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Shoalwater and Roleystone WA tornadoes
Wind damage to buildings

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TECHNICAL REPORT NO. 54

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PREFACE

Publication of this technical report continues the long standing cooperative research between the Cyclone Testing Station and TimberED. The authors Prof Boughton and Ms Falck have collaborated on other CTS damage investigations. Prof Boughton was formally a research fellow at the Cyclone Testing Station.

Logistically it was far more expedient for the TimberED team to investigate the wind damage in suburban Perth than for a CTS team to travel from Townsville. The CTS is most grateful to Geoff and Debbie for preparing this report and also to the WA Department of housing and Works for supporting this work.

Department of Housing and Works	CYCLONE TESTING STATION	TIMBERED SERVICES PTY LTD

Shoalwater and Roleystone WA Tornadoes – Wind damage to buildings

Executive Summary

Outer suburbs of Perth WA experienced tornadoes from two separate events in June 2008. Both tornadoes damaged buildings and vegetation. The report provides estimates of maximum wind speeds in the tornadoes and details the damage to houses caused by these events.

Although tornadoes are not covered in AS/NZS1170.2 [1], the estimated wind speeds generated by the tornadoes were similar to or less than the design wind speed at roof height for all affected houses.

Deficiencies in structural capacity were noted in the following details:

- Batten to rafter connections
- Rafter to top plate connections
- Roof structure connections
- Top plate to masonry connections
- Verandah details

Particular attention to tie-down detailing is required in sheet roofs where the light weight of the roofing means that net uplift forces are higher.

This investigation has also shown that some houses had been given incorrect wind classifications. Although this is usually not an issue for winds in a tornado, it would be important for other wind events.

Even short duration wind events such as tornadoes generate airborne debris. Some of this debris was instrumental in causing full internal pressurization, which in turn lead to significant structural damage. In other cases, failure of doors and windows lead to full internal pressurization. Standards Australia should give consideration to amending clause 5.3.2 in AS/NZS1170.2 [1] to include buildings in all regions.

Shoalwater and Roleystone WA Tornadoes – Wind damage to buildings

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Acknowledgements

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- The Bureau of Meteorology WA, and in particular, Joe Courtney.
- People of Roleystone, Shoalwater and Rockingham WA who allowed us to visit their houses and take photographs, and freely discussed their building damage with us.
- Department of Housing and Works WA for part funding of the work.

1. Introduction

At around 7.40 am on Monday, 9 June, 2008, a tornado caused localised damage in the Shoalwater and Rockingham areas. The path of the tornado stretched for approximately 7 kms and damage was noted over the first 6 kms from the coast.

At around 2.30 pm on Friday 27th June, 2008 another tornado caused localised damage in the Roleystone area. This tornado passed over undulating terrain and its path of damage was around 2.5 km long.

1.1 Objectives

This study estimates wind speeds during the event and investigates the damage to buildings in the area. The estimated wind speed is compared with the design winds for this region of Western Australia presented in AS/NZS1170.2 [1] and AS4055 [2].

2. Meteorological aspects

2.1 Shoalwater tornado 9th June 2008

The Shoalwater tornado was embedded in a cold front. Figure 2.1 shows a satellite image of the cold front as it crossed the South West of WA. The red circle shows the locality that was affected by the tornado. The same event is shown in Figure 2.2, as a radar image, and again, the location of Shoalwater is shown by the red circle.

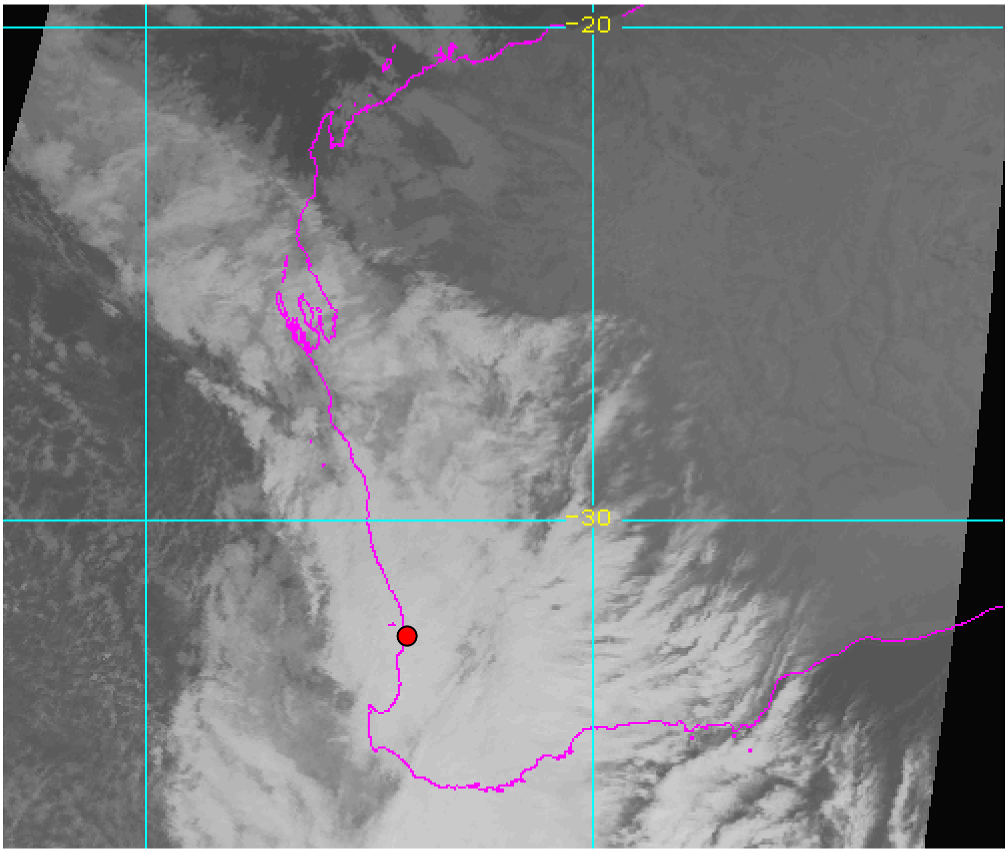

Figure 2.1 Satellite image 09/06/08 (Bureau of Meteorology WA)

Both the Bureau of Meteorology investigation and the structural investigation covered in this report noted strong evidence in the damage of a rotating column of air. This was confirmed by eye witness accounts of the same event. There is no doubt that the damage was caused by a tornado, and the diameter of the funnel was estimated to be about 30 m. This tornado was narrow enough to affect one house and leave the houses on either side completely unscathed.

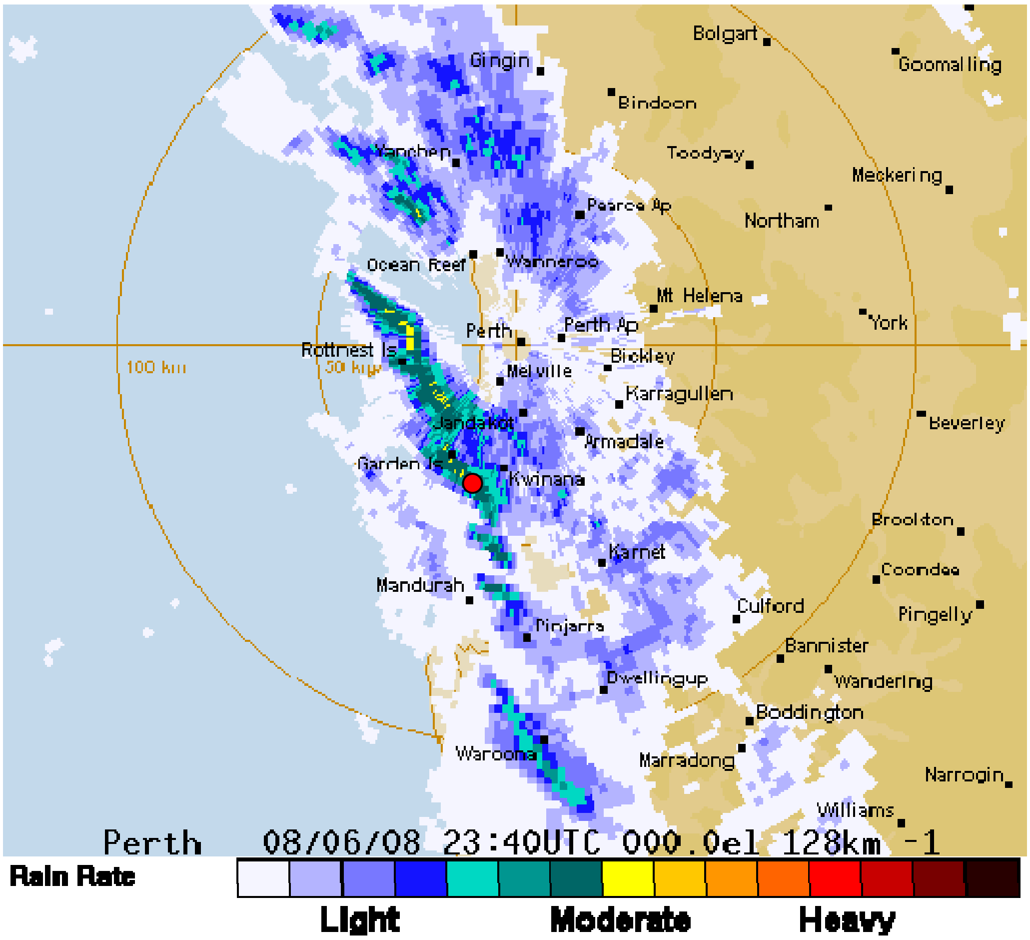

Figure 2.2 Radar capture 09/06/08 0740 WST (Bureau of Meteorology WA)

Figure 2.3 is a map of the tornado's path through the Shoalwater Bay area, highlighting some areas of damage. The full blue line is the path estimated by the Bureau of Meteorology and the dotted black line shows the path estimated from damage surveyed in this report. There is very little difference in the line except over Waikiki (the Eastern part of the path). In this part of the path, the estimation was based on assessment of tree damage and minor damage to roofs. The tornado travelled in a south-easterly direction, and the damage abruptly ceased at the end of the line indicating that the tornado had detached at that point.

Red circles show the location of structures used to estimate wind speeds. Green circles show locations of other damaged buildings featured in the report. The dotted black line confirms that the structural damage noted by the two green circles was on the tornado path.

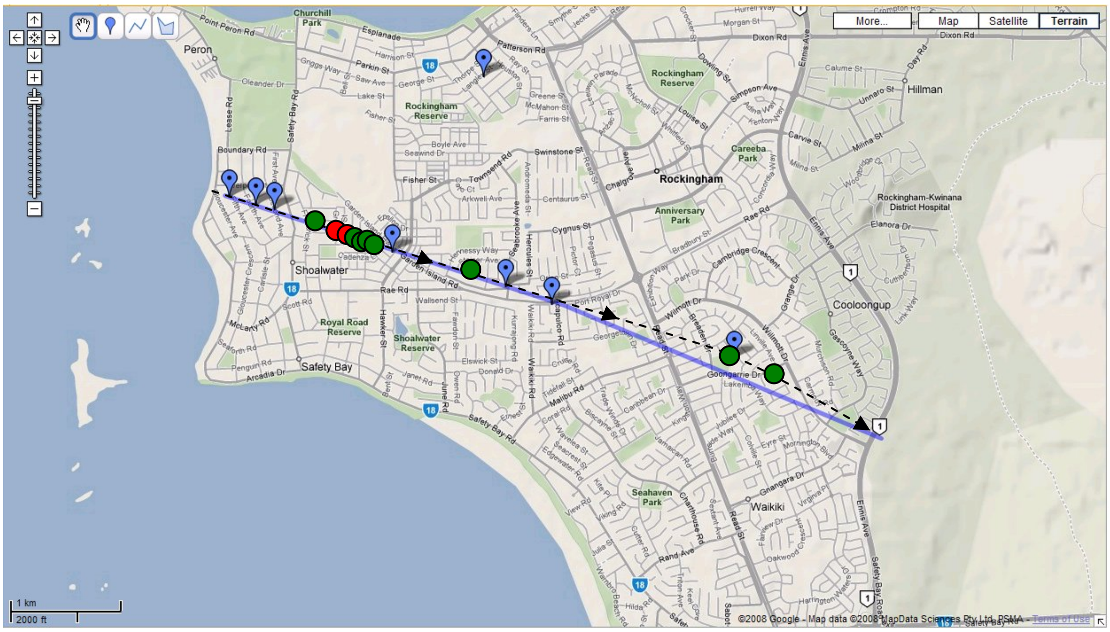

Figure 2.3 Shoalwater Tornado Track (Bureau of Meteorology WA)

2.2 Roleystone tornado 27th June 2008

The Roleystone tornado was also embedded in a cold front. Figure 2.4 shows a satellite image of the cold front as it crossed the South West of WA. The red circle shows the locality that was affected by the tornado. The same event is shown in Figure 2.5, as a radar image.

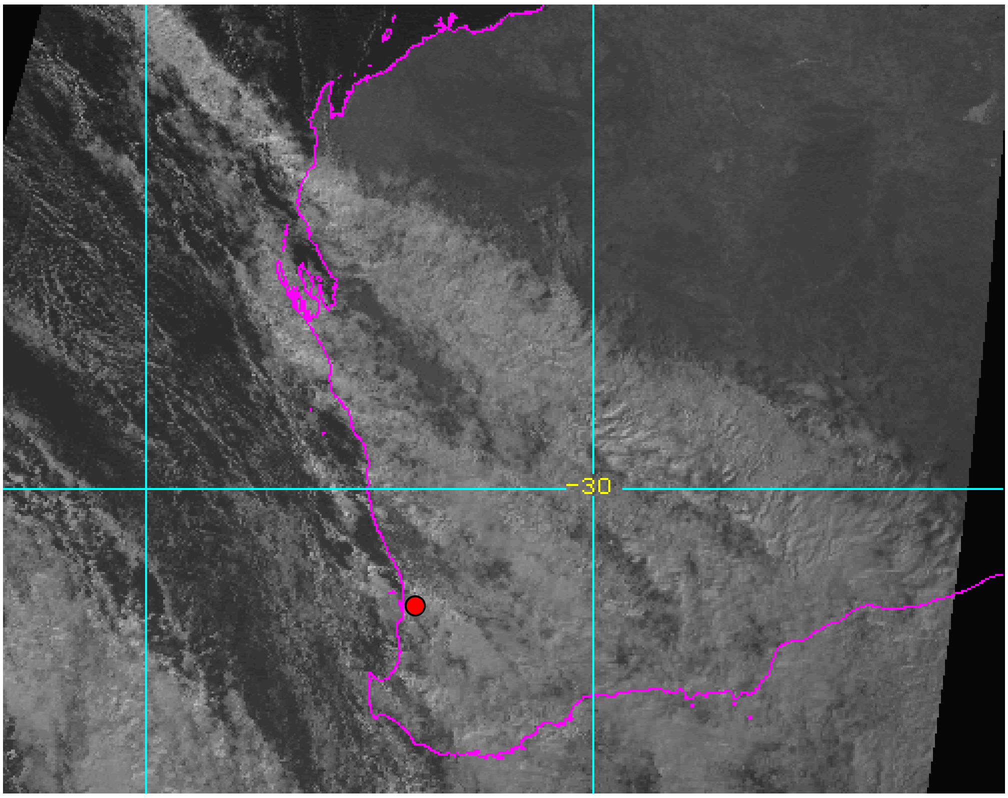

Figure 2.4 Satellite image 27/06/08 (Bureau of Meteorology WA)

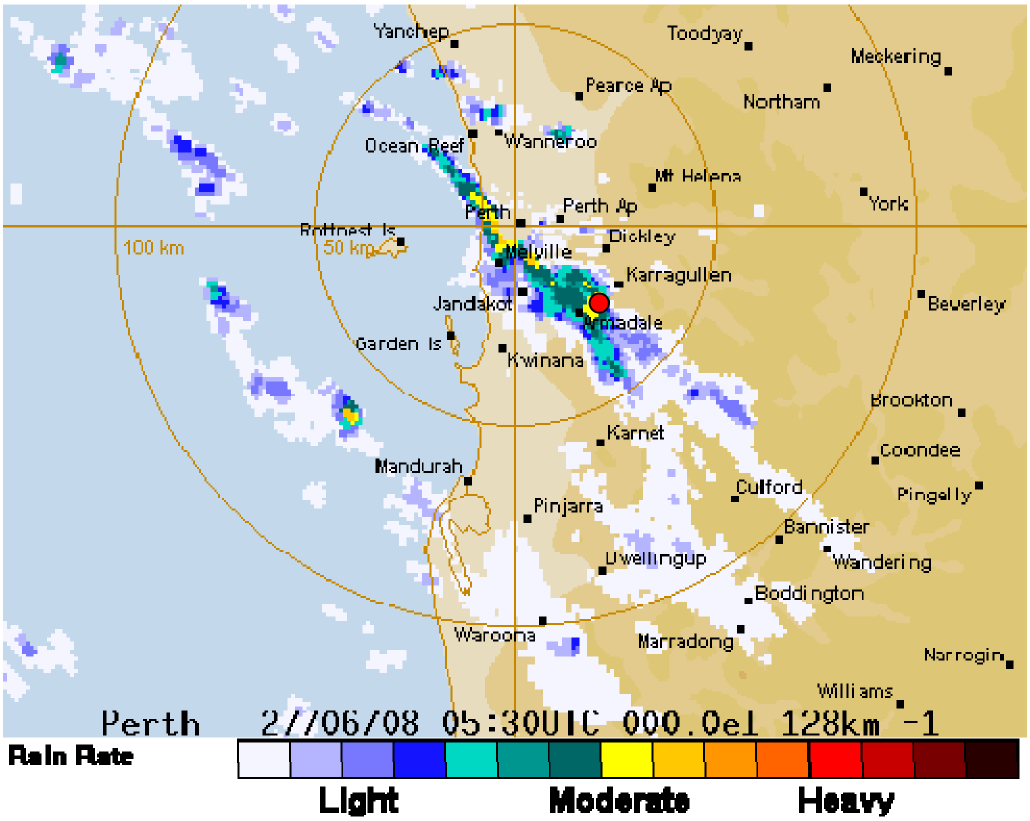

Figure 2.5 Radar capture 27/06/08 1430 WST (Bureau of Meteorology WA)

Figure 2.6 Roleystone Tornado Track (Google Earth)

The track of the tornado was estimated from damage to trees and houses, and was in a south-easterly direction. It is shown superimposed on a satellite photo taken from Google Earth. While many buildings sustained some damage, the green circles show some of the buildings that suffered significant roof loss. The tornado continued through bushland to the right of Figure 2.6.

3. Estimations of wind speed

3.1 Shoalwater tornado

The wind speed of the Shoalwater tornado was estimated at a point early in the track as shown in Figure 2.3. The maximum wind speed is reported as an estimated velocity at roof height at the site. The estimate draws inferences from damage to two structures and vegetation. There are errors in these inferences that are related to the complexity of the structure and other factors. The reliability is “moderate” and estimates are likely to be within +/- 15%.

3.1.1 Wind speeds estimated from damage to a sheet roof

Wind speeds at roof height were estimated at between 110 and 120 km/h or 32 to 34 m/s. This building was less than three years old and had sustained considerable damage including:

- Damage to front door fixings that meant the front door blew in as the strong winds first arrived.
- Loss of part of the roofing near a hip (roofing had battens attached).
- Partial separation of part of the roof structure from the walls including lifting of some bricks to which the top plate had been fastened.
- Partial separation of batten to rafter connections throughout the roof.
- Partial separation of some underpurlins from struts and some struts from strutting beams.

Figure 3.1 External (front) view of sheet roof house

This damage will be examined in more detail in section 4.

- The lower bound wind speed was estimated from the relatively simple structural system of roofing tied to battens which separated from the rafters. The failure required failure of approximately 30 nails at the batten to rafter connections, so the average nail withdrawal load could be used to estimate the resistance. The pressure coefficients were taken from wind tunnel studies on hip roofs reported by Xu and Reardon [3].
- The upper bound wind speed was estimated from the weight of the whole roof together with roof anchorage around the perimeter offered by skew nails at each rafter / top plate connection. Again average wind pressure coefficients were estimated for each hip roof surface from Xu and Reardon [3]. While the whole roof had lifted around 25 mm, it had not actually separated from the walls. It was estimated that the actual roof height wind speed was close to the upper bound.

Figure 3.1 shows a general view of the house viewed at 90 degrees to the direction of peak winds. There is no debris damage in this view, but the lifted roof is obvious by the gap over one column and the movement on the other. While the roof has moved, it did not become detached as a whole.

3.1.2 Wind speeds estimated from damage to a tiled roof

Wind speeds at roof height were estimated at between 110 and 160 km/h or 32 to 43 m/s. This recently completed building was located within 150 m of the one detailed in Section 3.1.1 and with the same relative positioning to the tornado track. This building had sustained damage to the roof including:

- Loss of some tiles near the hips.
- Subsequent collapse of ceiling due to water ingress.

Figure 3.2 shows a general view of the house showing damage to roof tiles near hips.

Figure 3.2 Damage to tiled roof due to wind loads

This damage will be examined in more detail in section 4.

- The lower bound wind speed was estimated from the relatively simple structural system of individual tiles. There were no signs of debris damage to this house. The pressure coefficients were taken from peak pressures in wind tunnel studies on hip roofs reported by Xu and Reardon [3].
- The upper bound wind speed was estimated from the weight of the whole roof. Again average wind pressure coefficients were estimated for each hip roof surface from Xu and Reardon [3]. There was no indication that the roof had lifted from the wall structure. It would not have mobilized anchorage/ tie-down forces in roof to wall connections.

3.2 Roleystone tornado

Observations of damage to vegetation indicated that the wind speeds in the Roleystone tornado seemed vary more over the distance travelled than those in the Shoalwater tornado. The vegetation damage was light over the first half of the track shown in Figure 2.6 and much more significant in the second half of the track.

It was very difficult to obtain actual estimates of the wind speed, however the following conclusions about the relative speed of the event could be drawn from the damage to trees. Figure 3.3 shows damage to trees in this event:

- In the first half of its path, the Roleystone tornado had a lower wind speed than the Shoalwater tornado. Here only branches less than 100 mm were broken and leaves remained on most trees in its path. Some deciduous trees even retained some autumn leaves.
- In the second half of its path, the Roleystone tornado had a higher wind speed than the Shoalwater tornado, but there were no buildings that were in the direct path of the tornado in this half. There were a number of buildings that were close to its path and some of these were damaged. An estimate of the wind speed in the wall of the tornado was 180 to 200 kph as some trees in excess of 400 mm diameter had been broken half way up the trunk.

(a) Damage in first half of path (b) damage in second half of path

Figure 3.3 Damage to trees in Roleystone tornado

3.3 Wind speeds compared with design wind speeds

3.3.1 Shoalwater tornado

The range of wind speeds estimated in the Shoalwater tornado for both houses was similar. The best estimate indicated in Section 3.1 is 120 km/h (34 m/s) at roof height, which is close to the design wind speeds at roof height for a single storey house in flat suburban terrain in Region A given in AS/NZS1170.2 [1] and AS4055 [2]. (In AS4055 [2], the ultimate limit state wind speed for an N1 house is 34 m/s and for N2, 40 m/s.)

This estimate of wind speed is compatible with damage to trees which unless damaged by flying debris was restricted to broken branches and uprooting of very shallow rooted species.

The event could be classified as an F1 tornado according to the Fujita scale for tornado wind speeds as indicated in Table 3.1 [4].

Table 3.1 Fujita Scale for measuring Tornado intensity (Bureau of Meteorology)

F number	Wind Speed	Damage
F0	64-116 kph	Some chimneys damaged, twigs and branches broken off trees, shallow-rooted trees pushed over, signboards damages, some windows broken
F1	117-180 kph	Surface of roofs peeled off, mobile homes pushed off foundations or overturned, outbuildings demolished, moving autos pushed off the roads, trees snapped or broken;
F2	181-253 kph	Roofs torn off frame houses, mobile homes demolished, frame houses with weak foundations lifted and moved, large trees snapped or uprooted, light-object missiles generated
F3	254-332 kph	Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted, heavy cars lifted off the ground and thrown, weak pavement blown off the roads
F4	333-418 kph	Well-constructed houses leveled, structures with weak foundations blown off the distance, cars thrown and disintegrated, trees in forest uprooted and carried some distance away
F5	419+ kph	Strong frame houses lifted off foundations and carried considerable distance to disintegrate, automobile-sized missiles fly through the air in excess of 300 feet, trees debarked, incredible phenomena will occur

Figure 2.3 shows that the buildings used to estimate the wind speed in the event were in the region with the maximum damage and quite early in the track of the Shoalwater tornado. Damage levels to buildings and trees alike were much lower for the last one third of this tornado, and no structural damage was observed for the last kilometre of its track.

The maximum intensity of the Shoalwater tornado appeared to be F1, and it is likely that it was F0 for the last two or three kilometres of its track.

3.3.2 Roleystone tornado

The first half of the Roleystone tornado passed over a large number of houses, and in this half, the wind speeds were estimated to be less than the wind speeds in the Shoalwater tornado. The tornado was likely an F0 event for this portion of its path.

In the second half of the Roleystone tornado, after the path had crossed a forested ridge, the intensity appeared to increase to a high F1 or low F2. There were no houses in the direct path of the tornado in this region, but some just outside the path were significantly affected. The wind speeds at those locations were difficult to estimate.

3.3.3 Wind speed at houses compared with design wind speed

The Scope of AS/NZS1170.2 [1] excludes its use for determining wind speeds and resulting wind actions caused by tornadoes. This is because of the following uncertainties in tornado wind actions:

- Both the variation of wind speed with height and turbulence intensity are not known for tornadoes, so the $M_{z,cat}$ term used to establish gust wind speed at the structure from the regional wind speed cannot be evaluated.
- Pressure fields in the tornado itself may complicate the differential pressures across building surfaces evaluated using AS/NZS1170.2 [1].

However, in this report, estimations of wind speed caused by the tornado at the building height can be compared directly with the wind speeds for which the buildings should have been designed.

- The maximum tornado wind speeds at the building height. This can be directly compared with structure height design wind speeds which have been derived from 10 m height regional wind speeds with $M_{z,cat}$ correction for building height and turbulence intensity. The maximum wind speed at roof height from the tornado can be directly compared with the design gust wind speed at the same height. The basis for the comparison is the same.
- The concern about very low tornado central pressures is that once a tornado envelopes a building there is a differential across the surface caused by the central pressure of the tornado that makes the building "explode". If this is the case, then damage may not be due to wind pressure, but the sudden pressure drop as the tornado passes. For this study, the damage was associated with door or window failure on a windward wall in which the glass or door was blown inward. This mode of failure could only have occurred under the action of wind pressures not localised low tornado pressures.

For these reasons, it is valid to use the wind speeds that caused the damage to predict the type of damage that would occur had the same wind speeds resulted from winds that were within the scope of the Australian Standards [1], [2].

Therefore, the design wind speeds for houses throughout the tornado tracks in this report were calculated using AS/NZS1170.2 [1] and AS4055 [2]. The entire path of the Shoalwater tornado was across flat topography and all but the start of the path, the terrain category would have been classed as Terrain Category 3. The shielding varies, but in the recent housing, it was sparse enough to be regarded as partial shielding. For only a small part of its track, could the housing be regarded as fully shielded. The entire path is in wind region A.

- The design wind speed of 34 m/s given in AS4055 [2] is the ultimate wind speed for N1 housing corresponding to the design conditions outlined above.
- The design wind speed of 33 m/s given in AS/NZS1170.2 [1] is the ultimate (500 year return period) wind speed for 3 metre high buildings designed for the conditions outlined above including partial shielding.

The estimated peak wind speed in the tornado was very close to the design wind velocity for all of the modern housing in its path.

The path of the tornado in Roleystone passed over undulating topography. Many of the houses had topography class T2 and partial shielding. This put them into wind classification N2 and N3. Their construction details should have been matched to wind speeds of 40 m/s or 50 m/s, well in excess of the wind speeds in the first half of the tornado. (In the first half of the Roleystone tornado, the wind speed was estimated to be significantly less than 34 m/s.) Hence, even houses in N1 locations on this path should not have experienced winds near their design wind speed, 34 m/s.

4. Damage to buildings

The damage indicated that the tornado had a width of around 30 m. It was estimated that over the 7 km of the track that it affected over 200 houses, and the State Emergency Service responded to around 250 calls from the suburbs that included the tornado path. Even though some of these may have been to deal with fallen trees, the figure is large enough to indicate that there were more houses affected by the tornado than those that were in its direct path. The SES also reported that around 15 houses had been 'unroofed', though this statistic may include a number that had lost less than half of the roof or roofing.

The roof damage observed was commensurate with wind pressures and suctions from high speed wind. The study did not attempt to examine each damaged building, but sought to examine in some detail damage that was seen as quite typical.

4.1 Wind damage to modern tiled roofs

(a) tiled roof with wind damage

(b) tile with nail in place on the ground

Figure 4.1 Wind damage to tiled roof

A number of tiled roofs suffered some damage. In the Perth metropolitan area, standard practice is to nail down every second tile, and every attempt is made to stagger the pattern at each row. Each tile that is not anchored has an anchored tile on either side of it, and in most cases, an anchored tile above and below it.

In a few cases, the damage could be entirely attributed to wind pressures alone. In most cases, the damage was associated with debris impact on the tiles.

Figure 4.1 shows a roof with incidental tile damage in areas of the roof that would have experienced very high suctions under wind actions alone. In the affected area, there was no sign of debris impact and many of the tiles had been removed with little breakage. In some cases, the nail used to anchor the tile was still in place in the tile.

The tiled roof used for wind speed estimation and illustrated in Figure 3.2 also experienced wind damage to tiles. In all of these cases, relatively small areas of roof were affected by the tile damage. It was only parts of the roof close to the intersections of roof planes (hips and ridges) that were subjected to tile loss. This indicates that at the design load, the highest loaded regions of the roof are close to their capacity.

Figure 4.2 shows a roof panel that experienced particularly high suctions, and it can be seen that while the tiles just below the ridge are still intact, they have almost lifted off. The tiles near the hip have been lifted by the wind.

Figure 4.2 tiles in high uplift regions of the roof.

The estimated tornado wind speed was sufficient to lift individual tiles under external suctions. As the estimated tornado wind speed was close to the design wind speed for this location, the design wind speed is also sufficient to lift individual unfastened tiles. In peak suction areas of hip roofs, uplift forces exceed the weight of the tile at gust wind speeds of between 25 and 30 m/s.

4.2 Wind damage to sheet roofs

Most of the more conspicuous damage along the path of the tornado involved damage to sheet roofs. All of the roofs we observed that had damage to more than 50% of the roof were sheet roofs.

4.2.1 Modern stick-built roofs

Some damage typical of "stick-built" roofs (roof framing using rafters and underpurlins instead of trusses) with sheet roofing that were in the direct path of the tornado is explored in Figures 4.3 to Figure 4.5.

Figure 4.3 shows a view of the roof from inside the house. The most obvious problems are that the roof has lifted over the room from which the photo was taken, and the ceiling has collapsed with the subsequent water damage. However, a more detailed investigation inside the roof showed that many of the structural connections in the roof had been significantly compromised and the whole roof structure was very close to a comprehensive failure. Figures 4.4 and 4.5 were taken from inside the roof space in an area in which the roof sheeting was still attached, and where from an external perspective, there were no problems.

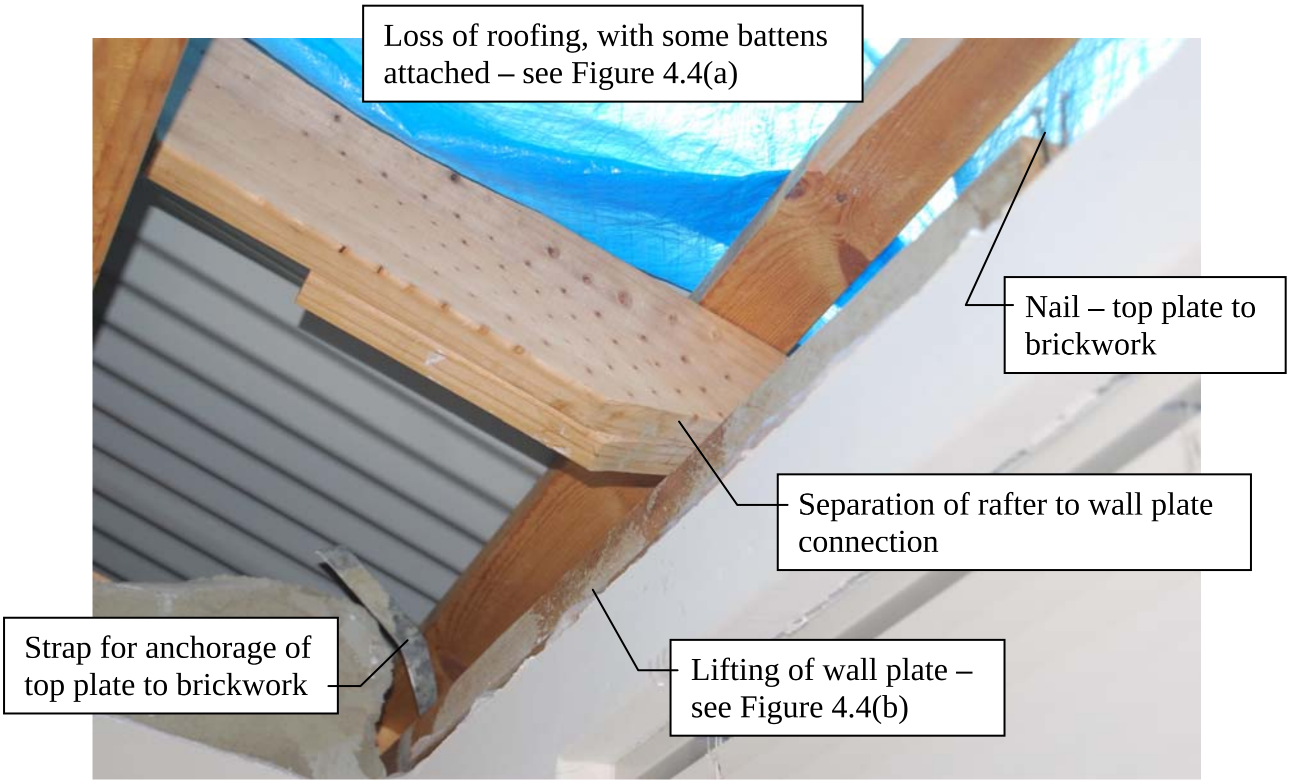

Figure 4.3 Wind uplift damage to sheet roof

Figure 4.4 (a) shows a batten to rafter connection in which three gun driven nails had been used. In other parts of the roof, only two nails were used. However, where the roof had detached, battens and the roof sheeting remained together. The batten to rafter connection was a weakness in the outer roof structure. In some places on this house, rafters had also separated from the wall plates.

(a) batten to rafter connection

(b) rafter to top plate connection

Figure 4.4 Separation of connections in the outer roof structure

(a) connection at top of strut

(b) connection at bottom of strut

(c) connection at hip rafter

Figure 4.5 Separation of connections in the inner roof structure

The anchorage of the rafters at the eaves consisted of skew nailing to the top plate as shown in Figure 4.4 (b), and the top wall plates were tied to the brickwork with nails through the top plate into the brickwork and straps over the top of the top plate. The top plate to wall connection details are shown in Figure 4.3.

In this house only 25% of the roof was lost due to failure of 2 nail batten to rafter connections. However, elsewhere in the house, where the roof remained attached to the roof structure, there was significant distress to the connections between underpurlins, struts and strutting beams. Figure 4.5 shows the movement opened up at these joints in spite of the use of a large number of skew nails.

In the strutting system, roof carpenters can appreciate the load path when the roof is loaded with gravity loads, but do not provide tie down through the same load path for uplift loads. With lightweight roof systems, wind uplift can be significantly more than the dead weight of the structure. AS1684.2 [5] has details for anchorage of underpurlins and struts under wind loads (AS1684.2 [5] Table 9.23). These details were not seen on any stick-built roofs in this study.

(a) Upper storey with loss of most of roof structure

(b) Detail where parts of structure remained

Figure 4.6 Loss of roof structure from second storey

Figure 4.6 shows another stick-built roof in which almost the entire structure was lost. The house was under construction at the time In this case, the rafter to top plate connections had failed, and the tie down from the struts was ineffective as well. Most of the struts had been lost with the house. In many rooms, the ceiling structure remained intact, but water damage to the plasterboard meant that it had fallen in.

Figure 4.6(b) shows enough detail of the structure remaining to identify it as a stick-built roof. Throughout the second storey, the top plate had lifted from the brickwork, but over much of the house, the weight of the ceiling and the action of the strap had kept it attached. However, the rest of the roof structure had largely been lost. This included lifting of the rafters at the eaves and struts in the central part of the roof. Over much of the roof, the struts, underpurlins and rafters were missing with the roof debris.

This house was nearing completion at the time of the tornado. All of the external construction had been completed, the internal walls and ceilings plastered, and fit out was near the end. All roofing, trims and flashings were fitted. The roof debris which was in one large piece cleared another two storey house and covered over 150 m before landing in public open space.

There was no sign of prescribed AS1684.2 [5] tie downs on struts in this house. The red circle in Figure 4.6(b) shows the top of a strut where the underpurlin has been lifted off the strut.

Figure 4.7 Loss of roof structure – two storey house

Figure 4.7 shows another house of recent construction in which most of the roof structure had lifted. Again, sufficient timber was left to be able to identify the construction as stick-built. On the little part of the roof structure remaining, the batten to rafter connection had failed.

The majority of the roof had lost all of the roof structure above the ceiling joists and top plate. Again, struts and underpurlins had all been lost with the rest of the roof structure.

The houses illustrated in Figures 4.6 and 4.7 were both two storey houses. AS4055 [2] assigns the same wind category to single and two storey houses, and in Terrain Category 2 or 3, the design wind speed derived from AS/NZS1170.2 [1] is the same. It is unlikely that there is a difference between wind speeds at 3 m and 6 m during tornadoes, as the wind in tornadoes does not usually travel a sufficient distance over land to develop a boundary layer. Therefore, the winds experienced in this event for these two houses would also have been close to the design wind speed.

In light weight (sheet) roofs, uplift forces exceed the weight of the roof at or below the design wind speed. Tie down of all structural elements in the roof is essential. A range of appropriate details of tie down connections in stick-built roofs is given in AS1684.2 [5]. However, there was little evidence of them being used in the badly damaged buildings in these events.

4.2.2 Modern trussed roofs

A number of sheet roofed houses that were substantially damaged had trussed roofs. Figure 4.8 shows one in which the roofing and battens have lifted.

(a) roof batten loss

(b) lifting of timber top plate at truss heel joint

Figure 4.8 wind uplift on trussed roof

In this case, the battens were light gauge top hat sections, and the light gauge steel tore over the batten fasteners. The trusses were nailed into timber top plates which were anchored by direct nailing to the brickwork and steel straps. Figure 4.8(b) shows that the top plate has lifted in some places, but the straps had held sufficiently to keep the roof attached to the top of the walls.

Figure 4.8 showed a house that had very recently been occupied and where the trusses were tied to brick walls. Figure 4.9 shows details of a house that had been occupied for around two years and the trusses had been anchored to framed walls.

(a) failure of truss anchorage

(b) lifted roof battens near corner of roof

Figure 4.9 Truss loss from framed walls

In Figure 4.9, all of the trusses had lifted a little from the walls. For two trusses, the lifting had not been stopped, but in all of the others, once the slack had been taken out of the connection, the upward movement stopped in a few mm. Figure 4.9(a) shows one of the truss heels that had lifted.

The main cause of the loss of roofing was the two nail connection between battens and rafters. On this house a bugle head screw had been used for the edge batten to rafter connection. Many of these connections were adequate, but the rest of the roof used two nails and in some cases, loss of the rest of the battens had increased load on the bugle head screws to cause them to withdraw as well. Figure 4.9(b) shows the corner of the roof where all of the battens had lifted but the roof had not completely detached in this area.

For this house, the topographic class from AS4055 was higher than T1, and this should have been taken into account in the design of the house. Its wind classification was N3.

In considering the construction details used for this house, AS1684.2 [5] Table 9.14 showed that the required batten to rafter force was 2.3 kN within 1200 mm of the edge of the roof and 1.2 kN in the remainder of the roof. AS1684.2 [5] Table 9.25 shows that two nails have a capacity of 0.64 kN, and one bugle head screw has 4.5 kN.

Thus in this roof, the edge batten had excess capacity 4.5 kN to meet an uplift demand of 2.3 kN, but the next batten in from the edge (also within the edge zone), had a connection capacity of only 0.64 kN to meet a demand of 2.3 kN. Elsewhere in the roof, the capacity was 0.64 kN to meet a demand of 1.2 kN. The batten to rafter connections did not satisfy the requirements of AS1684.2 [5].

In considering performance in the tornado, the two nail batten to rafter connection would have failed at wind speeds at the house of greater than 26 m/s or 95 kph. This is within the range of wind speeds expected in the tornado at that location.

In each case, the trusses themselves performed well, but the two areas of weakness were batten to truss connection and truss to wall anchorage. Had these details complied with AS1684.2 [5], there may have been less significant damage.

4.2.3 Older trussed roofs

A house that was estimated at 20 to 25 years old had batten loss from half of the roof. In this case, the roof structure consisted of nail-plated pine trusses and the roof was a simple gable shape. The battens were 50 × 50 hardwood sections and the 75 mm nails skew driven for the batten to truss connection had around 25 mm depth of penetration into the softwood as shown in the inset to Figure 4.10.

While this house pre-dated AS1684.2 [5], it is important to note that the detail would not have satisfied the current requirements.

Figure 4.10 Batten loss from older truss roof
(inset shows small depth of penetration of nails in softwood trusses)

4.3 Internal pressures

There was significant evidence that high internal pressures contributed to the loss of structural elements. In most cases, this could be traced directly to the action of high wind pressures on the windward wall rather than any suction effect on the outside from the tornado.

- Doors on the windward wall were blown into at least one house as shown in Figure 4.11(a). There was no evidence of debris damage on the door. The owner said that the door blew in and the blast of air forced her a few metres away from the door.
- On a number of different houses, windows on the windward wall were blown inwards, with broken glass spread for some distance inside the house. An example is shown in Figure 4.11(b).

The failure of doors and windows admitted high pressures through the windward wall and contributed to roof and wall loss.

Figure 4.12 shows a two storey house in which high external suctions on a side wall combined with high internal pressures to remove a wall panel. Parts of the roof were also taken off this house. A small gap between the roof and the remaining ceiling can be seen showing that the ceiling itself had lifted.

(a) broken door furniture

(b) broken glass blown inwards

Figure 4.11 Failure of doors and windows on windward walls

Figure 4.12 Loss of a side wall under combined internal pressure and external suction

It is well accepted that in Tropical Cyclone prone areas, designers must assume full internal pressurisation. This has been differentiated from other strong winds by the duration of the event. However in this event, the extreme winds lasted only a few seconds and internal pressure still played a significant role in structural damage.

4.4 Debris damage

Debris damage is not often considered for short duration wind events, but there are references to debris damage in tropical cyclones in the Australian wind code AS1170.2 [1].

However, there were a number of houses that were damaged by debris in both tornadoes. In some cases, the debris was released from the rotating column of air and struck buildings that were not directly in the path of the tornado.

Figure 4.13 Debris damage to tiled roofs

In Figure 4.13, the house on the left was clear of the tornado's path, but sustained debris damage to both the roof and window from sections of a neighbour's roof. The houses on the right were subjected to the tornado winds, and also sustained damage from a neighbour's garage door.

Figure 4.14 Debris strewn more than 50 metres from house

Figure 4.14 shows debris from just one house that produced at least five large sections of roof. Three of these can be seen in this photo together with some of the roof insulation. It is fortunate that this house was located in a rural setting, as it is clear that the debris generated would have substantially damaged any building it struck. However, in suburban areas, windows were broken by flying debris as shown on the left of Figure 4.13.

This report has demonstrated that short duration wind events generate debris. In a number of houses, wind borne debris broke windows that contributed to full internal pressurization.

4.5 Racking failure

A garage in the direct path of the tornado, shown in Figure 4.15, failed due to racking at loads well below the appropriate design load for the location.

The failure was due to inadequate fastening of the bracing. The bracing appeared to have been intended for squaring the garage during construction. rather than for resisting the wind forces. The single skin cladding was a weatherboard type product that was incapable of offering any resistance to racking.

Figure 4.15 Racking failure of garage

4.6 Maintenance

Lack of maintenance or deterioration did not contribute to any failures seen in this investigation.

5. Implications for Standards and BCA

Many of the failures were due to construction practices rather than deficiencies in the Standards. However, revision of AS/NZS1170.2 [1] should be considered to allow for debris damage that causes full internal pressurization in non-cyclone-prone areas as described in Section 5.5.

5.1 Batten to rafter connections

Poor performance of batten to rafter connections contributed to loss of sheet roofing in both tornado events. The information required to correctly select and apply this detail is clearly outlined in AS1684.2 [5]:

- The wind classification of the house is found from AS4055 [2].
- Table 9.14 in AS1684.2 [5] can be used to select a force from the roof type, wind classification, batten spacing and rafter spacing. Different forces are given for the edges of roof panels and general areas.
- Table 9.25 in AS1684.2 [5] can be used to select appropriate connections to resist wind uplift forces in edge areas and general roof areas.

Over the past 10 to 15 years, materials used in housing construction have changed, but some construction practices may not always have been modified to deliver satisfactory performance:

- There has been an increase in the number of sheet roofs used in house construction. Wind uplift forces are significantly higher for sheet roofs compared with tiled roofs.
- Softwood is now more commonly used than hardwood products in stick built roofs. Resistances for connectors in seasoned softwood are generally lower than those for hardwoods.

The top hat battens shown in Figure 4.8 were the only example seen, and they tore at the batten to truss connection. This detail may require checking in thin gauge battens used in Region A.

5.2 Rafter to top plate connections

Poor performance of rafter to wall connections contributed to loss of rafters under sheet roofing in both tornado events. The information required to correctly select and apply this detail is clearly outlined in AS1684.2 [5]:

- The wind classification of the house is found from AS4055 [2].
- Table 9.13 in AS1684.2 [5] can be used to select a force from the roof type, wind classification, roof load width, and rafter spacing.
- Table 9.21 in AS1684.2 [5] can be used to select appropriate connections to resist wind uplift forces. Even in N1 houses, skew nails do not offer enough resistance in softwood top plates for most sheet roofs. Framing anchors and straps are required.

5.3 Roof structure connections – struts, underpurlins and strutting beams

Poor performance of underpurlin, struts and strutting beam connections contributed to loss of the entire roof structure under sheet roofing in the Shoalwater tornado. The information required to correctly select and apply this detail is clearly outlined in AS1684.2 [5]:

- The wind classification of the house is found from AS4055 [2].
- Table 9.12 in AS1684.2 [5] can be used to select a force from the roof type, wind classification, roof load width, and fixing spacing.
- Table 9.23 in AS1684.2 [5] can be used to select appropriate connections to resist wind uplift forces. Even in N1 houses, skew nails do not offer enough resistance in softwood members for most sheet roofs. Looped straps are required.

5.4 Top plate to masonry connection

Failure of the top plate to masonry connection was noted in a number of houses with sheet roofs, and may have occurred in others where there was no visible external damage, but the cornices or ceilings were cracked.

Nailing the top plate to the top row of bricks does not offer sufficient resistance to uplift for any sheet roof. Straps anchoring the top plate must be secured to a sufficient depth of brickwork as indicated for rafters or trusses to external walls in Clause 3.3.3.3 of the BCA [7].

The BCA covers anchorage of rafters and trusses to external walls, but in stick-built roofs, there is also a need to anchor the base of struts and strutting beams that carry uplift forces to internal walls in the centre of the house:

- The wind classification of the house is found from AS4055 [2].
- Wherever the roof structure is tied to the top plate, an uplift force has been found from AS1684.2 [5] as detailed in Sections 5.2 and 5.3 above.
- The weight of brickwork into which the straps must be tied must resist the uplift forces generated by the wind tie-down in the roof structure. For standard WA internal brickwork, the depth at which the strap is anchored to deliver that weight is calculated by
    - $\text{depth} = \sqrt{\dfrac{force}{3.56}}$ (metres) or
    - as shown in Table 5.1.

Table 5.1 Depth of anchorage into brickwork for sheet roof tie down

Force	Depth
(kN)	(m)
1	0.53
2	0.75
3	0.92
4	1.06
8	1.50
12	1.84
>14	full height

5.5 Verandah details

In some cases, verandahs are not designed or constructed as rigorously as the rest of the house. Where verandahs are constructed under the main roof and verandah details have insufficient capacity to resist wind loads, failure of the verandah can lead to failure of sections of the house roof.

Verandah roofs can experience higher uplift loads than the remainder of the house roof. Verandahs always have full windward wall pressure pushing upwards on the underside of the roofing together with peak suction pressure on the upper surface of the roofing.

5.5.1 Batten and rafter spans

Figure 5.1 shows a verandah with batten spacings of 1.2 m when the house to which it was attached had spacings of 0.9 m.

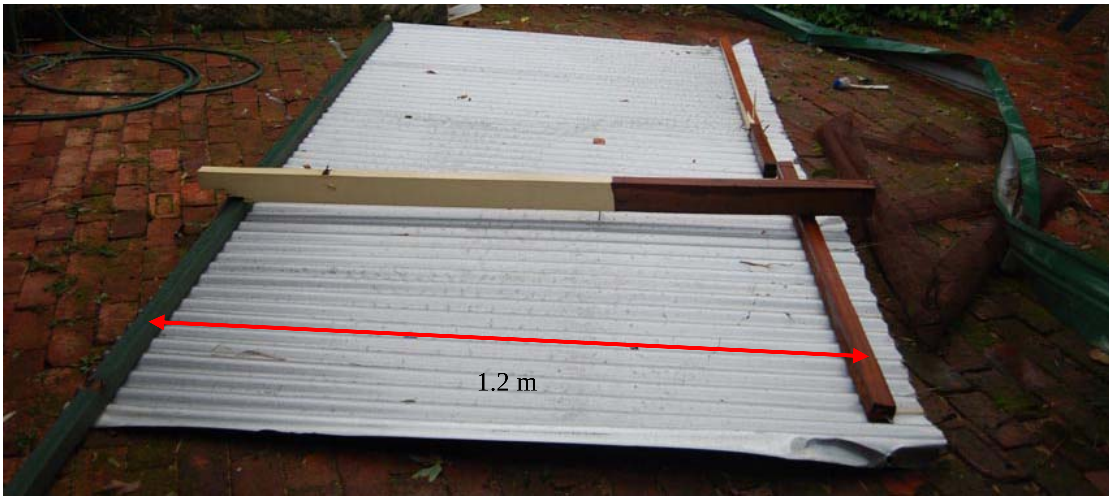

Figure 5.1 Batten spacing on verandah

The spacing of verandah battens and rafters must be smaller or equal to the spacings used in the main roof. Batten to rafter connections must have the same or greater capacity as the batten to rafter connections in the main roof.

5.5.2 Beam to post connection details

Figure 5.2 shows a verandah beam to post connection that failed under wind load leading to loss of both the verandah and main roofs. This connection was made with two nails, but two M16 bolts are specified in AS1684.2 [5].

The information required to correctly select and apply this detail is outlined in AS1684.2 [5]:

- The wind classification of the house is found from AS4055 [2].
- Table 9.13 in AS1684.2 [5] can be used to select a force from the roof type, wind classification, roof load width, and spacing between beam to post connections.
- Table 9.20 in AS1684.2 [5] can be used to select appropriate connections to resist wind uplift forces.

(a) Verandah beam

(b) Verandah post

Figure 5.2 Verandah beam to post connection

5.6 Wind Classification

A number of houses on sloping ground were in the direct path of the Roleystone tornado and sustained no structural damage. If these houses had been correctly classified as N3 houses, the construction details would have been more than adequate to resist the winds estimated for that event. However, in the same location, damage was caused to some buildings that had details more appropriate for N1 housing.

For tornado winds, topography is not a significant issue, but the use of N1 details in houses on N3 sites highlights some apparent deficiencies in construction practice.

"Tropical Cyclone Larry – Damage to Buildings in the Innisfail area" TR51 [6] found cases where some houses on hills had been given an incorrect wind classification. The same problem was observed in some of the houses in this investigation in Region A. It is essential that wind classifications to AS4055 [2] correctly take account of the topography and shielding of the site.

5.7 Debris and internal pressures

Full internal pressurisation of a number of buildings was noted. This followed failure of windows or doors. In some cases, debris impact triggered these failures. The tornadoes produced a significant amount of airborne debris, and eye witness accounts indicated that the rotating debris was more visible than the tornado funnel itself. The wind speed that affected all of the buildings investigated in this study was up to or around the design wind speed for the area.

The Australian Standard AS1170.2:2002 [1] Clause 5.3.2 requires that in Regions C and D internal pressure from a dominant opening shall be applied unless the building envelope can withstand an impact test. However, full internal pressurization was observed at wind speeds around the design wind speed for Region A. Consideration should be given to require all buildings to be designed to the same provisions as Clause 5.3.2 in Regions C [1].

6. Conclusions

Although tornadoes are not covered in AS/NZS1170.2 [1], the winds generated by the Shoalwater and Roleystone tornadoes could be compared with the design wind speeds, as discussed in Section 3.3.3. The maximum wind speeds of both the tornadoes were at or less than design wind speed for all affected houses. Therefore, the tornadoes should have produced little to no structural damage to correctly constructed buildings.

Section 5 details some areas of construction practice in which deficiencies were noted:

- Batten to rafter connections
- Rafter to top plate connections
- Roof structure connections
- Top plate to masonry connections
- Verandah details

This investigation has also shown that some houses had been given incorrect wind classifications. Although this is usually not an issue for winds in a tornado, it would be important for other wind events and more diligence is required in this area.

Even short duration wind events such as tornadoes generate airborne debris. Some of this debris was instrumental in causing full internal pressurization, which in turn lead to significant structural damage. In other cases, failure of doors and windows lead to full internal pressurization. Standards Australia should give consideration to amending clause 5.3.2 in AS/NZS1170.2 [1] to include buildings in all regions.

7. References

[1] Standards Australia (2002) “AS/NZS 1170.2 – Structural design actions, Part 2: Wind actions”, Standards Australia, Sydney NSW

[2] Standards Australia (2006) “AS4055 – Wind loads for housing", Standards Australia, Sydney NSW

[3] Xu, Y.L., and Reardon, G. F., (1998) "Variations of wind pressure on hip roofs with roof pitch", Journal of Wind Eng. Ind. Aerodyne. 73 pp. 267-284.

[4] Bureau of Meteorology (2008) Notes on tornadoes. Web address (*bom.gov.au*)

[5] Standards Australia (2006) “AS1684.2 – Residential timber framed construction. Part 2: Non-cyclonic areas", Standards Australia, Sydney NSW

[6] Cyclone Testing Station “Tropical Cyclone Larry – Damage to Buildings in the Innisfail area” TR51, Cyclone Testing Station, James Cook University, NQ.

[7] Australian Building Codes Board “Building Code of Australia – Volume 2; Class 1 and Class 10 Buildings, Housing Provisions".