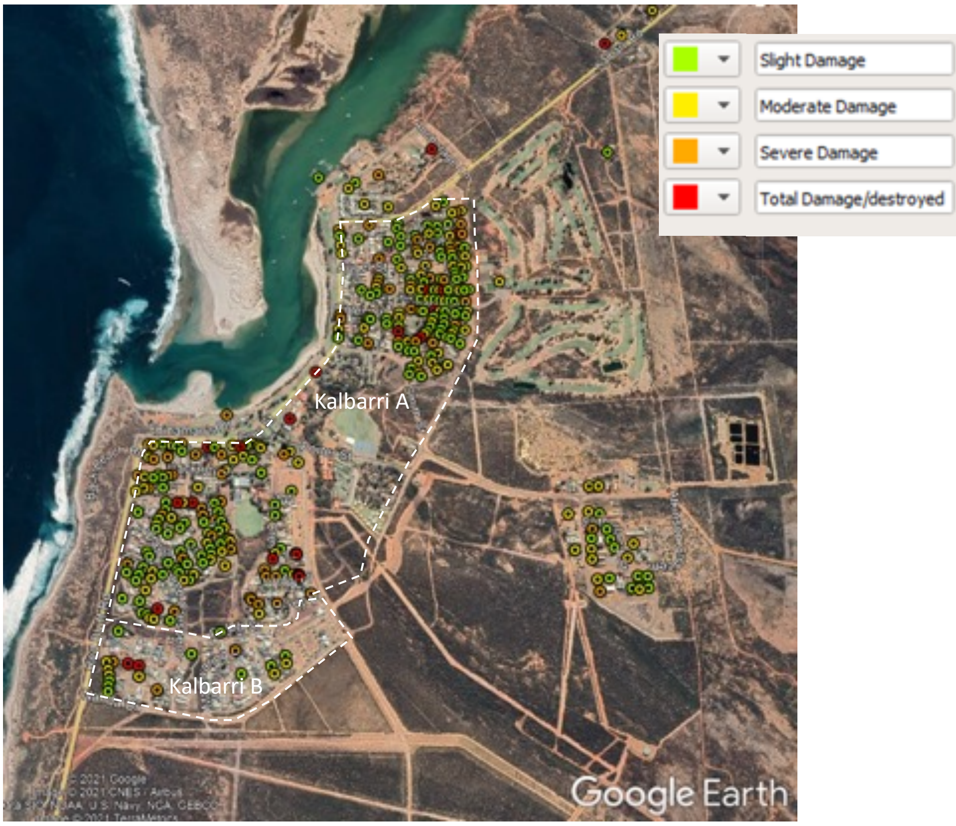


Figure 3-1 RDA damage points for buildings in north Kalbarri (undamaged buildings are not shown)

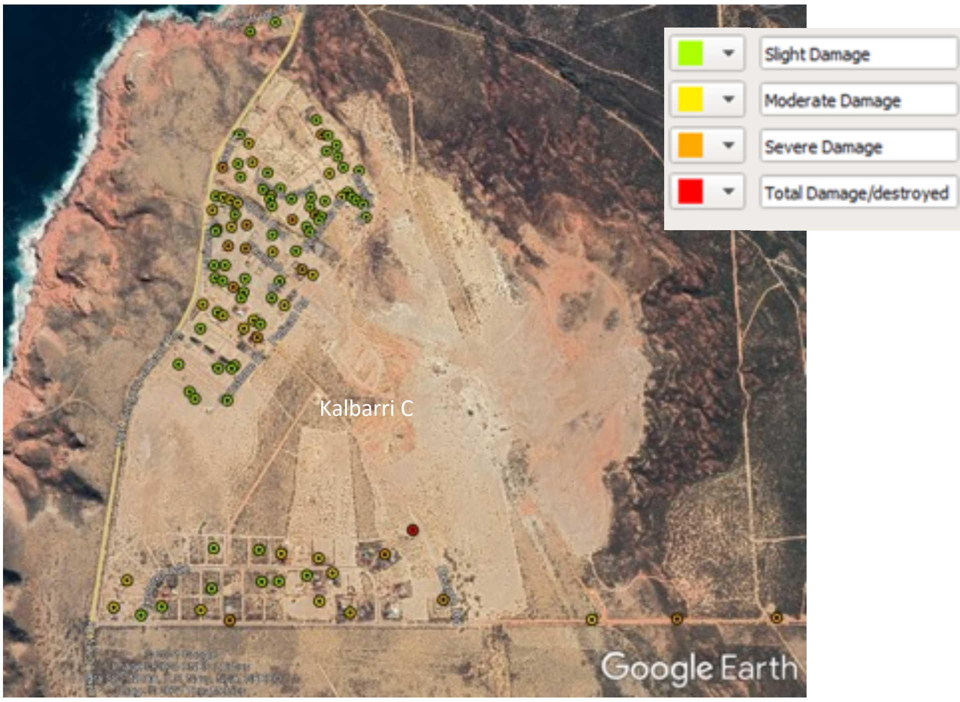


Figure 3-2 RDA damage points for contemporary houses in south Kalbarri (undamaged buildings are not shown)

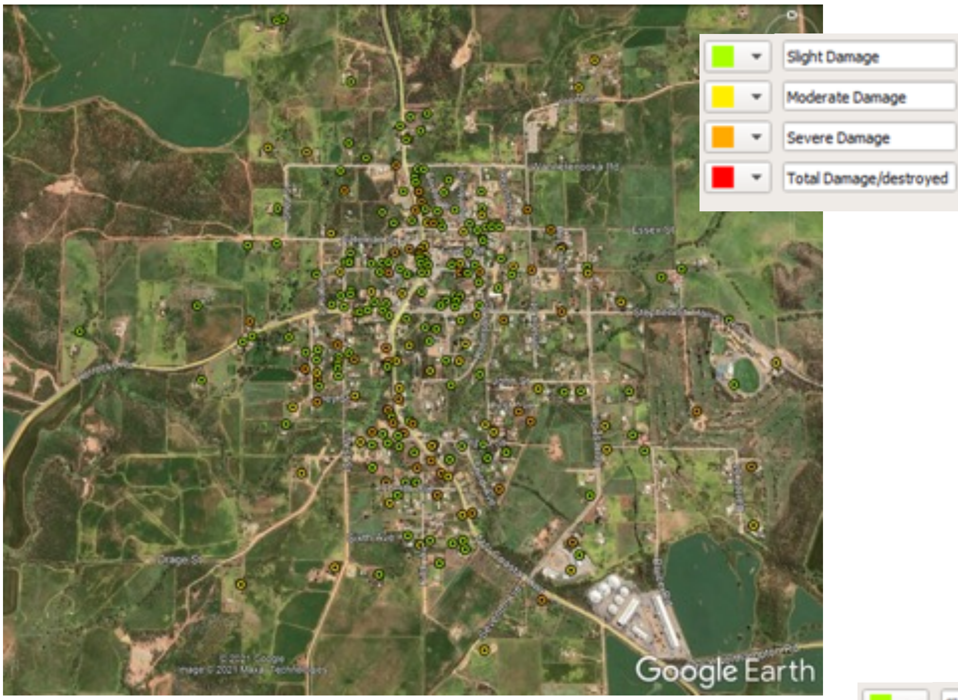


Figure 3-3 RDA damage points for buildings in Northampton (undamaged buildings are not shown)

Figure 3-4 RDA damage points for buildings in Port Gregory (undamaged buildings are not shown)

CTS extracted data relating to damage to the building envelope or structure. Table 3-1 summarises the information on damage to houses from the RDAs for Kalbarri, Northampton and Port Gregory. (The areas defined by Kalbarri A, Kalbarri B and Kalbarri C are shown in Figure 3-1 and Figure 3-2.) RDAs were not performed in Geraldton as the level of damage was significantly less than in the other areas.

Table 3-1 Summary of RDA – Percentage of damage to buildings observed from the street

		Levels of damage				
Locality	**Total No. buildings**	**Undamaged**	**Slight damage**	**Moderate damage**	**Severe damage**	**Total damage**
Kalbarri A	520	54%	21%	13%	9%	3%
Kalbarri B	177	84%	7%	5%	3%	1%
Kalbarri C	127	24%	43%	21%	10%	2%
Northampton	575	53%	26%	11%	10%	1%
Port Gregory	61	64%	21%	7%	5%	3%

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

Table 3-1 and Figure 3-5 show that:

- More than 10% of buildings in Kalbarri A (61 buildings), Kalbarri C (14 buildings), and Northampton (58 buildings) sustained damage evaluated as 'severe' or 'total'.
- Although the buildings in Kalbarri C are newer, the percentage of 'slight', 'moderate' and 'severe' damage were highest, and the percentage of 'undamaged' buildings was lowest.
- Kalbarri B had significantly lower 'severe' or 'total' damage and a higher percentage of undamaged buildings than other areas. This may be because the houses in that area were a little more protected by the surrounding topography.

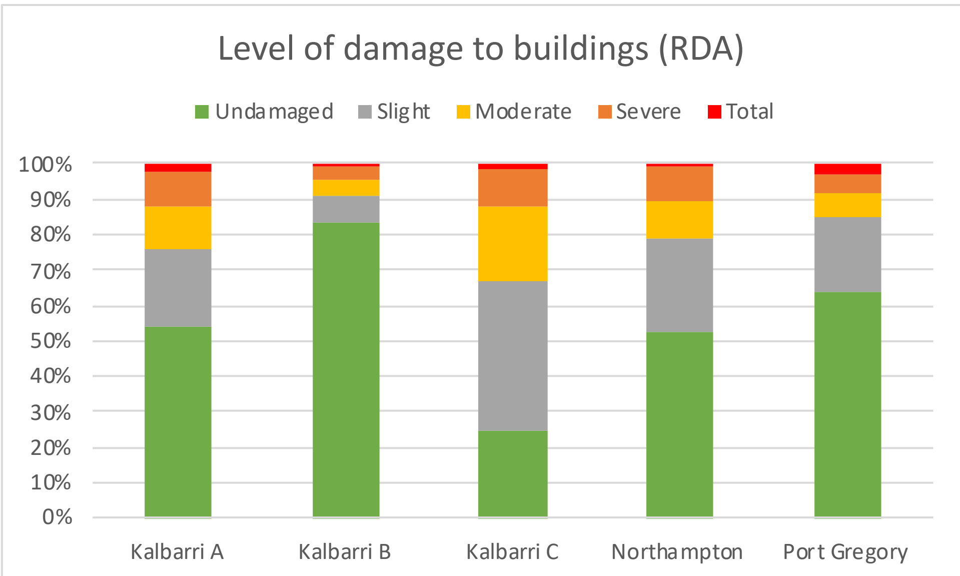


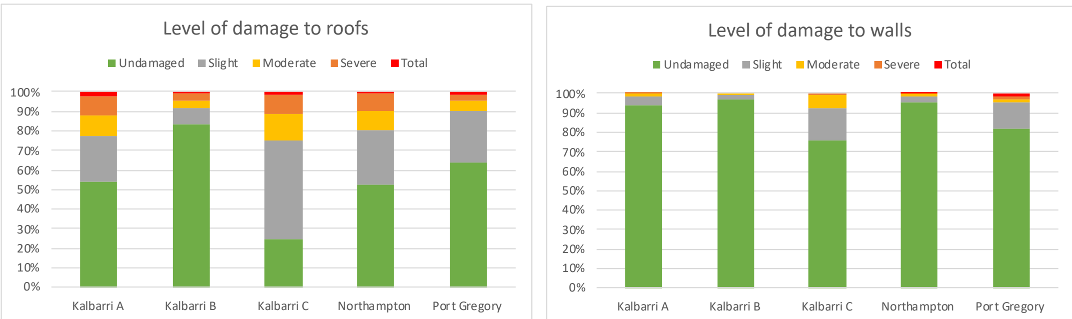
Figure 3-5 RDA damage levels

4. WIND DAMAGE TO CONTEMPORARY BUILDINGS

In this report, contemporary buildings are those constructed since the late 1990s. The most significant number of damaged contemporary houses in the study area was in Kalbarri, so this section focuses on damage to homes in Kalbarri – particularly Kalbarri B and Kalbarri C, where all the buildings were houses.

The maximum wind gusts in the worst affected areas of the study were around 80% to 90% of the design ultimate wind speed for houses (producing 65% to 80% of the design wind load). Under these loads, there were structural failures in many contemporary homes in Kalbarri. Section 2.4 indicated that the peak wind gust speeds in Geraldton were significantly lower than the design wind speed for their locations.

The RDAs evaluated the damage level for the whole building, then indicated whether the damage was mainly to the roof or the walls. Figure 4-1 shows significantly more damage to roofs than walls, and the contemporary houses in Kalbarri C were damaged more than buildings in other areas. The performance of roofs significantly influenced the level of overall damage to buildings. (Figure 3-5 is almost identical to Figure 4-1(a).) Wind actions apply uplift forces 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 4-2.



(a) % buildings with predominant damage to roofs (b) % buildings with predominant damage to walls

Figure 4-1 Level of damage to roofs and walls

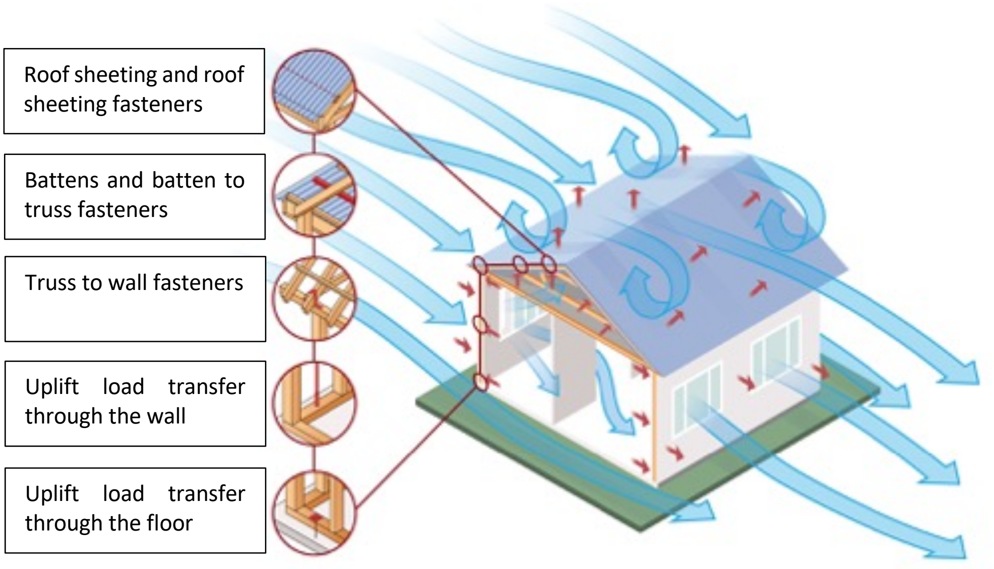


Figure 4-2 Tie-down chain

(excerpt from Weather the Storm https://weatherthestorm.com.au/

The elements that form part of this chain include:

- roof cladding (tiles or sheeting)
- roofing fasteners – carry loads from the sheeting to the battens/purlins;
- battens/purlins
- battens/purlins to rafters/trusses connections – carry loads from battens/purlins to the rafters/trusses;
- rafters or trusses
- tie-downs from rafters/trusses to the top of walls – carry loads from the rafter/trusses fasteners to the tops of the walls;
- uplift load transfer within the wall (from the top plate to the base of the wall for framed walls or within bricks for brick walls;
- uplift load transfer from the bottom of the wall to the floor system or concrete slab; and
- uplift load transfer through the floor and sub-floor systems to the ground.

The main cause of severe structural damage to houses in Kalbarri was an increase in internal pressure created by an opening in the building envelope (usually from debris breaking a door or window). The following sub-sections present observations of damage to components in the tie-down chain and other parts of the house that provide integrity of the building envelope to resist internal pressurisation and water ingress, such as windows and doors gutters and flashing.

4.1. Wind-borne debris

Figure 4-3 shows examples of debris from contemporary houses in the airstream during TC Seroja.

Figure 4-3 Examples of wind-borne debris

The wind-borne debris in this event included whole roofs, portions of roofs, verandas, and tree branches, similar to debris generated during cyclones in Wind Regions C and D. Parts of roof structures with sheeting attached were blown hundreds of metres. Some timber roofing elements speared into the ground or other houses. Figure 4-4 shows some of the damage caused to homes by wind-borne debris during TC Seroja. Many people were at risk of serious injury during this event.

(Photos from ABC News website supplied by Ella Curic)

Figure 4-4 Examples of wind-borne debris damage to houses

Many of the debris items that had penetrated buildings and are shown in Figure 4-4, were assemblies of building parts, such as large portions of a roof. In these cases, a screen that had resisted the debris impact loading test specified in AS/NZS 1170.2 may not have prevented penetration. Figure 4-4 shows some walls and a roof that were penetrated by debris; screens cannot protect walls and roofs.

The trajectories of some of the larger items of debris were tracked (see Figure 4-5). Some debris was blown over two hundred metres, similar to observations during damage investigations in Wind Regions C and D.

Figure 4-5 Debris trajectories

4.1.1. Internal pressure

Wind pressure and wind-borne debris that broke windward windows or doors of some houses created significant positive internal pressure that led to the loss of part or all the roof. Although there were security screens or wind-rated roller shutters on some homes, no screens that were likely to have been rated for debris impact were observed in the study.

Wind pressure or wind-borne debris broke windows or doors on the windward side of all the houses that the investigation team inspected where the whole roof was lost – Figure 4-6 shows an example. Also see Figure 4-7, Figure 4-22, Figure 4-25, Figure 4-28, Figure 4-31.

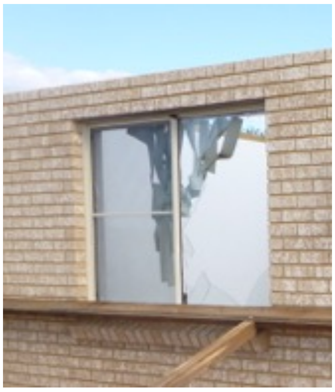


Figure 4-6 Broken window

Many people said that their home was undamaged until a window or door broke, and the roof detached at about the same time. This description of the failure is consistent with a house designed and built to resist the appropriate wind forces using a low design internal pressure. However, once the broken window or door created a dominant opening, the high internal pressure caused the net pressure on the roof tie-downs to nearly double, which led to the failure of critical tie-downs in the roof structure, usually those between the roof and wall.

> The investigation team estimates that more than 10% of contemporary houses in Kalbarri had significant damage to the roof due to internal pressure following damage to doors or windows. Refer to Appendix 2 for more detail on internal pressure and implications for designing houses in Wind Region B.

4.2. Roof to wall connections

Failure of connections between roof structures and walls contributed to significant damage or loss of sections of the roof structure in houses with sheet roofs. The detachment of the roof structure also generated large items of wind-borne debris. In some cases, the debris damaged other buildings (refer to Section 4.1).

Figure 4-7 shows a house where the entire roof was lost, and brickwork on the windward wall collapsed into the lounge room after a door failed and increased the internal pressure inside the house.

Figure 4-7 Loss of timber-framed roof due to failure of tie-down straps in brickwork

The tie-down straps on the windward wall of the house shown in Figure 4-8 were pulled out of the brickwork and cracked the wall at the level of embedment. The weight of the brickwork above the level of embedment was not enough to resist the net uplift load on the roof. There would have been sufficient weight if the tie-down straps had been embedded in the brickwork at the base of the wall. The tie-down straps in the wall under the gable end of the roof of this house hadn't been secured over the rafters. Although it is not required that tie-downs are installed in brickwork under the gable ends of roofs, it is recommended, as the highest uplift forces on the roof are at the gable if the gable wall is the windward wall.

Figure 4-8 Loss of roof structure due to the withdrawal of tie-down straps

Failure of garage doors and the front door of the house shown in Figure 4-9 created high internal pressure under the roof. The roof over the garage was only around one-fifth of the floor area of the house, but the roof over more than 80% of the house was lost. The only parts of the roof that remained were over regions with bedrooms that stayed sealed from the rest of the house by closed internal doors.

Figure 4-9 Roof loss following the failure of garage doors

Figure 4-10 shows the loss of a skillion roof where the wind was perpendicular to the high edge of the skillion. The part of the roof with the large overhang failed at the roof to wall connection. The tie-downs did not have sufficient capacity to resist the high uplift forces (uplift forces are higher on the overhang region of skillion roofs than the uplift forces on other roof shapes). The roof from this house was found more than 200 metres away.

Figure 4-10 Failure of a skillion roof at the roof to wall connection

The houses illustrated in Figure 4-7, Figure 4-8, Figure 4-9 and Figure 4-10 each had a timber-framed roof anchored to the double brick wall with tie-down straps.

The weight of brickwork in the internal leaf above the embedment point of the straps was not enough to anchor the uplift forces for region B wind forces combined with the internal pressure. None of the straps had broken but had withdrawn from the brickwork. The limit of performance of tie-downs between framed roofs and cavity brick walls was the weight of bricks engaged by the straps.

Figure 4-11(a) shows a transportable house that had been positioned on site, refurbished, and surrounded by a veranda. The house lost its roof, but the verandas remained intact. The verandas (Figure 4-11(b)) had been specifically designed for the site, but the wind design of the original transportable house was unknown. Although the building had been refurbished and the quality of the finishes was high, it appeared that the structural details in the roof were the original ones and may not have been appropriate for the wind classification for the site.

(a) Rear view of the transportable house

(b) Front view of transportable house showing verandas

Figure 4-11 Loss of house roof though large verandas remained

There were signs that the roofs of several houses had partially lifted off walls. An example is shown in Figure 4-12(a)and (b). These cases indicate that although the ultimate strength of the connections was sufficient, there was excessive deformation in the connections. In the house shown in Figure 4-12, the tiedown straps were angled to the outside of the building (highlighted by the red ellipse in Figure 4-12(c)), and they had cracked the outside upper courses of the external leaf when they straightened under uplift loads.

(a) Roof partially lifted off external walls

(b) Roof partially lifted off internal walls (c) Tie-down straps

Figure 4-12 Signs that the roof had lifted from the wall though not completely detached

Failures of the roof to wall connections discussed in this section were often associated with window failures, as shown in Figure 4-13. The link between this type of failure and internal pressure was demonstrated in many new and refurbished residential buildings in Kalbarri.

Figure 4-13 Refurbished buildings with broken windows and substantial roof loss

4.3. Batten to truss or rafter connections

Figure 4-10 shows a skillion roof that lost the whole roof structure. The skillion roof in Figure 4-14 (a) and (b) also failed, but in this case, it was the batten to rafter connections that failed due to tear out around the tek screws shown in Figure 4-14(c). The loss of a large windward window increased the net uplift forces in this part of the house, and the overall uplift forces on the room were enough to lift the room at floor level, as shown in Figure 4-14(d).

(a) Loss of roof (b) Batten to rafter failure

(c) Tear-out of battens around tek screws (d) Lifting of walls at floor level

Figure 4-14 Failure of a skillion roof at batten to rafter connections

Damage to a steel-framed house shown in Figure 4-15 was caused by the failure of batten to rafter connections after a double front door blew in. In this case, the small tek screws used to fasten the top hat battens pulled out of the truss top chords. Several screws were still in the batten flanges. Use of batten and rafter systems with recommended tek screws justified by test results can avoid the type of damage illustrated in Figure 4-13 and Figure 4-14.

Figure 4-15 Failure of batten to rafter connection by the withdrawal of tek screws

An upper storey of the house shown in Figure 4-16(a) sustained significant damage to the roof following full internal pressurisation of the roof space. Damage to the roof started with tension perpendicular to the grain in the rafters in the raked ceiling. Battens were fastened with screws, (c) Failure of rafters
Figure 4-16(b), and effectively gripped the upper surface of the deep rafters. As the rafters were anchored to the wall frames at the base of the rafters, the uplift from the batten screws caused tension in the rafters perpendicular to the grain. Several connections at the windward end of the roof failed in tension perpendicular to the grain, as highlighted in Figure 4-16(c).

Failure of timber in tension perpendicular to grain can be avoided by ensuring that the anchorage at each end of deep rafters (> 170 mm deep) attaches to the full height of the rafter.

(a) Damage to roof

(b) Screws at base of rafter

(c) Failure of rafters

Figure 4-16 Tension perpendicular to the grain in rafters

4.4. Roof cladding

The RDA data was used to investigate whether there is a difference in performance between different roof materials. Roofs in Kalbarri were categorised into tile, metal sheet and fibre cement roofs. Fibre cement roofs include products that may contain asbestos, and were only used on some buildings in Kalbarri A. There was a total of 55 clay or concrete tile roofs and 714 metal sheet roofs, and 55 fibre cement roofs (including those with asbestos) on houses in the RDA assessment of Kalbarri. Figure 4-17 presents a direct comparison of the damage to tile, fibre cement and metal sheet roofs aggregated for all areas in Kalbarri.

- No tile roofs had 'total damage', but many had 'slight' and 'moderate' levels of damage (44%).
- More metal sheet roofs were classified as 'undamaged' (66%) than tile roofs (53%).
- More metal sheet roofs were evaluated as 'severe' and 'total damage' (10%) than tile roofs (4%).
- Nearly all of the fibre cement roofs in Kalbarri suffered some damage, with around 30% 'moderate' or 'severe' (also refer to Section 5.4).

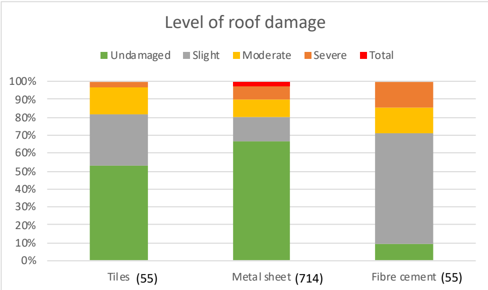


Figure 4-17 Comparison of damage to tile and sheet roofs

The damage to tile roofs was mainly the loss of individual tiles with the level of damage related to the area of tiles that were missing from the roof. There were no cases where all the tiles were blown off the roof. However, several entire metal sheet roofs failed at the wall connections. In most cases, the 'Total damage' and 'Severe damage' classifications represented the loss of the entire roof structure above the walls, as illustrated in Figure 4-7 and Figure 4-8. In other cases, the damage was the complete loss of the roofing with battens attached, as shown in Figure 5-2. There were many cases of metal sheet roofs with no damage or relatively minor damage. The 'Slight' damage to metal sheet roofs represented debris impact to the roof or damage at the edge of roofs.

4.4.1. Metal sheet roofs

The loss of many metal sheet roofs was caused by failures deeper in the structure, such as the roof to wall connections or batten-to-rafter connections. There were few cases where the sheeting had separated from the roof without battens.

However, the investigation team noted signs of cracking in roof sheeting like that seen in damage caused by cyclones in Wind Region C. TC Seroja was a short duration cyclone. The damage shown in Figure 4-18(a) was probably caused by local plastic deformation (LPD) over a small number of cycles due to the large spacing between fixings. A low-high-low test of the roofing system would have identified this failure mode if the fixing pattern contributed to LPD. Figure 4-18 shows some examples of failures in roof sheeting where fasteners had pulled through the sheeting.

Figure 4-18 Failures in roof sheeting by fastener pull-through

Roof sheeting systems need to be tested with cyclic loading regimes when used where the design wind speed is associated with tropical cyclones.

4.4.2. Tile roofs

No tile roofs were lost entirely, but many tile roofs had damage to ridge and hip capping or had lost individual tiles. Some examples of ridge tile damage are shown in Figure 4-19. Capping is always located in zones of high local pressure factors. AS 2050 requires mechanical fixing of capping, but there was little evidence of mechanical fixing in the separated ridge tiles.

Figure 4-19 Examples of damage to ridges and hips on tile roofs

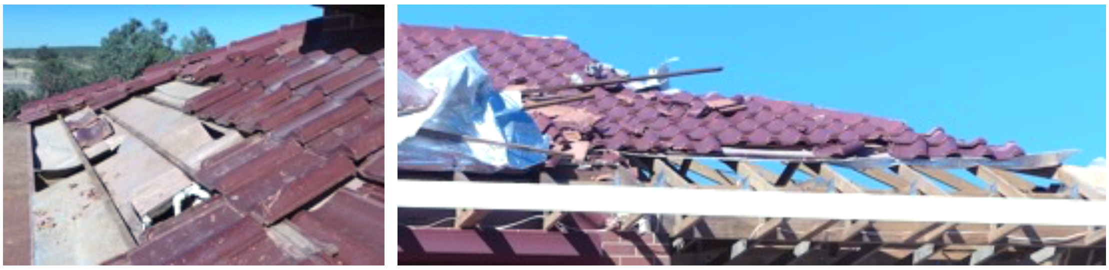
Figure 4-20 shows extensive damage to a home built in 2003. The wind started lifting the tiles along the edges of the roof. Many tiles and some tile battens were lost, and large volumes of rain entered the house. Tiles were lost from both the single and two-storey roofs. The tiles became wind-borne debris that damaged eaves linings, glass balustrades and other elements on the house.

The adjacent garage had the same tiles fixed in the same way as the house, but the roof tiles were not damaged. The roller doors on the garage failed so that the roof would have experienced full internal pressure. The only noticeable difference between the garage and the house was that the garage had eaves gutters, and the house didn't.

Figure 4-20 Loss of tile battens and roof tiles

The tile battens were fixed to the rafters with 50 mm nails (AS 2050 specifies 65 mm nails). Some rafters were hardwood, and others softwood. The nails held in the hardwood rafters, but not the softwood rafters. The shorter nails had adequate withdrawal capacity in the hardwood rafters that have a higher joint strength group (likely JD2) but inadequate capacity for the softwood rafters with a lower joint strength group (JD5). The detachment of the tile battens was only observed on one house. In most cases where tile roofs were damaged, the tile battens remained fixed to the rafters, and individual tiles came off.

Only some of the tiles were nailed to the battens. Figure 4-21(a) shows an area of the roof where the tiles were sporadically fixed, and the tiles had separated from the battens. In other parts of the roof, each tile along a batten was nailed, and the battens lifted off the rafters, as shown in Figure 4-21(b). Note that just behind the white fascia in the lower quarter of the photo, all the tile battens are missing. This is also an area that has softwood rafters.



(a) Tile battens still attached to hardwood rafters (b) Tile battens detached from rafters

Figure 4-21 Tile batten to rafter connections

Tile fixing methods have remained mostly the same over the past 60 years. There was little difference in the performance of tile roofs between the contemporary (Kalbarri B and C) and established areas of Kalbarri (Kalbarri A).

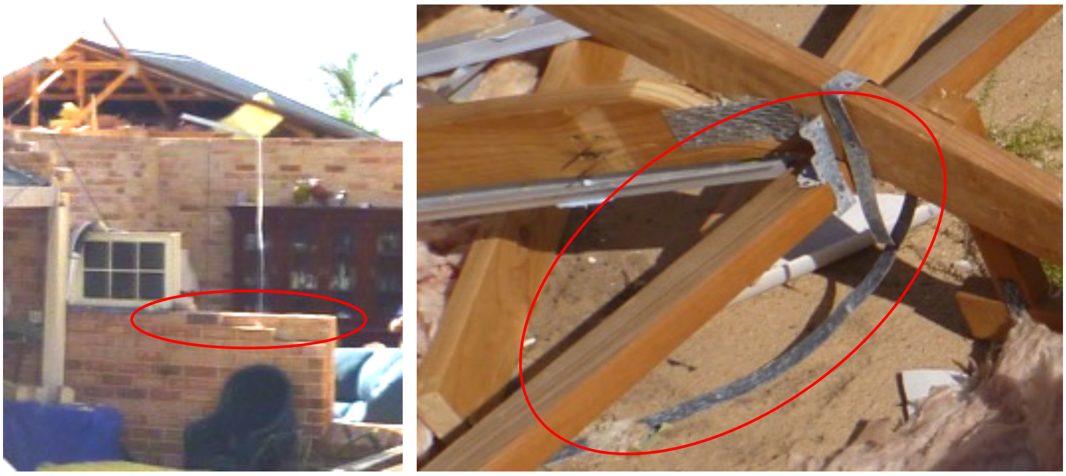
The number of houses with tile roofs that were damaged in Kalbarri indicates that roof tiles in Wind Region B should be fixed in a similar way to the cyclonic Wind Regions C and D. Metal tile fastenings in all Wind Regions affected by cyclones (including Wind Region B) should be tested for capacity under cyclic loading.

4.5. Walls

Many double brick walls in newer houses were damaged by wind or when roof structures were lifted from the walls during TC Seroja. Figure 4-22 shows an example of a windward wall that was blown into a lounge room. Windward walls that failed in this manner were generally external walls in open plan areas of the house and associated with large openings such as windows and doors. In the house shown in Figure 4-22, some of the roof timbers were on top of the wall debris, indicating that this wall may have failed before the roof loss.

Figure 4-22 Failure of a windward wall under wind actions.

Figure 4-23 shows a house where the roof was lost at the same time as the walls collapsed. The tie-down straps between the roof and the wall were still firmly attached to the roof structure and had pulled out of the brickwork. The inner leaf of the brickwork had broken cleanly along the line of embedment of the brick straps (highlighted by an ellipse). The uplift force on the straps was higher than the weight of the inner leaf above the embedment line and cracked the brickwork leading to its failure along that line.



(a) Failure of brickwork at embedment depth (b) Tie-down strap attached to roof members

Figure 4-23 Failure of a wall at the depth of tie-down strap embedment

Figure 4-24 shows a wall that failed after the roof had lifted. The lintels across the large openings were still on the wall. The debris on the floor indicated that a door had broken, then the roof lifted, the windows broke, and the wall collapsed. Finally, the veranda timbers fell into the room. The large openings made it difficult for the tie-down straps in the brickwork to mobilise enough weight to counter the net uplift on the roof after a dominant opening had developed. It underlines the importance of designing appropriate tie-downs beside large openings.

Figure 4-24 Failure of a wall with large openings

Walls on framed structures also showed signs of damage under the combined actions of external pressures and tensions induced by tie-downs. Figure 4-25(a) shows a steel-framed house, and Figure 4-25(b) shows a timber-framed house in which the windward walls had deflected inwards.

In Figure 4-25(a), the movement is obvious at the floor line. An inward deflection of around 150 mm was noted beside the large sliding door. The whole room had also moved upwards by 50 to 100 mm. These movements indicate that the connection between the wall and the floor was inadequate.

In Figure 4-25(b), the movement is obvious at the ceiling line. An inward deflection of around 50 mm was noted above the large window. The roof had separated from the top of the wall and allowed rainwater to enter through the temporary gap. In this case, the long lintel across the top of the window did not have sufficient minor axis stiffness to enable the framework between the ceiling and the top of the window to span between the jamb studs.

(a) Deflection at floor level (b) Deflection at ceiling level

Figure 4-25 Damage to framed walls

Several houses in the southern subdivisions of Kalbarri (Kalbarri C) had rendered magnesium oxide cladding. In several cases, the flexing of the house exposed the joints between the panels, as illustrated in Figure 4-26.

Figure 4-26 Movement cracks at panel joints

4.6. Verandas

If the veranda roof was part of the main house roof, damage to the veranda roof led to the failure of the house roof. This is illustrated in Figure 4-27. In this case, failure at the base of the veranda posts caused the loss of the verandas and most of the house roof. This observation has also been made in investigations following cyclones in Wind Regions C and D. Where the roof sheeting on the veranda was separate from the sheeting on the house, the two structures could behave independently.

Figure 4-27 Veranda loss

In most cases, the separation between the house roof and the veranda roof meant that the loss of a veranda roof did not lead to damage to the house roof. Figure 4-11(b) shows that the house roof was completely lost, but the verandas remained mostly undamaged.

4.7. Windows and doors

Most cases of complete roof loss discussed in Sections 4.2 and 4.3 occurred after a window or door failed – windows and doors determined the performance of the whole building in these cases. For example, of three adjacent houses: a front door failed on one house, a garage door failed on the second, and both houses had significant damage to their roofs. The windows and doors in the third house did not fail, and it sustained no roof damage.

4.7.1. Windows

Figure 4-28 shows an elevated house in which a windward wall window broke (highlighted by an ellipse). The occupants had opened doors on the sidewalls of the house, so the increase in pressure was vented. However, a complete window and frame on a side wall were sucked out and landed around 50 metres away. It appeared that the window may not have been appropriate for the site Wind classification and had been incorrectly installed into the timber frame.

Figure 4-28 Loss of complete side window after a windward wall window broke

The glass sliding doors shown in Figure 4-29 flexed under wind loads and distorted the sashes. Eventually, this led to the loss of both the sliding and fixed panels, and the increase in internal pressure led to the loss of the roof.

Figure 4-29 Detachment of glass sliding door frame under wind loads

Wind-borne debris or wind pressure (Figure 4-30(a)) broke many windows in contemporary and older houses. The consequences of wind-borne debris are discussed in Section 4.1.1. Although they had not been debris-rated, some metal roller shutters on a house protected windows from some wind-borne debris – there were dents in the roller shutters from roof tiles that had detached from the roof above (Figure 4-30(b)).

(a) Broken window (b) Roller shutter

Figure 4-30 Broken glass from wind-borne debris and protection by roller shutters

4.7.2. Doors

Figure 4-31(b) shows an example of a door latch that failed on a double entrance door, allowing full internal pressure into the house, causing failure of the roof. After the roof failed, the walls collapsed. The damage is also shown in Figure 4-8.

(a) Double door blew into house (b) Door latch failure

Figure 4-31 Failure of the front door

The latch on double front doors on a five-year-old house broke, and the bolt at the top of the door pulled out of the timber frame—the resulting increase in internal pressure caused loss of part of the roof. The owner was injured while making the temporary repairs to the doors during the cyclone. (The temporary repair to the doors is shown in Figure 4-32).

Figure 4-32 Temporary brace on the double front door

Entrance doors and entrance door hardware are not wind rated. Unless wind performance limits and appropriate detailing are applied to entrance doors, and their fittings, doors that fail under wind pressure can produce a dominant opening, leading to internal pressure.

4.7.3. Garage doors

Figure 4-33 shows examples of damage to garage doors on residential garages.

Figure 4-33 Failure of garage doors in Kalbarri

Where garage doors under house roofs failed, the internal pressure contributed to roof damage. In some cases, the garage doors could not be found.

Figure 4-34 shows a house in Geraldton where the wind speeds during TC Seroja were lower than in Kalbarri. However, the damage to the garage doors initiated roof loss, even at wind speeds around 60% of the design wind speed.

Figure 4-34 Failure of garage doors in Geraldton

(Photos courtesy of Denise McDonald, Waggrakine, Geraldton)

Currently, there are no requirements for garage doors in Wind Regions A and B to be wind rated. Unless wind performance limits are applied to garage doors, they can become a dominant opening if they fail under wind pressure that often leads to roof damage in those Wind Regions.

See Section 7.1 for examples of damage to garage and large access doors on sheds.

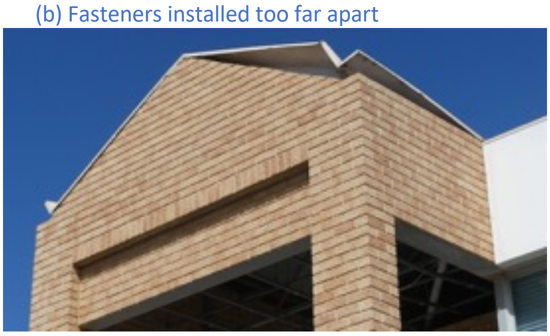
4.8. Flashings and gutters

Flashings were damaged on a significant number of buildings, including contemporary buildings. Some lifted flashings are shown in Figure 4-35. In each case, the lifted flashing allowed significant water entry into the roof space causing water damage, as discussed in Section 6.

(a) Flashings fastened too close to the edge

(b) Fasteners installed too far apart

(c) Flashings fastened with pop rivets



(d) Flashings not fastened

Figure 4-35 Examples of damage to flashings

The flashings shown in Figure 4-35(b) to (d) had details that would not have complied with the current version of AS 1562.1. However, the failure shown in Figure 4-35(a) indicates that even if the right number of screws are installed at the correct spacing, failures can still occur if the fasteners are positioned too close to the edge of the flashing.

4.9. Soffits (eaves linings)

Previous CTS reports on damage to buildings following wind events (e.g. Henderson *et al.*, 2006 and Boughton *et al.*, 2011) highlighted the high frequency of damage to soffits. Figure 4-36 shows an example of damage to soffits during TC Seroja. Again, the character of the damage reflects previous observations of damage in tropical cyclones in other Wind Regions.

Figure 4-36 Damage to eaves linings

5. Wind damage to older buildings

The investigation of damage to buildings after TC Seroja 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, and Reardon *et al*., 1999); older buildings are usually damaged more frequently and severely than newer ones unless they have been adequately upgraded or retrofitted. Figure 5-1 shows some examples of wind and debris damage to older buildings in Kalbarri.

Figure 5-1 Damage to older buildings

5.1. Debris damage

The role of wind forces and wind-borne debris that breaks doors and windows, leading to roof damage to contemporary houses, as discussed in Section 4.1 also applies to older homes. An example is shown in Figure 5-2. Deterioration of structural elements and connections that don't comply with current standards also contributed to roof damage in older houses.

Figure 5-2 Broken windows leading to failure of the roof structure in an older house

5.2. Damage due to deterioration

Some older buildings that failed during TC Seroja showed signs of deterioration in several structural elements.

5.2.1. Corrosion

Towns in the investigation area located on the coast are exposed to salt-laden prevailing onshore winds, accelerating atmospheric corrosion of steel elements. The galvanised straps embedded in brick walls that were used to tie down the roof structures to the walls in several houses had rusted, and this contributed to the loss of the roof structure above the walls.

Figure 5-3 shows some examples of corroded tie-down straps that led to the loss of the roof structure.

Figure 5-3 Corrosion in tie-down straps that led to the loss of timber-framed roofs

Corrosion also affected roof sheeting and flashings, as shown in Figure 5-4. In this case, the heads of the sheeting fasteners had started to corrode. The shafts also had similar levels of corrosion but remained effective.

Figure 5-4 Corrosion of flashings and fasteners

Figure 5-5 shows a corroded veranda post that led to the loss of the entire veranda and part of the house roof.

Figure 5-5 Corrosion in stirrups for veranda posts

Figure 5-6 shows deterioration at the end of the exposed rafter overhang, which may have weakened the connection to the edge batten. Local pressure factors increase the wind pressure on edge battens, and failure initiated at this location may have contributed to the roof loss.

Figure 5-6 Rot in exposed rafter ends

5.3. Damage due to detailing that doesn't comply with current standards

Some older buildings were damaged because the roof tie-down connections installed at the time of construction (which may have complied with building practices at the time) did not have the capacity to resist the net wind uplift loads on the roof. Figure 5-7 shows some examples of houses where the nailed batten to rafter connections or skew nailed rafter to wall connections failed.

Figure 5-7 Failure of nailed batten to rafter connections or skew nailed rafter to wall connections

5.4. Asbestos

Some older buildings in Kalbarri were constructed using fibre-cement building products that contain asbestos. The investigation team did not inspect these buildings but reiterate the problems associated with damage to asbestos buildings:

- The site may need to be isolated until an expert confirms the presence or absence of asbestos.
- Material containing asbestos needs to be removed from the damaged part of the building by a qualified operator, and in some cases, from the undamaged part before starting any repairs.
- 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.

5.5. Heritage Buildings

Heritage buildings were damaged in parts of the affected area. These buildings may have been re-roofed several times. Reconstruction of heritage buildings requires sensitivity to the building's character, but structural systems will need to be upgraded to meet current requirements.

Figure 5-8 Damage to the roof of a heritage hotel in Northampton

6. Damage from wind-driven rain

Although this investigation focused on structural damage to buildings, the team noted several houses with little or no structural damage but had damage caused by wind-driven rain.

TC Seroja was a fast-moving cyclone that delivered around 100 mm of rain at Kalbarri (much less than other tropical cyclones). Although there was only a relatively short time of strong winds and heavy rain, wind-driven rain still entered buildings through weep holes or gaps around seals in windows or doors; through lightweight frames that flexed too much under the wind actions; under doors with inadequate or missing seals; or under missing or damaged flashings and gutters. The observations made in the investigation following TC Seroja were similar to those made during investigations following TC Olwyn, TC Debbie and TC Damien (Boughton *et al.*, 2015; Boughton *et al.*, 2017; Boughton and Falck, 2020; and Reardon *et al.*, 1999).

The wind-driven rainwater caused damage to ceilings and walls, as shown in Figure 6-1. Damage to overlay timber floors was starting to become apparent during the investigation but would have become more obvious in later weeks.

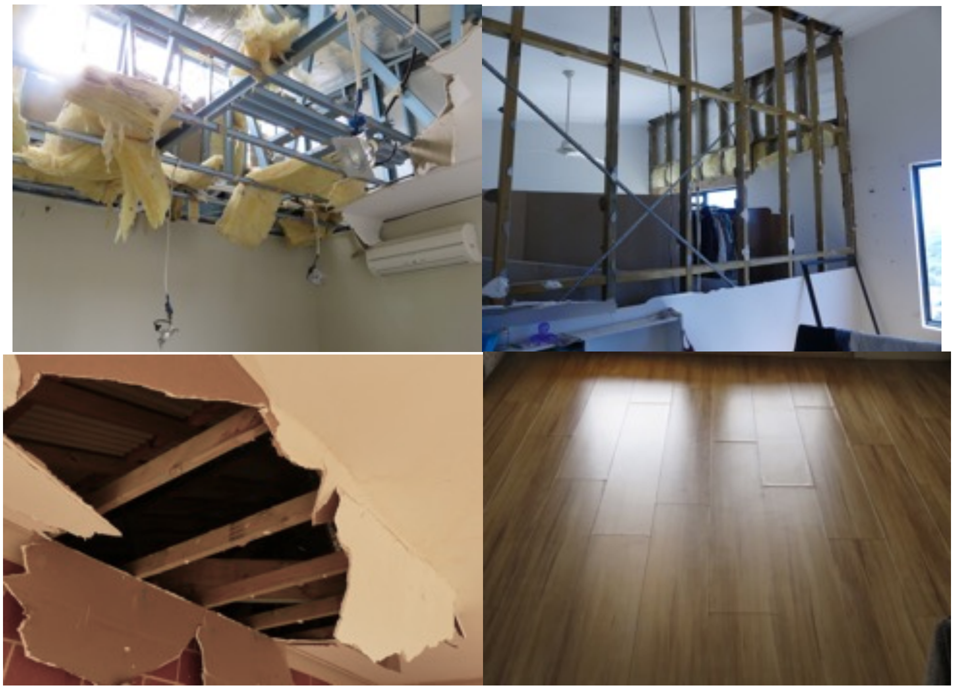


Figure 6-1 Damage to plasterboard wall and ceiling linings and timber floor

As noted in previous reports (Boughton et al., 2017, Boughton and Falck, 2020), people stood in front of windward windows and glass doors to take videos of the cyclone or mop up rainwater or to try to stop entrance doors from opening. They risked serious injury if debris or wind pressure broke the windows or doors.

6.1. Flashings, valley and box gutters

Flashings are designed to channel downward-moving rainwater away from buildings. However, fast-moving air can move rainwater upwards during a cyclone, and water can enter buildings under even correctly fixed flashings. If inadequate fastening of the flashing led to it being lost or partially detached, then even more water could enter through the gap. Water that entered houses through any flashings during TC Seroja caused the types of damage noted

in Figure 6-1. Figure 4-35 shows houses where sections of flashing were lost, causing significant rainwater to enter the buildings.
Figure 6-2(a) shows a valley gutter where wind-driven rain flowed over the top, entered the roof space and damaged ceilings below. The box gutters in Figure 6-2(b) also overflowed and caused damage to internal linings.

(a) Valley gutter (b) Box gutter

Figure 6-2 Wind-driven rain entered buildings with no structural damage

6.2. Windows and doors

The investigation team observed several houses where rain had been driven through undamaged windows and doors. Rainwater was driven under swinging doors without adequate seals or through weep holes in windows and glass sliding doors. Some sliding glass doors on windward walls flexed under wind loads, which allowed water to be driven through the gap between the sashes.

Refer to CTS report TR 61 (Boughton *et al.*, 2015) for further information on the mechanisms involved in wind-driven rain entering buildings with no structural damage and some relatively low-cost options to improve performance.

7. DAMAGE TO ANCILLARY ITEMS

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

7.1. Large sheds

Failure of large sliding doors on the shed shown in Figure 7-1 when the wind was blowing onto the corner of the shed caused high internal pressures and high external local suction on the end bay. This combination of wind pressures overloaded the purlins in the end bay.

Figure 7-1 Damage to purlins in a large shed

An industrial shed in Geraldton (Figure 7-2 and Figure 7-3) had ten large roller doors and six large roof ventilators. Two of the five doors on the windward side of the building blew in, and three of the five on the leeward side blew out. The ventilators could not dissipate all the internal pressure from the two failed roller doors on the windward side.

The internal pressure in the shed was probably very negative due to the large rooftop ventilators in areas in which the external pressure coefficient C_p would have been between 0.9 and –0.6. The negative internal pressure increased the differential pressure across the windward wall, including the large roller doors. After the windward doors failed, the internal pressure would have been positive as the area of the open doors significantly exceeded the throat area of the ventilators. The positive internal pressure increased the differential pressure across the leeward wall, including its large roller doors. The leeward roller doors were blown outwards and would have relieved some of the internal pressure.

Figure 7-2 Damage to large access roller doors – View from outside the shed

Figure 7-3 Damage to large access roller doors – View from inside shed

No wind locks or rated large doors were observed during the surveys of damage to sheds.

7.2. Fences

Many steel sheet fences were damaged during TC Seroja, as shown in Figure 7-4. Sheet metal panels that detached from fences became part of airborne debris that posed a risk to people and other buildings. Where the fence was part of the pool safety fence, then the loss of the fence presented pool safety risks as well. The images shown in Figure 7-4 were caused by wind pressures alone. Wind-borne debris also caused damage to fences.

(a) Kalbarri

(b) Geraldton

Figure 7-4 Wind damage to steel sheet fences

Figure 7-5 shows damage to fences constructed with reinforced masonry pillars and either metal infill or unreinforced masonry infill. Wind pressures damaged both types of fences. The reinforcement in the masonry pillars shown in Figure 7-5(a) was not bonded with the brickwork.

(a) Reinforced pillars with sheet steel infill panels (b) Reinforced pillars with unreinforced blockwork

Figure 7-5 Damage to masonry walls

In newer subdivisions, limestone retaining walls had been constructed as part of the development earthworks. It is common practice to cast the fence posts directly into holes bored vertically into the limestone wall. In Geraldton, the wind loads on the fence had caused some limestone walls to fail, as shown in Figure 7-6.

Figure 7-6 Damage to retaining walls caused by wind loads on attached fence panels

Some fibre cement fences broke off at ground level, as shown in Figure 7-7.

Figure 7-7 Damage to fibre cement fences

7.3. Outdoor ceiling fans

During TC Seroja, wind drag on the outdoor ceiling fans swung them against the ceiling and damaged their blades. In many cases, all blades and several ceiling panels were damaged. Figure 7-8 shows an example. This type of damage can be avoided by removing the blades as part of preparing for an approaching tropical cyclone (Boughton and Falck, 2020).

Figure 7-8 Damage to outdoor ceilings from ceiling fans

7.4. Roof-mounted items

Many solar hot water systems and solar photovoltaic systems installed on roofs were damaged. Figure 7-9 shows examples of damage to solar panels, and Figure 7-10 shows damage to or loss of roof-mounted hot water systems. Many satellite dishes and TV aerials were damaged when roofs on which they were mounted were damaged.

The following types of damage associated with solar photovoltaic panels were noted:

- Mounting systems that secured the panels to the roof had failed. This failure mode was more common in this event than in recent tropical cyclones in Wind Regions C or D. It is illustrated in Figure 7-9, and shows individual panels separated from the roof and the mounting rails still attached to the roof. The design wind speeds in Wind Region B are higher than those in Wind Region A, so the panels and fastening requirements need to be appropriate for the higher wind loads.
- The roof system under the solar panels had failed. This type of failure was discussed in Sections 4.2 and 4.3. In most cases, the internal pressure was the trigger for the failure, and it was difficult to determine the role of the solar panels in the failure. However, in at least one house, the only part of the roof removed was the portion that carried PV panels.

Figure 7-9 Damage to solar photovoltaic panels

Solar hot water systems were also damaged in a number of different ways that are illustrated in Figure 7-10:

- In some cases, the mounting system failed, and the whole system was lost;
- Just the tank or just the solar panels were blown off the roof;
- The solar panels were damaged by wind-borne debris.

Figure 7-10 Damage to hot water systems

7.5. Swimming pools

Swimming pools that collect wind-borne debris, as shown in Figure 7-11, are difficult to repair and restore to service.

Figure 7-11 Debris in a swimming pool

8. STORM TIDE IN TC SEROJA

Storm tide refers to the combination of storm surge on top of the normal (astronomical) tide. The tidal range at Kalbarri is just less than 1 m. There is no tide gauge at Kalbarri; the nearest gauge is at Geraldton, approximately 150 km to the south.

The peak storm surge that accompanied TC Seroja occurred near mid-tide. Figure 8-1 shows the anomaly above the tide gauge records at Carnarvon (around 300 km north of Kalbarri) and Geraldton.

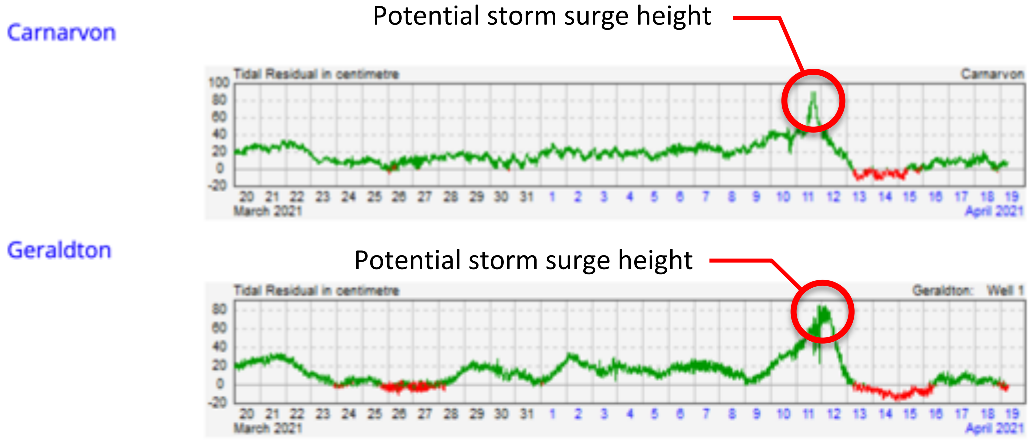


Figure 8-1 Storm surge anomaly from tide gauge data

The recorded maximum storm surge at Geraldton was 1.64 m. The winds during TC Seroja were mainly offshore at Geraldton and were onshore at Kalbarri. Likewise, Carnarvon experienced significantly lower onshore winds than Kalbarri and was further from the eye than Kalbarri. Therefore, the storm surge at Kalbarri would have been higher than that measured at Geraldton and Carnarvon. This is compatible with debris found around 2 m above the high tide level.

TC Seroja crossed the coast near mid tide when the astronomical tide was predicted to be 0.5 m below Highest Astronomical Tide. Figure 8-3 shows photos of the foreshore in Kalbarri. The yellow line shows the approximate position of the storm tide position inferred from the deposits of marine sediment. It appeared that the maximum storm tide height was near 2 m above high tide, at around the floor level of the amenities block shown in the photo. At this location, the sediment line would have included wave runup.

Because most buildings are not located close to the shore, the only potential storm surge damage to buildings would have been to the toilet block shown in Figure 8-2 where wave action may have contributed to the roof damage.

Figure 8-2 Inferred storm tide position at the mouth of the Murchison River at Kalbarri

A storm tide height of nearly 2 m is compatible with the marine debris line on the foreshore near the town centre, shown by the yellow line in Figure 8-3.

Figure 8-3 Inferred storm tide position at the foreshore near the town centre

9. BENEFITS OF STRONG ROOMS IN HOUSES

As discussed in Section 4, the investigation team assessed several houses where all the roof structure and some walls were lost or severely damaged. People sheltered in these houses during the cyclone and were at significant risk of severe injury. It was both surprising and fortunate that few people were seriously injured in this event, given the scale of the damage. The type of wind-borne debris that was in the airstream during TC Seroja is illustrated in Section 4.1.

Figure 9-1 shows the remains of a house where the occupant left the lounge room at the front of the house to take shelter in a back bedroom just minutes before the roof lifted off and the front walls collapsed. He remained unharmed in the small room.

Figure 9-1 Extensive damage to walls and roof

A family of five sheltered in their car in the garage of the house shown in Figure 9-2 after the roof was lost and the windows and walls were severely damaged. The team noted that several pieces of glass from one of the broken windows were embedded 10 to 20 mm into one of the internal brick walls.

Figure 9-2 Roof loss and damage to walls

Figure 9-3 shows a house that was almost destroyed. It also shows photos of the hallway and bathroom – spaces where people are usually advised to shelter during a cyclone. The walls of all the small rooms remained intact. But, if people had been sheltering in this house, they may have been injured by the debris that fell from the damaged roof.

Figure 9-3 Severe damage to a house including hallway and bathroom

The walls of small rooms could provide shelter during a cyclone, but in the space that occupants designate as a safe shelter, the ceiling needs to be reinforced and separate from the roof structure to provide protection if the roof structure and cladding is lost.

The CTS suggests that the concept of providing ‘strong rooms’ in new and existing houses should be investigated by further research and testing. *(Refer to Section 11 Recommendations.)* A ‘strong room’ would be a strengthened compartment within a residential building, in areas that will not be affected by storm tide, where occupants could shelter during extreme winds associated with tropical cyclones. It could be a section of an internal hallway, a small bedroom, a large walk-in wardrobe or pantry, or a bathroom. The strengthening in the walls and ceiling will offer enhanced protection against wind or debris damage if the rest of the house is significantly damaged in extreme wind. Strong rooms improve the chances of survival for occupants sheltering in their own homes. People in areas that could be affected by storm-tide should leave their homes when advised.

10. SUMMARY OF FINDINGS

- Severe Tropical Cyclone Seroja crossed the Western Australian coast within Wind Region B as a category 3 tropical cyclone. The maximum 0.2-sec gust wind speed at Kalbarri was estimated to have been between 46 and 51 m/s (166 and 184 km/h). This gust wind speed had an annual exceedance probability estimated to be between 1/70 and 1/180 based on Table 3.1A in AS/NZS 1170.2:2011.
- This range of wind speeds is between 80% and 90% of the design wind speed for Importance Level two buildings (houses) in Kalbarri. The 0.2-sec gust wind speed near Morawa (Wind Region A) was also estimated to have been 37 m/s (134 km/h), which was between 80% and 90% of the Wind Region A design wind speed for Importance Level two buildings.
- Around 10 % of buildings in Kalbarri and Northampton had damage that was classified as 'severe' or 'total'.
- The performance of roofs significantly influenced the level of overall damage to buildings.
- TC Seroja generated a large amount of wind-borne debris, similar to the type and amount observed during cyclones in Wind Regions C and D.
- The main cause of severe structural damage to houses in Kalbarri was a combination of suction on the upper surface of the roof and high positive internal pressures caused by broken windows or doors on windward walls.
- Tie-down details between framed roofs and double brick walls failed when the straps pulled out of the brickwork or cracked the bed joint in the brickwork at the depth of embedment.
- Poor design and construction contributed to some roof structural failures.
- Buildings more than 20 years old also experienced failures caused by internal pressure, but in some cases, deterioration of structural elements also contributed to the failure. This highlighted the importance of regular building inspections and maintenance.
- Failures of the anchorage for roof-mounted solar hot water systems and solar photovoltaic panels indicated that the connections may not have been designed and tested for the Region B wind speeds.
- Water damage due to wind-driven rain was observed in some buildings that did not have structural damage and had no sign of broken doors or windows. Water had been driven under flashings and up valley gutters and caused damage to plasterboard ceilings. These observations were similar to water damage following tropical cyclones in Wind Regions C and D.
- Building materials collapsed into hallways and small rooms (areas where people often shelter during tropical cyclones) when roofs were severely damaged. People in these houses were at risk of serious injury.
- The debris lines along the foreshore in Kalbarri indicated that the storm tide near the mouth of the Murchison River was near 2 m above Highest Astronomical tide.

11. RECOMMENDATIONS

Based on the findings of this investigation, the following recommendations aim to improve the performance of buildings in future wind events in Wind Region B.

1. **Submit proposals for change to Australian Standards and the National Construction Code**
   Complete a Project Proposal to change AS/NZS 1170.2 and submit to Standards Australia.
   - AS/NZS 1170.2:
     Classify Wind Region B (Region B2 in current publication draft) as cyclonic – *refer to Section 4.1 and Appendix 2.* Review internal pressures for buildings and houses in Wind Region B (Region B2 is cyclonic). These changes will enable buildings to comply with robustness requirements in the NCC.

   If this proposal is successful, then the following changes will also be proposed:
   - AS 4055
     Review internal pressures for buildings and houses in Wind Region B (potentially mirroring AS/NZS 1170.2 separation into Region B1 and Region B2) – *refer to Section 4.1 and Appendix 2.*
   - AS 1562.1 and AS 4040.3
     Include Low-High-Low tests on roof cladding in Wind Region B2 – *refer to Section 4.4.1.*
   - AS 2050
     Include tile fastenings for Wind Region B2 with cyclone regions and recognize cyclic loading of metal fastenings for tiles in cyclones – *refer to Section 4.4.2.*

   In addition, the findings from the investigation indicate that the following changes should also be proposed:
   - AS 4773.1
     Review capacities of tie-down straps into brickwork – *refer to Section 4.2 and Section 4.5.*
   - AS 4420 series
     Include wind rating tests for entrance doors – *refer to Section 4.7.2.*
   - NCC referencing of AS/NZS 4505
     Include wind rating of garage doors in Wind Region B2 – *refer to Section 4.7.3*

2. **Develop and promote guidelines for homeowners and builders on repair and reconstruction in Wind Region B.**
   A one-page leaflet on repair and reconstruction options has already been distributed to homeowners in the Northampton Shire, and a supporting web page has been developed https://www.jcu.edu.au/cyclone-testing-station/education/kalbarri.

   It is recommended that, CTS, DFES, Building and Energy and relevant industry associations, collaborate to develop and deliver more detailed training materials for repairs and reconstruction in Wind Region B:

3. **Promote maintenance and retrofitting options for homeowners and builders**
   Homeowners and builders need to be aware of options to improve the resilience of houses to future cyclones – *refer to the section on Resources.*

4. Develop **guidelines for the design and construction of strongrooms** in new and existing houses – *refer to Section 9.*

5. Undertake **further research** on wind loads on roofs that support **photovoltaic solar panels** – *refer to Section 7.4.*

6. Ensure that **transportable buildings** brought in from other regions have appropriate wind classifications for their new site.

7. Design **gable ends over double brick walls** to accommodate appropriate tie down straps.

8. To minimize wind-driven rainwater ingress through doors and windows:
   - Window manufacturers should **design weep holes in windows** (e.g., using rubber flaps or ball valves) to minimise water entry at serviceability wind pressures.
   - **Water penetration tests for windows and glass sliding doors** should include a requirement to declare the leakage rate at the serviceability wind pressure.
   - **Door systems** should 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.) Also refer to Recommendation 1 regarding AS 4420.

9. It is recommended that **structural elements** within the roof space, and where any steel elements contact concrete and mortar (such as veranda stirrups), are regularly **inspected, and maintained** in 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 a reasonable interval for general inspections – other inspections to detect progressive deterioration of building structure, such as pest inspections, are usually undertaken at one- or two-yearly intervals).

   Where inspections indicate there are problems in the tie-down chain (refer to Figure 4-2):
   - Replace components that don't have the required capacity, have deteriorated, or bypass the existing details by installing a new tie-down system.
   - 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.

Resources

For information on the **repair and reconstruction of houses in the Northampton Shire**: www.northampton.wa.gov.au/Profiles/northampton/Assets/ClientData/Document-Centre/Building_doc_combined.pdf

For detailed information on **repair and reconstruction of houses in Wind Region B**: www.jcu.edu.au/cyclone-testing-station/education/kalbarri

For information on **preparing your property for a cyclone**, refer to the **DFES guide**: www.dfes.wa.gov.au/safetyinformation/cyclone/CycloneManualsandGuides/tropical-cyclone-preparedness-guide.pdf This document provides information, basic building checks and maintenance checklists that are also relevant to building owners in the areas affected by TC Seroja.

Other options for improving the resilience of existing buildings are also available.

- For information on **structural upgrades for houses in Wind Regions B and C**, see the Weather the Storm website: www.weatherthestorm.com.au

- For information on upgrading the structural performance of buildings, refer to **Industry Bulletins prepared by Building and Energy**: www.commerce.wa.gov.au/publications/building-and-energy-industry-bulletins-complete-list.

- For information on **wind classification of houses and replacing roofs on houses**, see CTS educational videos: www.jcu.edu.au/cyclone-testing-station/education/educational-videos .

An example of the information provided in the resources include advice on upgrading existing houses to improve their performance in future wind events. Suggestions 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 – *refer to Section 4.7.3*

Other **Technical Reports** prepared by the Cyclone Testing Station www.jcu.edu.au/cyclone-testing-station/education/publications .

References

Australian Building Codes Board (2019) National Construction Code. Australian Building Codes Board. Canberra, Australia.

Bureau of Meteorology (2021) Website www.bom.gov.au, Bureau of Meteorology, April and May 2021.

Boughton, G.N, Falck, D.J (2007) “Tropical Cyclone George Damage to buildings in the Port Hedland area”, TR52, Cyclone Testing Station, James Cook University, Townsville.

Boughton, G.N, Henderson, D.J., Ginger, J.D., Holmes, J.D, Walker, G.R., Leitch, C.J., Somerville, L.R., Frye, U., Jayasinghe, N.C., and Kim, P.Y. (2011) “Tropical Cyclone Yasi – Structural damage to buildings”, TR57, Cyclone Testing Station, James Cook University, Townsville.

Boughton, G.N, Falck, D.J., and Henderson, D.J. (2015) “Tropical Cyclone Olwyn – Damage to buildings in Exmouth, Western Australia”, TR61, Cyclone Testing Station, James Cook University, Townsville.

Boughton, G.N., Falck, D.J., Henderson D.J., Smith, D.J., Parackal, K., Kloetzke, T., Mason, M., Krupar III, R., Humphreys, M., Navaratnam, S., Bodhinayake, G., Ingham, S., and Ginger, J.D. (2017) “Tropical Cyclone Debbie Damage to buildings in the Whitsunday Region”, TR63, Cyclone Testing Station, James Cook University, Townsville.

Boughton, G.N, Falck, D.J (2020) “Tropical Cyclone Damien – Damage to buildings in the Pilbara Region”, TR65, Cyclone Testing Station, James Cook University, Townsville.

Fogliani (2015) “Inquest into the deaths of Debra Alexandra Till and Craig Allan Raabe.” Coroner’s Court of Western Australia, Perth, WA.

Harper, B. (2020) SEA wind field and storm surge models for TC Seroja, personal communication. 18 February 2020.

Henderson, D.J., Ginger, J., Leitch, C., Boughton, G.N., and Falck, D.J. (2006) “Tropical Cyclone Larry – damage to buildings in the Innisfail area”, TR51, Cyclone Testing Station, James Cook University, Townsville.

NASH (2011) “Residential and low-rise steel framing Parts 1 and 2”, National Association of Steel-Framed Housing, Victoria, Australia

Reardon, G.F., Henderson, D.J., and Ginger, J. (1999) “A structural assessment of the effects of Cyclone Vance on houses in Exmouth WA”, TR48, Cyclone Testing Station, James Cook University, Townsville.

Standards Australia (1996) “AS/NZS 4420.0:1996 Windows – Methods of test Part 0: General introduction and list of methods.” Standards Australia, Sydney, NSW, Australia.

Standards Australia (2011) “AS/NZS 1170.2:2011 Structural design actions Part 2: Wind actions.” Standards Australia, Sydney, NSW, Australia.

Standards Australia (2020) “Public comment draft AS/NZS 1170.2:2011 Structural design actions Part 2: Wind actions.” Standards Australia, Sydney, NSW, Australia.

Standards Australia (2012) "AS 4055:2012 Wind loads for housing." Standards Australia, Sydney, NSW, Australia.

Standards Australia (2012) "AS/NZS 4505:2012 Garage doors and large access doors." Standards Australia, Sydney, NSW, Australia.

Standards Australia (2014) "AS 2047:2014 Windows and external glazed doors in buildings." Standards Australia, Sydney, NSW, Australia.

Standards Australia (2015) "HB 39:2015 Installation code for metal roof and wall cladding." Standards Australia, Sydney, NSW, Australia.

Standards Australia (2018) "AS 1562.1–2018 Design and installation of sheet roof and wall cladding – Metal." Standards Australia, Sydney, NSW, Australia.

Standards Australia (2018) "AS 4040.3:2018 Methods of testing sheet roof and wall cladding Part 3: Resistance to wind pressures for cyclone regions." Standards Australia, Sydney, NSW, Australia.

Appendix 1 – Windicators

The investigation team used measurements of 14 road signs around Kalbarri, Port Gregory and Northampton to estimate the wind speeds during TC Seroja. The locations are indicated in Figure App.1.1.

Figure App.1.1 Location of road signs used as 'windicators'

The analysis of the road signs provided upper and lower bounds as shown in Figure App.1.2:

- Signs that had a plastic hinge in the posts indicated that the maximum bending moment had exceeded the plastic moment capacity. A sign in this condition could be used to estimate a lower bound on the wind speed providing the sign was free of evidence of impact damage and the direction of fall was normal to the axis of the sign.

- The upwind terrain and topography were simple and unambiguous.
- The cross-section and steel grade of the posts could be used to establish the plastic moment capacity.
- Undamaged posts give an upper bound to the wind speed, while bent posts give a lower bound.
- The sign's dimensions could be used to infer the load that would have been required to exceed the plastic moment capacity.
- The load, the height of the sign, and the upwind terrain and topography were used to deduce the wind speed that caused the posts to fail.

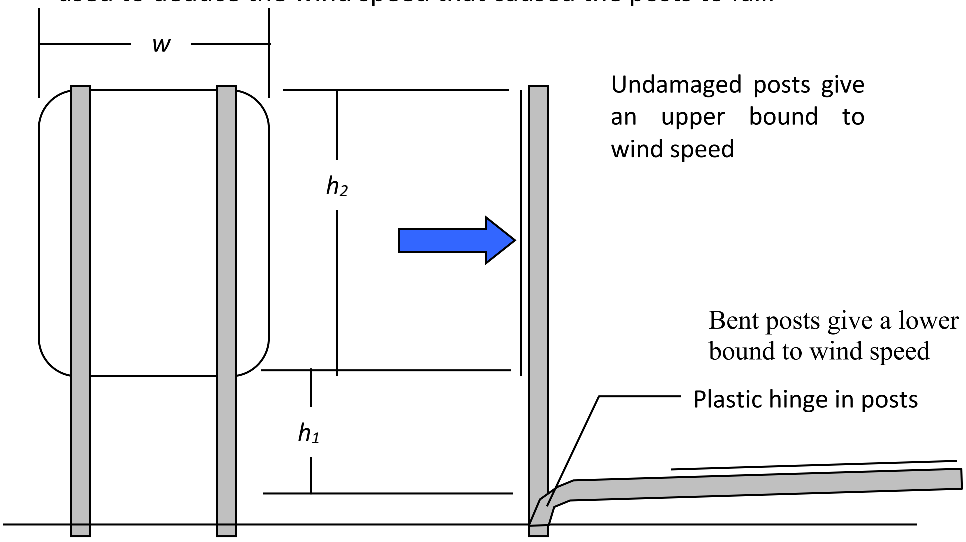


Figure App.1.2 Road sign analysis – upper and lower bounds to wind speed

Relating wind speed to sign measurements
The peak net wind load (F_n) across the sign can be given by Equation App.1.1

$$F_n = \tfrac{1}{2}\rho \hat{V}_h^{\,2}.C_{F,n}.A \qquad \text{(App.1.1)}$$

Here: $C_{F,n}$ is the net drag force coefficient, equivalent to C_{fig} in AS/NZS1170.2. [2]
A is the area of the plate (i.e. road sign)
ρ is the density of air = 1.2 kg/m^3
$\hat{V}_h$ is the 3s gust velocity at the centroid (i.e. $l = h_1 + 0.5h_2$) of the sign

where the plastic hinge is at ground level.
The resulting maximum (i.e. base) bending moment M_{max} on the post(s) is given by Equation App.1.2, where the lever-arm l is the distance between the base and centroid.

$$M_{\max} = F_n.l = (\tfrac{1}{2}\rho \hat{V}_h^{\,2}.C_{F,n}.A).l \qquad \text{(App.1.2)}$$

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

The plastic moment capacity of the posts M_p is given by Equation App.1.3, where f_y is the yield strength of the material and s is the plastic section modulus.

$$f_y = M_p / s \;;\; M_p = f_y.s \qquad \text{(App.1.3)}$$

A plastic hinge in the post(s) is created when the bending moment generated by the wind load exceeds the plastic moment capacity M_p of the post(s), as shown in Equation App.1.4. The failure wind speed at centroid height is then determined from Equation App.1.5.

$$M_{\max} \geq M_p \; ; \; (\tfrac{1}{2}\rho \hat{V}_h^{\,2}.C_{F,n}.A).l \geq f_y s \qquad \text{(App.1.4)}$$

$$\hat{V}_h^{\,2} \geq f_y s/[(\tfrac{1}{2}\rho.C_{F,n}.A).l] \; ; \; \hat{V}_h \geq \sqrt{f_y s/[(\tfrac{1}{2}\rho.C_{F,n}.A).l]} \qquad \text{(App.1.5)}$$

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

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

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

This process was used to determine upper and lower bounds to wind speed for several signs in the investigation area, as detailed in Table App.1.1.

Table App.1.1 Signs used to Estimate Wind Speeds

ID	**Vr** (kph)	V_r (m/s)	U/L	Location	TC	No. Legs
1	172	48	U	Red Bluff Kalbarri	2	1
2	172	48	U	Red Bluff Kalbarri	2	1
3	174	48	U	Red Bluff Kalbarri	2	1
4	135	38	L	Geraldton to Northampton Rd	2	2
5	145	40	L	Geraldton to Northampton Rd	2	1
6	176	49	L	Geraldton to Northampton Rd	2	2
7	111	31	L	Port Gregory	2	1
8	111	31	L	Port Gregory	2	1
9	168	47	L	Kalbarri	2	1
10	168	47	L	Kalbarri	2	1
11	*142*	*39*	U	Kalbarri	2	2
12	168	47	L	Kalbarri	2	1
13	168	47	U	Kalbarri	2	1
14	266	74	U	Kalbarri	2	1

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

Appendix 2 – Internal pressures for design in Wind Region B

Background on design internal pressures in AS/NZS 1170.2

AS/NZS 1170.2 is the primary Australian Standard for determining wind loads on structures referenced in the National Construction Code (NCC). It can be used on any building and requires the detailed calculation of design wind speed on the structure and individual calculations of pressures on each component.

AS 4055 is also a primary referenced document in the NCC, but its scope limits its application to houses, garages and sheds with limitations on the size and shape of the building. It applies simplified methods and derives a wind classification that can be used to specify many construction components, including structural members, cladding and windows.

Regardless of which Standard designers use to determine the wind loads on a building, the net loads and pressures on the roof, walls, structural and cladding components are a combination of internal and external pressures across the building envelope. The external pressures are represented in Figure App.2.1 with arrows away from the surface showing suction. Suction pressures on the roof apply upward forces that will lift the roof if it isn't tied down properly. The windward wall has pressures towards the surface, tending to push the wall into the building. Figure App.2.1 shows a sealed building; there are no openings that would allow air into the internal spaces. The consequences of a window or door breaking, which would allow air into the building, are discussed below.

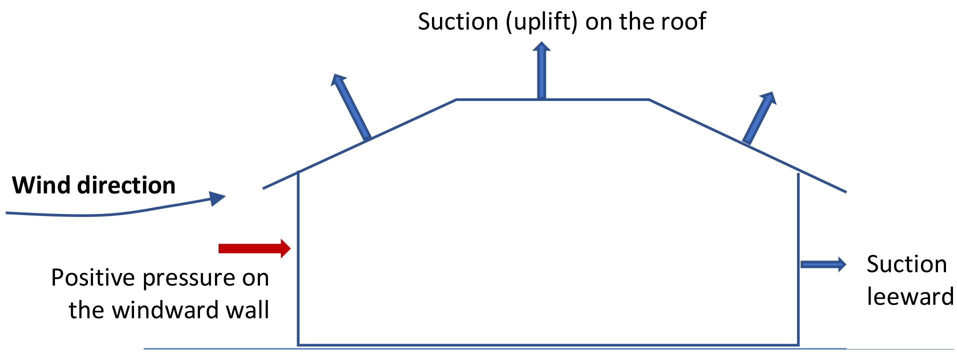


Figure App.2.1 Typical external pressures on a building

Internal pressure

Whenever there is an opening, the internal pressure will be affected by the external pressure adjacent to the opening. Where there are multiple openings, the net effect on the internal pressure is a function of the size of the openings and the external pressures at the location of the opening. If there is a single large opening in a windward wall, the internal pressure will be very close to the positive pressure next to the opening.

This situation is illustrated in Figure App.2.2 and shows that the net pressure across the roof is the sum of upward pressure on the underside of the roof and upward suction on the upper side of the roof. The net pressure on the roof in Figure App.2.2 is significantly higher than the net pressure in Figure App.2.1. Therefore, large openings in the windward wall can substantially affect the net pressures on all the building elements.

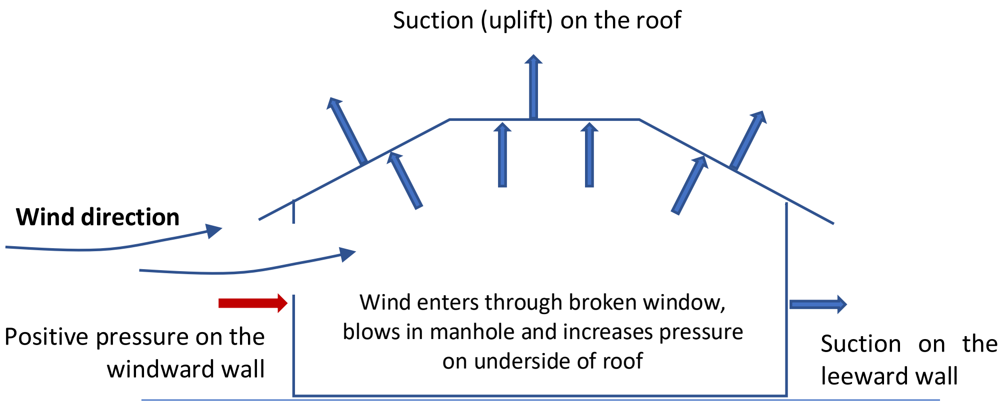


Figure App.2.2 Typical internal pressures on a building with an opening on a windward wall

A building's performance under the net pressures shown in Figure App.2.2 will be a function of whether the designer assumed there would be an opening in a windward wall (e.g., a broken window or door) in designing the tie-downs in the tie-down chain.

Table App.2.1 summarises common design assumptions made for internal pressures with the two wind loading standards.

Table App.2.1 Design assumptions on internal pressure

	Wind Regions A and B	**Wind Regions C and D**
AS 4055		
Assumed internal pressure Table 3.1 and 3.2(A)	+0.2 or –0.3, whichever is worse	+0.7 or –0.65, whichever is worse
AS/NZS 1170.2		
Combination of openings	Worst combination assumed. Assume windows or doors may be open, have failed or holed by debris	
<u>Must</u> be considered as openings	Non-wind-rated windows and doors	Non-wind-rated windows and doors and any rated elements that are susceptible to debris damage
Normal internal pressure table	Table 5.1(A) or Table 5.1(B)	Table 5.1(B) with a ratio of openings 2 or more
Common positive internal pressure in design	Designers have often chosen +0.2	+0.5 to +0.7

Robustness

The NCC requires that buildings can sustain local damage:

BP1.1 Structural reliability

(a) A building or structure, during construction and use, with appropriate degrees of reliability, must—

(i) perform adequately under all reasonably expected design actions; and

(ii) withstand extreme or frequently repeated design actions; and

(iii) be designed to sustain local damage, with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage; and

(iv) avoid causing damage to *other properties*, by resisting the actions to which it may reasonably expect to be subjected.

The loss of a roof because a window or door breaks does not meet the requirement for robustness. Limitations on design internal pressure in Wind Regions C and D assume that windows and doors in cyclones can be broken. The buildings in Wind Regions C and D are designed to resist the resulting change in internal pressure. (See Section 0) As severe tropical cyclones can affect communities in Wind Region B, similar limitations on design internal pressure are needed to deliver robustness for buildings in Wind Region B.

Statement of the problem

Section 4.1.1 showed that in Kalbarri, failure of windows and doors under wind or debris loading led to the failure of even compliant roofs on both contemporary and older houses. The design assumptions for Wind Region B led to the use of internal pressure coefficients of +0.2/-0.3 for the design of these houses. After a windward window or door had broken, the actual internal pressure would have jumped to a value of +0.7. This effectively increased the net uplift on the roof between 1.5 and 2 times and caused the failure of the roof structure.

This failure mode violated the principle of robustness, as a window or door failure is considered local damage. It caused significant damage to the structural system as a whole, with damage disproportionate to the original local damage.

Table 3.1(A) in AS/NZS 1170.2:2011 distinguishes between non-cyclonic regions (A and B) and cyclonic regions (C and D). However, tropical cyclones are expected as the design wind event in region B:

- Wind Region B is a region that wraps around Wind Regions C and D, where tropical cyclones cause the design wind gusts.
- The direction multipliers M_d are the same in Wind Regions B and Wind Regions C and D. They account for the fact that in tropical cyclones, the wind directional multipliers cannot be predicted from historical records.

A revision of AS/NZS 1170.2 has nearly been completed at the time of writing this report. Two extra features of the revised version show that the portion of Wind Region B in the study area (known as wind region B2 in AS/NZS 1170.2:2021) is similar to Wind Regions C and D:

- A climate change factor models the potential for the intensity of tropical cyclones to increase with global warming. Climate change models indicate that in most climate change scenarios, the frequency of all cyclones may decrease, but the intensity of the stronger ones may increase in the Australian region. The climate change factor is applied to Wind Regions B2, C and D.
- In the draft, there is a linear interpolation of the design wind speed across Wind Regions B2, C and D to allow for the decay of tropical cyclones after making landfall.

While Wind Regions B in the current standard and B2 in the draft are classed as non-cyclonic, TC Seroja has demonstrated that the characteristics of wind actions in cyclones should be considered in the design of buildings in this region.

Solution

If a solution is to be implemented in a Standard, it will be in AS/NZS 1170.2:2021, so the solution will reference that version of the standard. AS/NZS 1170.2 must recognise that Wind Region B2 is cyclonic rather than non-cyclonic. This change will have the following implications:

- Wind Region B2 is to be classed as cyclonic in Table 3.1(A)
- In the limitations on internal pressure in Clause 5.3.1, in every case where a distinction is made between the Wind Regions, Wind Region B2 should be grouped

with Wind Regions C and D rather than Wind Region A. (Internal pressure coefficients will be taken from only Table 5.1(B), with a minimum positive internal pressure coefficient of +0.5.)
- There are a few other references to Wind Regions C and D, which will also require an amendment to include Wind Region B2. E.g. the note in Clause 2.5.5, which raises low-cycle fatigue in tropical cyclones.

There will also be implications for other Standards, including:
- AS/NZS 1562.1 and AS 4040.3, which define cyclic testing of cladding systems for cyclonic wind areas.
- AS 4055, which assigns C-classifications for cyclone areas and N classifications for non-cyclone areas.
- Other building component standards such as the tile standard (AS 2050), the window standard (AS 2047).

N classifications and C classifications
Two systems of wind classifications for houses are defined in AS 4055 (Standards Australia, 2012):
- N-classifications, currently used in Wind Regions A and B that includes inland parts of WA and coastal areas from Kalbarri south; and
- C-classifications, currently used in Wind Regions C and D that includes the coastal parts of WA from Shark Bay north.

The pressures evaluated for the N-classifications in AS 4055 assume that all doors and windows can resist the design wind forces and won't be damaged by wind-borne debris.

The pressures evaluated for the C-classifications consider wind-borne debris impact that may break doors and windows and form dominant openings. Wind-borne debris will always strike the windward side of a house, and the dominant opening causes the internal pressure to be close to the external pressure on the windward wall. Also, once the wind direction changes, the dominant opening may be on a side or leeward wall and cause negative internal pressures.

The assumed internal pressures for the N-classifications and the C-classifications are summarised in Table App.2.1. Stronger tie-downs in the roof structure are required for houses with C classifications compared with those required for homes with N-classifications with the same wind speed at the house site.

Figure App.2.3 plots the net uplift pressure used to evaluate tie-down requirements between the roof structure and walls for houses with sheet roofs for each of the N and C Wind classifications. It is derived from Tables 2.1 and 4.1 in AS 4055 and indicates:
- The wind speed at house level is the same for N3 and C1, N4 and C2, etc.
- The net uplift pressures for the C classifications are higher than those for the N classifications for the same wind speed by around 50% of the uplift pressures for the N classifications.

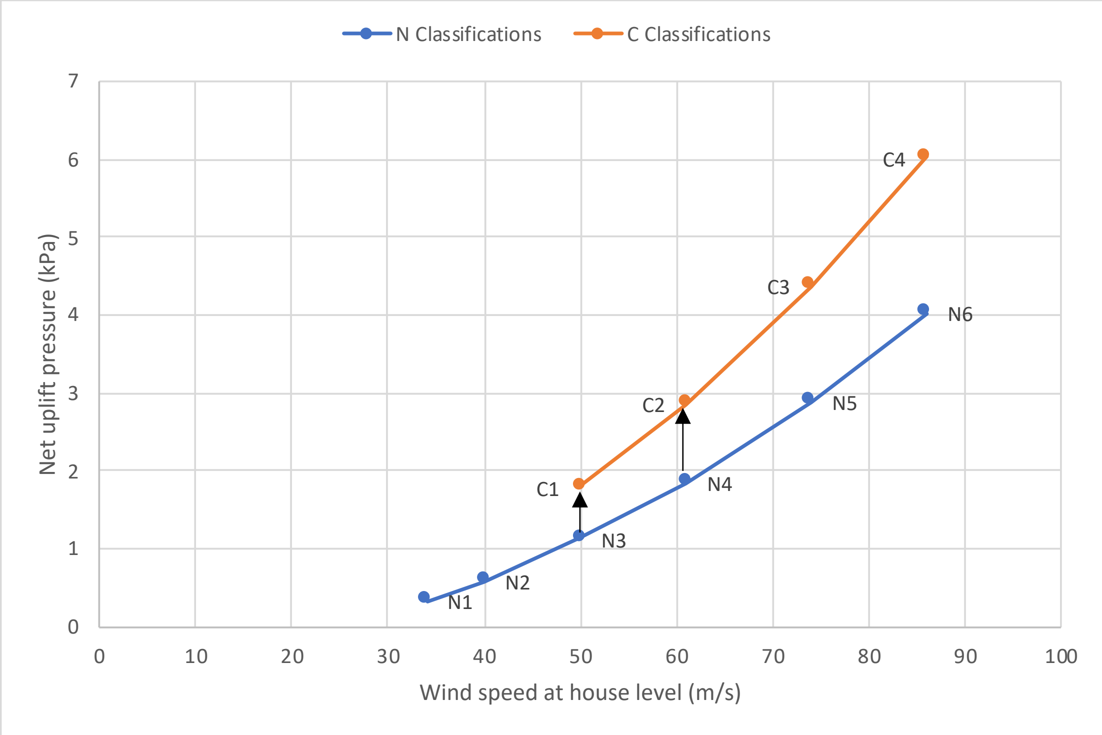


Figure App.2.2 Net uplift pressures for N and C Wind classifications for sheet roofs

The following table gives wind speed equivalent C Wind classifications for each of the N Wind classifications based on design wind speed. e.g., C2 is the wind speed equivalent to N4. The design wind speed is the same for both classifications, but the C classification means the roof structure will be strong enough to cope if a window or door breaks during a cyclone.

N classification	C Classification
N2*	C1
N3	C1
N4	C2
N5	C3
N6	C4

**There is no direct equivalence between N2 and a C-classification, but it is conservative to use C1 for N2 house sites.*

The higher net pressure on a house roof and the higher internal pressure associated with the C classification rather than the equivalent N classification leads to higher wind forces on components such as roof structural elements and windows. This may increase the cost of construction.

An example of the difference between tie-down details for N and C wind classifications for sheet roofs

The examples in Tables App.2.1 and App.2.2 present the difference in tie-downs required for sheet roofs if C Wind classifications rather than N Wind classifications are used in the design of houses in Wind Region B.

Table App.2.1 Replace N3 requirements with C1 requirements

Roof element	Reference	N3 details	C1 details	Cost implications
Roof cladding	Refer to manufacturer's specifications			Additional fasteners and perhaps closer batten spacings
Batten to rafter connections	AS 1684 for 900 mm rafter spacing and 900 mm batten spacing			
	Load per fastener	1.2 kN general areas 2.3 kN edge areas	1.9 kN general areas 3.0 kN edge areas	Extra battens and screws
	Connections	75 mm Type 17 screw (3.6 kN)	75 mm Type 17 screw (3.6 kN)	No difference
Truss/rafter	AS 1684 for rafter selection; or Truss manufacturer	120 x 35 MGP10	120 x 45 MGP10	Larger width member Slightly more expensive truss
Truss/rafter to wall connections	AS 1684 for 6000 mm ½ RLW; and 900 mm truss spacing			
	Load per truss/wall connection	7.1 kN	11 kN	
	Connection	Looped strap (13 kN)	Looped strap (13 kN)	No difference
Windows	Ultimate test pressure	1400 Pa	1800 Pa	Additional cost for higher wind rated window

Table App.2.2 Replace N4 requirements with C2 requirements

Roof element	Reference	N4 details	C2 details	Cost implications
Roof cladding	Refer to manufacturer's specifications			Additional fasteners and perhaps closer batten spacings
Batten to rafter connections	AS 1684 for 900 mm rafter spacing and 900 mm batten spacing			
	Load per fastener	1.9 kN general areas 3.5 kN edge areas	2.8 kN general areas 4.5 kN edge areas	Extra battens and screws
	Connections	75 mm Type 17 screw (3.6 kN)	100 mm Type 17 screw (4.7 kN)	Longer screws
Truss/rafter	AS 1684 for rafter selection; or Truss manufacturer	120 x 35 MGP10	120 x 45 MGP10	Larger width member Slightly more expensive truss
Truss/rafter to wall connections	AS 1684 for 6000 mm ½ RLW; and 900 mm truss spacing			
	Load per truss/wall connection	11 kN	18 kN	
	Connection	Looped strap (13 kN)	2 x Looped strap (26 kN)	Extra looped strap per connection
Windows	Ultimate test pressure	2000 Pa	2700 Pa	Additional cost for higher wind rated window

Houses with N2 Wind classifications could also use the details for C1.

Appendix 3 – Wind classification

Indicative wind classifications for Kalbarri using AS 4055 (Standards Australia, 2012) were estimated from satellite imagery, contour maps and experience in the town during the investigation. (Figure App 3.1 and Figure App 3.2.) These were not rigorous determinations and were only used to investigate any potential link between the level of damage and wind classification.

Terrain Category

The more established parts of Kalbarri are just south of the Murchison River estuary, where it meets the sea. Parts of the town are within 500 m of the ocean (Terrain Category 1.5), and parts are within 500 m of the estuary (Terrain Category 1). The newer subdivisions south of the town, just east of the Port Gregory – Kalbarri Rd, are all more than 500 m from the sea.

All parts of Kalbarri are less than 500 m from open country, so the highest terrain category achievable in Kalbarri is Terrain Category 2.

Topography

Many houses in Kalbarri have good views as the town is on land that rises from the river. The more established part of the town is at elevations less than 30 m on a hill that rises to 200 m at Meanarra Hill. Most of the more established part of town is in the lower third of a high hill and has a topographic classification of T0. The only exception is the very western edge of town, where the sea cliffs can be considered an escarpment. Several rows of houses on the western edge of the more established part of Kalbarri are in the over-the-top zone of this escarpment and have a T1 topographic classification.

The newer subdivisions east of the Port Gregory – Kalbarri Rd are at a higher elevation. Only the southernmost part of these subdivisions is in the upper third of the hill and can be considered a T1 topographic classification.

Shielding

In the more established parts of Kalbarri, the subdivisions are nearly entirely developed. It is reasonable to assume that any vacant blocks could be developed within the next five years.

The newer sub-divisions to the south of Kalbarri east of the Port Gregory – Kalbarri Rd were developed in the 1990s and 2000s.

- The allotments in the most northern of these subdivisions (accessed via Flora Boulevard) are small enough to have full shielding (FS) if the subdivision was fully developed. But, after at least ten years, the housing is sparse, and no houses in the subdivision have FS. All current houses in the subdivision are not shielded (NS).
- The allotments in the other subdivisions (generally south of Jaques Boulevard) are larger. It was not possible to achieve ten houses per hectare even if the subdivision was fully developed. The maximum possible shielding was partial shielding (PS), but again, the current housing is so sparse that no houses in the subdivision have PS.

All houses in all the newer subdivisions 4 to 7 km south of the town centre are not shielded (NS). As the subdivisions are at least ten years old, it is unlikely that they will be sufficiently developed to achieve their maximum possible shielding within the next five years.

Wind classification

Figures App.3.1 and App.3.2 present indicative wind classifications for the more established part of Kalbarri and the southern subdivisions.

These classifications are only a guide for this report. Site wind classifications for construction or repair of individual houses must be evaluated by an appropriately trained person who visits the site.

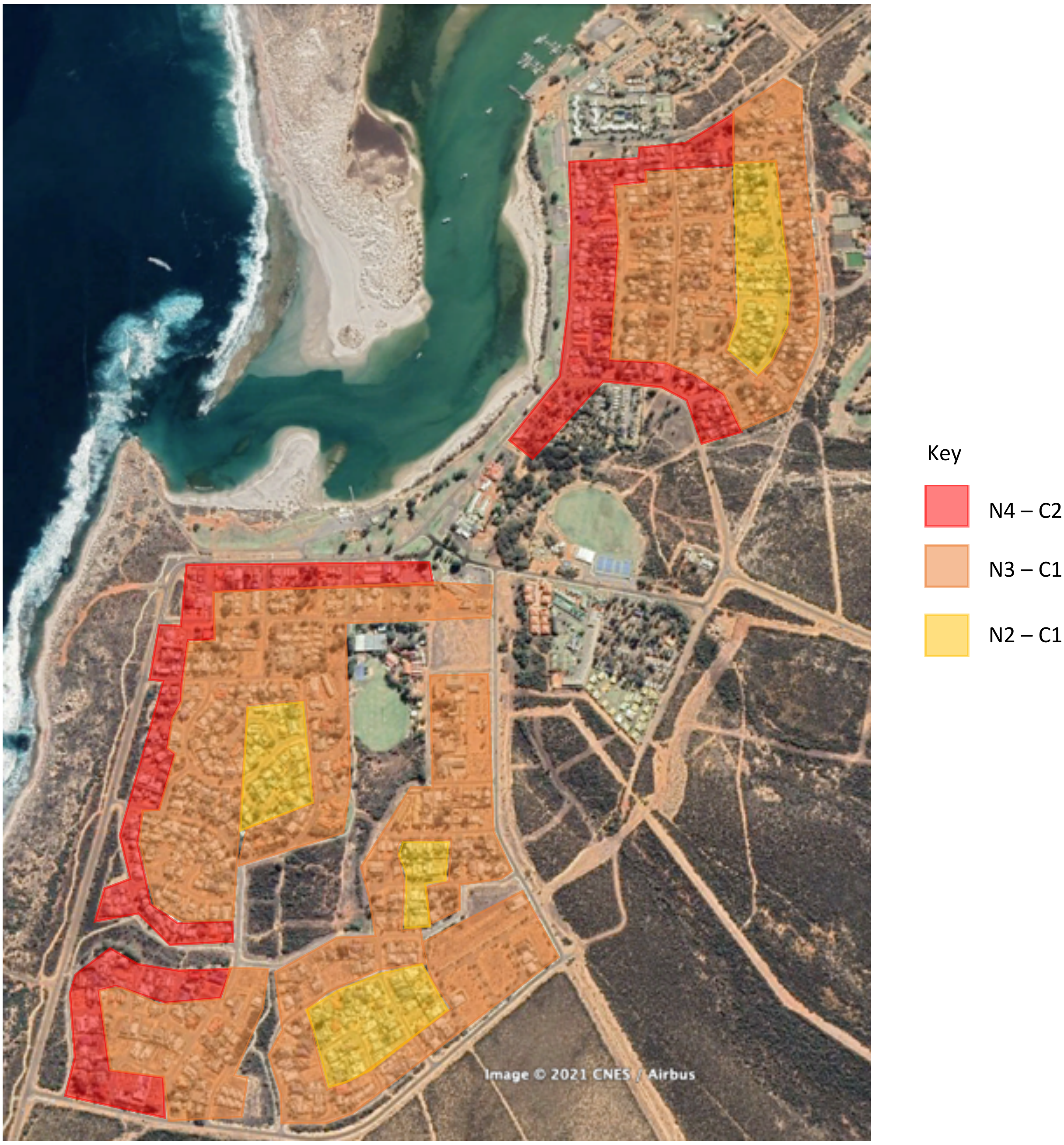


Figure App.3.1 Wind classifications to AS 4055 for house sites in the more established part of Kalbarri

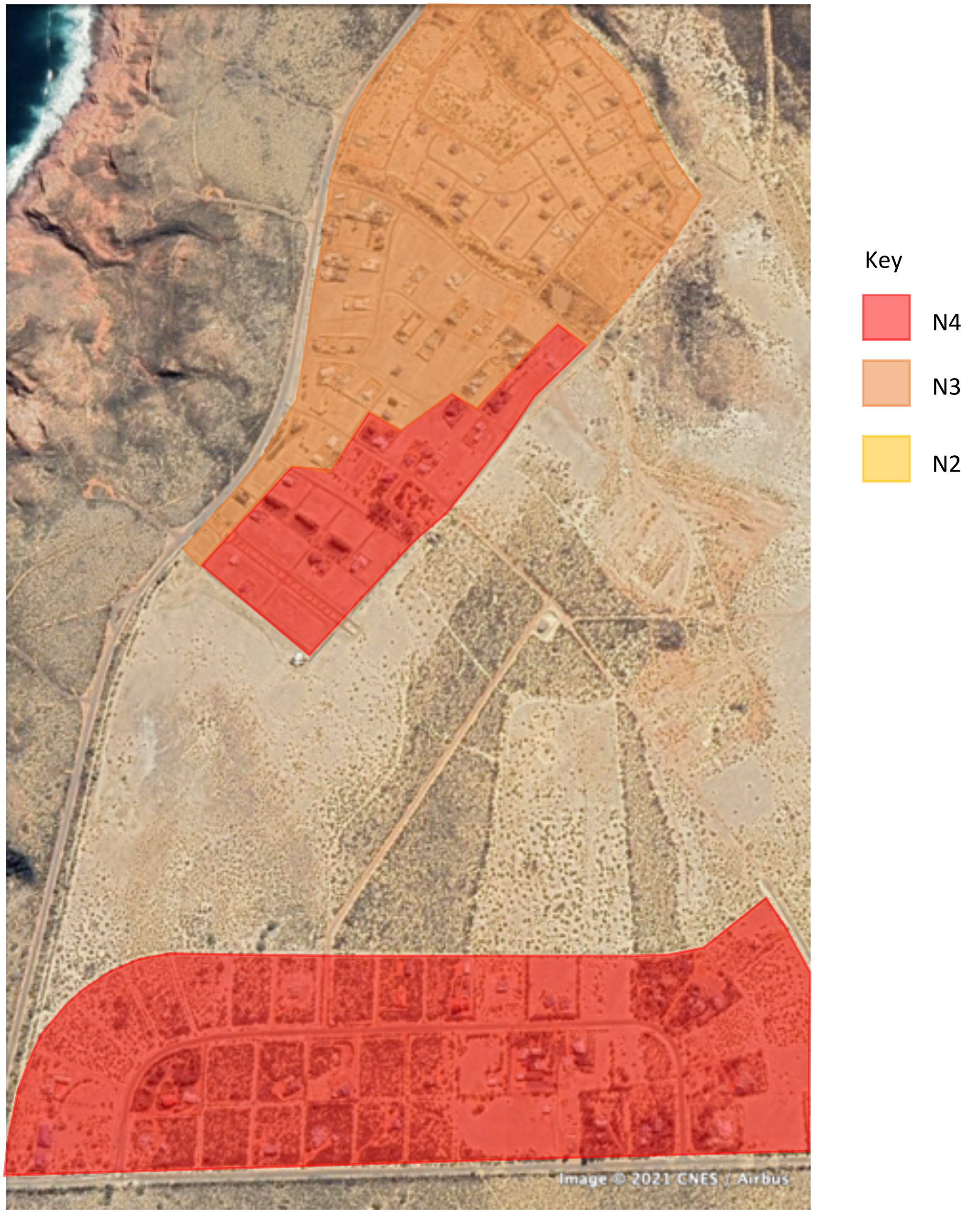


Figure App.3.2 Wind classifications to AS 4055 for house sites in newer subdivisions of Kalbarri

The RDA data for houses in Kalbarri was matched with the estimated wind classifications shown in Figure App.3.1 and Figure App.3.2. The results are presented in Figure App 3.3.

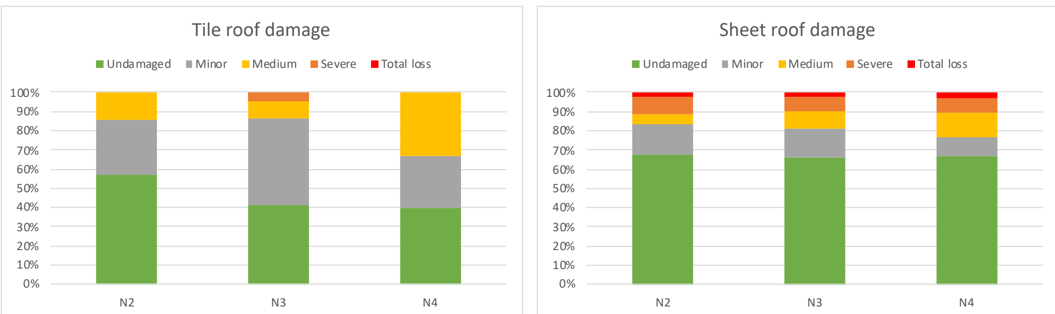


Figure App.3.3 Damage to roofs in different Wind classifications

Figure App.3.3 shows that:

- The level of damage to tile roofs increased slightly with wind classification.
- Levels of damage to sheet roofs were similar for all wind classifications.

This indicates that the level of damage to roofs in Kalbarri was influenced more by the effects of increased internal pressure than the wind classification.