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FOR A SAFER STATE

2024 Severe storms in Bunbury, WA
Damage to Houses

CTS Technical Report No 68

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TECHNICAL REPORT NO. 68

2024 Severe Storms in Bunbury, WA

Damage to houses

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Investigation Bunbury,WA tornado 10/5/2024 – Damage to houses
1. Bunbury tornado 2024 2. Wind speed 3. Damage to houses 4. Damage to carports and patios 5. Damage to buildings – Natural disaster effects 6. Wind damage

LIMITATIONS OF THE REPORT

Executive Summary

At around 4 pm on Friday 10th May 2024, a tornado passed through the suburbs of South Bunbury, Withers and College Grove in Bunbury, WA in wind region A. The winds caused damage to more than 100 houses along a path approximately 40 m wide.

At around 9.45 pm on Saturday 1st June 2024, a downburst passed through the suburbs of East Bunbury, Glen Iris and Picton and also caused damage to more than 100 houses and a number of commercial buildings along a 300 m wide path.

A road sign was used to estimate the wind speeds in the 10/5/2024 tornado at around 160 km/h, which corresponds to an EF1 tornado. This was around the design wind speed for importance level 2 buildings in Bunbury. A different sign was used to estimate that the wind speeds did not exceed 120 km/h in the downburst on 1/6/2024. This wind speed was around 75% of the design wind speed for importance level 2 buildings in Bunbury.

Investigations of damage to houses after the two events concluded that wind-borne debris was an issue in wind region A and caused openings in a significant number of houses and the resulting internal pressures increased the level of damage to roofs. In both events, wind-borne debris included branches from trees, loose items around yards including trampolines and rubbish bins, lightweight carports and patio roofs and building components including roofing and solar panels.

Roof structures were lost where the tie-downs had not been strengthened following the replacement of heavy tiled or Asbestos Cement roofs with lighter sheet roofs. Recommendations are made to publicise the need for building permits whenever the weight of roofing material is changed in a roof replacement. Damage to some roofs in the tornado confirmed that straps into the bed joint mortar of brickwork intended to anchor the roof structure to the walls did not have sufficient strength near the design wind speed to resist the net uplift on many sheet roofs.

Tiles were lost from tile roofs in both events in winds at around the design wind speed or less. All tile roofs in the direct path of the tornado (that experienced the design wind speed) were damaged. This suggests that anchorage for tiles in N wind classifications need to be strengthened.

Recommendations are made for wind standards AS/NZS 1170.2 and AS 4055. These include:

- examining external roof pressures on skillion (monoslope roofs);
- reconsidering the internal pressures used in design of buildings in the non-cyclonic regions due to the large amounts of wind-borne debris that caused damage to wind region A buildings in both the EF1 tornado and the downburst; and
- inserting a note in the scope about the wind actions being appropriate for low intensity tornados.

Recommendations are also made for changes to AS 2050 *Installation of roof tiles* and AS 4773.1 *Masonry in small buildings – Part 1 Design*. It is also recommended that all garage doors in regions A and B1 be mandated to comply with AS/NZS 4505. This will limit damage to buildings due internal pressures created by garage door failures.

Acknowledgements

The authors thank the residents of the affected Bunbury communities who generously assisted with this study by volunteering information and inviting the authors onto their properties.

During this investigation, the CTS team worked closely with Building and Energy, and the Department of Fire and Emergency Services (DFES) WA. 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. The outcomes of the study will ultimately contribute to improved community resilience to future extreme wind events in all parts of Australia. The authors particularly acknowledge the support given by:

- **Building and Energy** – particularly Paul Gronow, Mark Riordan and Sean de Prazer.
- **DFES** – provided information and data on the location of damaged properties and contact details of people in the area that could facilitate visits to properties. The team particularly appreciated the assistance of Matt Zanini and Adrian Brannigan.
- **The Bureau of Meteorology** – especially Dean Sgarbossa and Melody Sturm for providing feedback and the BoM summary information.

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Table of contents

1. Introduction

This report covers damage to houses from two separate wind events within 3 weeks in Bunbury, WA in wind region A.

1.1. Overview of the Bunbury tornado on 10th May 2024

At around 4pm on 10th May 2024, a tornado passed through the suburbs of South Bunbury, Withers and College Grove. Early reports indicated that there had been no deaths, two injuries and damage to more than 100 houses, the Police and Citizens Youth Centre (PCYC) and some buildings at the Bunbury Regional Prison.

Figure 1-1 shows captures from the ABC news showing the distinct form of a tornado with some debris caught up in the rotational air around the vortex.

Figure 1-1 Capture from media coverage of the 10/5/2024 event (ABC news)

1.2. Overview of the Bunbury downburst on 1st June 2024

At around 9:45pm on 1st June 2024, a downburst embedded in a severe thunderstorm passed through the suburbs of East Bunbury, Glen Iris and Picton. Early reports indicated that there had been no deaths, no injuries and wind damage to around 30 houses, the Parade Hotel, the Koombana Bay Sailing Club and some commercial buildings, mainly in Picton. These early reports significantly underestimated the extent of the damage. (Some early media reports also indicated that this event may have been a second tornado.)

Residents reported that a lot of lightning activity accompanied the storm. Figure 1-2 shows a capture from the ABC news showing the rain lit up by lightning.

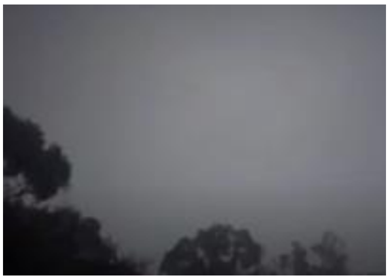


Figure 1-2 Capture from media coverage of the 1/6/2024 event (ABC news)

1.3. Purpose of the report

This report presents the outcomes of the joint Cyclone Testing Station (CTS), the Department of Energy, Mines, Industry Regulation and Safety, Building and Energy Division (Building and Energy), and the WA Department of Fire and Emergency Services (DFES) field investigations. The aim of the investigations was to learn from damage to buildings in the affected area.

The report identifies problems in building performance and highlights some issues that need to be considered for changes to building practices, and for revision of Codes and Standards.

1.4. Investigations

- The first field study into the tornado on 10/5/2024 commenced on Saturday, 11 May 2024 and was augmented by information, and trips by Building and Energy inspectors throughout the following week. DFES provided data on Damage Assessments on the damaged buildings for the 10/5/2024 tornado.
- The second field study into the storm on 1/6/2024 commenced on Monday 3 June 2024. DFES provided data on building Damage Assessments for the 1/6/2024 downburst.

Figure 1-3 shows the location of damaged buildings from the two events. Both events started the damage at the coast and progressed generally east southeast inland:

- The locations of extensively damaged buildings in the 10/5/2024 tornado are shown with circles, with the path of the tornado shown in blue. The path of damage was estimated to be around 40 to 60 m wide. The level of damage was consistent along the path.
- Buildings with at least moderate damage in the 1/6/2024 downburst are shown with squares and the damaged area highlighted in red. The path of the damage was estimated to be between 300 and 500 m wide.

In both events, the investigation team focused on structural damage to houses and attachments such as solar panels, carports and patio roofs.

Damage Assessments of more than 730 buildings were undertaken by DFES in the first few days after the 10/5/2024 tornado and of 680 buildings in the first few days after the 1/6/2024 storm event. More commercial and light industrial buildings were along the path of the downburst in the 1/6/2024 storm event compared with the 10/5/2024 tornado.

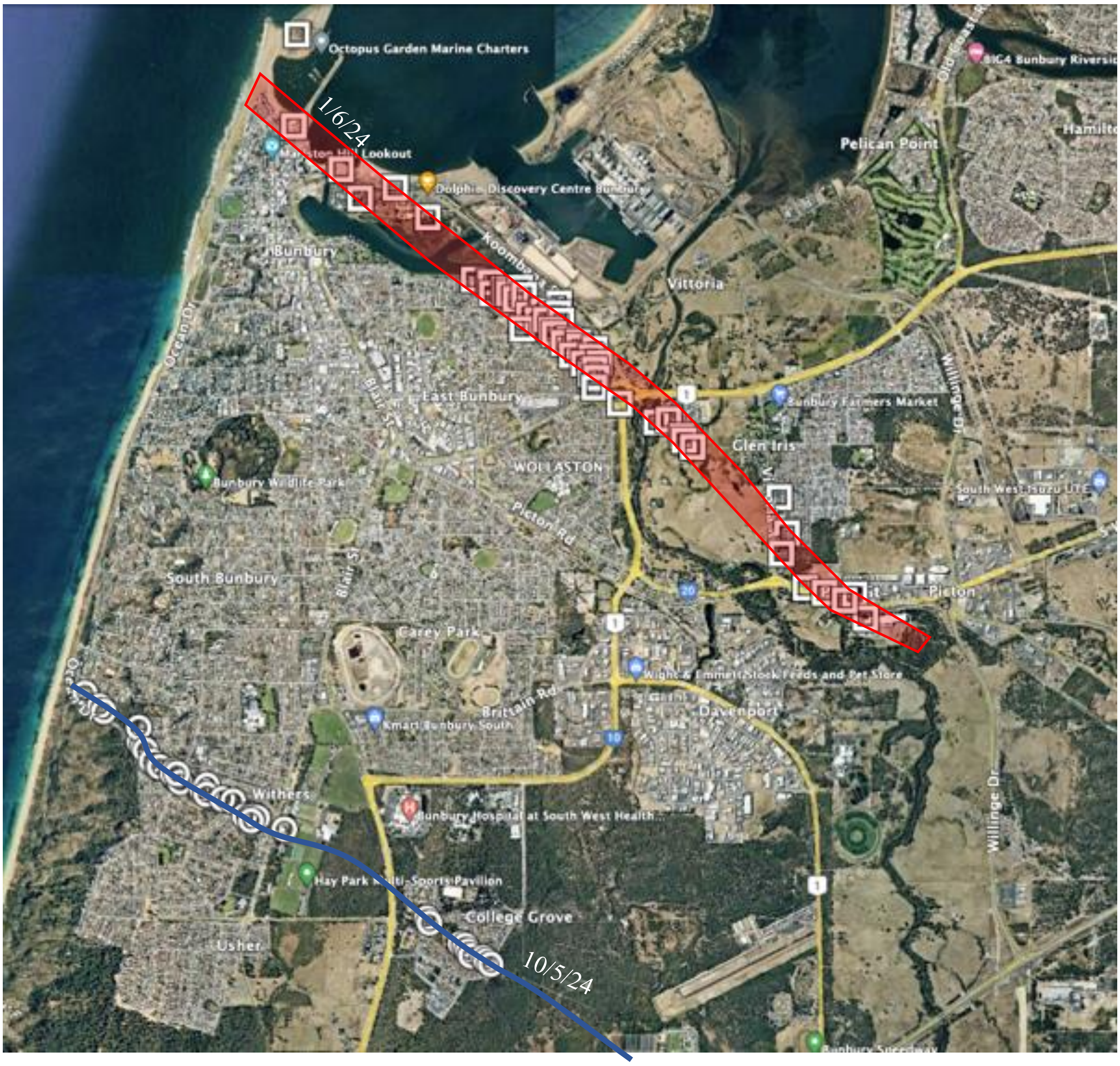


Figure 1-3 Buildings extensively damaged in the two 2024 Bunbury storm events showing their paths

2. Bunbury tornado 10/5/2024

2.1. Generation

The following information was provided by the Bureau of Meteorology:

> *A cold front combined with strong upper-level forcing formed a band of thunderstorms as it approached WA's southwest coast. The band of thunderstorms upscaled to a Quasi-Linear Convective System (QLCS), a type of larger scale convective system that typically forms in low instability but high wind shear environments that can produce damaging to destructive wind gusts and at times tornadoes, as the cold front moved onshore. A tornado embedded within this band of thunderstorms developed near the South Bunbury coast around 4 pm AWST and moved inland towards the east-southeast at approximately 60 km/h, leaving a swathe of damage across the suburbs of South Bunbury, Withers and College Grove.*

Interrogation of the Perth (Serpentine) radar (located 110 km north of the impacted area) suggests that the tornado may have formed at the inflection point of two thunderstorm cores within the broader band of thunderstorms, a favourable location for tornadoes and destructive wind gusts within QLCS. Relatively weak rotation was observed on radar, but due to the distance of the radar from the impacted area whereby the lowest radar tilt (0.5° elevation) was observing at a height of 1,744 m above sea level, it was not possible to observe Tornado Vortex Signature (TVS) or Tornado Debris Signature (TDS) to confirm tornado occurrence from radar data alone.

Figure 2-1 shows a capture of weather radar supplied by the Bureau of Meteorology at the time the event was occurring with the white arrow highlighting the location of the tornado at the time of the image and the white line showing the approximate path noted in this report.

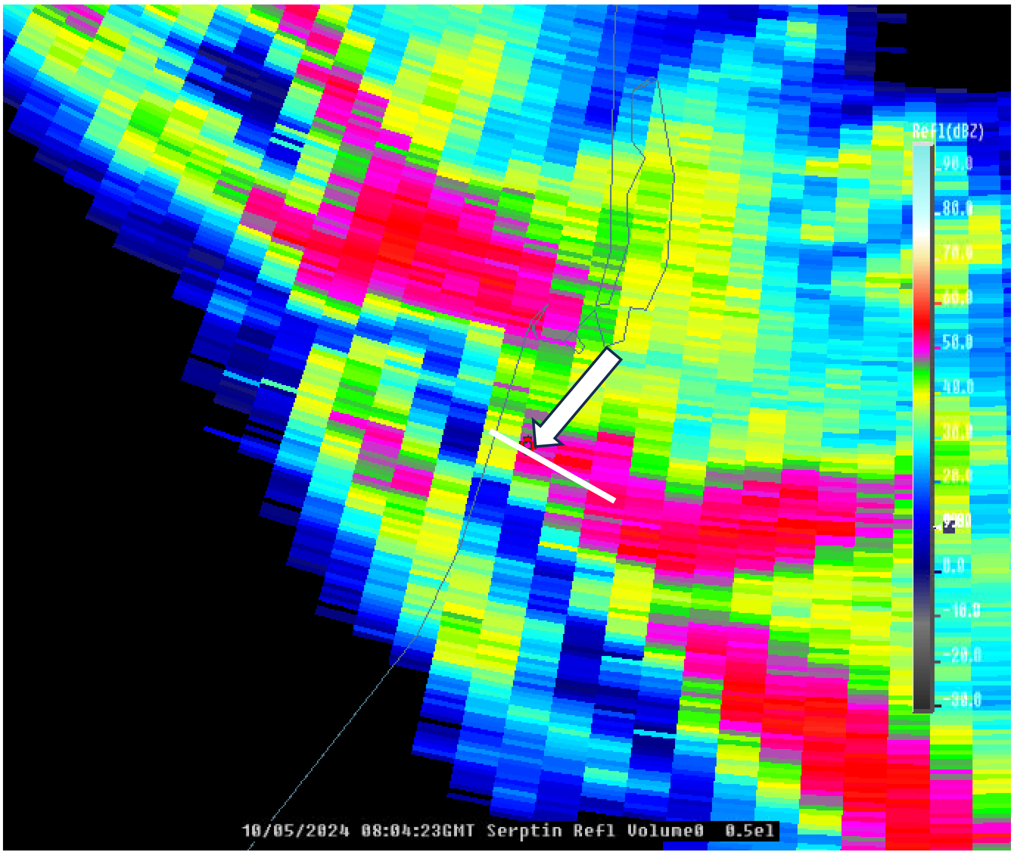


Figure 2-1 Weather radar capture at the time of the tornado (Bureau of Meteorology)

2.2. Estimation of wind speed

Figure 2-2 shows a single road sign that was used to estimate the wind speeds associated with the tornado. It was on the path indicated in blue in Figure 1-3. The sign gave no indication that it had been struck by debris. The post had started to form a plastic hinge just below ground level and was used as a ‘windicator’ – a simple structure that can be used to give an indication of the wind speed.

While it is desirable to use a number of ‘windicators’, in this very local event there were only two signs that were on the path. One was not affected by debris (Figure 2-2) and the other was impacted by a large branch (Figure 4-18). Only the sign shown in Figure 2-2 could be used to estimate the wind speed in the event.

Figure 2-2 A road sign used to estimate wind speed.

In previous wind damage investigations, upper and lower-bound wind speeds were estimated using damage to a number of road signs along the path of the event.

- Lower-bound signs were those which had failed by bending the posts (forming ‘plastic hinges’). The wind speed to cause the damage was higher than the wind speed that would have created enough load to fail the post, and this is shown in the photo of Figure 2-2.
- Upper-bound signs had not failed by forming plastic hinges in the posts and remained upright. The wind speed cannot have exceeded the speed that would have created enough load to fail the post. This is shown in Figure 3-2.
- Where the pole had just started to fail but hadn’t developed a full plastic hinge, the lower-bound wind speed was likely close to the actual wind speed. This is the case for the sign in Figure 2-2.

The wind speed calculated from the measurements of the sign was estimated to be close to the actual wind speed as it was a lower bound sign that had just started to fail. The calculations gave a wind speed corrected for standard conditions (0.2 sec gust, 10 m height over flat, relatively smooth terrain) of 47 m/s. Within the calculation tolerances, this is about the same as the design wind speed (V_{500}) for wind region A (45 m/s) in which Bunbury is situated.

As the measurements had been made on a sign that was about 2.5 m above the ground, the wind speeds were valid for structures at about that height, including walls, single storey houses, carports, garages and patio roofs. The calculated wind speeds are valid for heights of buildings 2 to 5 m, even if the vertical profile of wind in the tornado was not the same as that used in the standard AS/NZS 1170.2 (Standards Australia, 2021a). The sign showed that within the tolerances of the calculations, the wind speed that affected buildings in this tornado can be regarded as about the same as the wind speed used for designing Importance Level 2 buildings in Bunbury.

The estimates of wind speed were appropriate for a tornado classified as EF1 on the Enhanced Fujita scale (roughly equivalent to F1 on the original Fujita scale). This is commensurate with the damage to trees and buildings observed. Figure 2-3 shows examples of the maximum damage to trees along the path. The trees shown are eucalyptus species, mainly tuarts (*eucalyptus gomphocephala*).

Figure 2-3 Peak damage to vegetation along the track of the tornado.

2.3. Tornadoes and AS/NZS 1170.2

AS/NZS 1170.2 (Standards Australia, 2021a) does not include the design of buildings to resist tornados as shown in the excerpt shown in Figure 2-4.

> **1.1 Scope**
>
> This Standard sets out procedures for determining wind speeds and resulting wind actions to be used in the structural design of structures subjected to wind actions other than those caused by tornadoes.

Figure 2-4 Scope of AS/NZS 1170.2.

The reason for the exclusion is that very strong tornadoes create actions that exceed the design loads given in AS/NZS 1170.2 for wind regions A and B, but have a very low probability of occurrence. It is outlined in the AWES handbook – with an excerpt shown in Figure 2-5.

> The effects of tornadoes are also excluded in *Clause 1.1*. In Australia, only about sixteen confirmed tornadoes occur on average each year, over the whole country. The risk of a direct strike on an individual structure is minimal; however a structure designed to satisfy AS/NZS 1170.2 should perform satisfactorily in weaker tornadoes – i.e. Categories F1 and F2 on the Enhanced Fujita scale, as used in the United States.

Figure 2-5 Commentary on design for tornadoes in AWES handbook.

Section 2.2 showed that the tornado was estimated to be an EF1 event. This accords with the estimations by the Bureau of Meteorology. This intensity gives wind actions equivalent to the design wind actions for region A. The damage discussed in this report could all be explained by the actions of wind generated by the tornado.

Discussion of the failure of buildings and other structures under the wind loads created by this event are therefore valid. Wind speeds estimated at the height of the structures presented in the report are comparable with the relevant design wind speeds for the same structures.

> *Recommendation*
> Include a note in the scope of AS/NZS 1170.2 reflecting the information given in the AWES Handbook about the adequacy of the loads in the standard to resist low intensity tornadoes (EF0 and EF1 for wind region A, and EF0, EF1 and EF2 for wind region B).

3. Bunbury downburst on 1/6/2024

3.1. Generation

The following information was provided by the Bureau of Meteorology:

> *During the evening of Saturday, 1 June 2024, a band of thunderstorms known as a Quasi-Linear Convective System (QLCS), a type of larger scale convective system that typically forms in low instability but high wind shear environments that can produce damaging to destructive wind gusts and at times tornadoes, traversed WA's southwest coast. Within this band of thunderstorms, two individual thunderstorm cells merged over the Bunbury area, that combined with well above average moisture through depth of the atmosphere, resulted in enhanced downdrafts and subsequent damaging wind gusts that resulted in an approximate 300 m wide swathe of damage. Interrogation of radar data, observed impacts including direct photographic/ videographic evidence and on the ground analysis suggests that the primary cause of damage in the area was not likely to be a tornado, but rather the significant enhancement of wind speeds between the two merging severe thunderstorm cells and strong downdrafts. It is estimated that wind speeds of 110-120 km/h were the likely cause of observed impacts.*

Figure 3-1shows captures of weather radar supplied by the Bureau of Meteorology at the time the event was occurring with the blue arrows highlighting the converging movement of systems and the white line showing the approximate damage path noted in this report.

The field investigation of this event found evidence that the strong winds were primarily from the WNW (parallel to the white line in Figure 3-1). This supports the fact that the strong winds on 1/6/2024 were longitudinal and not rotational – a downburst rather than a tornado.

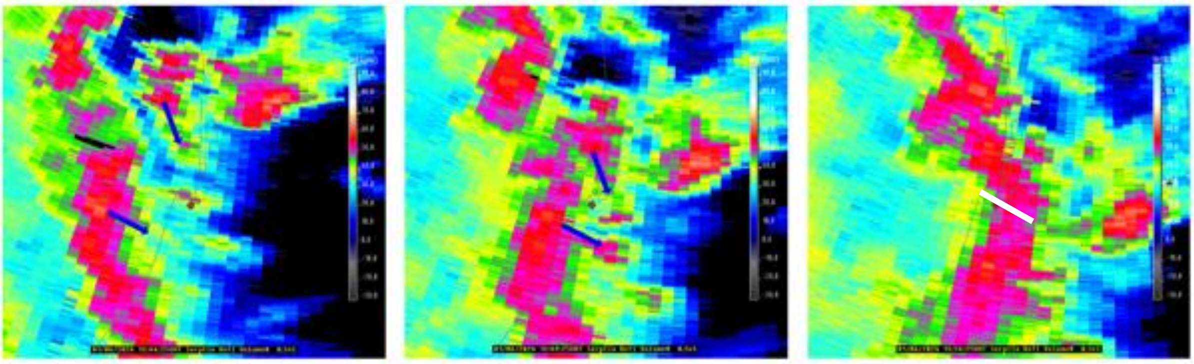


Figure 3-1 Weather radar capture at the time of the downburst (Bureau of Meteorology)

3.2. Estimation of wind speed

Figure 3-2 shows a sign in Glen Iris that was used to estimate the wind speeds associated with the downburst. It was on the path indicated in Figure 1-3 and the wind direction was directly onto the face of the sign. The sign gave no indication that it had been struck by debris. The posts were leaning slightly though this may have been due to rotation of the footing below ground level.

Another damaged sign was observed along the path of this event, but the failure was not a simple one involving multiple failure modes and the sign could not be used as a 'windicator'.

Figure 3-2 Sign at Glen Iris used to estimate an upper bound for the wind speed

Because this sign had not started to develop a plastic hinge in the posts, the sign could be used to calculate an upper bound to the wind speed at that location. The calculations showed an upper bound to the wind speed of 120 km/h or 34 m/s as a 0.2 sec gust which was around 75% of the design wind speed for importance level 2 buildings in Bunbury.

Again, it would have been desirable to use more than one ‘windicator’, but within the tolerances of the wind speed calculation, the wind speed was less than around 75% of the design wind speed and the wind loads were less than around 50% of the design wind loads for Importance Level 2 buildings in Bunbury.

Figure 3-3 shows the extent of tree damage along the path of the downburst. It is not as significant as the damage to the same tree species in the tornado and illustrated in Figure 2-3.

Figure 3-3 Tree damage along the path of the downburst

4. Performance of Houses

4.1. Damage assessments

DFES damage assessments were conducted in the days after the two wind events. Figure 4-1 shows examples of the damage in each of the 4 damage classifications used by the assessors.


(a) Slight damage (b) Moderate damage


(b) Severe damage (d) Total damage

Figure 4-1 Examples of damage classification.

4.1.1. Damage assessments following the 10/5/2024 tornado

DFES damage assessments indicated that after the 10/5/2024 tornado, around 220 houses showed some levels of damage. Of these, around 150 were slight damage leaving around 70 with moderate, severe or total damage. The results of the DFES damage assessment are shown in Table 1. The houses with total, severe or moderate damage (survival index of 3 or less) were all located directly on the path of the tornado. Those with slight damage were either on the edge of the path or nearby and were affected mainly by wind-borne debris.

The damage assessments were performed on buildings within more than 100 metres both sides of the path in order to pick up any damage from debris that fell outside the area of maximum winds. The tabulated data only shows the data for damaged houses and includes those along the path of the tornado and those outside the path that were affected by debris (usually classed as Slight Damage). The roofing material was only noted in the damage assessment if it was damaged. Where only the wall was damaged, the roof material was not noted.

Table 1 Results of DFES Damage assessment.

Damage level	Survival index	Number	Metal roof	Tile roof
Slight damage	4	150	>19	>88
Moderate damage	3	45	8	31
Severe damage	2	18	7	11
Total Damage or destroyed	1	10	6	3

Around 10% of the houses in the affected area had metal roofs (estimated from Google Earth imagery). The percentage of damaged roofs that were metal increased with the damage level, as shown in Figure 4-2. This indicates that lightweight roofs were more susceptible to total loss, and tile roofs were more susceptible to loss of individual tiles or small areas of roof tiles.

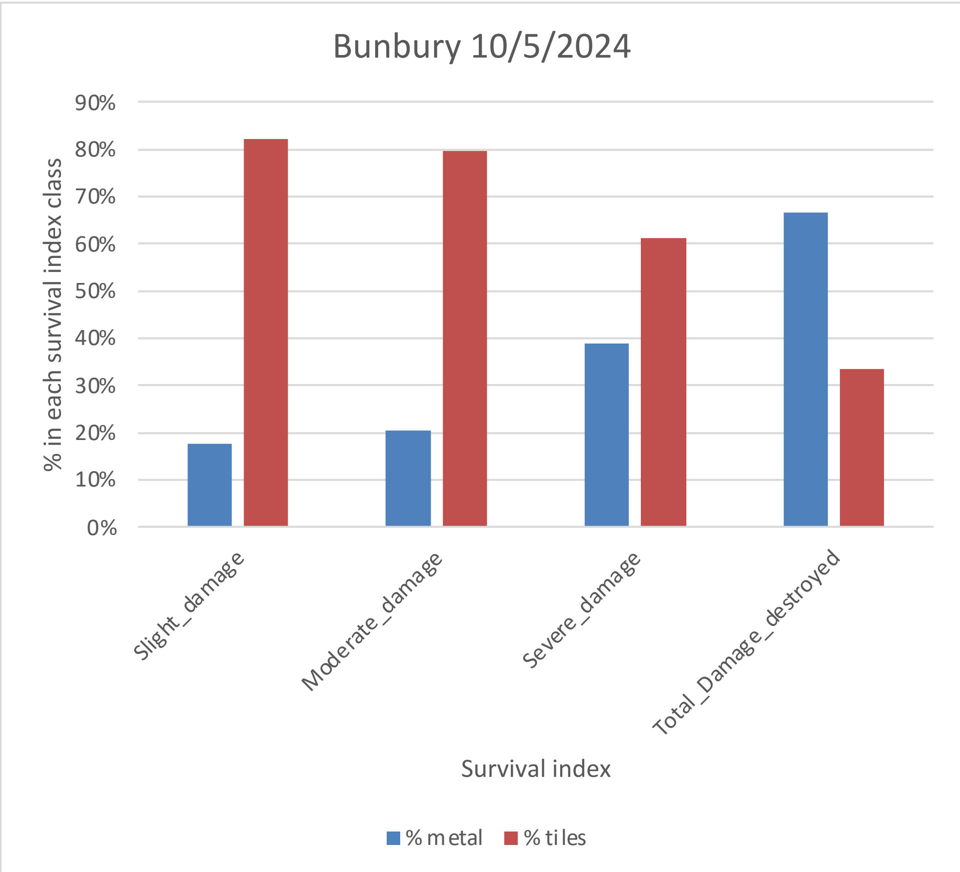


Figure 4-2 Percentage of roofs that were damaged and either metal or tile.

4.1.2. Damage assessments following the 1/6/2024 downburst

DFES damage assessments indicated that after the 1/6/2024 downburst, around 170 houses showed some levels of damage. Of these, around 140 were slight damage leaving around 30 with moderate, severe or total damage, significantly fewer badly damaged houses than in the higher wind speed tornado event. The results of the damage assessment after the 1/6/2024 downburst are shown in Table 2. Note that commercial buildings are not presented in this table and much of the publicised damage in this event was to commercial buildings.

Table 2 Results of DFES Damage assessment.

Damage level	Survival index	Number	Metal roof	Tile roof
Slight damage	4	144	>24	>80
Moderate damage	3	23	9	13
Severe damage	2	4	1	2
Total Damage or destroyed	1	2	1	0

The relationship between tile roof damage and metal roof damage for this event was similar to that shown in Figure 4-2, however the smaller number of roofs that had severe or total damage meant that the plot had less definition at the right-hand end. The trends in this event were the same as those discussed in Section 4.1.1.

4.1.3. Comparison of the damage between the two events

Comparing the results in Table 1 for the 10/5/2024 tornado with the results in Table 2 for the 1/6/2024 downburst, it can be seen that there are significantly more houses with severe and total damage in the tornado compared with the downburst. The area impacted in the downburst is significantly larger as shown in Figure 1-3. The smaller number of buildings damaged is a function of the lower wind speed in the downburst compared with the tornado. The wind speeds in the downburst were estimated at 75% of the wind speeds in the tornado which means the wind loads in the downburst were around 50% of the wind loads in the tornado.

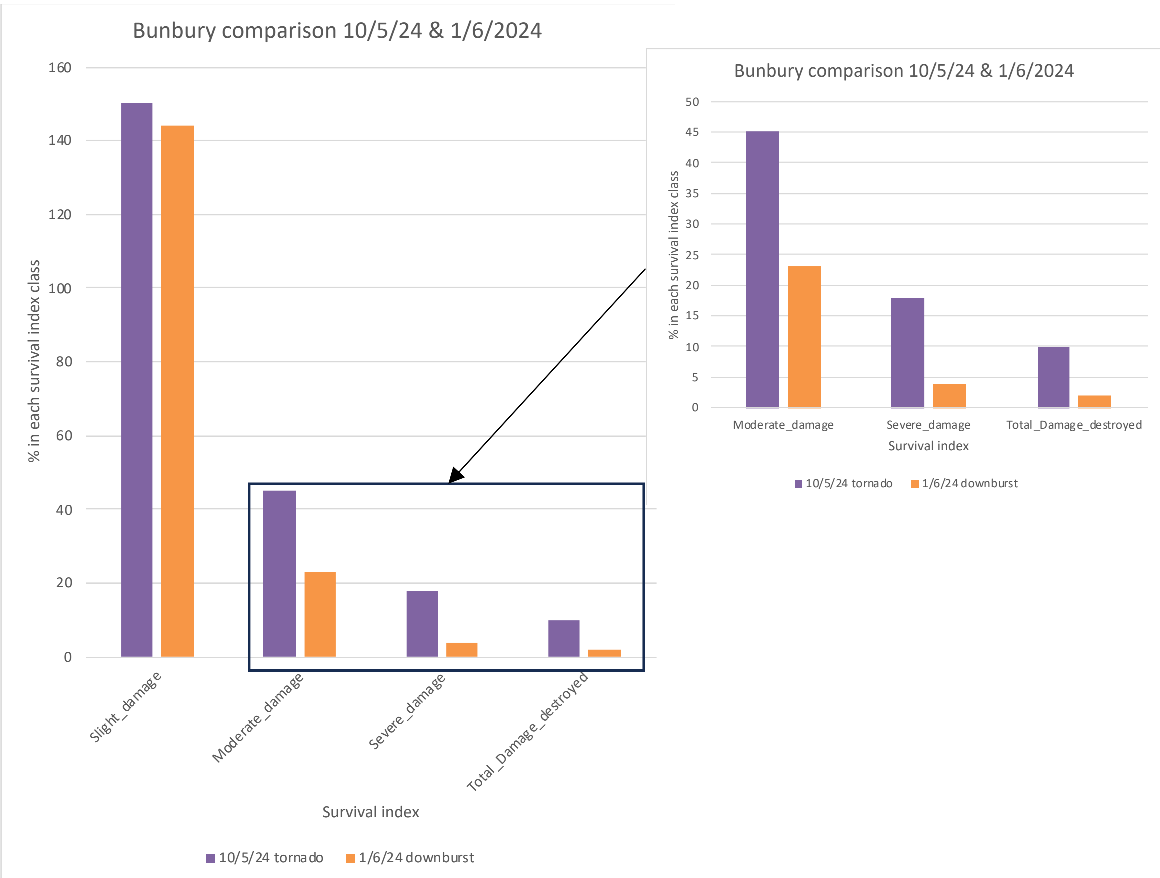


Figure 4-3 Comparison of Damage Assessment results for the 10/5/24 tornado and the 1/6/24 downburst.

The comparison of the numbers of buildings at each damage level are shown in Figure 4-3. The inset shows a magnification of the more severe levels of damage. While there is little difference at the slight damage level, there is a more significant difference at the higher levels of damage.

Because the trends in the damage were similar in the two events and the wind speed in the 10/5/2024 tornado was very close to the design wind speed, the discussion in the rest of the report will centre on the 10/5/2024 tornado. Where a building investigated in the 1/6/2024 downburst is used to illustrate a point, it will be clearly noted.

4.2. Roof damage in 10/5/2024 tornado

4.2.1. Tile roofs

Table 1 shows that most houses that were at least slightly damaged had tile roofs. In southern WA, the practice was to tie down every second tile in a roof. If work on the roof or in the roof space was required, nails through some tiles would be removed to give access. Therefore, in practice, fewer than half of the tiles were fastened and this allowed the wind to dislodge many tiles. Figure 4-4 shows damage to different extents to both old and new tile roofs. There was little difference in the extent (area affected and severity) of the damage between older and newer tile roofs and the damage patterns (near roof edges and ridges) were similar.

The extent of the damage to the roof was related to whether the roof was in the direct path of the tornado or in the periphery. However, some tile roofs directly in the path of the tornado had significantly more tile loss if the inside of the building experienced internal pressure. This was the case for the building shown in Figure 4-5. This issue is further discussed in Section 4.3.

In each of these cases, the dislodged tiles had also damaged the ceiling, and water ingress through the tile damage had also caused loss of ceilings and damage to contents, as shown in Figure 4-5(a). In some cases, the entire tile roof had lifted off the walls, as shown in Figure 4-5(b).

Figure 4-4 Damage to tile roofs.

(a) Ceiling loss (b) complete tile roof structure lifted

Figure 4-5 Ceiling damage under a damaged tile roof.

Winds less than the design wind speed were able to dislodge any tiles that were not anchored. This caused damage to a significant number of tile roofs even where there was no internal pressure. This finding has previously been presented in other reports of wind events in region A, whether or not a tornado was involved.

Recommendation
Amend AS 2050 to require anchorage of all tiles as the minimum tie-down requirement in N wind classifications.

4.2.2. Sheet roofs

Most of the damaged sheet roofs had lifted because the tie down was inadequate. Figure 4-6 shows failure of different items in the tie-down chain. Figure 4-6(a) shows withdrawal of roofing screws from lightweight metal battens; Figure 4-6(b) shows failure of nailed battens and Figure 4-6(c) shows failures of connections between the roof structure and double brick walls.

In Figure 4-6(a) the capacity of the screw through the thin batten was not sufficient to cope with the pressure differential across the skillion roof once the garage door had failed and increased the internal pressure.

In Figure 4-6(b) the tile roof had recently been replaced by a new sheet roof and the nailed connection between the battens and the rafters had not been strengthened (see Section 4.2.3).

In Figure 4-6(c) the connection between the brickwork and the cavity straps used to tie down the roof did not have sufficient capacity to resist the net loads on the lightweight roof. Internal pressure played a part in the failure shown in both the left-hand photo, and the right-hand photo.

Figure 4-6(d) shows the detail of a failure at the base of a roof tie down strap commonly used for anchoring framed roofs to double brickwork walls. In this case, the roof was a steel-framed structure, but the strap pulled out of the internal leaf of brickwork. In pulling out, it broke the internal leaf at the bed joint into which the straps had been embedded. AS 4773.1 presents these straps as having a capacity of 6.5 kN (Standards Australia, 2015), but testing of the embedment of the strap into brickwork has shown a characteristic capacity around 3.5 kN (Tolentino, 2022). Failure of the straps in this and other houses in this event supports the limiting capacity of 3.5 kN.

(a) Roofing screw failure

(b) Batten fastener failure

(c) Failures of roof to wall connections

(d) Failure of strap/brickwork connection

Figure 4-6 Tie-down failures in sheet roofs.

Failure of a roof-to-wall connection for sheet roofs is further illustrated in Figure 4-7.

- Figure 4-7(a) shows a roof in which the tie-down straps secured the top plate, but the rafters had only been skew nailed to the top plates. This connection did not have enough capacity to resist the net uplift loads.
- Figure 4-7(b) shows a roof where the straps were fastened to the rafters and the failure was a mixture of straps pulling out of the brickwork within the cavity of the wall and nails pulling out of the roof structure. It is likely that the failure was precipitated by strap withdrawal from the brickwork and overloading of adjacent straps caused the nail withdrawal.

(a) Connection of brickwork to top plate (b) Connection of brickwork to rafters

Figure 4-7 Failure of roof to wall connections under sheet roofs.

Figure 4-8 Shows the failure of a skillion roof. The wind that caused the damage was normal (perpendicular) to the high edge of the skillion (the roof was a downwind slope as defined in AS/NZS 1170.2). The roof lifted off the tops of the walls and the roof section on the ground showed that some of the straps had withdrawn from the brickwork. Pressure coefficients for the design of skillion roofs in AS/NZS 1170.2 (Standards Australia, 2021a) may need to be checked and AS 4055 (Standards Australia, 2021b) should be brought in line with AS/NZS 1170.2 once the skillion roof coefficients are revised. Preliminary research on skillion roofs indicate that the uplift on the high edge can be higher than indicated in the current standard for some wind directions (Parackal et al, 2022)

> *Recommendation*
> Amend the capacities of cavity straps for double brick construction in AS 4773.1 to values that reflect test results on the embedment of these straps in brickwork. (Tolentino, 2022).

> *Recommendation*
> Check the external pressure coefficients for skillion or monoslope roofs in AS/NZS 1170.2. AS 4055 should also reflect the pressures on skillion or monoslope roofs used in AS/NZS 1170.2.

Figure 4-8 Failure of a skillion (monoslope) roof.

4.2.3. Replacement of tile roofs with sheet roofs

Some of the sheet roofs damaged in this event had replaced tile roofs. The tiles had been replaced with a metal roof relatively recently (within the last 10 years). The mass of a sheet roof is significantly less than the mass of a tile roof, which means that the design wind uplift produces a higher net uplift at the top of the wall. The increase in net uplift requires a strengthened tie-down system.

Figure 4-9 shows a roof where the original tile battens were still visible under the damaged sheet roof (highlighted by the red ellipses). In this case, the capacity of the roof to wall connections originally installed with the tile roof was lower than the net uplift causing separation of the roof from the walls.

Figure 4-9 Failure of a sheet roof that had replaced a tile roof.

This type of failure is also shown in the total loss of the sheet roofs in Figure 4-10. In both of these houses, there was no sign of improved tiedown of the roof to the brick walls.

Figure 4-10 Total loss of a sheet roof that had replaced a tile roof.

Figure 4-11 shows a replacement metal roof where the roof had remained connected to the battens, but the battens had separated from the rafters at nailed connections. Although nailed connections worked for the smaller tributary area of the tile batten to rafter connection that has lower net uplift loads, they did not work for the wider spaced battens under the lighter sheet roof. Building and Energy had previously highlighted these issues in a General Inspection Report (DEMIRS, 2021).

In Western Australia, work that adversely affects the structural soundness of a building requires a building permit. (DEMIRS, 2015). This section shows cases where the replacement of a heavy roofing material with a lighter roofing material adversely affected the structural soundness of the building and will require a structural check and a building permit.

In other states, guidance is available from the building regulator. For example, in Queensland, undertaking repair work affecting the structural components of a building will require a building approval (QBCC, 2024).

Figure 4-11 Loss of a sheet roof that had replaced a tile roof – failure at batten to rafter connection.

At least one house that had severe roof damage in the 1/6/2024 downburst had been re-roofed with lighter roofing than the original roofing. The observations from the 10/5/2024 tornado event also apply to other storm events and failures can be initiated even though the wind loads are significantly less than the design wind actions.

> *Recommendation*
> Provide education on strengthening the roof tie-down system for the roof replacement industry. Replacing roofing material changes the potential structural capacity of the roof tiedowns to resist wind actions. The WA public and the reroofing industry needs to be informed that building approval is required when changing the weight of the roofing as part of replacing roofing material. Similar requirements may exist in other states.

4.3. Internal pressure

The tie-down system is loaded by forces derived from the differential pressure across the roof system. This pressure is the sum of the external pressure and the internal pressure. It is illustrated in Figure 4-12 and shows that the loads on the roof can be increased markedly where an opening in the building allows pressure on the windward wall to enter the building and pressurise the underside of the roof.

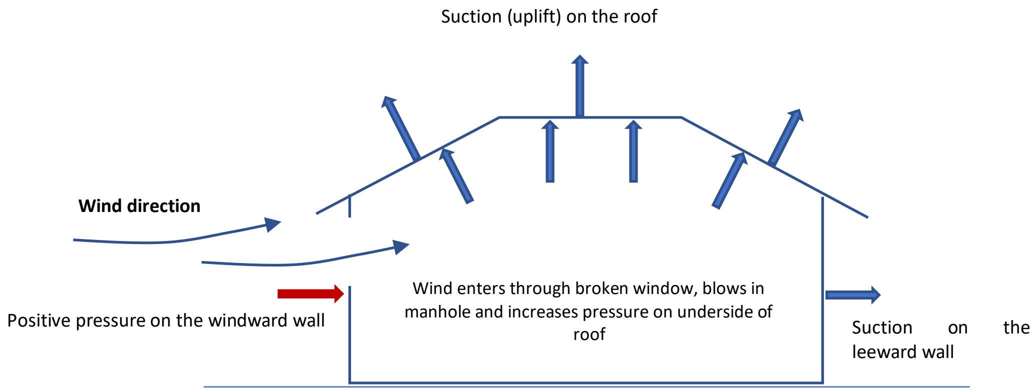


Figure 4-12 Net pressures across a roof

4.3.1. Internal pressure in houses during the 10/5/2024 tornado

Figure 4-13 shows one photo of two houses that were under the direct path of the tornado. Both experienced similar external pressures.

- The garage door on the house in the left of the photo was blown in, but there was no access to the roof space in the garage and the rest of the house had no broken doors or windows. The loss of the garage door only pressurised the garage but not the rest of the house. There was some minor tile loss over the garage, but not throughout the rest of the house.
- The house in the right of the photo had a number of broken windows that allowed windward wall pressures into the house. The roof space access was blown in and the whole roof pressurised from the internal pressure within the house.

The internal pressure on the house on the right in Figure 4-13 significantly increased the level of damage to the tiles, compared with the damage to tiles on the house on the left.

Figure 4-13 Tile roof damage affected by internal pressure.

In this event, failure of either a garage door or a window caused an opening that affected the internal pressure.

- Figure 4-14 shows a collage of photos of garage door failures. In each case, the loss of the garage door caused an increase in the damage to the roof in the area that was affected by the increased internal pressure. In the lower right photo, the damage to the garage door caused not only failure of the whole roof structure above the garage, but also an outward failure of the single leaf brick wall on the outside of the garage.
- Figure 4-15 shows photos of broken windows. Some of these were initiated by wind-borne debris, but others were caused by wind pressure. In the lower right photo, the force of the wind-borne debris broke the window frame out of the internal leaf of brickwork and blew the internal door out.

Figure 4-14 Failure of garage doors in 10/5/2024 tornado.

Figure 4-15 Window failures in 10/5/2024 tornado.

The National Construction Code (ABCB 2022) requires that garage doors in cyclonic regions comply with AS/NZS 4505. This standard requires testing to give a wind rating for doors. However, in wind regions A and B1 there is no requirement for installing doors that comply with AS/NZS 4505, so doors installed in Bunbury are usually not wind rated and can fail at less than the design wind speed even if not affected by debris. Requiring all garage doors under the house roof to be wind rated will lower chance of their failure subjecting the whole house to high internal pressure.

> *Recommendation*
> All garage doors on houses should be wind rated and comply with AS/NZS 4505. This will limit the impact of failure due to high internal pressures.

4.3.2. Internal pressure in houses during the 1/6/2024 downburst

Even though the wind speed in the event was around 75% of the design wind speed, there were still cases in which internal pressure was created, often by failure of garage doors.

Figure 4-16 shows several garage doors that failed in the 1/6/2024 downburst and caused internal pressures that led to other structural failures in the house. In the lower left photo, the owner had been able to push the garage doors back into the guides, but both of them had blown in during the downburst. These garage doors all failed at loads just over 50% of the design wind loads and the internal pressure that resulted from the door failures increased the level of damage to the roof structure.

Figure 4-16 Failure of garage doors in 1/6/2024 downburst.

Window failures also caused an increase in internal pressure. Figure 4-17 shows photos of windows that had failed and most of them had contributed to internal pressure. In these cases, impact by wind-borne debris may have caused the failure. The lower right photo shows a laminated glass panel that had been damaged by debris, but had remained in place and had not contributed to the internal pressure. (Failure of another window in the same building that was float glass had contributed to the internal pressure that was instrumental in partial roof loss of the building.)

Figure 4-17 Window failures in 1/6/2024 downburst.

4.4. Wind-borne debris

4.4.1. Debris observed in 10/5/2024 tornado

Wind-borne debris created openings in many buildings. Some items of wind-borne debris observed in this investigation included:

- Rubbish bins (Figure 4-18)
- Trampolines (Figure 4-19)
- Branches (Figure 4-18)
- Kayaks or parts of kayaks
- Pieces of building materials from houses
- Lightweight roofed patios or carports (Figure 4-19)
- Roof tiles
- Solar panels (Figure 4-19)

Many of these items have higher mass and a larger cross-sectional area for acceleration in the wind stream than the standard debris item defined in AS/NZS 1170.2 (Standards Australia, 2021a). Therefore, they had more kinetic energy than the standard debris item used primarily for tests of elements for debris resistance in cyclone areas.

Figure 4-18 shows some large wind-borne debris. The left-hand photo is from the inside of a house and shows that two rubbish bins pushed the entire window frame inwards. It broke out the internal leaf of brickwork up to the internal abutting wall on one side and one to two brick lengths beyond the opening on the other side. The high internal pressure contributed to the significant net uplift forces that led to the loss of the complete roof structure.

Figure 4-18 Rubbish bins and large branches as wind-borne debris.

Figure 4-19 shows three items of wind-borne debris caught in trees at a significant height. They travelled more than 50 metres before landing. The trampoline is circled in the centre photo. The right-hand photo shows a portion of a solar panel. There were also cases where lightweight roofs, trampolines and solar panels impacted houses, but the debris was less obvious than in these photos.

Windborne debris occurs when garden items such as bins, trampolines and furniture have not been safely stowed prior to the event. There is rarely enough warning of severe thunderstorms, downbursts and tornados in regions A and B1 to allow lightweight items to be stored. Elements of damaged buildings and lightweight roofs can become wind-borne debris that can impact other buildings.

Investigations of extreme wind events in regions A and B1 caused by severe thunderstorms, such as the Gap storm of 2008 (Leitch et al, 2009), downbursts such as the Port Stephens storm in 2014 or tornadoes such as the Shoalwater tornado of 2008 (Boughton and Falck, 2008) all reported wind-borne debris that had created large openings in the envelope of houses. Wind-borne debris will be generated in every wind region by winds at the ultimate limit states design level.

Figure 4-19 A light weight roofed patio, a trampoline and part of a solar panel as wind-borne debris.

4.4.2. Debris observed in 1/6/2024 downburst

Many of the same items of wind-borne debris observed in Section 4.4.1 after the 10/5/2024 tornado were also observed in the investigation after the 1/6/2024 downburst.

- Rubbish bins (A number of owners reported that their rubbish bins had been blown away and were still missing.)
- Trampolines (Figure 4-20(a))
- Branches (Figure 4-20(b))
- Pieces of building materials from houses
- Lightweight roofed patios or carports (Figure 4-20(c))
- Solar panels (Figure 4-20(a))

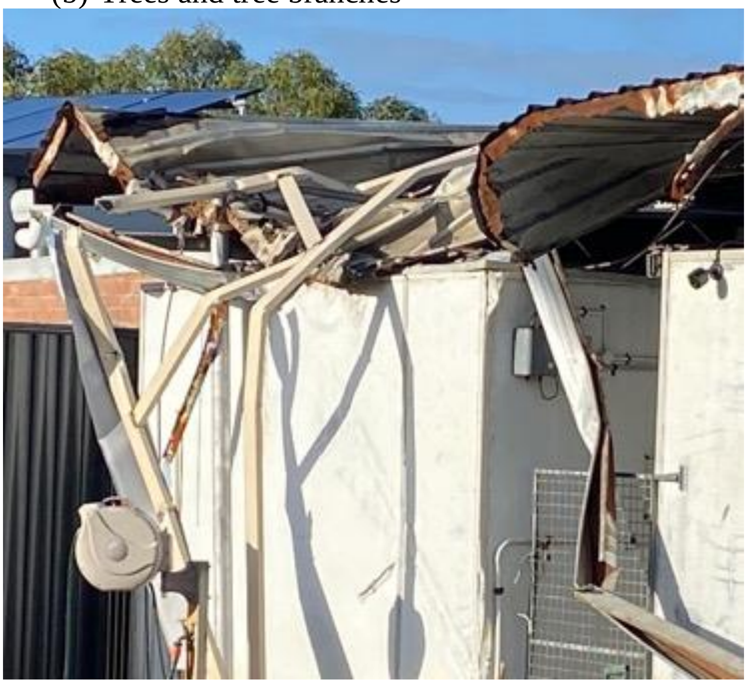
The fact that these items of wind-borne debris could cause damage to buildings at wind speeds of around75% of the design wind speed indicates that in events with only a few gusts, it is possible that gusts lower than the design wind speed can cause openings in a building. This means that there is high internal pressure when a subsequent higher wind gust arrives.

Both of these events (the 10/5/2024 tornado and the 1/6/2024 downburst) demonstrated the role of wind-borne debris in creating openings in buildings in wind region A. At the ultimate limit states design wind speed, even in the non-cyclone regions, wind-borne debris can play a role in causing openings in the building envelope that contribute to higher internal pressures.

Recommendation Revise the internal pressures for houses in wind regions A and B1 to give housing more resilience in cases where doors or windows are open at the time of the extreme winds or openings are created by wind-borne debris.

(a) Solar panels and trampolines

(b) Trees and tree branches



(c) Lightweight patio (cream coloured framing embedded in the roof)

Figure 4-20 Wind-borne debris observed after 1/6/2024 downburst.

4.5. Performance of solar panels

The following terminology is used in this section:

Array – a group of panels that effectively presents a single surface

Panel – a glass-mounted photovoltaic element with a metal chassis. This is a single manufactured unit that is fixed into position to become part of an array.

Chassis – the rectangular metal frame that contains the glass-mounted photovoltaic element. This term is used to differentiate the chassis from a rail that may support several panels.

Upward-facing – the face of the panel that faces the sun to generate electricity

Downward-facing – the lower face of a panel

Roof-mounted – arrays fixed parallel to the roof (see Figure 4-21).

Figure 4-21 shows some roof mounted solar panels that were in the path of the tornado. It shows that four of the panels in the array of 10 panels bowed downwards under pressure loading.

Figure 4-21 Pressure failure of roof-mounted solar panels.

The solar panels on some roofs failed by withdrawal of the roofing screws that secured the rail to the roof battens. It is usual to fit solar panels by installing a larger roof screw to hold down the bracket at the bottom of the rail. Figure 4-22(a) shows a portion of roof where the rails and the panels they supported were lost. The rail is shown in Figure 4-22(b). The solar panels bridged two different roof types.

- On the left of Figure 4-22(a), the roof was a more recent addition with lightweight steel trusses and steel top hat battens – the screws pulled out of the battens and remained in the brackets. The screws are missing from the roof, but are still in the brackets, as shown by the red circles in the lower photo.
- On the right of Figure 4-22(a), the missing portion of roof is a re-roofed part of the original house with hardwood battens that remained attached to the sheeting. In the original house, the only part of the roof that was lost was the part under the solar panels. The aerodynamic wind actions across the roof and panels may have been increased by the presence of the panels.

(a) Missing solar panels over two different types of roof structure

(b) Detached solar panel rail

Figure 4-22 Loss of rails under solar panels.

Solar panels that had been dislodged from house roofs became wind-borne debris and damaged other houses, or were caught up in vegetation. As they bounced over the ground they generally broke up into smaller pieces as shown in Figure 4-19.

Some solar panels were directly in the path of the event but did not fail as shown in Figure 4-23. This house was in the path of the tornado, and was damaged in part, but most of the solar panels were undamaged by the wind and neither was the roof underneath the solar panels. In this case, nearly the whole roof panel was covered by solar panels, whereas many of the installations that were damaged had smaller portions of the roof covered by panels.

Figure 4-23 Good performance of solar panels on a damaged house.

Many of these findings are similar to the findings from recent studies of solar panels in tropical cyclones (Boughton et al, 2023).

Note that some solar panels were also removed from roofs in the 1/6/2024 downburst at wind loads around 50% of the design wind loads. This suggests that the solar panel anchorage systems in some installations are unable to resist even low wind actions.

> *Recommendation*
> To improve accuracy of design loads for solar panels, undertake studies on the wind actions on rail to roof connections for solar panel systems and on the additional loads these connections apply to the roof structure.

> *Recommendation*
> Design panels and the fixings to ensure that the capacities of all elements on the load path through the panels (including the panels themselves and the screws into the battens) exceed the wind loads for V_{500} in order to reduce the risk of damaging other buildings.

4.6. Modern construction

Some relatively recent construction (built in the last 15 or so years), performed poorly in the 10/5/2024 tornado, as illustrated in Figure 4-6(c) and Figure 4-8. However, there were at least 3 new houses or recently renovated houses that were in the path of the tornado that performed well. Figure 4-24 shows a house between two older houses that were badly damaged, but the only damage to the newer house was debris damage to the roof from one of the neighbouring houses. The debris still lying on the roof is shown in the right-hand photo in Figure 4-24.

Figure 4-24 Good performance of a new house in the 10/5/2024 tornado.

Figure 4-25 shows a street of relatively new houses with a mixture of roofing materials. Some ridge tiles had been damaged, but most of the sheet roofs were undamaged by the event. While the roof loads were approximately 50% of the design wind loads, this good performance cannot be taken as demonstration that modern construction is adequate; it shows that in areas affected by the downburst, some modern construction remained undamaged.

Figure 4-25 Good performance of new houses in the 1/6/2024 downburst.

5. Lightweight carports and roofed patios

5.1. Performance of lightweight additions

5.1.1. Lightweight additions in the 10/5/2024 tornado

Many lightweight additions to buildings such as carports and roofed patios failed during the 10/5/2024 tornado and became wind-borne debris. The left-hand photo in Figure 4-19 shows a roofed patio that failed and became a large piece of wind-borne debris. This failure involved the separation of the patio roof from the top of its columns. The debris was a single large piece and would have had much more kinetic energy than the standard debris item defined in AS/NZS 1170.2 (Standards Australia, 2021a).

In some cases, members from these patios broke windows, as shown in the top right photo in Figure 4-15. Figure 5-1 shows a lightweight carport that illustrates several different failure modes:

- One batten was left on the rafters and the cladding fasteners had withdrawn from this batten. (1)
- The roofing and battens separated from the rest of the structure and were blown more than 50 metres. The single large piece of roof caused damage to at least two other houses in its path. (2)
- Some of the rafters separated from the top of the posts. (3)
- Most of the posts developed a hinge at ground level and bent over. Lateral bracing is rarely designed for these types of structures. (4)

Figure 5-1 Failure of a lightweight carport during the 10/5/2024 tornado.

The failure of these lightweight structures caused property damage that contributed to repair costs and the potential for significant damage to other buildings or structures.

The lightweight structures discussed in this section are all open buildings rather than enclosed buildings and are not affected by the very low pressure in the centre of the tornado that causes a differential pressure across the building envelope in an enclosed building. They were only loaded by the wind pressures.

5.1.2. Lightweight additions in the 1/6/2024 downburst

Very similar failures occurred to lightweight open structures during the 1/6/2024 downburst. These failures occurred at loads significantly less than the design wind loads. Figure 5-2 shows several lightweight carports and patio roofs that failed at loads around 50% of the design wind loads during the 1/6/2024 downburst. The modes of failure were very similar to those discussed in Section 5.1.1, with failures of tek screw connections between light gauge steel elements.

5.2. Connections between poles and veranda beams

Figure 5-3 shows a large, isolated carport that lost its roof during the 10/5/2024 tornado. The failure was clearly at the top of the posts. The connection incorporated a bracket that was screwed to the underside of the rafters and then tek screwed into the posts. The two tek screws into the underside of the rafters did not have the withdrawal capacity to carry the loads. The load carrying capacity is dependent on the diameter of the tek screws, the thickness of the plate in the rafter and the configuration of the hidden connection plate in the top of the post.

Similar details that had three tek screws in the underside of the rafter (top right hand photo in Figure 5-2 did not have sufficient capacity for the lower wind loads during the 1/6/2024 downburst.

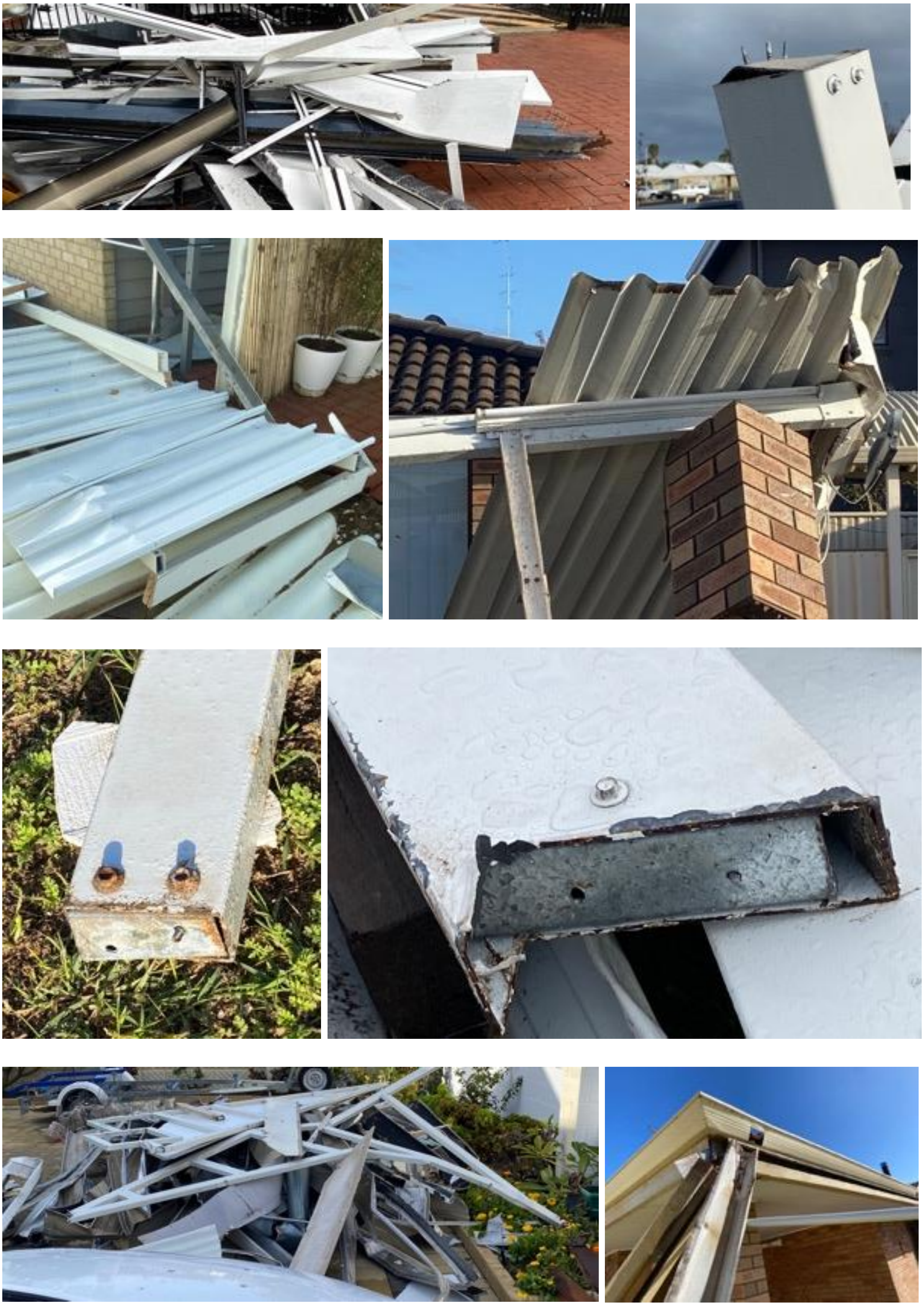


Figure 5-2 Failure of lightweight carports and patio roofs during the 1/6/2024 downburst

A number of the connections that failed during the 1/6/2024 downburst and were shown in Figure 5-2 had similar characteristics as the ones shown in Figure 5-3. This indicates that many of these lightweight structures did not have enough capacity to resist the lower wind loads (around 50% of the design wind actions) in the 1/6/2024 downburst.

Figure 5-3 Missing carport roof after 10/5/2024 tornado.

Recommendation
Engineers should design all structural elements in lightweight carports and patio roofs. Connections must have sufficient capacity to resist the design wind loads for each location in which these lightweight structures are installed.

6. Commercial buildings

The scope of this report was on performance of houses, but many of the findings on debris impact and internal pressure apply to commercial buildings.

Figure 6-1 presents some damage to garage and large access doors on commercial buildings during the 1/6/2024 downburst with wind loads generally around 50% of the ultimate limit states design level. Conclusions and recommendations made about garage doors on houses also apply to commercial buildings.

Figure 6-2 shows an automatic glass door that had failed and three commercial buildings with envelope damage that was the result of high internal pressures following the creation of an opening. Likewise, conclusions and recommendations made about internal pressure in houses also apply to commercial buildings.

Figure 6-1 Damage to garage and large access doors on commercial buildings during the 1/6/2024 downburst

Figure 6-2 Effects of internal pressure on commercial buildings in the 1/6/2024 downburst.

7. Conclusions

The wind event in Bunbury on 10th May 2024 was a tornado estimated to have had the wind speeds of an EF1 event. The estimated wind speed was around the design wind speed for buildings in wind region A. A significant number of buildings were damaged by wind actions or wind-borne debris. Theoretically, there should have been no structural damage to houses that were not impacted by wind-borne debris in this event.

The wind event in Bunbury on 1st June 2024 was not a tornado, but a downburst covering an area around 300 m wide and at least 7 km long. The wind speeds were estimated to be less than 120 km/h and were approximately 75% of the ultimate limit states wind speed for the area. Again, theoretically there should have been no structural damage to houses in this event. A similar number of houses were damaged in the downburst to those damaged in the tornado, but fewer houses were significantly damaged in the 1/6/2024 downburst.

Nearly all tile roofs in the path of the 10/5/2024 tornado were damaged. Some tile roofs were a total loss. At the wind speeds experienced in the tornado, anchorage of every tile instead of every second tile would have reduced the damage significantly.

Most of the houses that experienced severe levels of damage had sheet roofs, even though in the area affected, only around 10% of houses had sheet roofs. Severe damage to sheet roofs was attributed to the inadequacy of tie downs. Wind uplift loads on lightweight sheet roofs place larger loads on cavity tie-down straps in double brick construction and some straps failed by withdrawing from the brickwork.

Several severely damaged sheet roofs had been recently fitted to houses that previously had tile roofs. The replacement of heavy roofing material with lightweight roofing material results in significantly higher net uplift loads on the tie-down system and requires the whole tie-down chain to be checked and upgraded as necessary. It appeared that the tie-downs in the damaged houses had not been strengthened.

It was clear from the damage to roofs in both events that internal pressures contributed to the severity of the roof structure damage, even though it was in wind region A. Where elements on the windward wall failed due to either wind pressure or wind-driven debris impact, the extent of the roof damage was higher. A contributing factor on some houses was that failure of garage doors under the house roof increased the internal pressure throughout the house.

Several roof-top solar systems failed due to either wind pressures on the panels or failure of the anchorage of the panels to the roof. This finding is similar to the findings of investigations of damage following tropical cyclones (Boughton et al, 2023).

There was significant damage to most of the lightweight carports or roofed patios that were in the path of the tornado and the downburst. The wind loads on these structures were not affected by the fact that the winds were generated by a tornado; the failures were due to the wind pressures generated by the local wind speed. The high failure rates in both events cast doubt on the design and structural adequacy of this type of structure.

8. Recommendations

- Include a note in the scope of AS/NZS 1170.2 reflecting the information given in the AWES Handbook about the adequacy of the loads in the standard to resist low intensity tornadoes (EF0 and EF1 for wind region A, and EF0, EF1 and EF2 for wind region B).
- Check the external pressure coefficients for skillion or monoslope roofs in AS/NZS 1170.2. AS 4055 should also reflect the pressures on skillion or monoslope roofs used in AS/NZS 1170.2.
- Revise the internal pressures for buildings in wind regions A and B1 in AS/NZS 1170.2 and AS 4055 to give them more resilience in cases where doors or windows are open at the time of the extreme winds or openings are created by wind-borne debris.
- Undertake studies on the wind actions on rail-to-roof connections for solar panel systems and on the additional loads these connections apply to the roof structure. Design panels and the fixings to ensure that the capacities of all elements on the load path through the panels (including the panels themselves and the screws into the battens) exceed the wind loads for V_{500}.
- Amend AS 2050 to require anchorage of all tiles as the minimum tie-down requirement in N wind classifications.
- Amend the capacities of cavity tie-down straps for double brick construction in AS 4773.1 to values that reflect test results on the embedment of these straps in brickwork (Tolentino,2022).
- Regulations should be changed so that all garage doors on houses (including those in regions A and B1) should be wind rated and comply with AS/NZS 4505. Improvements in the resilience of commercial properties will also result if wind rated doors are used on commercial buildings in these wind regions. This will limit the impact of door failure on high internal pressures.
- Provide education on strengthening the roof tie-down system for the roof replacement industry. Replacing roofing material changes the potential structural capacity of the roof tiedowns to resist wind actions. The public and the reroofing industry needs to be informed that building approval is required when changing the weight of the roofing as part of replacing roofing material. The building approval process should ensure that the tie down system is upgraded to comply with NCC structural requirements recognising that the mass of the roof has been significantly decreased.
- Engineers should design all structural elements in lightweight carports and patio roofs. Connections must have sufficient capacity to resist the design wind loads for each location in which these lightweight structures are installed.

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