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Investigation of Performance of Housing in Brisbane Following Storms on 16 and 19 November 2008

Report: TR55
April, 2009

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JAMES COOK UNIVERSITY

TECHNICAL REPORT NO. 55

Investigation of Performance of Housing in Brisbane Following Storms on 16 and 19 November 2008

April 2009

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Executive Summary

The Bureau of Meteorology recorded a significant level of storm activity in the South-East part of Queensland during the period 16 to 20 November 2008. These storms caused damage to housing in many parts of Brisbane. Teams from the CTS conducted surveys of housing damage in The Gap and Redbank Plains from the 16 November storm, and in Paddington from the 19 November storm. The peak gust wind speed for both events were estimated to be less than the current design wind speed for Brisbane.

Street surveys performed on a sample of 97 houses in The Gap indicated that Post 1980 houses built after the introduction of the Queensland Government's "*Appendix 4 to the Standard Building By-Laws (1975-1984)*" performed better than Pre 1980 houses built earlier.

The most common types of damage observed were:

- A significant amount of damage was caused by falling trees.
- Water ingress, either through failed doors or windows, or very often water penetration caused by differential pressure across doors or windows that had not failed.
- Water ingress through intact unsarked tiled roofs in Redbank Plains.
- Inadequate tie-down, with connection details that were not in accordance with AS1684.2.
- Flying debris breaking windward windows or doors causing a sudden increase in internal pressure, sometimes leading to subsequent failure.
- Some cases of windows or doors not being adequately fixed to their supporting structural members and allowing the complete door or window to fail.
- Reports of failures to skylights, either from hail or wind or a combination of both.

Based on the observations and analysis of this damage investigation, the main report recommendations include the following:

- Initiatives to better enable ground level wind speeds to be measured in extreme events
- Review the factors used to determine design wind speeds in AS4055 to be consistent with AS/NZS1170.2.
- Review AS 2047 to consider increasing the differential pressure limit across windows/doors at which they must remain water tight and to specify suitable fixing details to the supporting structure that are strong enough to resist the design wind loads.
- Investigate the need for requiring housing in non-cyclone areas be designed for higher internal pressure, unless the windows and doors are capable of resisting the applied wind loads and an appropriate level of flying debris impact loading..
- Review AS/NZS 4505 to ensure that design and installation specifications for garage doors are adequate.

The report also recommends that the BCA be reviewed to investigate possible amendments to the following areas:

- Weatherproofing requirements so as to minimize the loss of amenity caused by water penetration through windows and doors.
- Include appropriate requirements for roof lights to resist both wind and hail loading.
- Specify that tile roofs constructed in all wind areas be required to have sarking installed.

Finally the report recommends a study to investigate the extent of housing connection details not being constructed in accordance with the relevant standards.

Table of Contents

1. Introduction

The Bureau of Meteorology recorded a significant level of storm activity in the South-East part of Queensland during the period 16 to 20 November 2008. These storms caused damage to housing in many parts of Brisbane. Teams from the CTS conducted surveys of housing damage in The Gap and Redbank Plains from the 16 November storm, and in Paddington from the 19 November storm. Analysis of Bureau radar images show a strong “downdraft” structure in the 16 November storm, and a “peak” gust wind speed of about 50 m/sec (~ 180 kph) at a high elevation (nominally 450 m), at The Gap. The 19 November storm damage indicated a locally severe storm cell, likely to have been associated with a weak and transient tornado. A general view of the study area is shown in Figure 1.1.

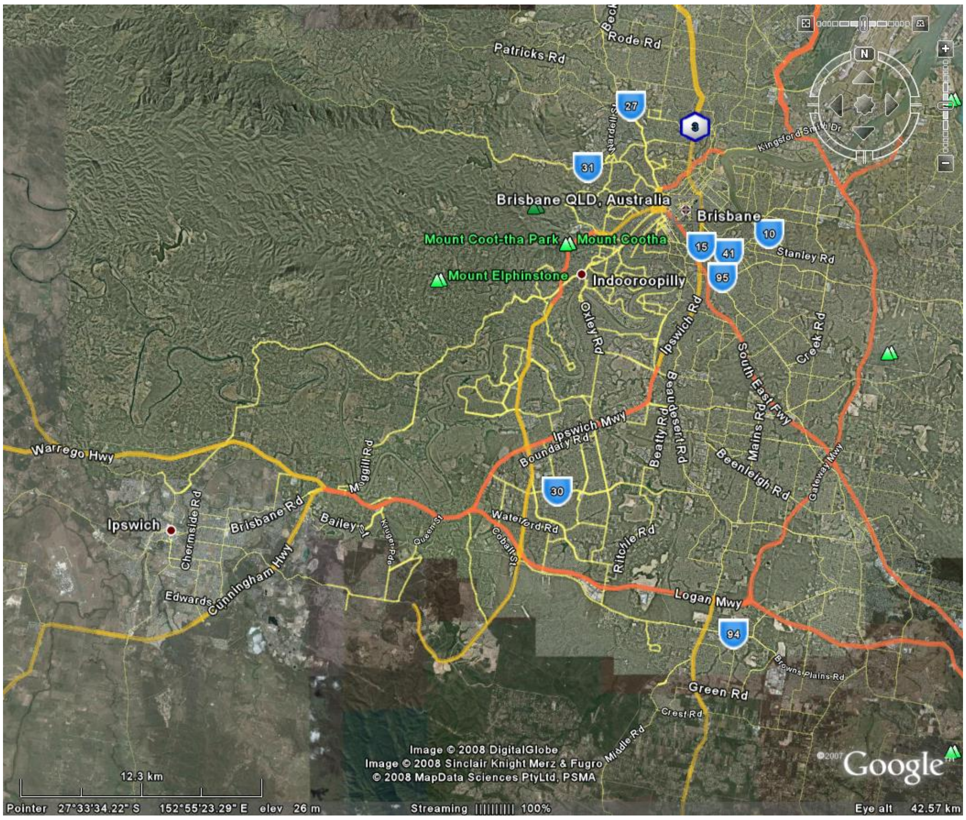

Figure 1.1: Locality of investigation area
(Image from Google maps)

The storms caused significant community disruption within the affected area. Lifelines (e.g. power, roads) were severely disrupted. Fallen trees were a significant feature of the events and did contribute to much of the damage.

- This report examines wind damage caused by the storms on 16 and 19 November 2008 and focuses on the performance of housing, which experienced strong winds in the areas in and around The Gap, Redbank Plains and Paddington in Brisbane.
- The report presents details of the wind storm and wind damage, including an indication as to the extent of wind damage to different types of housing.

1.1 Objective

The overall objective was to *investigate wind related damage to domestic housing in The Gap, Redbank Plains and Paddington in Brisbane.*

More specifically the study:

- Investigates wind related damage to housing in three suburbs of Brisbane, The Gap and Redbank Plains, caused by the storms of 16 November and Paddington, caused by the storm of 19 November.
- Provides estimated wind speeds for these events, based on Bureau of Meteorology radar images etc.
- Estimates the wind swathe of the 16 November storms in the study area centred on The Gap.
- Provides details and some case studies on areas of more concentrated damage.
- Provides possible reasons for failures of structural components and examines if there are any issues in relation to the application of building codes and standards.
- Provides initial recommendations for review of current codes and standards.

1.2 Strategy

In order to achieve the objectives within the constraints of the rapid clean-up and the limited time available for the investigation, the following strategy was adopted:

- A CTS investigation team was assembled comprising:
  - Cam Leitch, John Ginger, Peter Kim and Chana Jayasinghe from the CTS, Lex Somerville from BMCC Services and Bruce Harper from Systems Engineering Australia.
- Street-side assessments (Housing Surveys) were performed on small samples of housing to set the damage investigations in a context of the extent of damage to two house-age categories.
- Another priority was to obtain information from detailed studies of buildings of interest before debris was cleared away. This study aimed at establishing the elements at which failure was initiated, and any factors that may have contributed to poor performance of buildings.
- Inspections of new houses in Redbank Plains to investigate water ingress, apparently through undamaged tiled roofs.

2. Estimates of Wind Speed and Direction

2.1 General

In order to analyse the structural performance of the buildings, it is also necessary to estimate the wind field (i.e. wind speed and direction) in the study area. In particular, it is necessary to determine the relationship of the estimated wind speed to the current design wind speed.

The wind speeds in the study area were estimated from advice obtained from the Bureau of Meteorology and interpretation of radar images performed by Systems Engineering Australia. Estimation of wind speeds is difficult due to the absence of instrumentation in the area, the localized nature of the storm events and the complex topography in the locations affected by the storms. However, from an approximate analysis of the available data , the maximum gust wind speeds were estimated to be less than Brisbane's ultimate limit state design wind speed of 57 m/s,

2.2 Overview of the Storm Impacts

The period from 16 November to 20 November represented one of the most prolonged episodes of severe storm activity in the Brisbane region for many years and was reminiscent of the disruption caused by the 18 January 1985 severe hailstorm that impacted many parts of the northern suburbs, e.g. Jhamb et al (1985).

The first and most significant wind events on Sunday 16 were triggered by a SE change and comprised a large number of severe storm cells moving east and north across the region. A very severe cell passed over the Mt Tamborine and Gold Coast areas but only caused isolated damage. A more complex system passing north but just west of the CBD then delivered a swath of much more widespread damage, particularly in the suburb of The Gap. This severe downdraft event, referred to here as "The Gap" storm, also continued to cause wind-related damage right across the northern suburbs.

Next, on the night of Wednesday 19 November, an unusual mesoscale low formed over the Brisbane region and created an ideal environment for severe rainfall, creating flash flooding throughout the area. Associated with the many storm cells that formed within that environment was a localised wind event that affected a small number of properties in the inner city suburb of Paddington. Finally, on the night of the 20 November, further severe storm activity was widespread and some isolated wind damage occurred on the Redcliffe Peninsula. The events of the 20 November are not considered here.

Figure 2.1 provides direct evidence for the extent and location of damage caused by these sequences of storms. The top map shows the distribution of Brisbane City Council SES address responses for (a) the period from the 16 to 19 November (1432# yellow dots) and (b) the period from 20 November onwards (510# green dots).

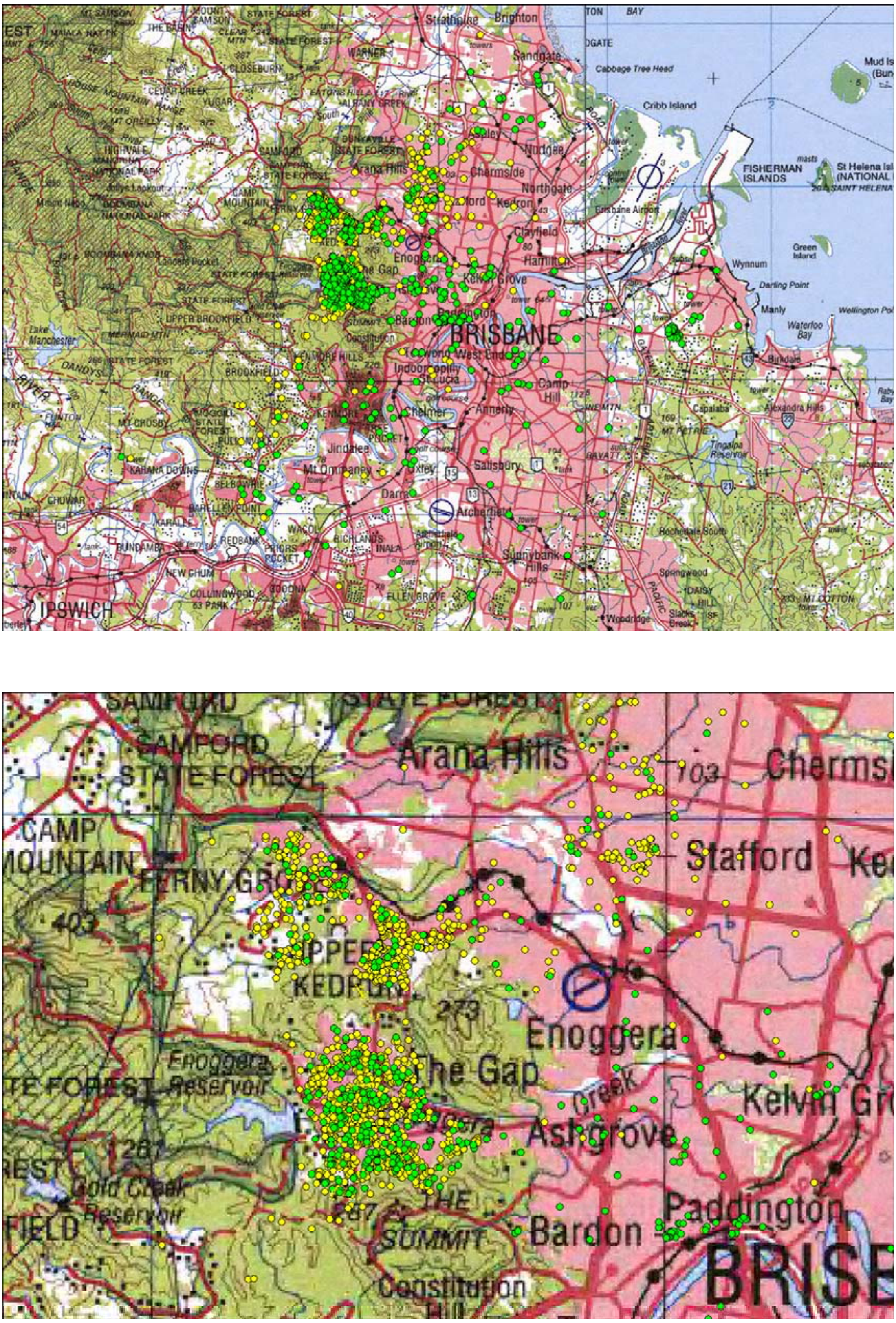

Figure 2.1: Brisbane City SES responses 16th to 22nd November 2008.
[Yellow: Between 16-Nov-2008 00:00 and 19-Nov-2008 21:00; Green: Between 19-Nov-2008 21:00 and 22-Nov-2008 23:59]
Data supplied by Wade Harrison, SES Local Controller.

This clearly shows the concentration of damage in and around The Gap (bottom panel), as well as the swath of damage right across the city on the 16 November (top panel). Furthermore, it also shows the effect of the flooding rains on the $19^{th}/20^{th}$ whereby many of the originally (perhaps minor) roof-damaged residents from the original storm required assistance in making their properties waterproof. Other local government SES responders also assisted many other residents across the area.

2.3 Overview of the 16 and 19 November Storm Environments, Movements and Coverage

With November always being an active month, the period 16 to 20 November 2008 was especially conducive to severe thunderstorm development in South East Queensland. This section provides a basic description of the storms during the period of interest. Interpretation of the events has been greatly assisted by the presence of three radars in the area at Mt Stapylton, Marburg and Redbank Plains. Both the Mt Stapylton and Redbank Plains radars had Doppler velocity capability but only above several hundred metres in elevation.

Appendix A provides a technical overview of severe thunderstorm meteorology and a classification of some identified types of synoptic situations (A, B, C and D) that create severe storms in this region.

2.3.1 16 November Event

The storm environment was very similar to the infamous 18 January 1985 “Type A” storm with a strengthening Mean Sea Level (MSL) coastal ridge developing south of a cold front (J. Callaghan, personal communication).

The following comments are from official Bureau of Meteorology (BoM) notes (courtesy T. Wedd):

> *Large, potentially thunderous clouds started forming over northern NSW early in the afternoon, with mature storms soon spilling off the border ranges into southeast Queensland. A north-easterly track then carried the storms over Wonglepong, Canungra and Mt Tamborine, where the first reports of wind and hail damage were documented. The offending storm subsequently merged with a second cell – also originating from across the border – resulting in a new cell that tracked across Redbank Plains through the western and north-western suburbs of Brisbane, culminating in an extremely intense wind storm at the Gap. After advancing through Caboolture, the storm eventually decayed on the Sunshine Coast.*

As further detailed by the BoM, the broad impact of the storms included:

> *Damaging hailstones were observed at several locations along the storm’s path, including Wonglepong, Yatala, Guanaba, and Ferny Hills, some as large as golf balls. Intense rainfall and flash flooding also occurred at many locations. Recorded rainfall intensities included 36mm in 10 minutes at Enoggera and Everton Hills and 60mm in 20 minutes at Ferny Hills. However the intensity and duration of the damaging wind was the standout feature of the storm, particularly in the north-western suburbs of The Gap, Keperra, Arana Hills, Upper Kedron, Ferny Grove, and Ferny Hills. There was widespread damage to trees, power lines and some structures. Many of these areas were without electricity for over 24 hours. Damage was also reported from other suburbs including Everton Hills, Albany Creek, and Narangba. Emergency Services documented 716 damage incidents in the Brisbane, Moreton Bay and Caboolture areas on the morning following the storms, with an estimated 23,000 residents without power.*

Numerous unofficial reports were also received, most notably 3-4 cm hail at Mt Tamborine, a possible tornado at Canungra, and a rainfall report of 52mm in just 15 minutes at Morayfield.

Due to the small scale of the individual severe storm cells, maximum wind speeds were not captured by the limited number of anemometer sites, but many experienced significant gusts as summarised in Table 2.1.

Table 2.1: Maximum BoM recorded wind gusts in the Brisbane region on 16/11/2008

Station	Time	Direction		Peak Gust Wind Speed		
	(EST)	deg		kts	km/h	m/s
Amberley AMO	16:21	116	ESE	45	83	23.1
Cape Moreton Lighthouse	23:33	150	SSE	35	65	18.1
University Of Queensland Gatton	16:08	157	SSE	38	70	19.4
Archerfield Airport	16:37	183	S	30	55	15.3
Gold Coast Seaway	19:35	165	SSE	32	59	16.4
Redcliffe	17:55	133	SE	32	59	16.4

The sequence of hourly radar images from the Mt Stapylton site shown in Figure 2.2 illustrates the BoM description of events and has been annotated here with the broad red arrows for clarity. The first image is 0300 UTC (1300 EST) and the last is 0800 UTC (1800 EST) on the afternoon of the 16 November. The initial severe Canungra - Mt Tamborine system from the WSW develops first and is followed by another wave of storms, which tend to merge and move more northerly with “The Gap” event being highlighted by the yellow circle in the 0600 UTC (1600 EST) frame. The time of maximum winds experienced at The Gap and suburbs further north appears to be around 0630 to 0700 UTC (1600 to 1700 EST). These radar images indicate the degree of reflectivity from the hydrometeors (rain, hail etc) within the cloud structures and are normally correlated to a rainfall (precipitation) rate for public consumption. In this presentation they also represent an averaged reflectivity over several km of elevation.

These hourly images suggest significant variability of the many complex storm structures in both space and time. However individual cells at various times develop strong organisation characteristic of the super-cellular storm type, which can change significantly within each 6 min radar scan.

Figure 2.3 provides greater detail of the specific storm cell that impacted The Gap. This combined horizontal scan and vertical cross-section at 0624 UTC (1624 EST) is just before the storm makes its dramatic impact. The colour reflectivity scale this time is in decibels (dBZ), with the red 60 dBZ normally associated with very severe weather, especially strong updrafts and large hail. The top panel shows the radar located about 45 km SE of the location of The Gap and the white arrow is the line of radial section. The bottom pane (with radar origin reversed to LHS) shows the vertical scan along that radial section, with significant reflectivity as high as 12 km. Of specific interest here is the structural detail in the cell at this time, whereby a so-called Bounded Weak Echo Region (BWER) is identifiable, which indicates an area of relatively low reflectivity surrounded by higher reflectivity. This feature is evidence of the high level of cell organisation; a likely mesocyclone circulation that is feeding the strong updrafts and downdrafts of a supercell.

A more detailed examination of The Gap storm event is provided later, where the detailed Doppler radar information is considered in association with the on-ground impacts.

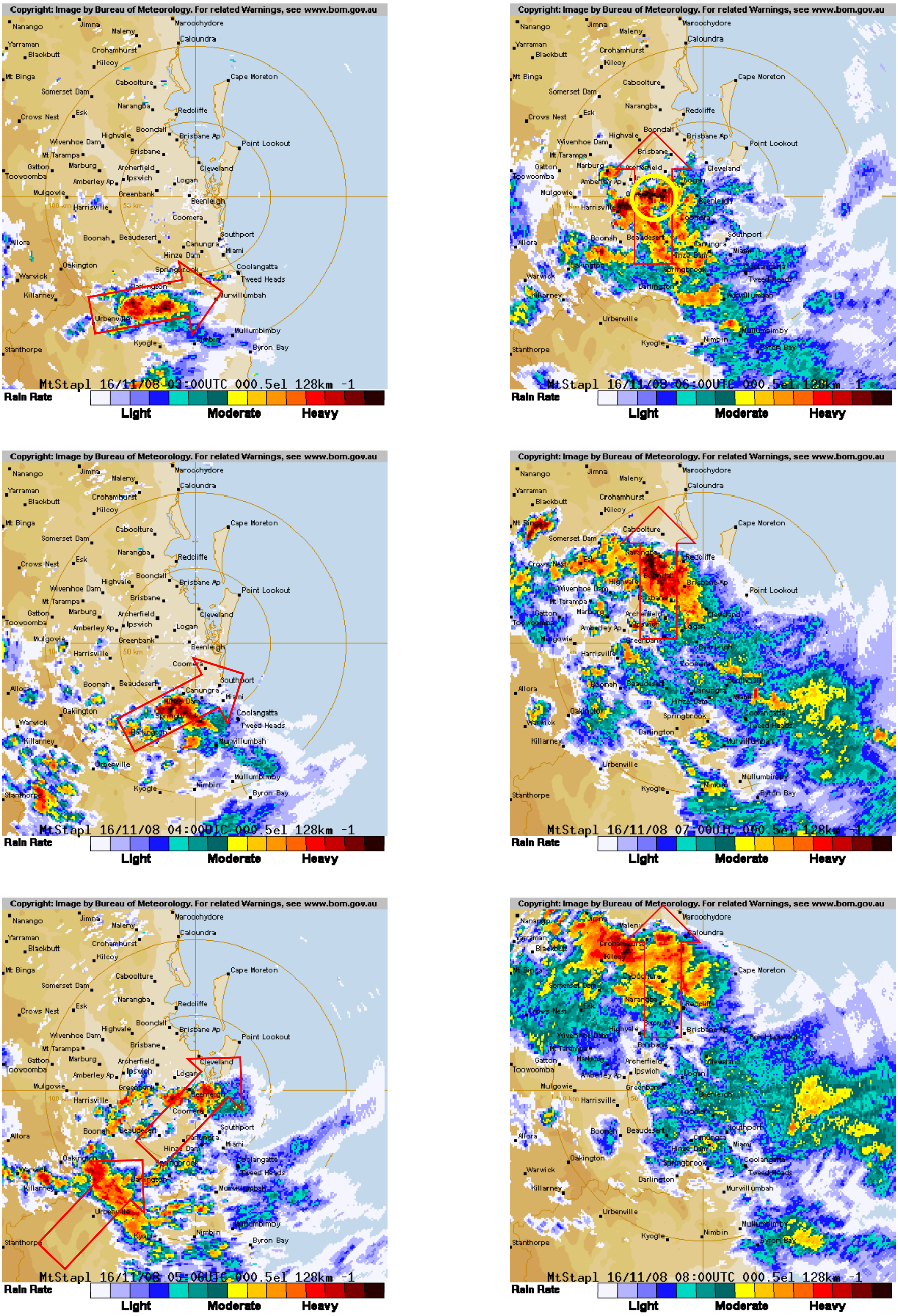

Figure 2.2: Bureau of Meteorology Mt Stapylton Radar images for 16/11/2008

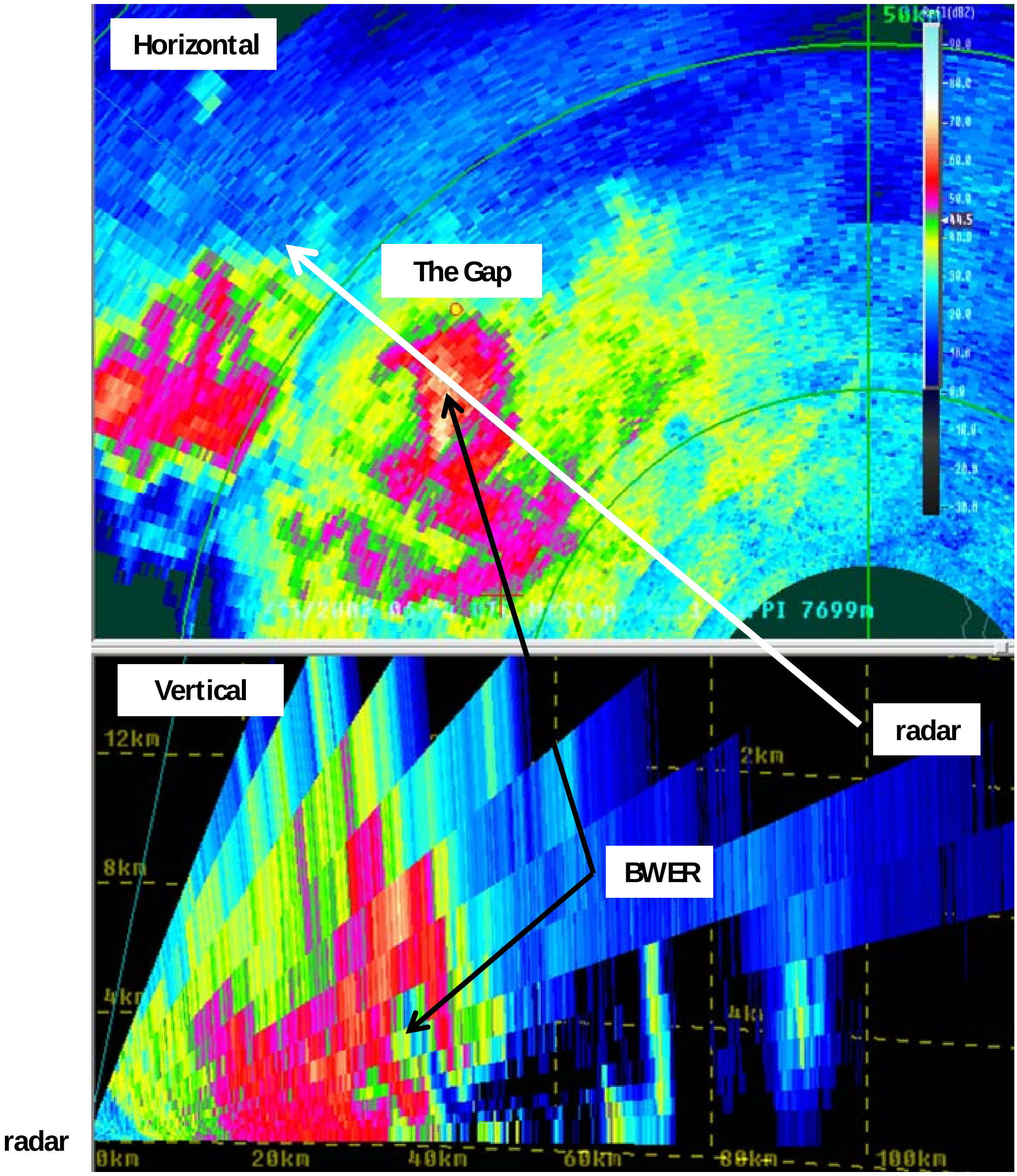

Figure 2.3: Mt Stapylton Radar with vertical crossection at 0624 UTC 16/11/2008.

2.3.2 19 November Event

This represented a new development compared with the 16 November event, whose influences had moved out to sea (J. Callaghan, personal communication). A broad inland trough interacting with the moist tropical air over eastern parts was the precursor but a significant mesoscale surface low then developed over southeast Queensland on the evening of the 19 November that was particularly conducive to producing extreme rainfall. A prolonged sequence of thunderstorms accompanied the low throughout the night and early hours of 20 November, classified here as a "Type D" event according to the Appendix A nomenclature.

The following comments are again from official Bureau of Meteorology (BoM) notes (courtesy T. Wedd):

> *Thunderstorm cells first became visible around mid-afternoon across the eastern escarpment of the Darling Downs, where they rapidly grew to maturity. By sundown, the storms had merged into a more or less continuous rain sheet, spreading from the Lockyer Valley to the Gold Coast Hinterland. At about 6.30pm, 3cm hail was unofficially reported south of Toowoomba from a severe storm cell embedded within the rain mass. By 10.30pm, several more of these cells had developed into an organised complex, slowly advancing north-eastward through Ipswich, the Brisbane Valley and eventually Caboolture. Moderate to heavy rain then persisted until the early hours of the 20th, causing extensive flooding to homes and waterways in the Lockyer Valley and Brisbane's western suburbs, many still recovering from the previous episode of storms. The most intense rainfall was 187mm in 2 hours and 109mm in 1 hour recorded at Tallegalla Alert (near Rosewood), however numerous locations through the Lockyer Valley and Ipswich areas recorded 2 hour totals of greater than 100mm with Average Recurrence Intervals (ARIs) of 50 to 100 years. Though wind was not the principal category of severity, Archerfield recorded a gust of 70 km/h just after midnight, with extensive roof damage to at least 5 homes at Beck Street, Paddington in Brisbane's inner west.*

In contrast to the event 3 days earlier, the radar images in Figure 2.4 show very broad areas of convection and widespread heavy rain late on the night of the 19th. The sequence begins at 1400 UTC (0000 EST 20/11) and shows (approximately) each half-hour up until 1600 UTC (0200 EST 20/11). The circular mesoscale low is highlighted by the black annotations, about and within which are numerous thunderstorm cells. Based on an eyewitness report (resident on the corner of Elizabeth and Beck St, Paddington), a severe wind event occurred in the early hours of the morning of the 20th. This would appear to correlate with the radar image of 1442 UTC (0042 EST 20/11) and the marked storm cell passing to the east in the vicinity of Brisbane CBD. This appears to be one of the more severe storm cells at around that time and, based on the damage inspection described in Section 5.3, is concluded likely to have been associated with a weak and transient tornado. As the wind-related impacts of this event were mainly confined to a few houses no further investigation of the radar data has been undertaken. As mentioned elsewhere, it is expected that the occurrence of weak tornadoes is much higher than previously thought and had this event occurred during daylight hours it may well have been sighted by residents.

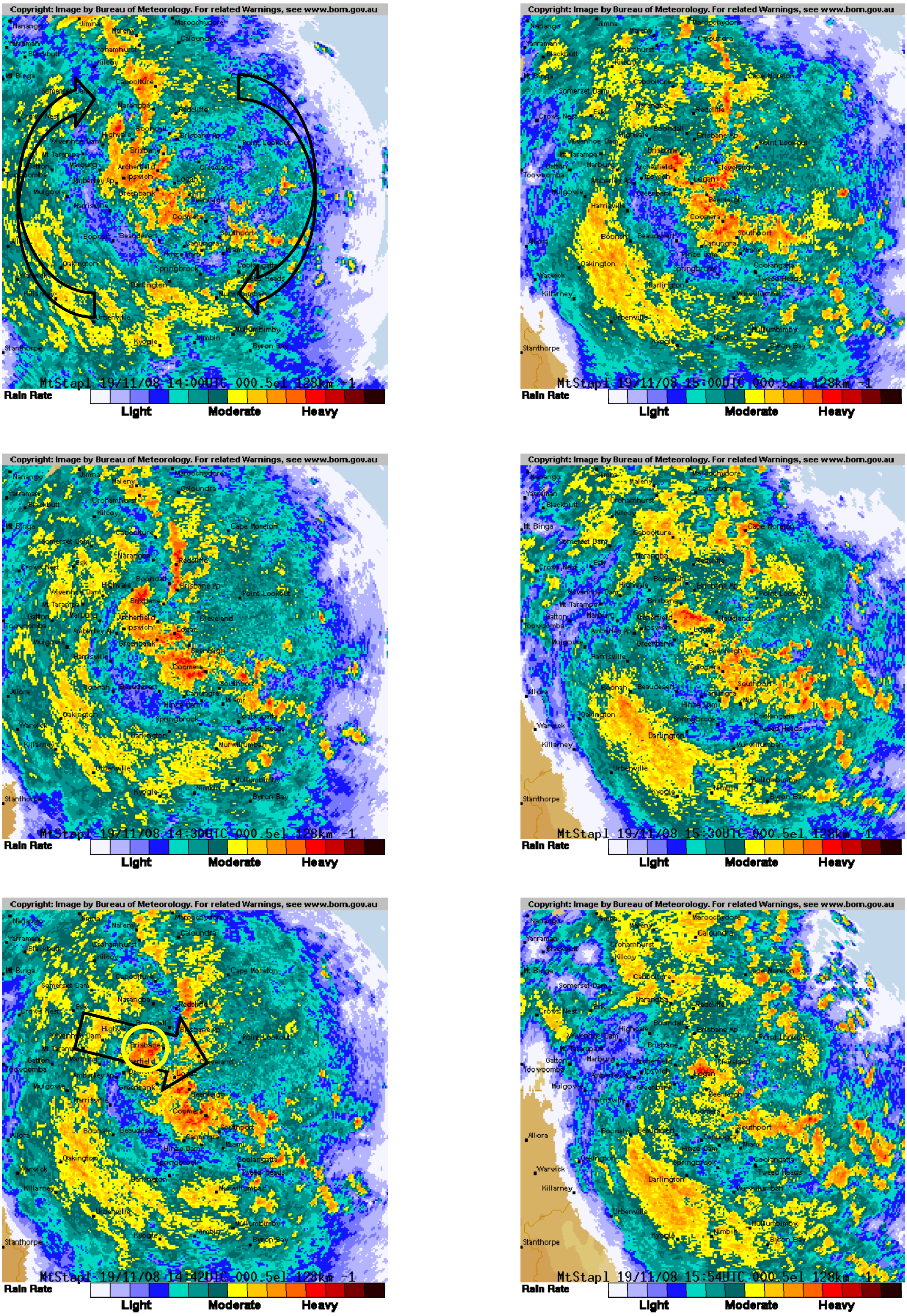

Figure 2.4: Bureau of Meteorology Mt Stapylton Radar images for 19/11/2008

2.4 A Detailed Assessment of "The Gap" Storm

2.4.1 Available Data

The principal data sources for this detailed investigation are the BoM radars, details of which are provided in Table 2.2 with parameters referenced to a nominal location in The Gap. The Mt Staplyton and Redbank Plains radars are both Doppler instruments, the latter being a research radar optimised for fine hydrometeor detection as part of a cloud seeding project. Each radar performs a series of azimuthal scans (1.0 deg), beginning at the lowest beam angle (0.5 deg) and then 14 vertical scans over a period of about 10 minutes. The series of snapshots are then temporally separated by 12 minutes, implicitly containing some skewing of returns in the vertical.

Table 2.2: BoM Radar Parameters Referenced to The Gap

							"Surface" Beam Cell Dimensions		
Station	Type	Lat deg	Lon deg	Elev m	Range km	Bearing deg	Elevation m	Height m	Azimuth m
Mt Stapylton	doppler	-27.7180	153.2400	150	42	313	798	743	736
Redbank Plains	doppler	-27.6692	152.8620	168	26	20	506	451	459
Marburg	3d	-27.6066	152.5400	370	44	68	1049	994	761
The Gap	NA	-27.4436	152.9438	55			55		

As Doppler radars only measure speed along the radial component, the relative location of the radars to the storm track and their ability to "see" the principal impact site at The Gap is of interest. The radar with the best (and closest) view is the Redbank Plains instrument. Although The Gap is surrounded by low hills between 150 and 300m in height, the Redbank Plains radar (itself at an elevation of 168m) has a reasonably clear line of site over The Gap just to the east of Mt Cootha.

2.4.2 Storm Track

The Mt Staplyton radar has been used as the reference instrument for determining the basic storm track parameters whereby the plan of the high reflectivity region (50 to 60dBZ) was traced over time and the location of the approximate centroid used to infer speed and direction of movement. Also, the approximate elliptical dimensions were recorded and the height of the 30 dBZ used as a proxy for "cloud tops", which is a crude indicator of intensity. These parameters are summarised in Table 2.3

Table 2.3: Storm parameters derived from Mt Stapylton

Time		Approx Centroid		Av.	30dbZ	60dbZ		Elliptical
UTC	EST	Lat deg	Lon deg	Speed km/h	Tops km	Width E km	Length L km	Area km^2
16/11/2008 6:18	16/11/2008 16:18	-27.649	153.582		14	55.7	48.0	2099.1
16/11/2008 6:30	16/11/2008 16:30	-27.554	153.543	57.2	16	57.6	38.4	1737.2
16/11/2008 6:42	16/11/2008 16:42	-27.485	153.524	40.4	16	62.4	38.4	1881.9
16/11/2008 6:54	16/11/2008 16:54	-27.407	153.494	46.4	18	62.4	38.4	1881.9
16/11/2008 7:06	16/11/2008 17:06	-27.303	153.514	59.6		33.6	86.4	2280.0
16/11/2008 7:18	16/11/2008 17:18	-27.217	153.504	49.2		33.6	86.4	2280.0
			Av =	50.5	(14 m/s)			
			Bearing=	17	deg			

A sequence of before and after impact horizontal (dBZ and Doppler) and vertical slices is shown in Figure 2.5. The location of The Gap is indicated by the black circle in each horizontal scan and the black arrows indicate the radial position on the vertical scans. The vertical scans are located along the radial lines shown in each horizontal image, which are not necessarily located on The Gap. Note also that the scales do vary between some images.
Of interest in the precipitation images (left hand side) are the clearly visible BWER regions and the dark red areas show the downbursts extending to the surface. Meanwhile, the Doppler images (right hand side) are somewhat featureless and indicate radial speeds of the order of 10 to 20 m/s, with some isolated higher pixels to 35 m/s, which may be associated with terrain.
The radial from Mt Stapylton is almost perpendicular to the assessed storm track, whereby the cross track component of the 14 m/s advection is about 6 m/s. This indicates that the cross track downburst component is relatively low, probably only 5 to 10 m/s. This is highlighted by the absence of white or blue colours in the Doppler images, which would indicate calm or winds coming towards the radar respectively. Hence, while there is some structure in this speed field, the principal impression is of a fairly broad gust front likely associated with a Rear Flank Downdraft. Certainly there is no evidence of a strong symmetric microburst footprint, whereby winds would be detected both going away and coming towards this radar.

In contrast to Mt Stapylton, the Redbank Plains radar is almost exactly aligned with the advection of the storm system and so is ideally located to measure the along-track speeds. A series of images from this radar is shown in Figure 2.6, which now highlights the lowest level structure of the gust front passing over The Gap. It should be noted that the velocity colouring from this radar differs from the Mt Stapylton images and the scales are also different. Importantly, the velocity colours “wrap” beyond +27.2 m/s from purple to green (normally -27.2 m/s). Hence, green surrounded by purple is (+27.2+27.2-27.2 = 27.2), white surrounded by blue is (+27.2+27.2.-0. = 54.4). Because of this, together with the radial-speed-only context, the images are difficult to decipher by eye. The values summarised below in Table 2.4 have been supplied by the BoM (T. Wedd).

Table 2.4: Maximum Doppler wind speeds from Redbank Plains radar on a radial to The Gap

Time		Doppler Max “Surface” Speed m/s	Timing relative to The Gap
UTC	EST		
16/11/2008 6:30	16/11/2008 16:30	21	Before
16/11/2008 6:36	16/11/2008 16:36	53	After
16/11/2008 6:42	16/11/2008 16:42	42	After
16/11/2008 6:48	16/11/2008 16:48	49	after

This indicates peak (gust) winds of the order of 50 m/s passed about 450 m above The Gap.

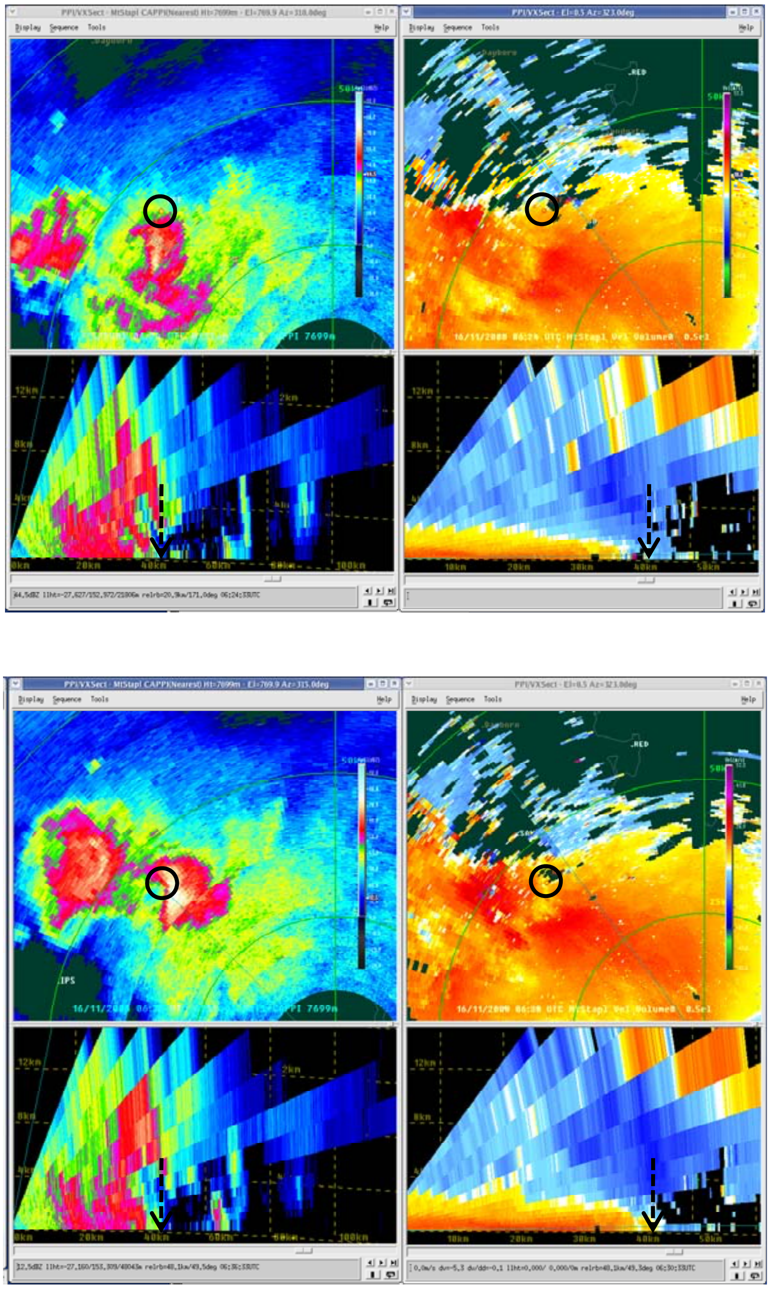

Figure 2.5: Mt Staplyton radar images (16/11/2008)

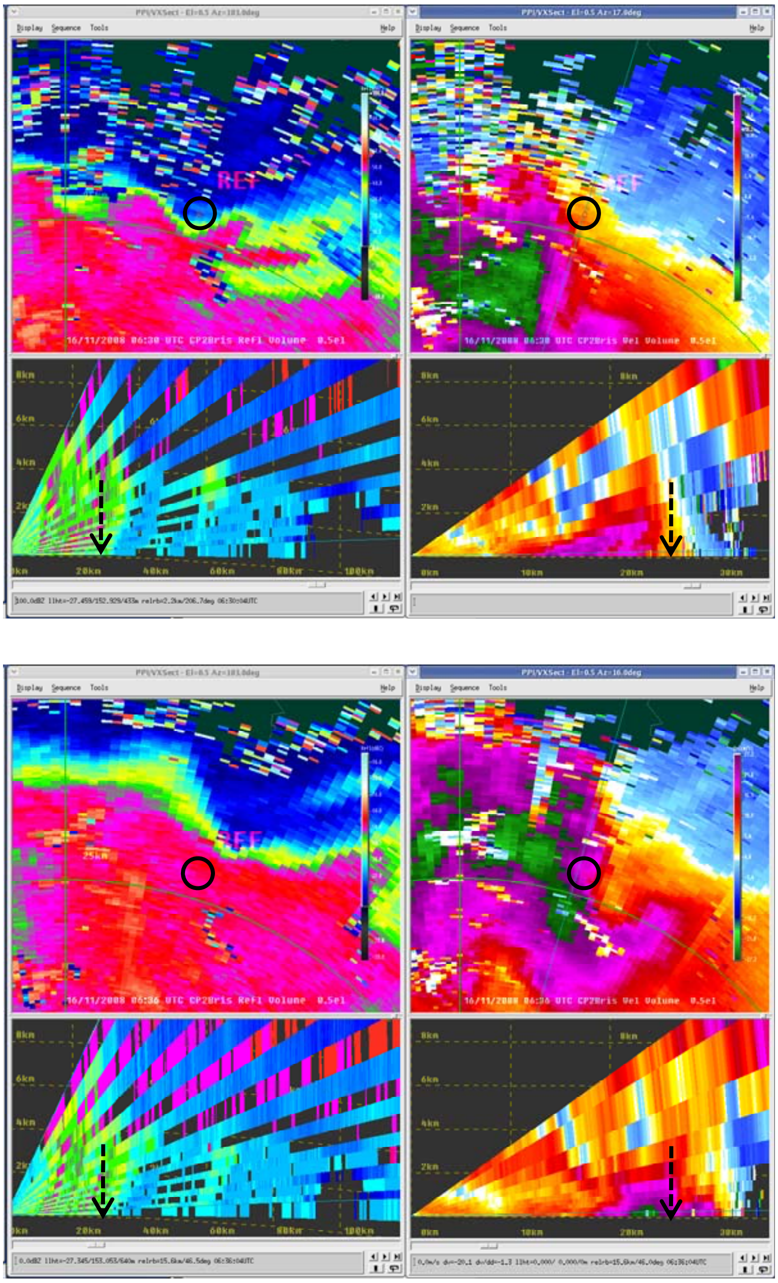

Figure 2.6: Storm Redbank Plains radar images (16/11/2008)

2.5 Damage Swath

To facilitate mapping of the impacted areas a Quickbird 4-band satellite image was commissioned through Geoimage Australia Pty Ltd[1]. A 64 sq km area at 0.6 m horizontal resolution was obtained on 2nd December, which was one of the first opportunities without substantial cloud cover following the 16th November event. By this time, much of the vegetation damage had been removed from the main impact area at The Gap. The image is just sufficiently clear to allow detection of fallen trees in many of the wooded areas surrounding The Gap and these have been manually mapped to assist in interpretation of the wind flow patterns.
An overview of the 8km x 8km satellite image area is given in Figure 2.7 extending from The Gap in the south and north to Everton Hills. The yellow markings are locations of fallen trees and/or areas cleared of damaged trees, the details of which are evident in subsequent higher resolution images. For example**,** Figure 2.8 and Figure 2.9 show increasing detail in the image of the northern and southern parts of The Gap. The individual fallen trees are solid yellow lines and the damaged areas are dashed yellow ellipses.
Greater detail from the satellite image of the southern part of The Gap is given in Figure 2.10 showing the SES call-out locations. Figure 2.11 shows that large fallen trees are clearly visible and throughout the area the tree canopies have been stripped of leaves. This latter case is one of the few areas where there is clear evidence of divergence in the flow that may not be associated with the topography, thus hinting at a microburst signature at the southern entry into The Gap.

The visibly most-damaged area (houses and trees) is of the order of 4 km in width and about 8 km in length, aligned approximately NNW towards Upper Kedron and Ferny Grove, although extensive tree damage was also experienced between Keppera and Arana Hills, north of The Gap. The main swath is bounded in the east by the low range (250 m) separating The Gap from the Enoggera Military Barracks and in the west by the foothills of the D'Aguilar Range. Based on the tree-fall directions, severe winds can be seen to have forced their way through the various gullies and over the northern part of The Gap and into Keperra. It seems possible, based on the radar, that there could also be extensive tree damage further west in the mostly unsettled Brisbane Forest Park foothills. Based on the SES data, a separate line of lesser damage also follows the storm track, extending NNE across Everton Park and McDowall towards Aspley and Albany Creek.

Overall, it seems likely that the high level of damaging winds in and around The Gap were caused by a combination of topographically enhanced winds from a vigorous Rear Flank Downdraft and possibly an imbedded microburst. Adjacent areas also experienced significant winds that likely well-exceeded the storm translation speed of 50 to 60 km/h strength over a swath width of more than 10 km and a length of about 40 km.

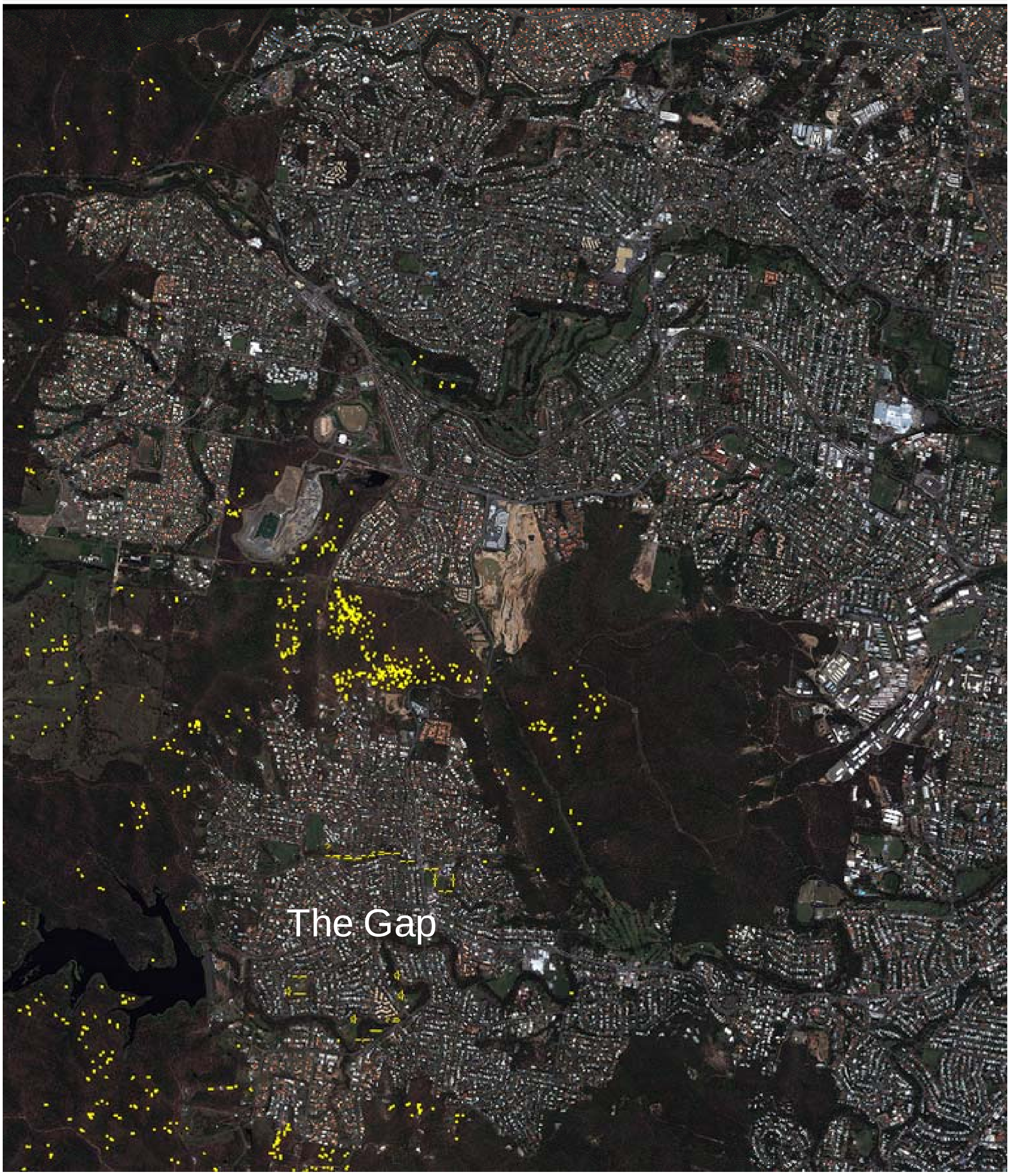

Figure 2.7: Satellite image of the main impact area.

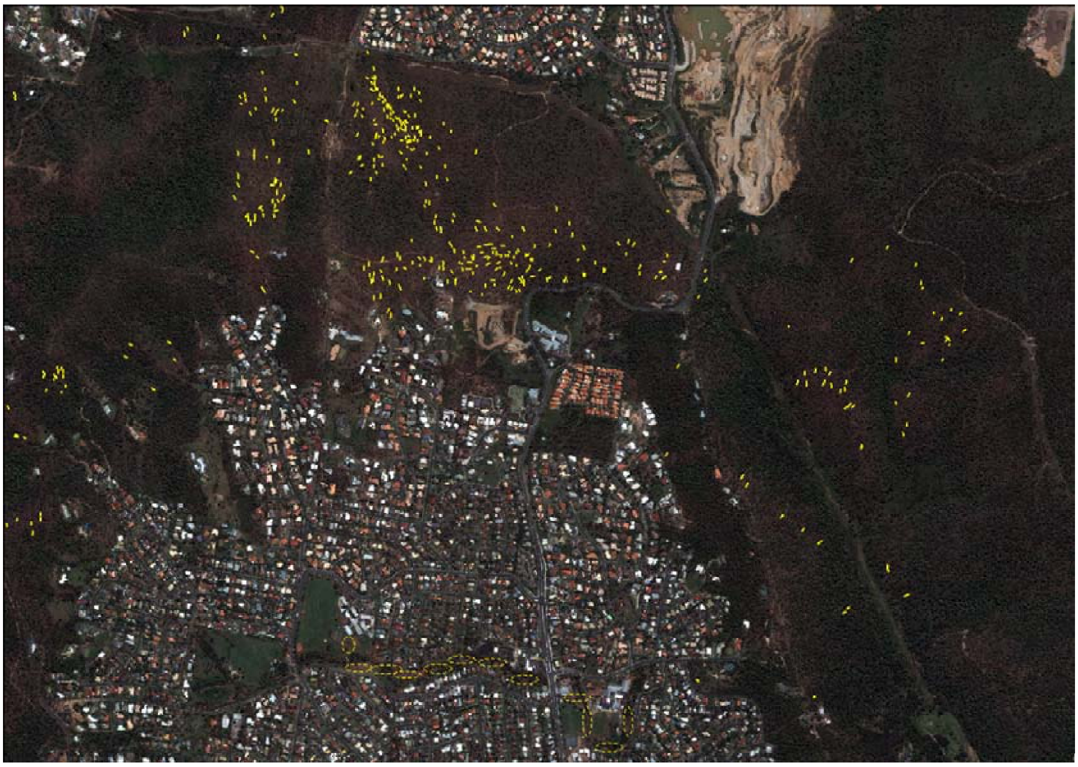

Figure 2.8: Increasing detail in the northern part of The Gap

Figure 2.9: Increasing detail in the southern part of The Gap

Figure 2.10: SES call-outs in the southern part of The Gap

Figure 2.11: Fallen trees visible on the satellite image just south of The Gap

2.6 Estimated Maximum Surface Winds for 16 November Storm

2.6.1 Based on Analysis Using Typical Vertical Wind Profiles

Although there is an extensive literature on downburst phenomena, the majority of knowledge is derived from a combination of field experimentation (e.g. Fujita 1981, Hjelmfelt 1988), laboratory physical modelling (e.g. Mason et al. 2005) and associated empirical approximations (e.g. Vicroy 1992). Importantly, it can be expected that complex terrain of the type present at The Gap will also significantly modify what might otherwise be regarded as "conventional" forms of these events when observed over flat terrain. With that in mind, an initial attempt was made to place the available metrics into an analytical context.

The well-located along-track Doppler radar data from the Redbank Plains instrument remains the only quantitative estimate of wind speeds for this event, suggesting peak winds of about 50 m/s passed above The Gap at a height of about 450 m. Due to the nature of radars, this estimate is not equivalent to a point (e.g. anemometer) reading but rather is based on finite volume and time sampling of the air column. This amounts to an averaged radial speed over a volume of approximately 500m (V), 500m (H) and 300m (R), nominally centred within that volume (Personal communication, Scott Collis, CAWCR). In the present context we also assume that this averaged wind is likely roughly equivalent to the 3 s gust due to expected high coherence across the wind turbulence spectrum.

Neglecting topographic influences, the simplified vertical wind profiles proposed by Vicroy (1992) and Wood and Kwok (1998) were applied in an attempt to provide some insight into the possible vertical wind speed structure and to estimate peak gust wind speeds at nominally 10 m above ground. It should be noted that such vertical profiles differ considerably from broad-scale boundary layer flows as assumed by AS/NZS 1170.2 (refer Figure 2.12). Fitting of the radar measured winds to these idealised downburst profiles suggested that the maximum winds in the event could have been greater than measured by the radar somewhere about 100 to 200 m above ground, assuming flat terrain. However, this approach generated a wide range of possible speeds at the surface and so was abandoned in the context of the complex topography present, which likely significantly concentrated the downburst outflow within The Gap**.**

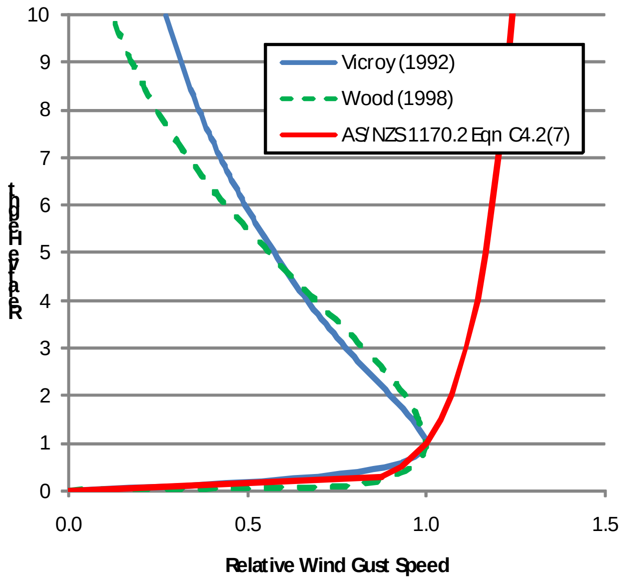

Figure 2.12: Example vertical wind profiles

2.6.2 Based on Observed Road Sign Damage and Damage inspections

Damage to road signs has been used successfully in some previous extreme wind investigations (e.g. TC Larry, Henderson et al (2006)) to infer near-ground wind speeds. However, in The Gap event, although there was damage to some illuminated plastic advertising signs in commercial areas, no obviously wind-damaged street signs were seen during the various inspections. This suggests that wind speeds were likely less than the typical lower limit of failure observed during TC Larry, which was about 45 m/s in relatively open terrain. The undulating heavily vegetated and dense suburban terrain of The Gap, however, makes such interpretation even more difficult.

On a subsequent inspection that specifically targeted potentially weak road signs, one sign did exhibit early indications of a plastic hinge. This sign was located on Settlement Road, just north of Kaloma Rd, and would have had good exposure to the peak winds in the area from the south. Calculations on the wind drag force and lever arm to form a plastic hinge, using the range of common pipe wall thicknesses, give an estimated wind gust speed of between 40 and 50 m/s at the standard height of 10 m.

Based on inspection of the damage in the study area it is estimated that the peak gust wind speeds at the standard reference height of 10 m was in the order of 40 m/sec.

2.6.3 Estimated Wind Speed

Based on the various sources of information discussed above, it is estimated that the maximum wind gust at the standard reference height of 10 m in open terrain was of the order of 45 m/s (~160 kph). This compares with the regional design wind speed of 57 m/s.

2.7 Estimated Maximum Surface Winds for 19 November Storm

As noted in Section 2.3.2, the extent of significant damage from the November 19 storm was very limited and so a full analysis of radar data was not completed and so a high level peak gust wind speed estimate was not prepared.

However, based on the inspections of the very small area of damaged housing at Beck Street, Paddington, the peak gust wind speed near ground level was estimated to be likely significantly less than Brisbane’s design wind speed of 57 m/sec. However, given that a small scale tornado is the most likely explanation for the observed damage, it is possible that the houses that were affected may have experienced very brief winds as high as 40 m/s. Notwithstanding this, it must be noted that the wind loading standard, AS/NZS1170.2, does not account for the effect of tornadoes.

3. Wind Loading on Buildings

Velocity fluctuations in the approach wind flow and the flow around a building generate a spatially and temporally varying pressure field on its surface. Generally the windward wall is subjected to positive external pressures whilst the other walls and roof experience suction pressures, as shown in Figure 3.1. Flow separation takes place at edge discontinuities (i.e. windward roof edges) generating large suction pressures in these local regions, making the roof edges most vulnerable to failure. The internal pressures in a nominally sealed building are generally negative and have smaller fluctuations than the external surface pressures. However, a breach in the building envelope on a windward wall such as from a broken window or failed door will significantly increase the internal pressure, as shown in Figure 3.2. These internal pressures act together with the external pressures greatly increasing the net load on the roof and this is a common cause of its failure in windstorms.

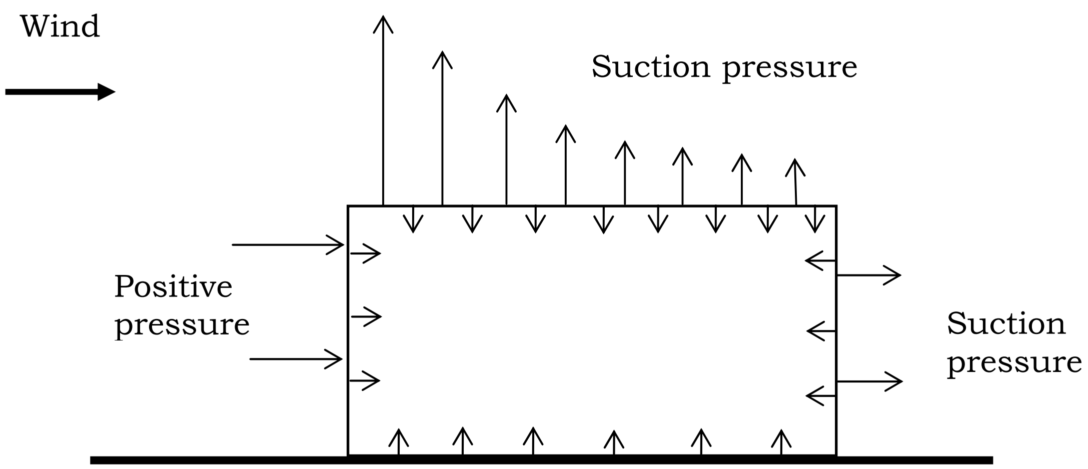

Figure 3.1. External and internal pressure distribution for a nominally sealed building

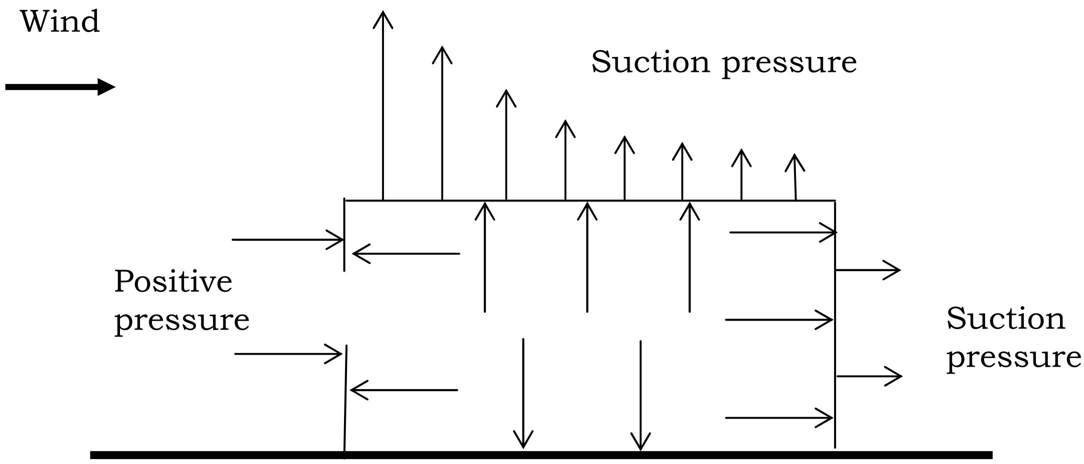

Figure 3.2: Wind forces with a dominant opening in windward wall

3.1 Wind Loading Design Considerations

The Australian Building Codes Board (ABCB) publishes the Building Code of Australia (BCA 2008) which stipulates design considerations for housing in Australia. These requirements are met by compliance with a range of standards relating to building construction (e.g. AS/NZS1170.2 (2002)). A suite of codes and standards based on AS/NZS 1170.2 have been used in the design and construction of houses and their components in Australia, for several years.

Significant damage to houses in Townsville and Darwin during Cyclone Althea and Cyclone Tracy, respectively in the 1970s, precipitated the development of the Home Building Code of Queensland (1975 -1984) as Appendix 4 to Standard Building by-laws. These were in widespread use by the mid 1980s, requiring sites to be categorised by design wind speed at roof height, and containing deemed to satisfy detailing for houses in each of these categories. Related standards, such as wind loads for housing AS 4055 (2006), and residential timber framed construction for non-cyclonic regions AS1684.2 (2006), are used in more recent housing design and construction.

Brisbane is located in Wind Region B as defined in AS/NZS1170.2 (2002), where the 500 year return period ultimate limit state design wind speed (in flat approach terrain category 2) is 57 m/s. The design wind speed at the roof height of a building has factors to account for the height, upwind shielding, terrain and topography. This factored design wind speed impacting on the building can be related to the pressures exerted on its elements through a series of coefficients defined in the wind loading standard, AS/NZS1170.2.

AS 4055 (2006) provides design wind speeds and wind loads (which are based on AS/NZS 1170.2) for the design of typical housing. A wind classification is stipulated depending on the wind region (i.e. non-cyclonic or cyclonic) and terrain, topography and shielding at the site. In region B, site classifications N2, N3 N4, N5 and N6 represent increasing design wind speed. For instance a N2 classification represents a site with terrain category 3 exposure (suburban housing) with full or partial shielding on flat land. An N4 classification represents a site with terrain category 2 exposure with partial or no shielding at the mid third zone of a hill with a slope of between 1:5 to 1:3. The ultimate limit state wind speeds at roof height (6.5m) for N2, N3, N4, N5 and N6 classifications are 40, 50, 61, 74 and 86 m/s respectively, accounting for the effects of wind speed-up over steep topography and terrain category (roughness). Full internal pressurisation is not stipulated for ultimate strength limit state design of houses in non-cyclone regions. Therefore an under-classification of a site (i.e. N2 house built in a N4 site) can result in inadequate design detailing for the house. Furthermore, a dominant wall opening can generate large net pressures across the building envelope and also increase the likelihood of component failures.

For timber framed housing, the construction methods specified in AS1684.2 are based on the design wind load data given in AS/NZS1170.2 and AS 4055. For each classification N1 to N6, AS1684.2 gives design (uplift) wind load on roof battens and roof framing for some typical batten and frame spacings. In addition, AS1684.2 also specifies uplift capacities for typical batten-truss/rafter connections, rafter-rafter connections and truss/rafter-top plate connections (nails, screws, framing anchors, straps etc).

Standards on windows in buildings, AS 2047 (1999) and domestic garage doors, AS/NZS 4505 (1998) use the design wind speeds and classifications given in AS/NZS1170.2 and AS 4055 to specify design requirements for windows and garage doors respectively.

Design data given in AS 4055 provides an easy to use means of obtaining wind loads for typical houses, and for the selection and detailing of components. However, in an attempt to simplify the design and to accommodate the design of a group of “similar” houses located in suburbs (with typical terrain, topography and shielding features), AS 4055 has some incompatibilities with AS/NZS1170.2, leading to significantly lower design loads, in some cases. One such case is a house located close to the top of a hill and exposed to high winds from the direction leading up to the hill-top. Interpretation of AS 4055 and its inherent simplifications will lead to unconservative design wind loads for this case, compared with AS/NZS 1170.2, as detailed in Appendix B.

4. Housing Stock in Study Area

This section contains a summary of the character of the housing in the study area and describes typical characteristics for each broad grouping.

Towns have a mixture of house types. Differences in size, shape, window size, cladding type, roof shape, age, and methods of construction have an effect on the resilience of the house to resist wind forces.

One very important parameter is the building standards that were applicable at the time of the construction of the house. In Brisbane, the building regulations were made significantly more stringent with the introduction of the Queensland Government's "*Home Building Code – Appendix 4 to the Standard Building By-Laws 1975*", Qld Govt (1975-1984). For this report, the age of houses has been separated into Pre 1980 and Post 1980. However, it must also be remembered that many of the older houses, in the Pre 1980 group, have been refurbished, to greater or lesser extents.

The Post 1980 houses investigated for this study were all built quite recently and so could also be called "contemporary" houses.

Houses also have varying degrees of exposure to wind forces, with those dwellings located in a suburban environment gaining shelter from surrounding structures as distinct from those exposed houses in open terrain or on top of ridges or hills. Topographical features such as hills can concentrate or divert wind flow. Wind speeds impacting on a community will vary according to a windstorm's intensity, size and distance from the community. Therefore an assessment of the wind resistance of housing requires knowledge of house types and their distribution throughout the community. Two age categories of houses were studied in the course of the investigation, classified by estimated age of original construction, as summarised in Table 4.1.

Table 4.1: Age categories used for housing

Age class	Features
Pre 1980	Mostly rectangular floor plans and typically using flat to low pitch roofs.
Post 1980	Often used more complex floor plans and typically with a higher roof pitch.

4.1 Pre 1980 Housing

Houses in the study area, built prior to 1980, were predominantly of two storey construction, with about half using brick walls. Figure 4.1 shows a typical two storey brick house with a tiled roof.

Figure 4.1: Typical two storey brick Pre 1980 house

Based on the survey data, about 65% of the roofs were constructed using metal cladding, about 30% using tiles and the remaining using fibre cement sheeting.

There were also about 20% of the houses using slab-on-ground construction. Figure 4.2 shows a typical single storey brick house with a tiled roof.

Figure 4.2: Typical single storey Pre 1980 house

4.2 Post 1980 Housing

There was a much smaller group of post 1980 housing in the study area (11 in total) and they were all were constructed quite recently and so could also be classified as contemporary. Most of the houses had metal roof cladding. There were only two one-storey houses in this age category and Figure 4.3 shows a front elevation of one of these low-set houses.

Figure 4.3: One-storey Post 1980 house

Figure 4.4 shows a typical two storey house.

Figure 4.4: Two storey Post 1980 house

5. Overview of Damage

Damage surveys can show trends that can be used to suggest improvements in the resistance of buildings to future events. In this section, the results of street surveys are used to draw conclusions about the general features of housing that proved more susceptible to wind damage during the Brisbane storms.

5.1 Street Survey Damage Classification System

The street survey damage classification system was based on the one developed by Geoff Boughton and presented at CTS wind vulnerability workshop held in Townsville in February 2006.

It ranks the amount of visible structural damage using a three digit Damage Index to grade the levels of damage for roof, amount of wall openings and wall damage. A "*Damage Number*" is assigned for a defined level of damage for each of the three parameters measured, as detailed in Table 5.1.

Table 5.1: Housing Survey Damage Measure Using Three Digits

Damage Number	Description of Damage for		
	Roof (R)	**Openings (O)**	**Walls (W)**
0	None	None	None
1	Gutters downpipes	debris not pierced	debris not pierced
2	Debris damage to roof	debris pierced	debris pierced
3	Roof lifted <10%	windows/doors leaked	Carport/verandah damage
4	lost roofing <50%	Windward broken <30%	One wall panel fallen
5	lost battens <50%	frames lost <30%	> 1 wall panels fallen
6	lost battens >50%	Windward broken 30%-70%	racking damage, cladding attached
7	Lost battens > 50% and lifted rafters	Windward broken >70%	racking damage and lost cladding
8	Lost battens > 50% and damaged tie down	Windward broken >70% and suction loss	only small rooms intact
9	Lost roof structure > 50% incl. ceiling	100% broken / missing	No walls remaining

Notes:
1. R3 = any combination of loss of roofing, battens, rafters but limited to less than 10% roof area.
2. Damage to carports and verandahs that is under the main roof is treated as roof damage.

The overall Damage Index for any house being surveyed is then a three digit number, one digit from each of the three columns, *R*, *O* and *W*.

Table 5.2 provides four examples on how to use this system and illustrates that a house with no damage to the roof, no damage to openings (windows or doors) and no damage to the walls, will have a *Damage Index* of "000".

Note that this system does give a lot more detail about the levels of damage to the three main external envelope areas of a house. However, other simpler systems with a single digit damage level index classification do have the advantage of allowing a direct comparison of damage levels between different houses.

Table 5.2: Examples of Three Digit Damage Index for Housing

Damage Index	Description of damage for		
	Roof (R)	Openings (O)	Walls (W)
000	None	None	None
222	Debris damage to roof	debris pierced	debris pierced
341	Roof lifted <10%	Windward broken <30%	debris not pierced
845	Lost battens > 50% and damaged tie down	Windward broken <30%	> 1 wall panels fallen

Roof damage caused by falling trees was classified as "Debris damage to roof" (R = 2) and if the tree also broke windows and walls, a Damage Index of 222 was assigned, as in the second example in Table 5.2.

It is likely that some lower level damage such as debris impact or even damaged roofing would have been missed. Therefore the survey results should be taken as being indicative rather than definitive of the damage trends

5.2 Street survey – The Gap (Storm of 16 November 2008)

A street survey of a sample of houses from five streets in The Gap was undertaken, following the storm of 16 November 2008, using the damage classification system described in Table 5.1. This survey was performed with the following constraints:

- The age and type of housing was classified as described in Section 4. This would enable extent of damage to be evaluated separately for each type or age of house.
- A total of 97 houses were surveyed, comprising 86 Pre 1980 houses and 11 post 1980 houses.
- All houses in each of the streets were surveyed, to ensure that those with no sign of damage were included, along with those that were obviously damaged.
- The damage number was assessed by viewing the houses from the street, but sometimes with additional guidance from any house kerb-side collection piles.
- Damaged roofs were often covered with tarpaulins and so the extent of damage to the roof was estimated by the amount of roof covered by tarpaulins.

Table 5.3 presents a damage summary for all of the housing surveyed at The Gap (97 houses), by showing the percentage damage for each of the three Damage Numbers for *Roof*, *Openings* and *Walls*.

Table 5.3: Percentage Damage for Roof, Openings and Walls for all housing surveyed at The Gap

Damage No.	Percentage Damage for each Damage No.		
	Roof	Openings	Walls
0	70%	86%	91%
1	2%	1%	2%
2	7%	5%	3%
3	9%	0%	3%
4	2%	8%	0%
5	0%	0%	1%
6	0%	0%	0%
7	1%	0%	0%
8	3%	0%	0%
9	5%	0%	0%

The results are also presented as separate plots of Percent of housing damaged (for each of the two age categories) versus Damage Number for the each of the three parameters used, roofs, openings and walls, in Figure 5.1, Figure 5.2 and Figure 5.3 respectively.

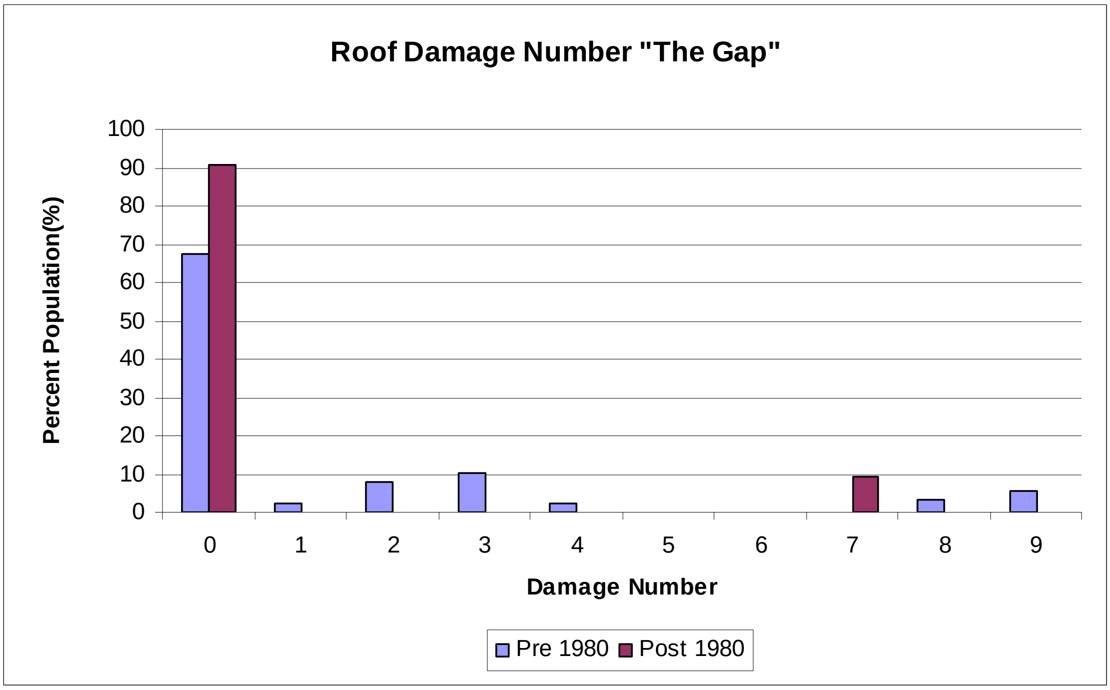

Figure 5.1: Percentage of Houses vs *Roof* Damage Number

The data from Figure 5.1 shows that there was significantly more roof damage to the Pre 1980 houses, compared to the Post 1980 houses.

Figure 5.2 highlights that there were a significant number of houses with an Openings Damage Number of 4 and the implications of these houses being very likely subjected to full internal pressure are examined in Section 9.1.1.

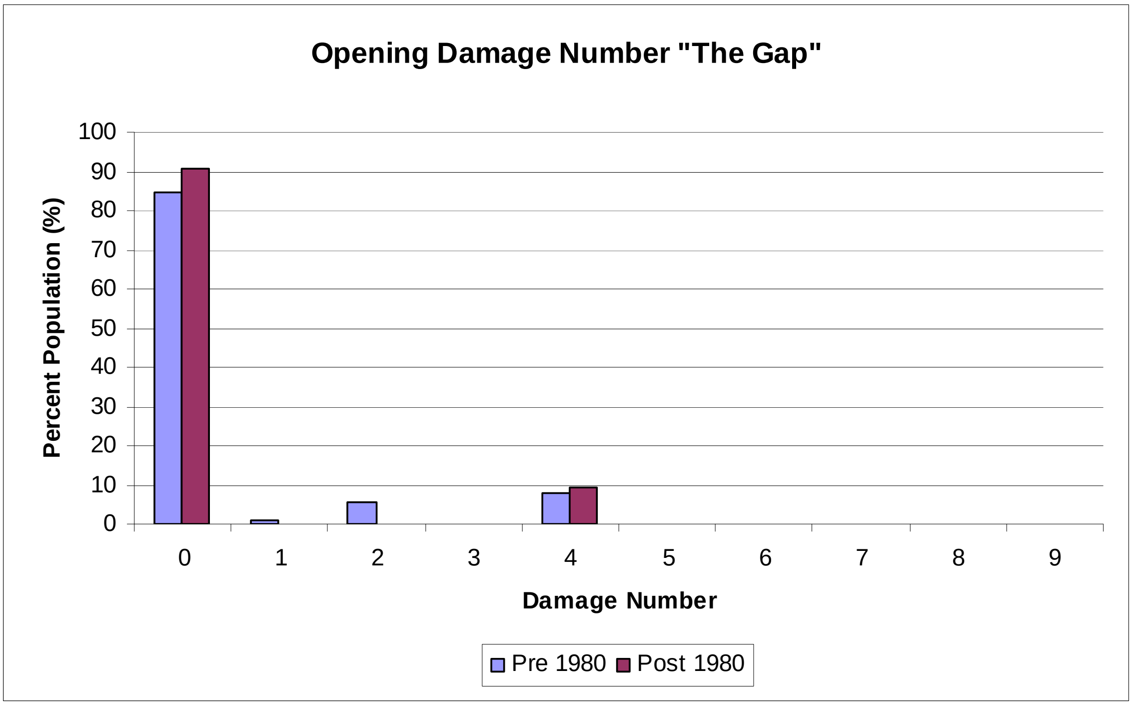

Figure 5.2: Percentage of Houses vs *Openings* Damage Number

Figure 5.3 shows that there was no wall damage to the Post 1980 houses.

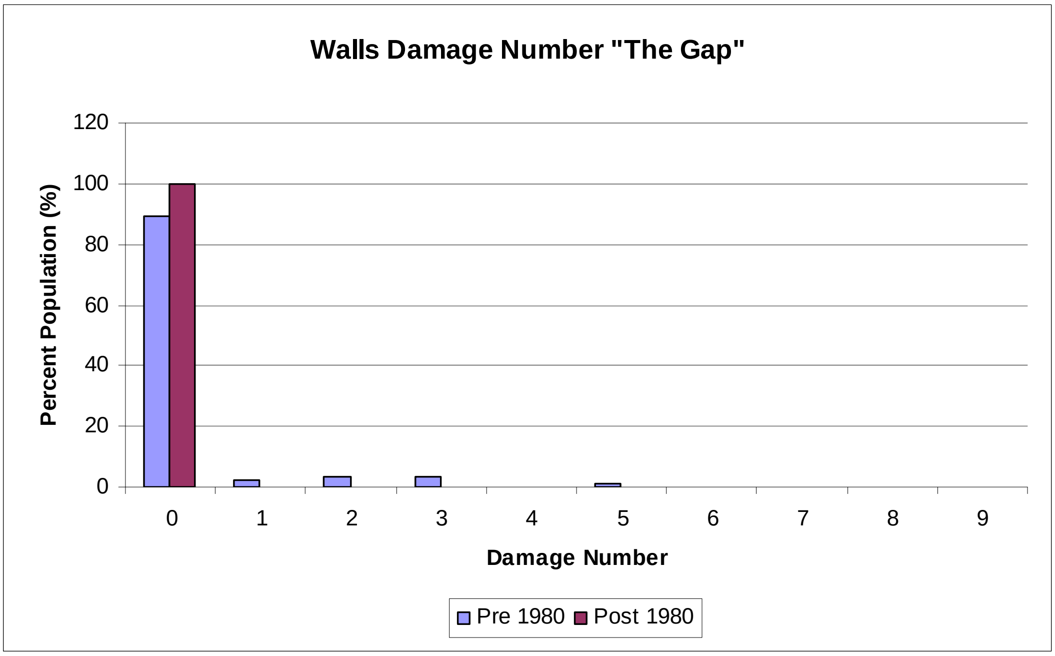

Figure 5.3: Percentage of Houses vs *Wall* Damage Number

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5.3 Street Survey - Paddington (Storm of 19 November 2008)

A separate storm cell (likely to have been associated with a weak and transient tornado) on the 19 November 2008 caused a narrow swathe of very localized of damage to houses in Beck Street, Paddington.

A street survey was performed for all 20 houses along Beck Street. Only one of the houses was built after 1980 and 19 houses had metal roof cladding, with the other having a tiled roof.

Table 5.4 presents a damage summary for the housing surveyed by showing the percentage damage for each of the three Damage Numbers for *Roof*, *Openings* and *Walls*.

The predominant form of damage observed was damage to the roof, with 7 houses having an estimated Damage Number of 3, (R3 = 35 %). As detailed in Table 5.1, R3 is used when roof damage is estimated to comprise up to 10% of the roof lifted.

Table 5.4: Percentage Damage for Roof, Openings and Wall

Damage No.	Percentage Damage for each Damage No.		
	Roof	Openings	Walls
0	50%	90%	95%
1	0%	0%	0%
2	5%	0%	0%
3	35%	0%	5%
4	0%	5%	0%
5	5%	0%	0%
6	0%	5%	0%
7	5%	0%	0%
8	0%	0%	0%
9	0%	0%	0%

Figure 5.4 shows a Pre 1980 house with metal roof, with a Damage Index of 303.

As this damage was caused by a very localized storm event, detailed analysis of this damage is not considered any further in this report.

Figure 5.4: General view of a Pre 1980 house with Damage Index of 303

5.4 Leakage Through Undamaged Tile Roofs of New Housing at Redbank Plains

The investigations into the damage to new housing at Redbank Plains indicated that there was a significant water ingress problem through unsarked tiled roofs. This leakage allowed water ingress onto the top of plasterboard ceilings, which became waterlogged and then collapsed. Figure 5.5 shows a typical example of a small area of plasterboard ceiling to a garage, which had collapsed.

Figure 5.5: General view of typical ceiling collapse due to water penetration

Five houses in Redbank Plains were inspected, all with unsarked tiled roofs and all with water ingress related damage.

The detailed investigations into this issue are described in Section 6.

5.5 Other Damage – Roof Lights

Although none of the Station team members observed roof light damage, officers from Queensland Department of Infrastructure and Planning advised that they had received a number of reports from the public concerning damage to roof lights, caused by these storms. It is not clear if this damage was caused by hail, wind or a combination of these effects, but the overall result was water penetration leading to a loss of amenity.

It is understood that there are no regulations in the current BCA to cover the strength or installation of roof lights, and this is discussed further in Section 10.4.

6. Leakage Through Unsarked Tiled Roofs

In this section, the investigation into the water penetration through undamaged tiled roofs to contemporary homes in Redbank Plains is described.

6.1 Tile Roof Installation

Figure 6.1 shows a general view of the exposed timber trusses supporting a tiled roof (without sarking), after the collapse of a plasterboard ceiling, caused by water ingress through the tiled roof.

Figure 6.1: General view of typical ceiling collapse (unsarked tile roof)

Typical construction details used timber trusses at 600 mm centres supporting metal top hat or timber roof battens at about 330 mm centres supporting concrete tiles. Tile hold down used tile clips to every second tile.
Figure 6.2 shows a typical tile clip connection to a metal top hat batten.

Figure 6.2: Detailed view of a typical tile clip to metal roof batten

Figure 6.3 shows two examples of construction errors for a tile roof fixed to timber battens. Figure 6.3 (a) shows both a construction error where a batten nail has been installed too close to the truss edge and missed the supporting truss member and also shows a typical tile clip to timber batten connection. Figure 6.3 (b) shows a tile clip not fully secured to the supporting timber batten.

(a) Batten nail missed truss and tile clip to batten

(b) Tile clip not fully secured to timber batten

Figure 6.3: Detailed views of errors for tile hold down to timber roof battens

For the three *ceiling collapse* houses visited in Redbank Plains, two of them had no sarking at all and one of them used sarking for about the first metre of roof, closest to the fascia, as shown in Figure 6.4. Note that the BCA requires sarking where the roof run exceeds 6000 mm, for example a roof run of 7500 mm requires the roof to be sarked 1500 mm up from the fascia.

Figure 6.4: Tiled roof with sarking to lower 1m of roof

This tile manufacturer does not require sarking to be installed for the pitch of theses roofs, except as noted above.

Figure 6.5 shows a general view of typical gaps to a tiled roof.

Figure 6.5: Detail of gaps to tiled roof

6.2 Typical Failure of Plasterboard Ceiling

A first hand account from a resident about the timeline for one of these plasterboard ceiling collapses, is as follows:

- On Sunday, 16 November 2008, at about 5PM, there was a severe storm with strong winds, followed by some hail.
- About 5 minutes into the storm, the resident noticed water dripping through the light fittings from the plasterboard ceilings.
- The plasterboard ceiling collapsed in the early morning hours of Monday, 17 November 2008.

6.3 Likely Cause of Failure of Ceilings

It appears likely that the collapse of the plasterboard ceilings was caused by wind driven rain being forced up the roof slope and through the relatively large gaps between the tiles. This water dripped down onto the plasterboard ceiling and soon was leaking through some of the electrical light fittings mounted in the ceiling. The plasterboard ceiling absorbed water and gradually lost strength, until it failed.

In summary, these unsarked tile roofs were not weather-tight under the actions of wind driven rain.

7. Performance of Housing

In this section, building performance is examined using four broad categories:

1. **Tree Damage.** This is debris damage caused by falling trees or other vegetation.
2. **Water Ingress.** Water penetration through the undamaged external building envelope (doors, windows and roof and wall cladding systems).
3. **Roof Failure.** This was typically failures in joint connections in some part of the roof tie-down system.
4. **Window and Door Failure.** There were a number of examples where windows or doors were dislodged from their supporting members.

For Items 3 and 4, poor performance could generally be attributed to poor construction practices and the use of one or more inappropriate details for the site design wind speeds.

Window or door failure which caused a dominant opening to the windward wall resulting in large internal pressure is also discussed.

7.1 Tree Damage

As noted in Section 2, The Gap is a suburb with a heavy density of tress and many trees were felled during the storms. The smaller sizes of vegetation ranged from shredded leaf litter that was driven into window gaps and gutters (sometimes contributing to blocked gutters) to smaller trees and shrubs that either became flying debris or part of tangled mulch around the suburbs. Larger trees did not become airborne, but sometimes caused major damage to houses when they fell directly onto part of the building structure.

Photographs of the typical effects caused by these three broad sizes of vegetation are provided in the following sections.

7.1.1 Shredded Leaf Litter

For many houses wind-driven shredded leaf litter was observed still stuck on the walls and windows of houses, three days after the storm struck**.**

Figure 7.1 shows two views of windows to a house in The Gap, with this shredded leaf litter still in place.

(a) Leaf litter around a closed window

(b) Leaf litter driven into the gaps around the frame of a hopper window

Figure 7.1: Shredded leaf litter stuck on the windows of a house in The Gap

7.1.2 Small Shrubs or Trees

Figure 7.2 shows damage to smaller trees and shrubs contributing to housing damage around *The Gap*.

Figure 7.2: Typical shrub and smaller tree damage near housing in The Gap

7.1.3 Large Trees Falling on Houses

For this report, roof damage caused by falling trees was recorded as a Damage Number of 2. Figure 7.3 shows two houses in The Gap that suffered damage, caused by large trees falling on the roof.

Figure 7.3: Damage to housing caused by large falling trees in The Gap

7.2 Water Ingress

Water ingress is one of the major causes of losses caused by these storms. As was noted by Henderson et al (2006) following the Cyclone Larry damage investigation: "*Water ingress can lead to damage to contents and fittings in buildings that otherwise had little damage. As community life styles and building contents becomes more vulnerable to water damage, this is an area that warrants a serious study to determine methods of improving performance of buildings against water ingress in severe winds.*"

This comment is still applicable to this damage investigation.

7.2.1 Through Unbroken Windows and Doors

Many people reported that their windows leaked during the height of the storm. This could be caused by the high wind pressure on the outside surface being able to drive water through any small gaps or even upwards under flashings.

7.2.2 Through Unsarked Tile Roofs

The water ingress problem affecting tiled roofs of new housing in Redbank Plains has already been described in Section 6. However, there was no direct evidence of this problem during the damage inspections performed in The Gap. This may have been due to the limited use of plasterboard ceilings.

7.2.3 Overflow from Blocked Gutters

Several residents reported on the water ingress problems caused by blocked gutters and downpipes, which allowed water to be driven over the fascia board and into the ceiling space**.**

Figure 7.4 shows a damaged house in The Gap, where the gutters were filled with hailstones. Wind driven rain then penetrated into the ceiling space, wetting one panel of plasterboard, which collapsed.

(a) View of hole in ceiling, after collapse of one plasterboard panel

(b) View inside ceiling space showing water staining on rafter overhang

Figure 7.4: Overflow of gutter water into ceiling space

7.3 Roof Failure

As can be seen in Table 5.3, roof damage was the major impact from the storm, with about 30 % of all housing surveyed having a Damage Number of 1 or larger. However, as shown in Figure 5.1, there was significantly more roof damage to the Pre 1980 house class.

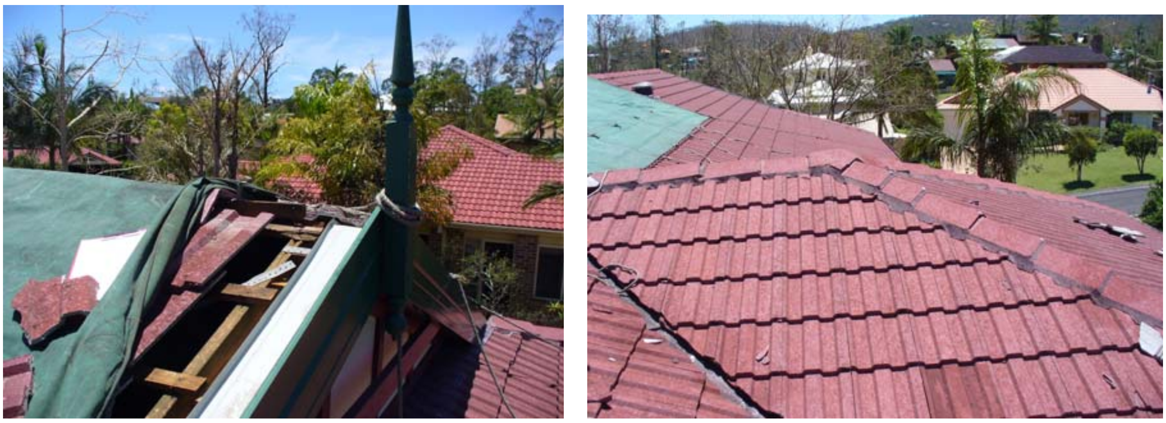
7.3.1 Inadequate Connection Details

All of the detailed investigations that were performed on damaged houses indicated that the cause of failure could be attributed to an inadequate or under-strength detail in one of the connections in the roof tie-down load path. The three Case Studies in Section 8 of this report provide more details.

7.3.2 Tile Roofs

Figure 7.5 shows two views of a tiled roof that suffered damage. Some ridge and barge roof tiles were dislodged during the storm of 16th November and allowed water into the ceiling space which led to failure of the wet plasterboard ceiling**.**

Figure 7.5 (b) clearly shows that many of the ridge and hip tiles were not fixed in accordance with AS2050 (2002) which requires every ridge, hip and barge tiles to be mechanically fastened for all wind classifications.



(a) View of failed ridge tiles under tarpaulin **(b) View of ridge and hip tiles – still in place but some without mechanical fasteners**

Figure 7.5: Details of ridge tile roof failure and hip tiles without mechanical fastening

7.4 Window and Door Failure

During the street side surveys, some residents commented that their windward doors or windows failed during the storm. This is reflected in the survey results, where Figure 5.2 and Table 5.3 show that about 8% of all housing surveyed had an Openings Damage Number of 4 (O4 = 8 %). "O4" means that up to 30 % of the windward openings for the house being inspected were broken.

As noted in Section 5.2, this category of openings damage would very likely have allowed higher internal pressure (an increase in loading) to develop inside the house. However, houses in non-cyclone areas are designed such that they are not required to resist full internal pressure. Therefore for a design wind event, any houses with failed windows or doors will be subjected to larger wind loads than they have been designed for and so will have an increased risk of failure. This suggests further investigation is warranted, as outlined in Section 9.1.1.

7.4.1 Hail and Wind Pressure Damage to Windows and Doors

One resident reported that one bank of windows had a small hole punched through it by hail and that another was pushed inwards, the bank of hopper windows (under a tarpaulin) is shown in Figure 7.6 (a).

Another case involved a complete sliding door failing as shown in Figure 7.6 (b).

(a) Hail damage and window pushed in

(b) Sliding door failed

Figure 7.6: Typical windows and doors failure

7.4.2 Windows and Doors Broken by Flying Debris

Figure 7.7 shows broken windows from two different houses, typical of this type of damage observed.

There were also some instances where asbestos cement corrugated roof cladding had failed, dislodged and become flying debris to impact and damage the doors and windows of downwind houses.

Figure 7.7: Typical flying debris damage to windows

7.4.3 Windows and Doors Failure – Inadequate Fixing to Structural Supports

One Pre 1980 house in The Gap had a sliding door (facing the strongest wind direction) that was dislodged and pushed inwards, without the glass being broken, demonstrating that this door was not adequately connected to the supporting jamb studs.

A Post 1980 house that is described in Section 8.3 also had five windows (facing the strongest wind direction) fail due to inadequate fixing to the supports. The remaining two windows in this same windward wall were significantly dislodged from their supports.

7.4.4 Garage Door Failure

Some garage doors (both roller doors and panel-lift doors) failed during the event. Figure 7.8 shows two typical failed roller doors from houses in The Gap.

Figure 7.8: Typical roller door failures

7.5 Consequential Failure

Several cases were recorded where residents reported that after their windows or doors failed, the sudden increase in internal pressure caused subsequent failure in part or all of the roof.

In one case, the windward window was broken and then between 10 and 20 tiles were dislodged from the roof.

In a second case, a large glass sliding door on the windward wall of Pre 1980 house failed and then a large section of roof structure failed. This failure is described in more detail in a Case Study in Section 8.1.

8. Case Studies

8.1 Inadequate Tie-Down – Pre 1980 House

A Pre 1980 house (originally built in 1966) lost the full width of the roof (about 12 m wide) to the front balcony and rooms immediately behind. This house was located on flat terrain, in The Gap and had large glass doors and windows facing into the wind direction of the 16 November storm. Residents advised that during the storm one of the large glass windows to the front balcony failed and then a large section of the roof (the whole roof width of about 12 m and a length of about 7 m) was lifted up from the house and deposited in the back yard in an upside-down position.

The original roof had been re-clad incorporating another timber frame over the existing. This roof structure used a system of timber battens and struts supported by 250 x 70 Oregon timber beams, spanning about 9 m across the house width, cantilevering about 1.6 m on both sides and spaced at about 2.8 m. These timber beams were held down with mortice and tenon joints to timber columns. The roof failed as a large unit when the timber beam to column mortice and tenon joints failed in uplift, caused by the sudden increase in internal pressure load when the windward windows failed. This house was not included in the street survey but had a Damage Index of 864.

Figure 8.1 shows a view of the front of the house, without the roof. The tenon joint to the top of one of the timber columns used to support the timber beams is circled, in the photograph.

Figure 8.1: General view of front of house without roof

Figure 8.2 is a general view of the section of roof that had been broken away from the house and deposited upside-down in the backyard. A typical mortice to the beam is circled in this photograph.

Figure 8.2: General view of upside-down roof

Figure 8.3 is a detailed view of a typical mortice to the roof beam, showing where the mortice and tenon joints failed.

Figure 8.3: Typical view of a failed mortice joint to roof beam

These mortice and tenon joints from the timber column to main roof beams were too weak to support the large uplift loads that needed to be resisted, especially with the extra load caused by the sudden addition of full internal pressure.

8.2 Incorrect Tie-down – Post 1980 House

A new two-storey house lost all of the patio roof structure (cladding, battens and extended truss top chords) with roof failure extending into the area above the main living area. Figure 8.4 (a) shows a general view of the upper level of the house and the location of the missing patio roof that failed. Two white lines have been added to this photograph to indicate the typical locations of the former extended truss top chords. These main roof trusses had the top chord extended by about 4 m and were supported at their far ends by a single span structural timber beam, located towards the bottom and inside non-structural FC cladding, as also shown in Figure 8.4 (a). Figure 8.4 (b) is a view from underneath the patio roof and shows some typical failures of the extended truss top chords. This house was included in the street survey with a Damage Index of 700.

(a) General view showing extent of the loss of the patio roof

(b) View from underneath patio roof showing failed truss tails

Figure 8.4: Failed patio roof structure

Failure of the patio roof was initiated by inadequate tie-down of the extended truss top chords to the patio beam/lintel. A closer examination of the members inside the non-structural FC cladding showed that there was a structural timber patio roof beam at the lower level, then short vertical studs (jack studs) supporting a single 70 x 35 MGP10 top plate towards the top. The truss top chords were fixed using looped metal straps to this top 70 x 35 MGP10 top plate, but this top plate was only nailed into the end grain of the jack studs sitting on top of the main structural patio beam. The patio roof was lifted off when the nailed connections from the top plate into the top of the jack stud members failed.

This tie-down configuration was not in accordance with any of the possible alternative details provided in AS1684.2, Table 9.20 (a) to (e) inclusive, which all require that: "The top plate shall be fixed or tied to the lintel within 100 mm of each rafter/truss, or the rafter/truss fixed directly to the lintel with a fixing of equivalent tie-down strength to that required for the rafter/truss."

Figure 8.5 is a detailed view inside the FC cladding and shows some of the nails remaining from the failed joints between the jack studs and the top plate.

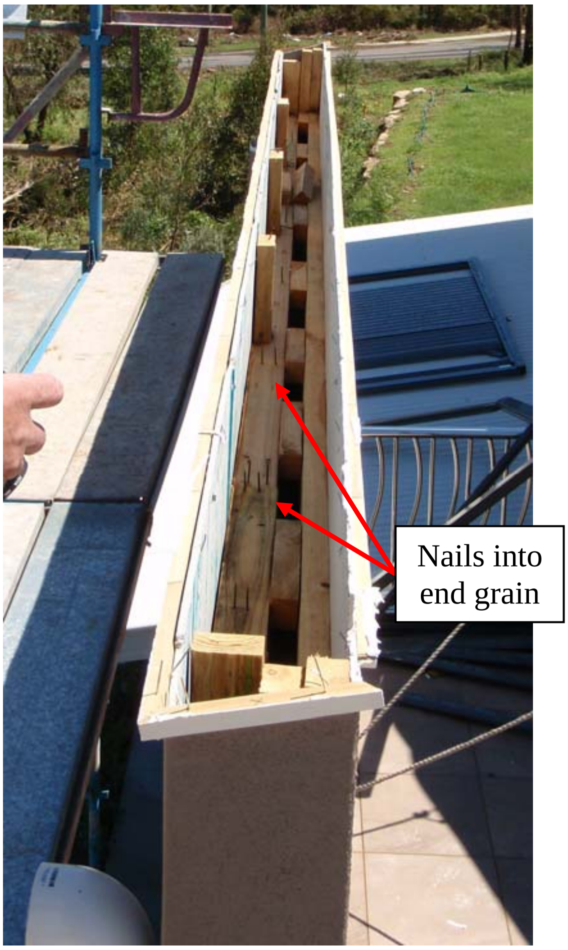


Figure 8.5: Detailed view inside FC cladding showing failure of nailed joints to jack studs

Figure 8.6 shows a large section of the failed patio roof located about 200 m away from the house. The photograph shows the metal straps from the extended truss top chords to the top plate and also some of the jack studs over the beam/lintel and failed nailed joints.

The patio system failed when the wind uplift loads exceeded the capacity of the nails into the end grain of the jack studs. The extended truss top chords then failed in bending over the patio due to the added tributary area and finally a large part of patio roof structure was lifted off the house and deposited about 200m downwind from the house.

Also on this house, a nominally 1.0 m wide gable overhang failed (the overhang was torn off the roof) due to inadequate tie-down fixings of the out-riggers forming the overhang to the raking and standard trusses. The small approximately 300 mm back span of the out-riggers exacerbated the problem.

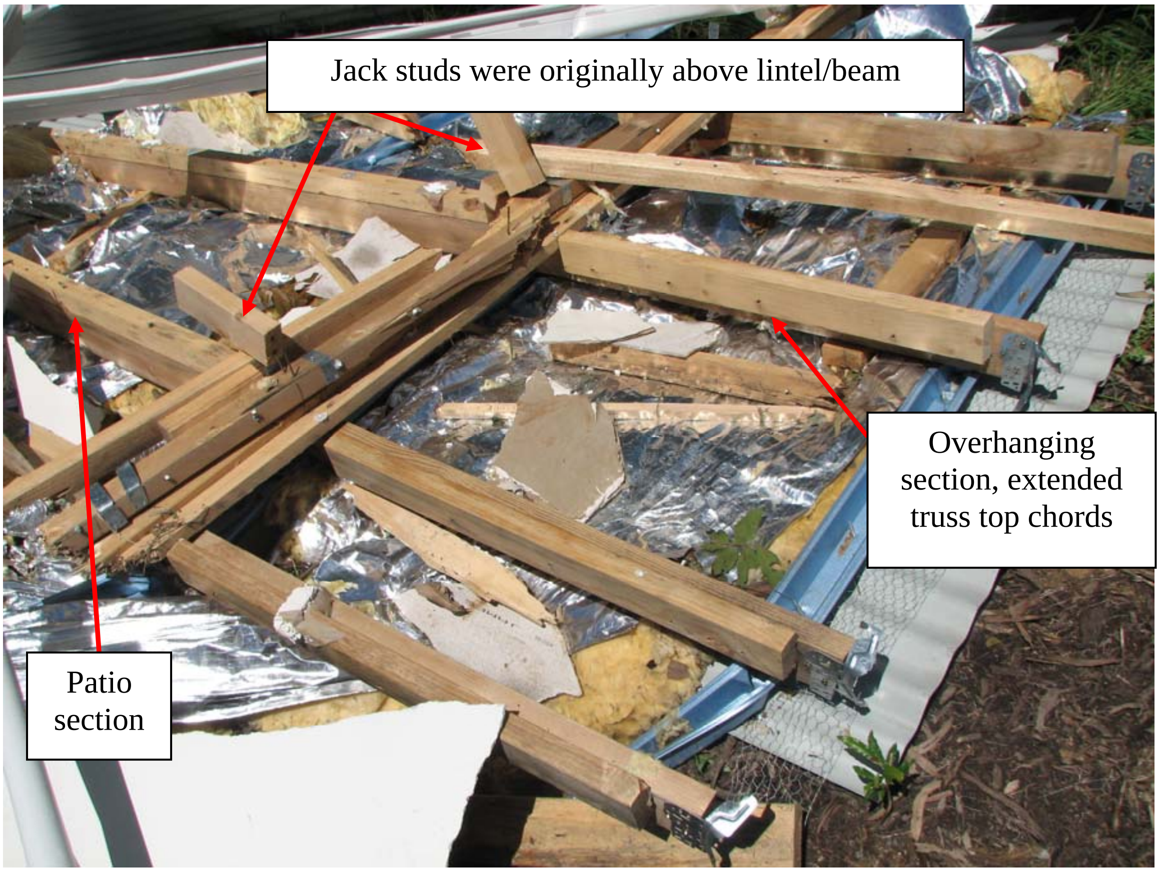


Figure 8.6: Failed patio roof structure about 200m downwind from house

The failures described here allowed significant water ingress to the house, causing loss of ceilings at several locations on both storeys.

8.3 Incorrect Tie-down and Window Frame Connections – Post 1980 House

A relatively new two storey house (reportedly less than one year old) built near the top of a steep ridge, in The Gap, sustained extensive damage. About half of the roof structure and upper walls/windows to the eastern end of the house were lifted off the house. This house was not included in the damage survey but had a Damage Index 987. The house had a clear view over the edge of this ridge looking to the south, in the direction of the expected strongest winds and so was likely subjected to a large topographic wind speed-up effect.

Two upper storey rooms facing south had failure of the tie-down beside the lintels over large windows subsequently causing the loss of the roof. It appears that the tie-down provided for these lintels used M16 rods in some cases and double metal straps for others.

Figure 8.7 (a) shows the remains of a top plate that was fitted above a lintel. This top plate still has a long double metal strap attached that has failed. An M12 bolt was also connected through the end of this top plate near the far end of a plywood bracing panel nominally 600 mm wide.

Figure 8.7 (b) shows an M16 rod beside another opening and it appears likely that the failure of the top plate was caused by excessive shear due to the M16 rod not being configured as required by AS1684 Table 9.20 (d) or (e).

(a) One end of top plate– strap failed & M12 bolt too far away

(b) M16 bolt too far from lintel and not configured as per AS1684.

Figure 8.7: Lintel hold-down – Combination of metal straps and HD bolts at far end of ply bracing frame

Note that it appears that the plywood bracing was being used as the tie-down beside the opening shown in Figure 8.7 (a).

Figure 8.8: Lintel to back window – held down by ply bracing panel

It also appears that opening on the rear wall was using the plywood bracing panel as the tie-down beside the opening, as shown in Figure 8.8. This assumption is based on the absence of bolts or straps beside these openings. Using plywood as tie-down beside an opening is not in accordance with AS1684.

Figure 8.9 shows one of the configurations required by AS1684 for M16 rods. As can be seen from this detail, shear in the top plate is virtually eliminated as opposed to the configuration shown in Figure 8.7 (b) which requires the top plate to transfer the uplift forces to the tie-down rod and is only applicable to tie-down capacities requiring rods up to M12.

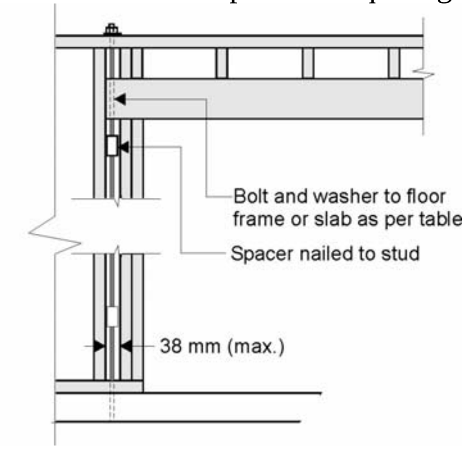


Figure 8.9: One method for lintel tie-down using M16 rods (as specified in AS1684.2)

This house also had all windows (facing the strongest wind direction) fail or substantially dislodged from supporting jamb studs, as shown in Figure 8.10. Note that the fixings from these window panels to their supports failed and that the glass itself was unbroken.

(a) Complete unbroken window pushed in

(b) Window dislodged from jamb studs

Figure 8.10: Failure of windward window panels

Therefore these failures were caused by inadequate fixings from the window frames to the main structural window supporting members.

9. Design Criteria

The majority of modern houses experienced little or no structural damage in these windstorms. This would indicate that the provisions of the current codes and standards are generally adequate in the affected areas, notwithstanding that the wind speeds in the storm are estimated to have been less than ultimate limit state design values. However there are some anomalies in AS 4055 that will affect other related standards such as AS1684.2 etc.

The relevant design provisions are detailed in the BCA, *Building Code of Australia*, for the design and construction of buildings and other structures covered by building law. Standards, such as AS/NZS1170.2, AS 4055 and AS1684.2 provide a detailed means of complying with the requirements of the BCA as a part of their deemed to satisfy (DTS) provisions.

9.1 Standards

9.1.1 Wind Loading Standards

The building designs in the investigation area were covered by two wind loading standards.

AS/NZS1170.2 - *Structural design actions Part 2: Wind actions*

- The maximum gust wind speeds (referenced to flat open country at a height of 10 m) in the study area were estimated to be in the order of 45 m/s. This is much less than the regional design wind velocity of 57 m/s for the same area, as specified in AS/NZS1170.2.
- In calculating the design wind speed for individual buildings, AS/NZS1170.2 uses topographic multipliers that will increase the design wind speed for specific buildings in exposed hilltop locations.

AS 4055 - *Wind loads for housing*

- This uses a simplified means for calculating site wind speeds, but is still required to address shielding, topography and ground roughness.
- Based on the survey data presented in this report, the winds experienced at all structures studied were likely less than the design wind speed calculated from AS/NZS1170.2. However, some contemporary houses suffered significant levels of structural damage, but in all cases the failures could be related to connection details that were not in accordance with the relevant standards.
- The classification from the current version of AS 4055 can give reduced design wind speed for some houses in exposed elevated positions when compared to calculations using AS/NZS 1170.2. This can result in the under-classification of the site (e.g. building a N3 house on a N5 site). Appendix B provides a comparison between the two standards for design wind speeds and pressures for two houses, one on flat terrain and one on top of a steep hill.
- Furthermore, the failure of inadequately fixed doors and windows from wind pressure or from flying debris will generate higher internal pressures than that specified in AS 4055 and can also lead to extensive damage.

AS/NZS1170.2 and AS 4055 do not explicitly require nominally sealed buildings in Region B to resist high internal pressures arising from a dominant opening. There were a number of cases in which door or window frame fixings failed under wind loads producing high internal pressure, and other cases in which flying debris caused damage to houses that led to internal pressurisation. In a design wind speed event, all of the houses for these cases would have significantly larger than design uplift loads applied to their roof structure. Therefore, there is a need for the standards to be more explicit about requiring design for the ultimate limit state using full internal pressure unless the windows and doors are capable of resisting the applied wind pressures and an appropriate level of flying debris impact loading.

In order to maintain progress in the ability of buildings to resist windstorms, it is important to ensure that AS 4055 is revised so that the specifications are consistent with those given in the wind loading standard AS/NZS1170.2.

9.1.2 Windows and Glazing Standard

Heavy rain usually accompanies most windstorms as they generate large differential pressures across the building envelope. These pressure differentials could easily exceed 1kPa across windows and doors on the windward face of a building. According to the applicable glazing standard AS 2047 (1999) the water penetration resistance test pressures are set at between 150 to 450 Pa for windows and 150 to 200 Pa for adjustable louvre windows for wind classes N2 to N6. This appears to be a serviceability design requirement, which would not prevent water ingress into the building in extreme wind events (i.e. ultimate limit state). During the investigation, many examples of damage to contents resulting from water ingress were observed.

In some cases, failure of window frame to supporting jamb studs connections occurred. Where these failures were observed, the frames of the windows were connected to the jamb studs using nails spaced at large intervals and/or not of sufficient size to adequately restrain the window against the imposed wind loads. There is anecdotal evidence to suggest that builders assume that internal linings etc. provide additional support to the window frame. However, this does not appear to satisfy requirements in AS 2047, as the strength of frame connections in these cases are not adequate, even if the glass panes and frame are able to resist the wind pressure. There does not appear to be any standards or industry recommendations etc that adequately specify the appropriate fixings of windows and doors to the supporting structure. With regards to installation, Clause 7.2 of AS2047 states that "*Window assemblies shall be fixed into the building using recognized building practices*" but more explicit guidance should be provided.

This should be of concern to the building industry (and insurance industry), as the failure of a window on the windward face will create more water damage and will result in high internal pressures and potentially instigate more severe failures.

9.1.3 Garage Doors

Garage doors on some buildings performed poorly. It is clear that many of these doors, (both roller doors and panel lift doors) , do not comply with requirements in wind loading standards and the domestic garage doors standard AS/NZS4505 (1998), as failures occurred at loads likely to be significantly less than the design values.

The building industry must ensure that garage doors are properly rated, or at the very least that buildings are designed for the appropriate internal pressures by assuming that the garage door will fail under moderately strong wind speeds, with the potential for creating a dominant opening.

9.2 Progress in Building Quality

The performance of contemporary houses was overall better than the performance of the older houses and reflects the improvement in building regulation and general building practices for new construction. However, this is to be expected as the estimated wind speed for this event was less than the design wind speed for the investigation area.

Some contemporary houses performed poorly, but in all cases this poor performance was caused by connection details not being built in accordance with the relevant standards. However, even if these connection details had been built correctly, they could still have failed due to possible incorrect site classification of site design wind speeds by AS4055 or by being subjected to additional loading from full internal pressure when windows/doors failed.

10. Conclusions

The main findings and conclusions from this damage investigation are detailed in this section. Note that some of the findings could have been classified under several sub-headings, but have only been listed once.

10.1 Wind Loading

10.1.1 Estimated Wind Speeds for Storm of 16 Nov

Based on the analysis of radar and damage patterns, it seems likely that the high level of damaging winds in and around The Gap on the 16 November were caused by a combination of topographically enhanced winds from a vigorous Rear Flank Downdraft and possibly an imbedded microburst. The most damaging swath was about 4 km in width, and 8km in length, although adjacent areas also experienced significant winds that likely well-exceeded the storm translation speed of 50 to 60 km/h strength over a swath width of more than 10 km and a length of about 40 km. A peak gust wind speed of about 50 m/sec is estimated at a height of about 450 m, based on analysis of Doppler radar images. Near surface gust wind speeds are estimated to be in the order of 45 m/s (160 km/h).

10.1.2 Estimated Wind Speeds for Storm of 19 Nov

As detailed in Section 2.3.2, the damage caused by the mini-tornado at Paddington on 19 November was effectively limited to just one street, Becks Street and so a detailed analysis of radar imagery was not performed. However, based on the damage observed during the inspections undertaken in Beck Street, the peak gust wind speeds were estimated to be significantly less than the current design wind speed of 57 m/s for Brisbane.

10.1.3 Comparison of Estimated and Design Wind Speeds

The estimated peak wind speeds for both wind storms were less than the regional design wind speed for the study area which is 57 m/s, so all houses inspected were judged to have been subjected to peak gusts at the structure of lower speed than the design standards would have indicated as being the site design wind speed.

10.2 General Observations on Damage

A predominant type of damage to housing in The Gap was caused by falling trees, which is independent of the age of the housing.

Members of the investigation team were also told of cases where shredded leaf litter, often along with hailstones, combined to block gutters and downpipes, which caused water penetration into the ceiling space.

Other main causes of damage included:

- Water ingress, either through failed doors and/or windows or very often water ingress through doors and windows that had not failed.

- Failure of windward doors or windows causing a sudden increase in internal pressure, sometimes leading to a subsequent failure of part of the roof structure.

10.3 Design Issues

Some of failures observed would have been exacerbated by the design criteria used to specify the construction details needed. These factors include:

- When determining the effect of typical terrain, topographic and shielding features on the site design wind speed, there are inconsistencies between AS 4055 and AS/NZS1170.2. One such case is where AS 4055 specifies significantly less severe topographic effects than AS/NZS1170.2 for houses located near the top of steep ridges, as detailed in Appendix B.
- As noted in Section 5.5, there were reports of damage to skylights, either from hail or wind or a combination of both. There does not appear to be any requirements for skylights to be designed to resist these loadings and this should be examined.
- There was significant water ingress through undamaged tile roofs that were installed without sarking, as detailed in Section 6.
- Flying debris did cause breakages to windows and doors resulting in a sudden increase in internal pressure. However, there is no requirement for housing in non-cyclonic regions to be designed to resist full internal pressure to cover this design loading case.

10.4 Construction Issues

Overall, Post 1980 houses performed better than Pre 1980 houses and this reflects the improvements resulting from the introduction of the Queensland Government's *Appendix 4 to the Standard Building By-Laws* (1975-1984) and subsequent TRADAC timber framing manuals (published between 1979 and 1999). The Post 1980 houses would be expected to perform well, as the peak gust wind speeds were estimated to be less than the design wind speed.

Although this investigation looked at only a relatively small sample of housing, for all of the cases where failure occurred, the failure could be attributed to poor or inadequate construction details. Some of these inadequate details included:

- Inadequate tie-down, with connection details that were not strong enough. A number of such cases included Pre 1980 houses that had been recently re-roofed, but the newly installed connection details were not adequate.
- Failures in Post 1980 houses were due to tie-down connections not in accordance with the relevant standards (AS1684.2 for example).
- Some cases were observed where window or doors were not adequately fixed to their supporting structural members (jamb studs) and the complete window or door assembly was pushed in as a unit, apparently because the fixings were not strong enough to support the wind pressure loading.
- As reported in Section 7.4.4, some instances of garage door failure were observed. However, it was not clear whether these failures were due to poor construction details or the garage doors not having an adequate design capacity.

11. Recommendations

This section summarizes recommendations arising from this report.

11.1 Wind Monitoring Needs

The small scale of severe thunderstorm winds, combined with the generally sparse network of surface wind monitoring stations means that it is very unlikely that the peak winds from such events can be captured. The present knowledge of thunderstorm outflow characteristics, terrain and topography is also very limited. This makes comparisons of the expected and observed damage almost impossible to reconcile. It is recommended that a program of enhanced surface wind speed monitoring should form an important part of future investigations into building performance under severe winds.

11.2 Review of Standards

It is recommended that some aspects of the following standards should be reviewed:

- Revise the factors used determine design wind speeds in AS 4055 to be consistent with AS/NZS 1170.2.
- Consider increasing the differential pressure difference limit across windows at which they must remain watertight in AS 2047.
- Provide explicit guidance on the fixing of windows and door frames to their supporting structure for the various wind classifications in AS 2047.
- Investigate the need for requiring all houses in non-cyclone areas be designed for full internal pressure, unless the windows and doors are capable of resisting the applied wind pressures and an appropriate level of flying debris impact loading.
- Ensure that design and installation specifications for domestic garage doors are adequate in AS/NZS 4505.

11.3 Review of BCA

It is recommended that the following areas covered in the Building Code of Australia be reviewed:

- **Water penetration through windows and doors** – to minimize the loss of amenity for occupants of housing, review the application of the weatherproofing requirements, (see Clause P2.2.2 in BCA 2008, Vol Two for example).

- **Roof lights** –include requirements for resistance to both wind loading and impact from hailstones.

- **Sarking to tile roofs** –require tile roofs to all wind areas (i.e. both cyclonic and non-cyclonic) have sarking installed over the full roof area.

11.4 Investigate the Use of Correct Construction Details

All of the failures observed were caused by inadequate construction details. For the Post 1980 houses investigated, failures could be attributed to connection details not in accordance with relevant standards. This suggests that there may be a need to focus on improving the standards of building construction quality, both from a builder education perspective and for the building certification system that allows these mistakes to be passed. However, this investigation covered a relatively small sample of housing. Therefore it is recommended that a study be performed to investigate the extent of housing connection details not complying with the relevant standards.

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Appendix A – A Background to Severe Thunderstorm Meteorology

The following brief overview of severe thunderstorm meteorology and climatology is provided to help illustrate the characteristics of these severe mesoscale storms, which differ significantly from larger scale synoptic systems such as tropical cyclones.

Thunderstorms often develop under specific moist and unstable conditions in the troposphere (lowest 10 km) that allows convective clouds to develop and potentially grow up to 20 km in height (Bureau of Meteorology 1995). The name “thunderstorm” relates to the typical occurrence of lightning and associated thunder with these events, which is due to the separation of charged particles in the storm circulation. There is, however, no known direct relationship between the incidence of lightning and the potential severity of other storm characteristics such as damaging wind or hail. In basic terms, the thunderstorm is capable of accumulating vast amounts of potential energy that can then be converted into dangerous turbulence and shear in the atmosphere and often damaging impacts at the surface. The most fundamental concept is that a single thunderstorm may consist of one or more convective building blocks termed “cells”. A cell is a compact region of relatively strong upward air motion, triggered by atmospheric instability due to the temperature and density differences in the vertical.
Conceptually there are two types of thunderstorm cells, classified as follows:
(a) The *Ordinary* Cell

- is the most common type and forms in weak vertical windshear environments
- may be isolated but commonly occurs with other similar cells (multi-cellular)
- a lifetime typically up to 1 hour and on-ground horizontal scale of 5 to 10 km
- can produce short bursts of severe weather

(b) The *Supercell*

- is rarer and forms in strong vertical windshear environments
- is usually isolated and exhibits a deep, persistent rotating updraft (a mesocyclone)
- a lifetime of 1 to 2 hours or more and an on-ground horizontal scale of 10 to 40 km
- almost always produces severe weather

A schematic diagram of a mature supercell thunderstorm is presented in Figure A1. The primary feature is the deep and persistent rotating updraft that originates as low-level moist inflow ahead of the storm. Much of this updraft is dissipated at the upper levels, forming the characteristic cloud anvil and overshoot, but some recirculates as downdraft that appears at the surface as the familiar gust front. Hail and heavy rain areas are also associated with the downdraft zones, in addition to the severe winds. Under specific sets of conditions, which are not fully understood, a tornado may form towards the left rear flank of the supercell (southern hemisphere, observer travelling with the storm). The tornado is thought to result from the tilting of horizontal vorticity present in the lower layers. This allows a small but rapidly rotating column of air to descend below the cloud base, often reaching the surface with devastating consequences. Supercell sub-categories include “high” and “low” precipitation varieties, the “high” being more common on the Australian east coast.

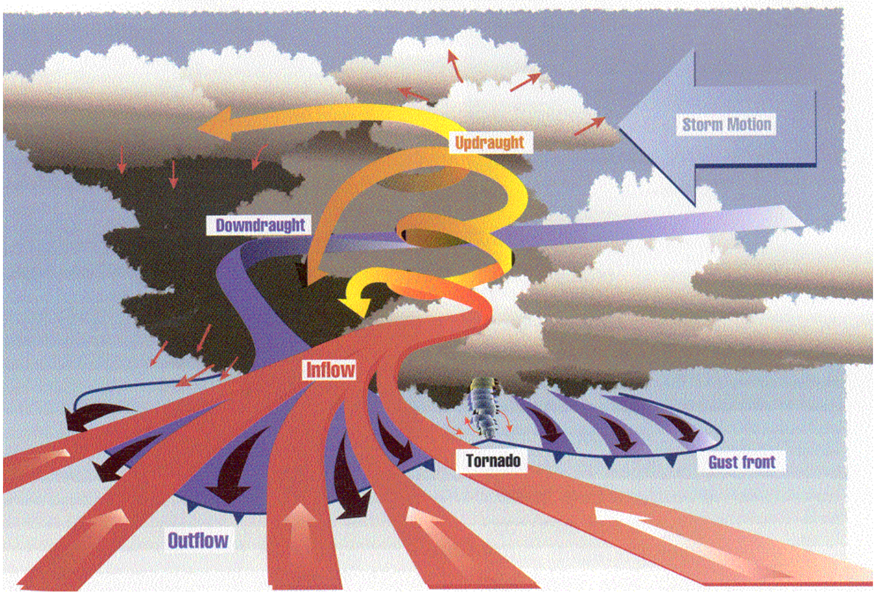

Figure A1 Schematic structure of a "supercell" severe thunderstorm.
[Bureau of Meteorology figure]

As summarised by Fujita (1981), there are essentially three types of severe wind phenomena known to be associated with severe thunderstorms (refer Figure A2):

- Straight-line winds (non-divergent), typically associated with advancing gust fronts;
- Downbursts (high pressure flows), highly divergent with straight or curved paths, divergence increasing at smaller scales;
- Tornadoes (low pressure flows), highly convergent, narrow paths but much more common in Australia than previously thought.

Figure A2a shows the upper limit of scale of interest in the thunderstorm problem where severe but essentially straight-line winds can accompany a gust front, typically ahead of a cold frontal system. This scale of motion is typically of order 100 km. Within a gust front, Figure A2b shows the potential further development of a macroburst within this flow at a scale of order 10 km. Finally, a microburst may develop at a scale of order 1 km as shown in Figure A2c. Tornadoes occur at a scale similar to microbursts but, being convergent flows, exhibit long narrow paths that are often characterised by an intermittent surface contact.

Often distinguishing between downburst and tornado damage is difficult. A fast moving tornado may also exhibit near-straight-line damage characteristics. Where a radial pattern of damage is indicated, microbursts are likely. Tornado damage, on a large scale, may show evidence of circumferential flow but at small scale is similar to any form of damage. "Twisting" of trees, for example, will likely occur due to asymmetry of the tree form under all types of wind load.

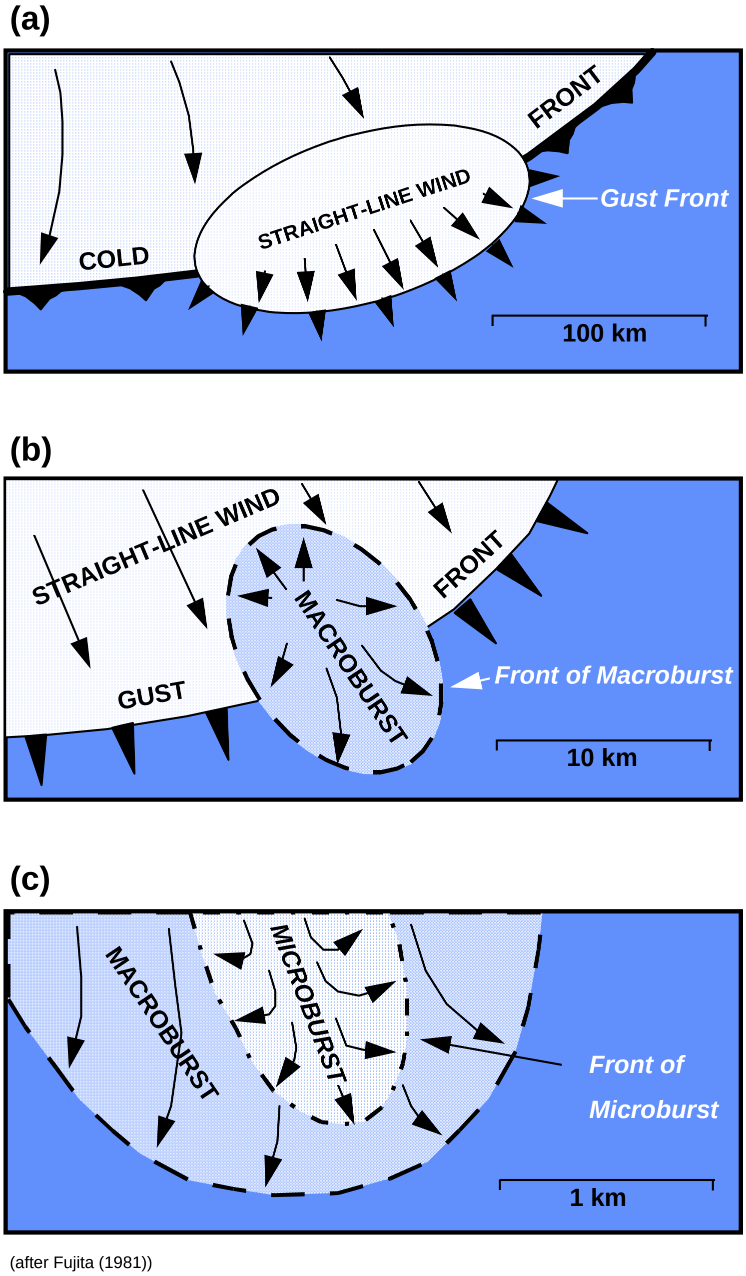

Figure A2 Typical scales of motion of ground level winds.

The most common manifestation of unexpectedly high winds is due to the (naturally intermittent) severe downburst, which is conceptually illustrated in Figure A3. The source of the severe surface winds is from high within the storm where a column of very cold air becomes unstable and rapidly descends from above 4 km over several minutes. When it impacts the surface, the winds spread essentially radially away from the centre but, combined with the forward motion of the storm cell, an elongated “footprint” is formed with the most severe winds at the leading edge. The upper magnitude limit for downbursts is thought to be about 80 m/s.

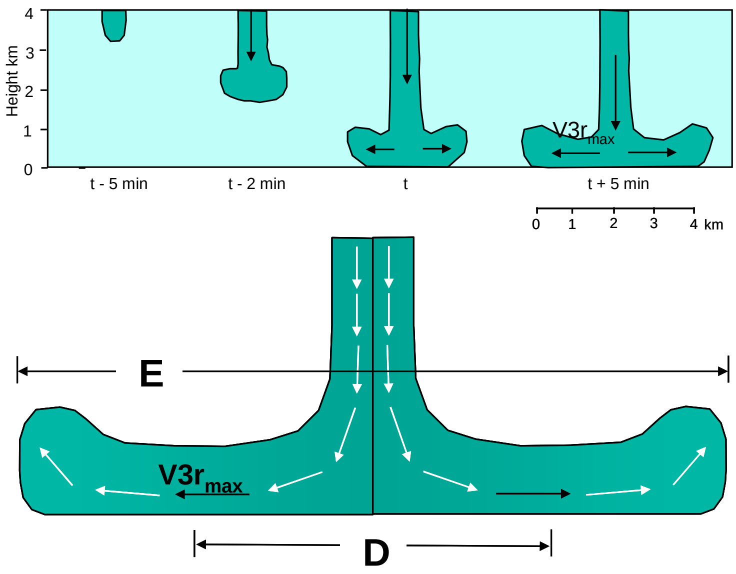

Figure A3 Schematic of a severe thunderstorm downburst.
[after Hjelmfelt (1988)]

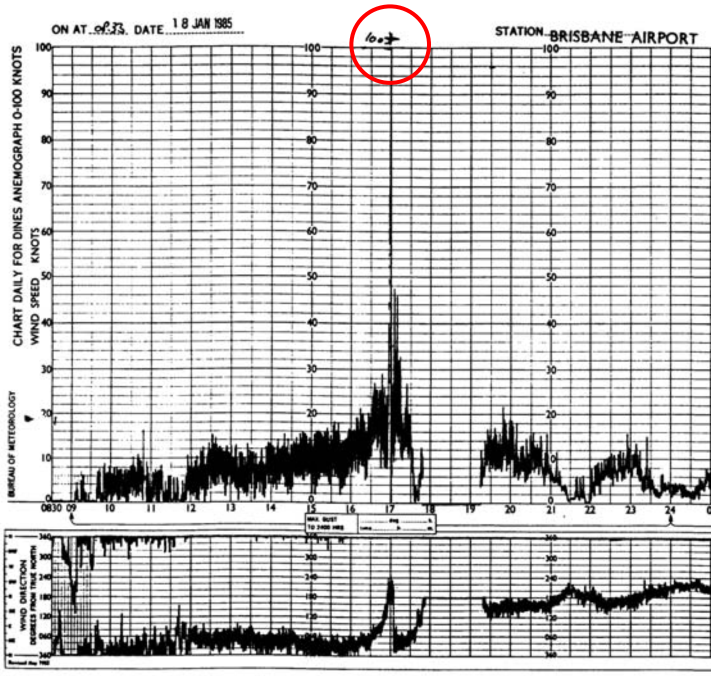

Figure A4 The characteristic wind signal of a severe downburst event.
[Bureau of Meteorology anemograph]

The characteristic wind speed signal from a severe downburst is illustrated in Figure A4 Figure A4, showing the 100 kt gust recorded at Brisbane Airport in January 1985, from a background of only 25 kt a minute or so earlier. Figure A5 shows a downburst in action during a damaging storm in December 1989 that produced many small tornadoes in the Redcliffe Peninsula region and is seen here off the coast from Mooloolaba, executing another downburst. A common characteristic of such events is that downbursts tend to “cycle” and, once triggered, the storm may take some time (perhaps 15 to 20 minutes) to build-up a similar degree of instability that might initiate another downburst.

Figure A5 A supercell downburst near Mooloolaba, Dec 1989.
[Bureau of Meteorology photograph]

Knowledge of the thunderstorm climatology in South East Queensland has been increasing with the availability of improved satellite and radar coverage and also lightning detection and tracking systems. However, there is no definitive scientific climatology study available at this time, with the majority of knowledge gained from forecaster experience in conjunction with accumulated impact and damage statistics (e.g. Harper 1997). Improved knowledge is especially hampered by the sparse anemometer network, which rarely is able to capture the severe surface wind zone of specific storms.

However, many specific instances are known where the interplay of the topography and coastal plain convergence directly impact storm intensity and track over the Brisbane metropolitan area (Callaghan 1988). Harper and Callaghan (1998) proposed essentially 4 broad classes of severe thunderstorms in the South East Queensland region based on synoptic pre-cursor types as follows:

- Type A: SE Change (23%)
- Type B: Strong NW Flow (17%)
- Type C: Weak NW Flow (43%)
- Type D: Other (17%)

Figure A6 schematises the typical approach tracks for the severe storms in each of these categories, superimposed on a topographic map of the region. It is argued that there is a strong association between both storm intensity and track as a function of the regional topography; these being related to:

– the generally westerly steering current for storms in the region
– the highland regions to the south and west providing elevated convective heat sources
– vertical wind shearing created by the elevated regions
– low level convergence on the coastal plain

As summarised by Harper (1997) based on the information available at the time:

- the thunderstorm “season” is mainly October through April
- there are an average of about 20 days each year when severe thunderstorms affect the South East Queensland region
- on each of these days there are often up to 5 individual severe storm systems involved
- predominant approach direction is from the SW
- typical forward speed is 12 m/s
- approximately 30% of severe storm days involve severe hail
- tornadoes occur on average about 1 day per year in the region[1]

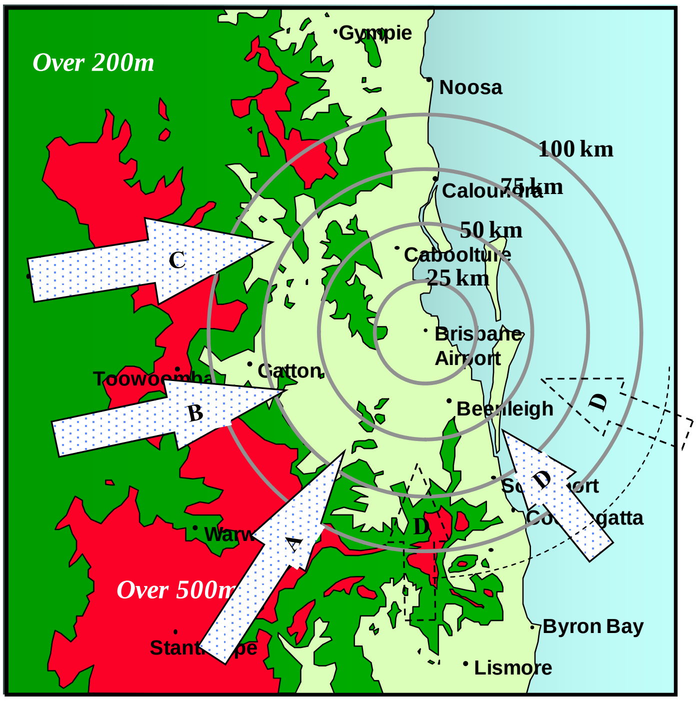

Figure A6 Schematised synoptic storm track classes in South East Queensland. [after Harper and Callaghan (1998)]

[1] This is likely an underestimate, with active “storm chasing” now suggesting a greater likelihood of at least weak tornadoes occurring.

Appendix B – Design wind loads using AS/NZS1170.2 and AS 4055

AS/NZS1170.2 (2002) sets out procedures for calculating wind speeds and resulting wind actions to be used in structural design. This standard covers onshore structures other than bridges and transmission towers that are less than 200m tall, with roof spans less than 100m.

The design wind pressure p_{design} is calculated from Equation B1

$$p_{design} = 0.5\rho_a V_{des,\theta}^2 C_{fig} C_{dyn} \qquad \text{(B1)}$$

For the majority of structures including low-rise buildings, the wind loading frequencies are generally much lower than the natural frequency of the structure, and the resonant response is negligible (i.e. C_{dyn} = 1.0). Wind loads (i.e. C_{fig} values) for the design of low-rise buildings are calculated from pressures derived from pressure coefficients, provided in Section 5 and Appendix C of AS/NZS1170.2 (2002).

- **External and Internal Pressures**

The design external pressures are derived from AS/NZS 1170.2 using Equation B2.

$$p_{e,design} = 0.5\rho V_{des,\theta}^2 C_{fig} = 0.5\rho V_{des,\theta}^2 C_{p,e}(K_a \times K_c \times K_l \times K_p) \qquad \text{(B2)}$$

Here $V_{des,\theta}$ is the design gust wind speed at mid-roof height, and $C_{fig} = C_{p,e} \times K_a \times K_c \times K_l \times K_p$. Factors K_a, K_c, K_l and K_p account for a reduction of loads on large areas, reduced loads acting on a combination of surfaces, high local loads on small areas near the edges and reduced loads on porous surfaces, respectively.

The design internal pressures are derived from AS/NZS 1170.2 using Equation B3.

$$p_{i,design} = 0.5\rho V_{des,\theta}^2 C_{fig} = 0.5\rho V_{des,\theta}^2 C_{p,i}(K_c) \qquad \text{(B3)}$$

The regional, 3s-peak gust wind speed at 10m elevation in terrain category 2 approach, for a R yr return period, V_R is modified by wind direction, terrain/height, shielding and topography multipliers M_d, $M_{z,cat}$, M_s and M_t respectively in Equation B4, are given in AS/NZS 1170.2 (2002) to calculate the gust wind speed V_h at a height h.

$$V_h = V_R M_d (M_{z,cat} M_s M_t) \qquad \text{(B4)}$$

The wind loads for housing standard AS 4055 (2006) has been developed from data given in AS/NZS1170.2 and is applicable for use in design of housing that would include the majority of one and two storey houses in Australia. This section summarises the scope of AS 4055 and identifies simplifications and limitations in AS 4055. Design wind speeds and design wind loads on roof cladding elements at a gable edge of typical one and two storey houses located on flat land and on a steep hill are calculated using AS/NZS 1170.2 and AS 4055 and compared in this section.

According to AS 4055, a house site is categorised as one of ten classes N1to N6 for non-cyclonic and C1 to C4 for cyclonic regions, based on the geographic wind speed region, terrain category, topography and shielding. AS 4055 provides serviceability and ultimate limit state design wind speeds at h = 6.5m for each of these ten classes, by considering a population of houses. In doing so, the standard acknowledges that there is a varying level of reliability of each house. As each house is required to be “assessed” individually, it is expected that the classifications should not result in “un-conservative” designs. However, the implementation of methods specified in AS 4055 can result in design loads that are much lower than those derived using AS/NZS 1170.2 especially for houses on exposed sites, producing un-conservative designs. Other standards such as AS1684.2 that are synchronised with the loads specified in AS 4055 are therefore likely to specify inadequate detailing for these houses.

A number of simplifications given in AS 4055 will most likely produce reduced design wind speeds. These are the 0.95 factor on wind speed allowed to account for variation of house orientations within a group of houses, where a directionality multiplier isn’t applicable, and the 5% margin allowed for assigning the classes presumably reduces the wind speed further.

The topographic multipliers have generally been calculated in a reasonable manner however, the example given Appendix B of AS 4055 calculates an “effective” slope as the average of maximum and minimum slopes at the site and hence will in most cases result in reduced design wind speeds for sites on steep topography. AS/NZS 1170.2 specifies that the effects of shielding are not applicable if the ground slope is greater than 0.2. It also implicitly indicates that only houses within a 45^{o} sector and a radius $20h$ upstream and of height equal or greater than the target house provides shielding. However, AS 4055 indicates that wooded areas can provide full or partial shielding even in regions C and D. The net result of this is that elevated sites with steep topography can be under classified resulting in an unconservatively designed house built on the site (i.e. N3 house built on a N5 or N6 site).

Some simplifications in AS 4055 will result in increased design loads especially on roof components of moderate roof pitch hip-ended houses. Also, design wind speeds for h = 6.5m would be conservative for typical one storey houses where h is about 3.2m. Furthermore, the design external pressures would be conservative for most roofs as they are based on the largest suction pressure coefficient on a low-pitch roof.

AS 4055 applies low internal pressure coefficients C_{pi} (+0.2, -0.3) for calculating design loads on house components in non-cyclonic regions. This is based on assuming that a dominant opening is not created during a windstorm. However, if a dominant wall opening is created from the failure of a window/door or the impact of flying debris then the internal pressures could be significantly higher than that assumed in the design and render the house more vulnerable to damage.

AS/NZS 1170.2 is used to calculate the ultimate limit state design wind speeds for a 1 storey and 2 storey (20^{o} pitch gable roof) houses located in open, terrain category 2.5 exposure on flat site and a site on top of Hill 1 (Figure B1 AS 4055). Following this, the net design pressures on a roof cladding element at the gable edge is calculated for winds approaching from two orthogonal directions. These are compared with the design values specified in AS 4055.

Design wind speeds V_h for 1-storey and 2-storey houses shown in Figure B1 and B2 are calculated and the design wind loads on cladding elements at the gable edge are determined using AS/NZS 1170.2 and compared with AS 4055.

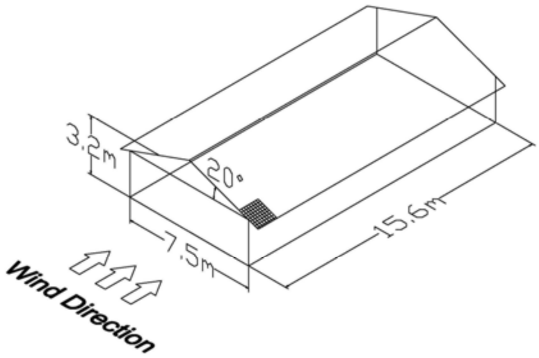

Figure B1. 1-storey house

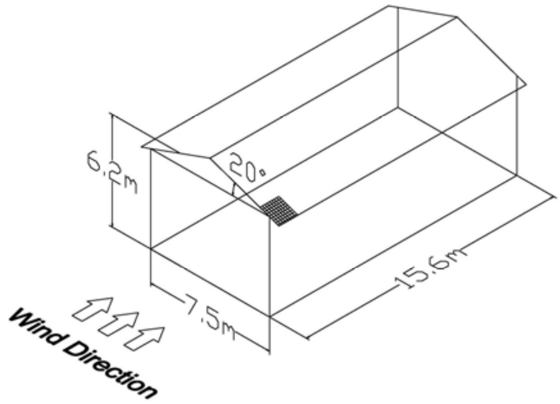

Figure B2 2 storey house

- ***Case 1: 1 storey and 2-sorey house on flat land***

Mid roof height h = 3.2 m, 6.2m
$M_{z,cat}$ = 0.87, 0.88
M_t = 1.0, M_s = 1.0, M_d =1.0
V_h = 49.6 m/s, 50.2 m/s
Corresponding AS 4055 classification N3: V_h = 50 m/s

$C_{p,e}$ = 2 x -0.9 = -1.8, $C_{p,i}$ = +0.2
Design wind pressure on roof edge = -2.95 kPa, -3.02 kPa
Corresponding AS 4055 design wind pressure = -3.00 kPa (Very close agreement)

- ***Case 2: 1 storey and 2-sorey house on top of Hill 1 (Figure B1 AS 4055)***

Mid roof height h = 3.2 m, 6.2m
$M_{z,cat}$ = 0.87, 0.88
$x = 0m$, $z = 3.2m, 6.2m$, M_t = 1.40, 1.38 {Eqn 4.4(2)}
M_s = 1.0, M_d = 1.0
V_h = 69 m/s
Corresponding AS 4055 classification N4: V_h = 61 m/s

$C_{p,e}$ = 2 x -0.9 = -1.8, $C_{p,i}$ = +0.2
Design wind pressure on roof edge = -5.71 kPa
Corresponding AS 4055 design wind pressure = -4.47 kPa (Ratio is 5.71/4.47 = **1.28**)