Case Study

Adaptation lessons from Cyclone Tracy

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Adaptation Lessons from Cyclone Tracy

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

Disclaimer

Preface

The National Climate Change Research Facility (NCCARF) is undertaking a program of Synthesis and Integrative Research to synthesise existing and emerging national and international research on climate change impacts and adaptation. The purpose of this program is to provide decision-makers with information they need to manage the risks of climate change.

This report on Cyclone Tracy forms part of a series of studies/reports commissioned by NCCARF that look at historical extreme weather events, their impacts and subsequent adaptations. These studies examine particular events – primarily extremes – and seek to explore prior vulnerabilities and resilience, the character and management of the event, subsequent adaptation and the effects on present-day vulnerability. The reports should inform thinking about adapting to climate change – capacity to adapt, barriers to adaptation and translating capacity into action. While it is recognised that the comparison is not and never can be exact, the over-arching goal is to better understand the requirements of successful adaptation to future climate change.

This report highlights Cyclone Tracy, which was a Category 4 cyclone that laid waste to the city of Darwin in the Northern Territory early on Christmas Day in 1974. Cyclone Tracy showed the nation just how devastating the impact of a cyclone could be, and awoke the engineering community – local and international – to the true risk of cyclonic wind storms. Tracy's small size minimised the spatial extent of damage, but her slow forward speed meant the areas beneath her storm track were completely devastated. Cyclone Tracy resulted in 71 deaths and 650 injuries. Fortunately for Darwin, flooding and storm surge were not major issues, or these numbers could have been far higher. In almost all cases, wind was the dominant factor in the ensuing structural damage, which left 94 per cent of housing uninhabitable and approximately 40 000 people homeless, and necessitated the evacuation of 80 per cent of the city's residents.

Other reports in the series are:

- *East Coast Lows and the Newcastle-Central Coast* Pasha Bulker *Storm*
- *The 2008 Floods in Queensland: Charleville and Mackay*
- *Storm Tides along East Coast Australia*
- *Heatwaves: The Southern Australian Experience of 2009*
- *Drought and the Future of Rural Communities: Drought Impacts and Adaptation in Regional Victoria, Australia*
- *Drought and Water Security: Kalgoorlie and Broken Hill*

To highlight common learnings from all the case studies, a Synthesis Report has been produced, which is a summary of responses and lessons learned.

All reports are available from the website at www.nccarf.edu.au.

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Key findings

1. The improved wind performance mandated in the construction of residential homes in cyclone-prone areas has proved effective, although there are concerns that decay and corrosion over time will reduce their performance under extreme wind loads.
2. Around the world, disaster losses from meteorological events are increasing and, to this point in time, these increases can be attributed to demographic changes – more people living in dangerous places with more to lose.
3. Global climate change may alter the frequency and intensity of future cyclonic activity, but the exact nature of these changes remains a difficult and as yet unsolved research question.
4. From public safety and policy perspectives, the most effective response to extreme winds, whatever their origin, is better building codes.
5. Evacuation should become a secondary consideration and, provided surge is not an issue, the primary focus during cyclonic events should be to ensure people are safely inside their homes or workplaces.
6. The desired level of wind performance of structures will always be a compromise between the likelihood of extreme winds and the cost of implementing the engineering improvements.
7. It is always possible for the design wind speeds to be exceeded and building failure to result, even if the code is scrupulously complied with.

Recommendations

1. Implementation of a lifetime inspection and maintenance program for buildings in cyclone regions should be considered. These inspections could be carried out at predefined times during a building's life, or be implemented as mandated structural inspections at the point of sale.
2. Funding of a regular (approximately five yearly) review of cyclonic wind speed utilising up-to-date observational data and modelling techniques. These studies should report point and area location risks.

The National Climate Change Adaptation Research Facility (NCCARF) has engaged Risk Frontiers to investigate the adaptive capacity of the Australian building industry using the changes made in light of Tropical Cyclone Tracy as a case in point. This goal was achieved by a review of historic reports, data sets, books and scientific journals, and through interview sessions with significant figures in the adaptive process. The capacity of emergency management and insurance industries for adaptation is also briefly addressed in the appendixes to this report.

Cyclone Tracy

Tropical Cyclone Tracy laid waste to the city of Darwin early on Christmas morning in 1974. Tracy was a small but intense cyclone with observed wind gusts up to 217 km/h (60 m/s), and predicted storm maximum wind gusts up to 20 per cent greater. At the time, the gust of 217 km/h was the highest such wind speed ever recorded on mainland Australia. Tracy's small size minimised the spatial extent of damage, but the cyclone's slow translational speed meant the areas damaged were completely devastated. Cyclone Tracy showed the engineering community that the magnitude and duration of cyclonic winds could be greater than anyone had previously thought possible, and awoke the community – local and international – to the true risk of cyclonic wind storms. Cyclone Tracy resulted in 71 deaths and 650 injuries;

fortunately for Darwin, flooding and storm surge were not major issues or this number could have been far greater. In almost all cases, wind was the dominant factor in the ensuing structural damage, and thus is the primary focus of this work.

Damage

After the cyclone passed, approximately 60 per cent of Darwin's houses were destroyed beyond repair, with only 6 per cent considered immediately habitable. Of the damaged homes, high-set houses performed worse than their low-set counterparts, with differences being driven by a lower level of structural redundancy built into the houses' framing systems. This was particularly prevalent in the newer (i.e. post-Cyclone Althea – 24 December 1971) housing, where a larger portion of a home's bracing resistance was required of the cladding system – which, in most cases, was lost relatively early or destroyed through impact of flying debris. Loss of roof cladding through fatiguing and its subsequent contribution to flying debris was a significant feature of the observed damage during Tracy. The destruction of large amounts of unreinforced masonry walling, and the enhanced damage generated by not accounting for rapid internal pressurisation, were also clearly highlighted.

The fact that the newer homes performed so poorly was a surprise to all, given that their design incorporated engineering lessons from the damage to Townsville after Cyclone Althea in December 1971.

Larger *engineered* structures in Darwin performed considerably better than housing, with the proportion of buildings completely destroyed dropping to around 20 per cent. Although these structures performed similarly in respect of maintaining cladding, their overall improved performance occurred because a suitable level of redundancy was built into them by the engineers who were legally required to design these structures. For the engineered buildings that did fail, it was generally found that engineering standards performed adequately, though it was evident that ambiguity in the wording of the standards led to the inappropriate application of some design specifications. An example of this was the ability for a designer to continue to rely on foliage for shielding at wind speeds that would blow the trees over. Some deficiencies in technical specifications were also found, with the hitherto unrecognised contribution of dynamic loading due to fluctuations in the wind probably being the most prominent.

The overall damage to structures left approximately 40 000 people homeless, and necessitated an evacuation of 80 per cent of the city's residents. Had structures performed better, the size of or necessity for this evacuation could have been reduced.

Response

The responsibility for the devastation that beset Darwin largely lay with those responsible for the construction of the city's buildings, which failed so spectacularly. The ensuing human catastrophe and evacuation all stemmed from the fact that the places people went to for shelter during and after the storm were not resilient enough to withstand cyclonic winds. Cyclone Tracy was therefore an engineering failure, and required an engineering response. Questions also needed to be answered as to why buildings failed in the ways they did, and any major reconstruction was pointless until these questions were answered. A moratorium was swiftly put on all rebuilding so that this could be done.

In the immediate aftermath of Tracy, engineers analysed most of the failed structures, determined general failure mechanisms, and developed interim – though conservative – design recommendations so reconstruction could begin. This process took less than three months to be achieved, with the first housing begun in six and the first reconstructed homes completed within a year. Taking a year to complete the first of the reconstructed homes could be perceived as inadequate, but the engineering input required to determine previously unknown failure mechanisms, develop and codify new testing and construction techniques, re-educate builders, inspectors and certifiers, and then actually build the homes, warranted this timeframe. The improved building standards were applied to large structures and housing alike, and – at least for the reconstruction phase – a certified engineer was required to approve all building designs. This was a huge step for a housing construction industry that typically had relied largely on a builder's experience to determine the most appropriate method of construction. The use of engineers and engineering principles for the construction of residential housing highlighted the adaptive capacity of both the engineering and building communities, and resulted in a step change in the safety afforded by these structures. Housing was now considered to be a level of importance comparable with larger buildings, and it was no longer acceptable to suggest that the low cost of housing justified an unscientific approach to its design, based on the fact that it could be replaced easily and cheaply in the event of failure. The human toll of this occurrence was shown to be too great. After all, housing was where the majority of the city's population sheltered during Tracy, and to ensure their future safety, these buildings had to be constructed with extreme events in mind.

The changes – particularly to housing construction – were at the time radical, but the national horror at the damage to Darwin meant the social and political will was right for such changes to be made, irrespective of any resistance by industry. Outside of a post-disaster timeframe, the extent and rapid implementation of such significant changes would have been impossible.

With the passage of time, new research has allowed refinement of the recommended design and construction methods, and these eventually made their way into national building standards and to other cyclone-prone regions of the country (though some were using them well before they were found in the standards). Because of the new rational (i.e. engineering based) approach to housing design, it was found that many of the post-Tracy recommendations were equally applicable to non-cyclone regions, and through the newly developed wind loading standard for housing, were applied in these regions as well. In principle, every home now built in Australia encompasses lessons learnt from Cyclone Tracy (Walker 2008).

Lessons

One of the clearest lessons learnt from the damage caused by Cyclone Tracy was that buildings with engineering input into their design and construction performed considerably better than those without. It was clear that the housing design and construction process had to be changed to incorporate these principles so their overall resilience could be enhanced. The introduction of engineering-based standards for the design of housing was the result of this, and the significantly improved resilience of housing – and not just in cyclone regions – is a continuing legacy of Cyclone Tracy. At the time, engineering input into housing construction was a radical concept, and its implementation required a change of thinking and attitude by both the engineering and building communities. The public horror at the devastation allowed these attitudes to change, and quickly.

Several important technical lessons were learnt from the damage to Darwin, with some of the most significant being:

- Wind loading is dynamic, not static, and engineering tests aimed at ensuring durability during cyclonic winds must reflect this. This point was most poignantly displayed by the loss of roof sheeting.
- During severe cyclones, flying debris can be significant, and design for its impact must be considered.
- During severe cyclones, vegetation cannot be relied upon to provide significant shielding.
- In an environment where flying debris is common, so too will be the occurrence of internal pressurisation. This must be allowed for.

Gradually, these changes were introduced into design standards, but engineering researchers, consulting engineers and government-based engineering/construction bodies ensured their inclusion into general engineering practice well before this time. This was achieved faster in regions such as Townsville where Althea was still fresh in local memory.

Tracy also highlighted the problems of using a design approach based on the everyday performance of a structure (i.e. permissible stress design), and showed how accounting for extreme events, such as the limit state design approach, was essential. Although Cyclone Tracy didn't initiate the shift from a permissible stress to limit state design approach, it clearly showed that not considering the most devastating events in regions prone to low-frequency, high-impact events was inappropriate. Philosophically, this lesson also pointed out why the then current housing construction process of trial and error was always doomed to be found wanting.

What impact have changes made?

To investigate the impact of improvements made to the wind-resistant design method, two studies that aimed at predicting present-day losses if Tracy were to recur were reviewed. In all, it is suggested that, in the event of recurrence, the average per-structure damage would be reduced by up to 85 per cent. This, importantly, represents a reduction in damage to a level that would no longer necessitate an evacuation. This would greatly reduce the monetary and sociological impact of the recurrence of a similar event. If factors such as structural degradation and inherent human error are considered, and the above improvements were not achieved, it is still felt that damage would be comparatively minimal.

What more can be done?

Despite the positive changes made, there are still issues with building methods that may increase the risk of failure under extreme wind conditions unnecessarily. The following are some of the recommendations made for minimising this risk:

- regular reanalysis of design wind speeds in cyclone prone regions using the most up-to-date information and techniques
- improved understanding and design for durability of structural elements
- collection of more cyclonic wind speed measurements
- better compatibility between design standards, and
- review of the building inspection process.

Many of the issues needing to be addressed can be handled by research institutions, but significantly greater funding is required above what which currently exists. Non-traditional sources of funding – that is, through private industry – should also be explored to fulfil this need. Issues with coordinating and running Standards however, require bodies such as Engineers Australia or the Australian Building Codes Board to play an integral role. Issues with building inspections must be addressed by state governing bodies that ultimately legislate the process.

Despite these comments, adaptive processes made in light of Cyclone Tracy have led to the development of a world-leading, wind-resistant design practice in this country.

1. Introduction

On Christmas morning 1974, Tropical Cyclone Tracy devastated the city of Darwin, causing unprecedented damage to buildings, communication networks and city infrastructure. The event and subsequent reconstruction of essential facilities uprooted an entire community and redefined the way Australians, if not the world, considered the potential impact of natural disasters. A total of 71 people lost their lives, with a further 650 hospitalised or injured. According to the Insurance Council of Australia's Disaster Statistics (Insurance Council of Australia 2009), the total insured loss from Cyclone Tracy was A$200 million (in 1974 dollars) which, normalised to current values, is shown to be the most costly meteorological disaster to ever impact Australia (Crompton & McAneney 2008). On top of more tangible monetary losses, the immediate and prolonged evacuation of 35 000 residents – approximately 75 per cent of the city's pre-Tracy population – caused significant and lasting psychological damage to many residents.

Following an event such as Cyclone Tracy, it is important that everything be done to learn from the lessons that nature inflicts so the risk to life and amenity can be minimised for future events. Once these lessons are identified, it is then essential that improved policy and regulations be implemented in order to mitigate the risk. Fortunately, in the case of Tracy and its impact on standardisation of wind-resistant building design, swift and thorough assessment was made in the immediate aftermath of the storm, and it is upon this information that a large part of the last three decades of this country's cyclonic wind resistant building regulations has been based. In many ways, the industry's response to Tracy is a clear example of a successful adaptation to a catastrophe.

This report uses Tropical Cyclone Tracy as a case study to investigate adaptive capacity in the aftermath of a disaster. In this, the first of two reports on Tracy, the primary focus is on the building industry, but the impacts upon the insurance industry will also briefly be explored, with specific reference to wind dominant cyclonic events. The use of building regulations as a means of enforcing specified design standards is explored extensively. A second report will consider the human dimension of the impact of Cyclone Tracy, and in particular what happened to the Indigenous communities affected by Tracy. This second report is due for completion in late 2011.

In considering the engineering and industry response to Tracy, this report considers the following specific questions:

- What deficiencies/strengths were highlighted by the disaster?
- How did the responsible bodies deal with these issues in the short term?
- How did these same bodies adapt in the long term?
- Have these changes served to strengthen resilience for future windstorm disasters?

Official reports, damage assessments, eyewitness accounts and peer-reviewed literature are all used to piece together the events precipitated by Cyclone Tracy and the ensuing response. These works are supplemented by interviews with key persons involved in Tracy's damage assessment and the subsequent rewriting of codes of practice.

The report begins with a description of the event that was Tropical Cyclone Tracy. In the next section, a background to the city of Darwin, its climatology, and a description of societal factors are important for an understanding of some pre-existing conditions that influenced the impact of and response to Cyclone Tracy. Section 3333 is rounded out by descriptions of the type of buildings as well as the standards/codes used for their construction in Darwin prior to Tracy. Section 4 follows with the observations and statistical results of two damage surveys conducted shortly after the event. Engineering explanations for failures of each type of construction are discussed with weaknesses in construction practice or design standards highlighted. Changes to building codes and standards made because of Tracy's damage and the subsequent lessons to be learnt from these processes are discussed in Section 5555. The report concludes with the assessment of two modelling studies aimed at investigating the usefulness of changes made to the building standards.

It should be stated from the outset that this report concentrates almost solely on the impact of wind damage, and on its implications for wind-resistant design. Tropical cyclones may inflict damage because of strong winds, heavy rains or storm surge, and in some cases all three could be implicated. In the case of Cyclone Tracy, however, wind alone was largely responsible for the observed damage, and it is therefore this element that is the focus of our report. This is not to imply that wind is more dangerous than the other variables, or that it presents a greater risk to Darwin than the other two factors in future events, but given their absence during Tracy, the available lessons were limited.

2. Cyclone Tracy

2.1 Chronology

Early on 20 December 1974, a large cloud mass developed in the Arafura Sea, approximately 700 km north-east of Darwin. The cumulonimbus structure was part of a fragmenting intertropical convergence zone (ITCZ) cloud structure that formed a continuous 60° band the previous day. The 0930 CST (all times are given in local Central Standard Time) surface pressure analysis showed a developing tropical low embedded in the *doldrum* trough, the precursor to Cyclone Tracy.

The low-pressure system moved slowly southwest, and by 4 pm on 21 December the first tropical cyclone alert was issued, advising of the possibility of tropical cyclone development. At 9.30 pm, based on spiralling cloud formations visible on infrared satellite photographs, it was decided that a tropical cyclone had formed and the first official warning was issued at 10 pm with the name Tracy assigned.

On 22 December, satellite images showed rapid signs of development, with the first echoes of an eye wall observed between 10.30 am and 1.30 pm. By 3.30 pm, the eye wall had clearly developed and had a diameter of 37 km. The eye was now located approximately 200 km north of Darwin, and was still moving slowly on a south-west track.

At 7.30 am on 23 December, Tracy's eye had shrunk to only 12 km and was located off the northern tip of Melville Island. For the remainder of the day, moderate winds and heavy rain were recorded on the island as Tracy continued on a south-westerly path. At midnight, however, as Tracy passed the tip of Bathurst Island, radar observations showed a change of track southward. This and subsequent changes are linked to the onset of monsoon westerlies initiated over Indonesia (Davidson 2002).

By early on 24 December, mean wind speeds of over 100 km/h were being recorded at Cape Fourcroy on Bathurst Island's western tip. As the morning wore on, recorded wind speeds continued to intensify to a maximum mean wind speed of 120 km/h as the eye moved to within 20 km of the anemometer station. By midday, Tracy's path had again changed and was now heading south-east towards Darwin. At 12.30 pm a Flash Cyclone Warning was issued, advising of expected landfall early the following morning.

Before 1 am on 25 December, wind gusts of over 100 km/h were being recorded at Darwin airport. After 1 am, reports of damage began filtering into the Bureau of Meteorology's Tropical Cyclone Warning Centre, but by 3 am lines of communication were lost as both radio stations failed. At 3.05 am, a wind gust of 217 km/h was recorded by the airport anemometer; this was shortly before, and prior to the passage of the storm's maximum wind speeds, it was destroyed by wind-borne debris. At 3.50 am, the eye passed directly over the Darwin airport and a period of calm ensued for 35 minutes. At 4.35 am, the calm at the airport ended and winds believed to be of greater intensity began from the opposite direction. This 'second' wind caused the radar to fail at 4.30 am. Tracy continued to move inland in an easterly direction, and began to decay rapidly; the further inland it moved the weaker it became. By 6.30 am, winds were abating in the Darwin area, and at 11 am winds recorded at Middle Point showed signs of weakening. After midday, Tracy degenerated into a rain depression and continued to move in a south-easterly direction across the Northern Territory and into Western Queensland.

2.2 Cyclone characteristics

Tracy's track is depicted in Figure 1. It is evident that as Tracy passed Bathurst Island, its direction shifted approximately from south-west back to the south-east by a process known as recurvature. Tropical cyclones move because they are embedded in larger scale regions of moving air (Pielke & Pielke 1997). The intensity of the central pressure dictates the volume of atmosphere that influences this movement (Holland 1993), but generally middle and upper tropospheric winds 'steer' the cyclone in the general direction of their movement. For Tracy, the initial south-westerly movement was driven by a high-pressure system (anticyclone) sitting in the Gulf of Carpentaria. Recurvature occurred late on 23 December as upper tropospheric winds transported another anticyclone, initially off the west coast of Australia, over the Northern Territory, the north-west quadrant of which interacted with Tracy and reoriented its movement. As seen in Figure 1, though, the cyclone track does not follow a smooth path, and in fact for Cyclone Tracy a somewhat cyclic path occurred on both the pre- and post-recurvature tracks. These oscillations about the mean steering flow direction are linked to eye wall thunderstorm dynamics, with the larger scale cyclonic system maintaining a smoother track. The earth's rotation, outflow jets and the interaction between thunderstorms and the steering flow also play a role in determining the cyclone track (Pielke & Pielke 1997).

As may be expected from this brief discussion, predicting cyclone tracks is complex, and is still not a precise science. Track uncertainty therefore plays an important role in the emergency management of tropical cyclones, because relatively sudden changes in cyclone direction close to land can significantly alter the impact they have on coastal communities and the need for evacuation or shelter.

The recurvature of Tropical Cyclone Selma only a few weeks prior to Tracy caused something of a 'false alarm' when warnings were put out that Selma would impact Darwin only to see the cyclone suddenly reverse direction and cause no damage to the city. This instilled a sense of complacency in some of the residents of Darwin, and perhaps impacted their pre-cyclone preparation (Stretton 1976; McKay 2004). Pre-cyclone preparation was, however, undertaken by many residents.

Imagery from the National Oceanic and Atmospheric Administration (NOAA) 4 satellite suggests that, after sustaining a central pressure of 950 hPa for over a day, Cyclone Tracy was at or near peak intensity as it made landfall at Darwin (Commonwealth Bureau of Meteorology 1977). The Dvorak (1975) technique estimates a maximum one-minute average wind speed of 189 km/h (52.5 m/s) at 10.18 pm on 23 December, and this speed was maintained for over 24 hours leading to landfall. Using a gust factor of 1.25 to convert from the mean to a gust wind speed, a maximum gust wind speed of 236 km/h (65.6 m/s) is predicted. This wind speed puts Tracy as a lower end Australian category 4 Severe Tropical Cyclone, or a category 3 Hurricane on the Saffir-Simpson scale when at maximum intensity. Greater maximum wind speeds have been suggested by some authors (e.g. Cook & Nicholls 2009); these estimates are discussed in the following section.

Source: C Arthur, pers. comm., 29 October 2009.

Figure 1: Path of Cyclone Tracy through Darwin

The role of satellite imagery during Tracy was to track the cyclone direction and to make predictions of intensity. In modern times, the use of satellite imagery has improved significantly. It is now possible to measure surface wind speeds, precipitation type and intensity, three-dimensional cloud structure and sea surface temperature – all to a higher resolution than possible at the time of Tracy.

As Cyclone Tracy moved closer to Darwin, the storm was tracked by local weather radar. This tracking continued until power was lost as the *second winds* hit early on 25 December. Radar information was used solely to observe the cyclone movement; however, subsequent analysis of images has allowed inference to be made with regard to storm structure, intensity and location of maximum winds. Although observed on the satellite images, what the radar highlighted was the extremely small size of Tracy, and with a main echo diameter of only 150 km, it was much smaller than many other significant cyclones that had previously impacted, or would subsequently impact, the Australian coastline. This was also reflected in measurements of the cyclone eye, which varied from 10–12 km for the period prior to landfall after intensification (i.e. after rounding Bathurst Island), but contracted to about 8 km at landfall. This size is also considered extremely small.

Averaged over time, and taken along the mean direction of the cyclone's path, the forward speed of the cyclone was approximately 7 km/h with fluctuations between 5 and 9 km/hr. This relatively slow forward speed made the potential impact greater because it increased the time for which any fixed location would experience high winds. This had a significant impact on the wind loading of buildings, as the extended period of highly fluctuating wind load instigated fatiguing failure mechanisms not well understood or appreciated by the engineering community at the time.

2.3 Wind field

As previously mentioned, the peak recorded wind speed during Cyclone Tracy was 217 km/h (60 m/s) at the Darwin Airport. This measurement was made only minutes prior to flying debris destroying the anemometer. Wind speeds were recorded using a Dines Anemometer designed and calibrated for wind speeds up to 240 km/h (67 m/s) with a response suitable for capturing three-second gusts. The anemometer was positioned at an elevation of 10 m and located in approximately the centre of the airport. It is therefore reasonable to assume that wind speeds measured in this location are representative of Terrain Category 2 winds in the current, and all previous wind loading standards (Standards Australia 2002). Figure 2 shows the original Dines chart reading up to the time of failure, and is considered accurate to within 5 km/h (1.4 m/s). The spike in wind speed at the time of failure is the by-product of an electrical failure and is not considered real.

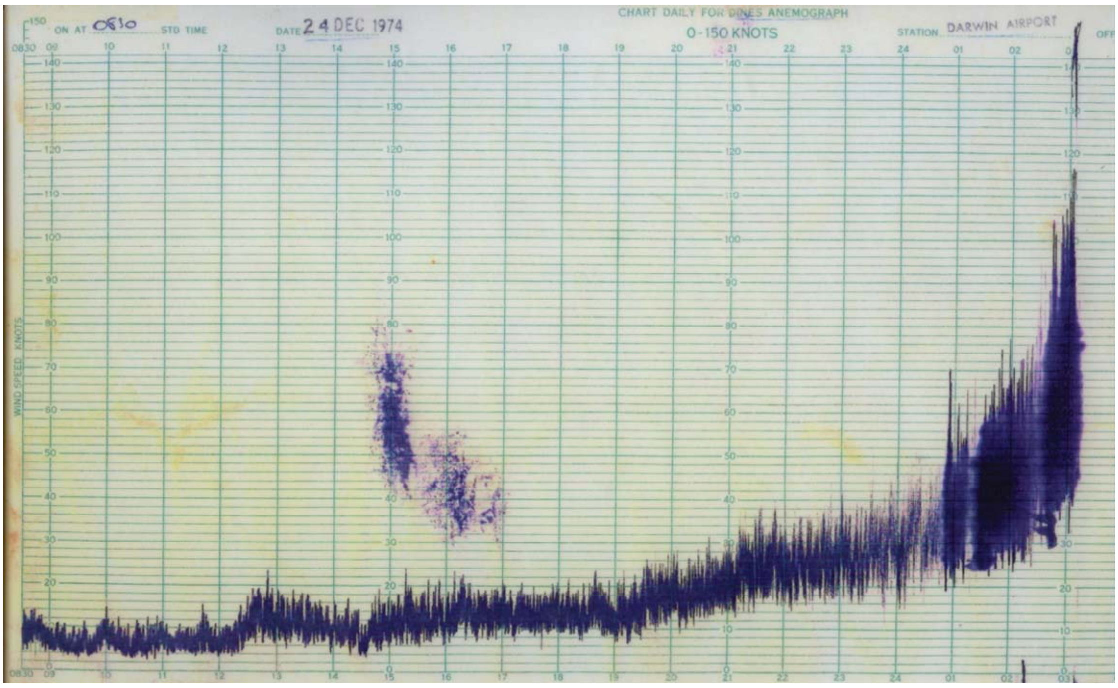


Figure 2: Dines anemograph from Darwin Airport – wind speed in knots

The time of anemometer failure correlates well with the arrival of the cyclone eye wall and the location of probable maximum winds for the storm. Wind speeds prior to the arrival of the eye (approximately 3.50 am) are not expected to have been significantly, if at all, greater than the recorded maximum at the site of the anemometer. Wind speeds equivalent to that at the time of failure persisted for only five minutes after the failure.

As the eye passed over Darwin and the so called *second wind* hit, several eyewitness reports suggest wind speeds were stronger than those prior to the eye (e.g. Walker 1975; McKay 2004). This claim cannot be substantiated, and is largely based on the sound of winds and the level of destruction of buildings. Both these will naturally increase, and thus seem worse, as buildings begin to fail. Walker (1975) postulates that the increase could actually be a real effect and be due to either a decreased fetch roughness for the approach of the second wind or an intensification of the central pressure as the eye moved over the city. Walker puts more credibility in the first of these postulations, and highlights the similarity to reports of stronger *second* wind speeds for the 1897 event that traversed a similar path. Walker therefore suggests that a peak wind speed at the anemometer location of 240–260 km/h (67–72 m/s) is possible.

Typically for a translating cyclone system, some translational momentum is directly transferred to the wind field, increasing wind speeds to one side of the eye and causing an asymmetry in the wind field. In the case of cyclonically rotating storm moving in a roughly easterly direction, wind speeds therefore should increase to the north of the storm and decrease to the south with reference to an ideal symmetric stationary cyclone. Given the relatively slow forward speed of Tracy, this effect was not pronounced in the wind field, though the damage assessment, to be discussed in Section 4.34., shows that it does occur to some extent. As a result of this assessment, observed meteorological information, and corrections for topography and the frictional affect of surface roughness and terrain, Walker (1975) suggests a basic maximum wind speed field at an elevation of 10 m as given in Figure 3. An asymmetry is evident in the wind speed with respect to the eye, but it is not large. A similar distribution is noted by Leicester and Reardon (1976), based on a CSIRO damage assessment. What is evident is that wind speeds were high enough to cause significant damage in all parts of Darwin.

2.4 Rainfall

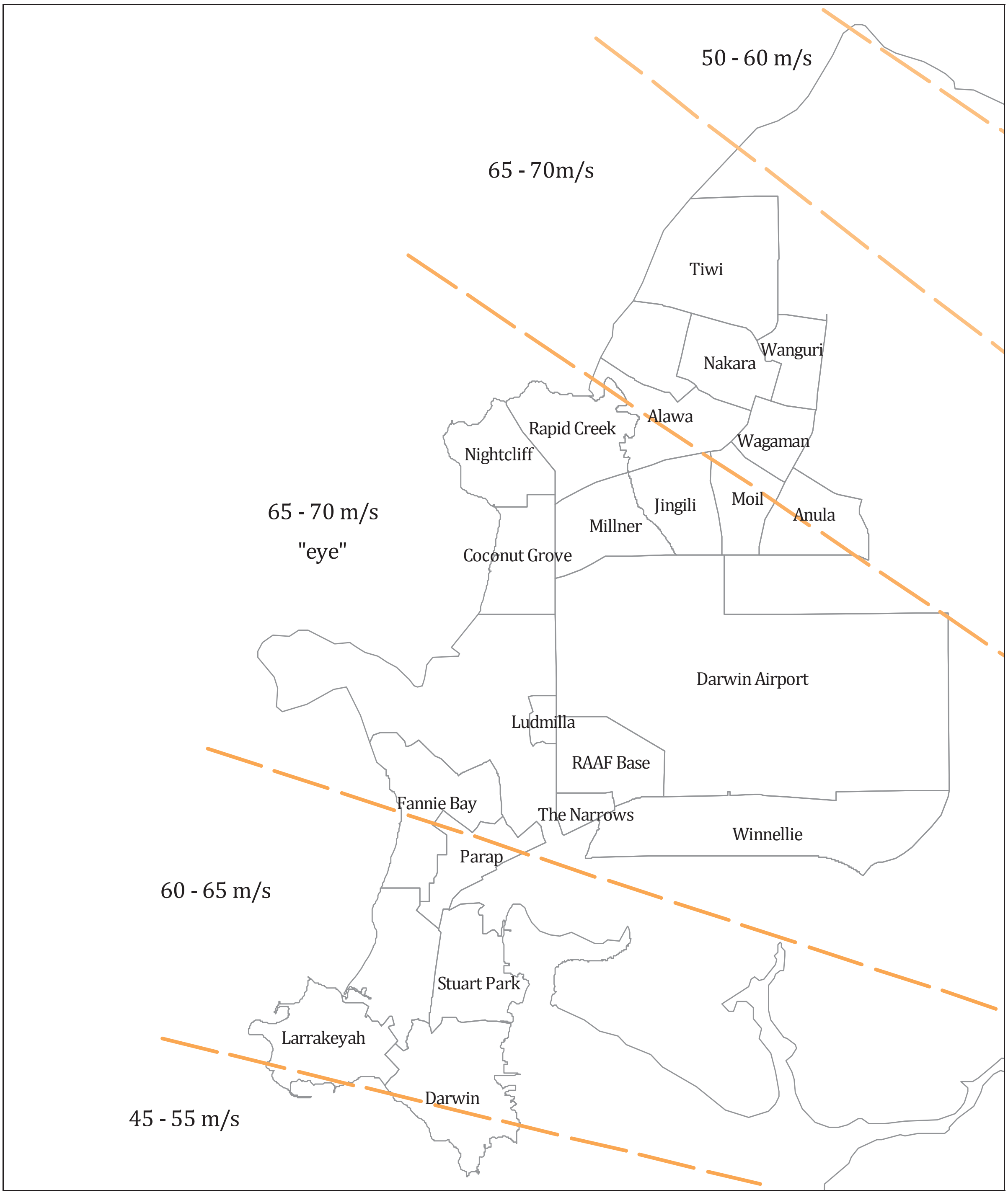
Rainfall intensity was measured at the Darwin Airport with a peak rate of 105 mm/h recorded in association with the initial eye wall passage between 2.45 am and 3.15 am. Rainfall was observed to drop to zero as the eye passed and the instrument failed with the incidence of the *second wind*. The estimated yield for the 24-hour period prior to 9 am on 25 December was 280 mm, though exact magnitudes are uncertain given the propensity for rain gauges to systematically under-represent rainfall in high wind speed environments (Commonwealth Bureau of Meteorology 1977). Assuming the peak intensity of 105 mm/h is accurate, this represents a five- to ten-year return period rainfall event for Darwin (Pilgrim 1987).

2.5 Storm surge

Of the natural hazards associated with tropical cyclones – that is, rainfall (flood), wind and sea action (storm surge) – wind ranks third when it comes to the ability to wreak havoc on communities. The fact that flooding and storm surge were not significant issues for Darwin certainly saved scores of lives and prevented further damage to buildings.

When strong low pressure systems move into the near-coast region, sea levels rise above the normal tide due to the reduction in atmospheric pressure at the storm's centre. This process, combined with high ocean surface stresses from strong winds, is referred to as storm surge. When storm surge exceeds typical astronomical tide levels, low-lying coastal regions can be inundated and wind-driven wave action can impact on structures not typically accustomed to these loads. Life safety becomes significantly more difficult on occasions of significant storm surge.

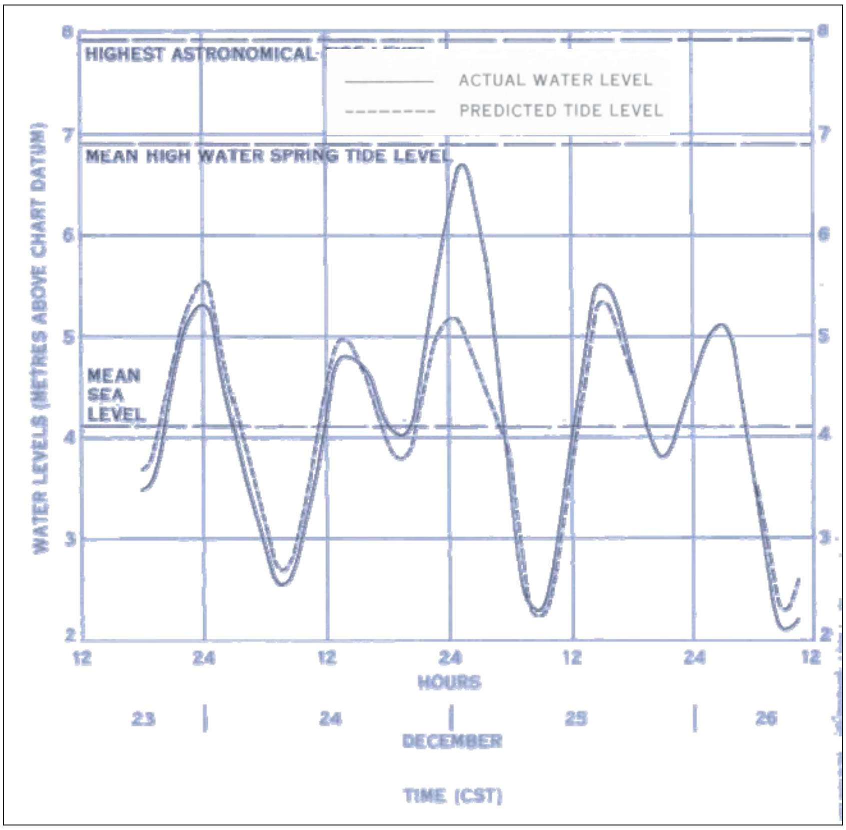
The height of storm surge is dependent on the characteristics and behaviour of the cyclone, wind strength and direction, as well as bathymetric features. For areas where the wind is blowing towards land, the wind drags the water towards the coast and elevates the local sea level. This process is called *wind set-up*, and is generally the principal cause of storm surge (Wilkinson 1975). A second important factor is the deep water wave height, which causes an increase in mean sea level as it breaks at the coast. This process is called *wave set-up*. A further issue influencing the elevation of storm surge is the tidal range of the location, and the time within this cycle that the cyclone makes landfall. In its simplest terms, the storm surge is superimposed upon the current tide, so if the cyclone makes landfall at high tide, the maximum surge height will be greater than if it occurred at low tide.



Source: After Walker (1975).

Figure 3: Approximate maximum wind field. Gust wind speeds at 10 m height over open terrain.

Fortunately for the residents of Darwin, Cyclone Tracy occurred during a period of neap tide (low tide of the lunar spring neap tide cycle). This meant that even though Tracy was associated with a high tide, the water level did not rise enough to be of concern to Darwin, which has an approximately 8 m tidal range. The Darwin Harbour tidal gauge measurement trace is shown in Figure 4 for 23–26 December. A maximum measured surge of only 1.6 m is shown through comparison of the measured and predicted tide levels. The surge in Fannie Bay was also indirectly measured to be between 1.7 and 2.0 m (Commonwealth Bureau of Meteorology 1977). However, because Darwin Harbour and Fannie Bay were to the south of Tracy's eye, these measurements are not representative of the maximum surge associated with the cyclone, which occurred to the left of the cyclone path (north), at Casuarina beach, where both wind and wave set-up were unimpeded. Field inspections of the area suggest the maximum surge height was 4 m above the predicted tide level (Commonwealth Bureau of Meteorology 1977). Had Tracy not made landfall at neap tide, but at the highest astronomical tide, inundation to 3 m with 2 m waves could have been expected in lower lying coastal regions (Commonwealth Bureau of Meteorology 1977). This would have caused further devastation to Darwin and posed significantly different emergency management issues.



Source: Commonwealth Bureau of Meteorology (1977).

Figure 4: Storm tide measured in Darwin Harbour. The difference between actual water level and predicted tide (in the absence of the cyclone) is due to the surge.

3. Pre-existing conditions: Why was Tracy so catastrophic?

Darwin is located on the Timor Sea at the north-west tip of what today is the Northern Territory, Australia (Figure 5). At the time Tracy hit, however, Darwin was under Commonwealth jurisdiction and response to the cyclone officially fell to the hands of the federal government and the newly formed Natural Disaster Organisation (NDO), based in Canberra.

Darwin is geographically isolated over 3000 km from any of Australia's other capital cities, and has only one major highway in and out of the city. Logistically, this makes disaster recovery or evacuation complicated. In 1974, Darwin's population was 46 700 (Australian Bureau of Statistics 2008) with at least 43 500 in the city at the time of Tracy (Northern Territory Library 1998). The population of Darwin had grown rapidly in the 30 years since the Japanese bombings during World War II reduced it to only a few thousand. To accommodate the influx of population, new suburbs were built and Darwin expanded to the north of the airport with significant development taking place in the 1960s and early 1970s. The city of Darwin is built on a low bluff overlooking Darwin Harbour, with the outer suburbs generally flat with some isolated topographic features. To the north, the Tiwi Islands (Bathurst and Melville) protect Darwin from oncoming storms, possibly ameliorating some of the cyclone threat to the area. A map of Darwin in her Australian context is shown in Figure 5, with Figure 6 showing the distribution of the suburbs of Darwin in 1974.

During the 1970s, Darwin was very much a government town, with 45 per cent of the labour force employed by the Commonwealth. Many of these government workers were on short-term contracts and had no strong ties to the city (Stretton 1976).

Figure 5: Map of Australia showing location of Darwin

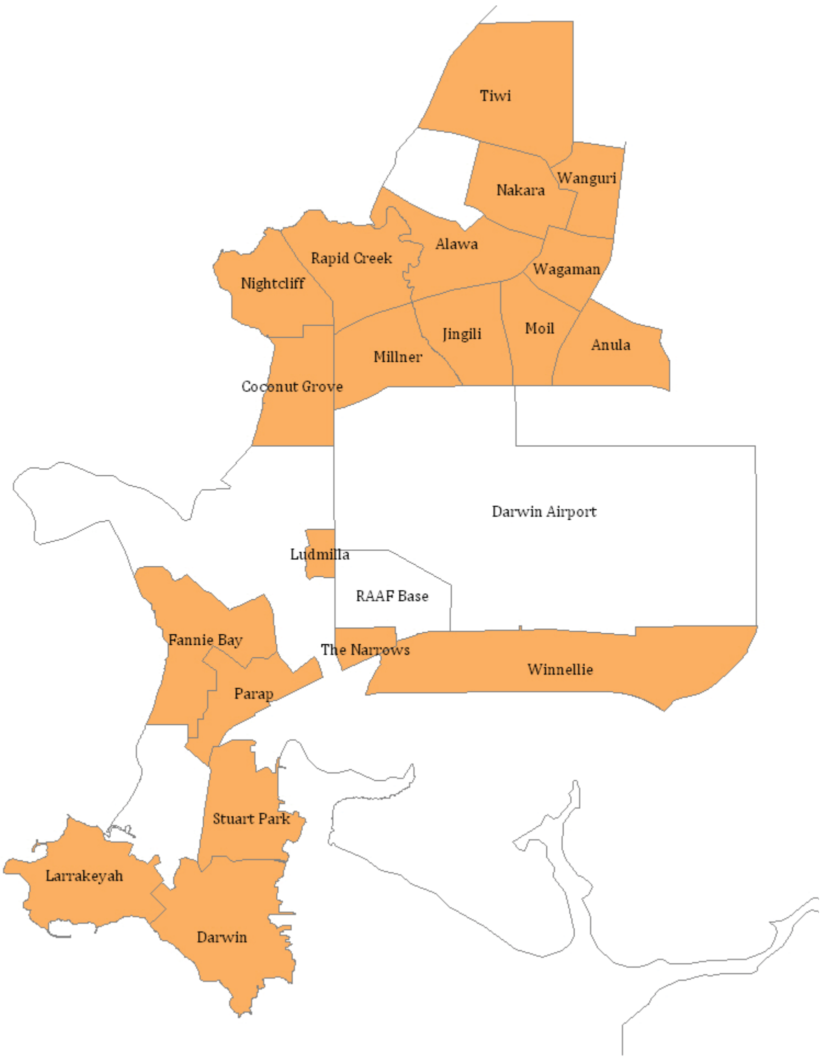


Figure 6: Darwin suburbs at the time of Tracy

3.1 Climatology of Darwin

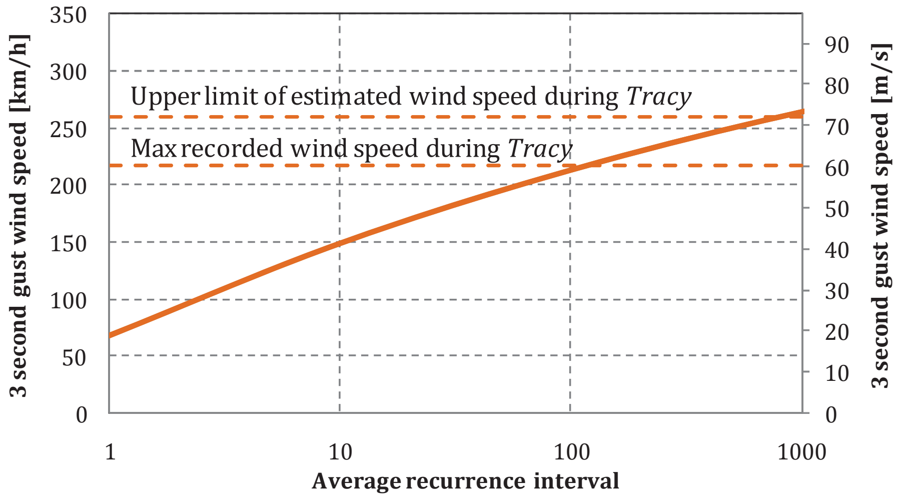
Located at latitude 12° south, Darwin exhibits a tropical savannah climate, with distinct wet and dry seasons and a relatively uniform temperature year round. The majority of rainfall occurs between December and March. This is also the period associated with the occurrence of tropical cyclones in the region.

Australia's tropical cyclone season officially runs from 1 November to 30 April. Of the storms that form in Australian waters, approximately one passes within 200 km of Darwin each year. Prior to Tracy, at least six tropical cyclones are known to have severely affected Darwin communities. The most destructive of these early cyclones passed over Darwin on 7 January 1897, most likely following a path similar to Tracy and with comparable wind speed and rainfall intensities (Commonwealth Bureau of Meteorology 1977). This storm killed 28 people and the damage exceeded £150 000 in the currency of the time. In the 35 years since Tracy, a further seven cyclones have passed within 50 km of the city, but none has caused significant damage.

To determine accurate Average Recurrence Intervals (ARI) for extreme events is exceedingly difficult, and due to short records, sampling errors are large. Nevertheless, using yearly gust wind speeds measured at Darwin Airport (without separating gust events), Whittingham (1964) used Extreme Value Analysis to show the maximum wind speed recorded during Cyclone Tracy (217 km/h, 60 m/s, see Section 2.32.3) had an average recurrence interval of approximately 125 years. Using the then-new technique of synthetic storm track modelling, Martin (1975) also attempted to predict wind gust recurrence intervals for the Darwin region obtaining a result of 202 km/h (56 m/s) for the 100-year gust, a figure roughly in accord with Whittingham's result (211 km/h, 59 m/s). This agreement was encouraging for the scientists and engineers of the day, and was seen as partial validation of the Extreme Value predictions despite their short record length. Note that throughout this document gust wind speed refers to a three-second gust, and the terms average recurrence interval, ARI, and return period are used interchangeably. The latter is a differentiation in nomenclature between meteorological and engineering communities and the former is based on the response time of the Dines anemometer historically used for recording gust wind speeds in this country.

These values could be considered appropriate levels of calculable risk for Darwin at the time of Tracy; whether this risk was perceived by the community at large is, however, another issue (Li 2008). The level of risk *was* considered by the engineering community when writing building standards, but was not considered explicitly for the design and construction of residential homes, a point taken up in later discussion (Section 3.3).

Today, the understood wind risk in Darwin is not much different, with a gust wind speed of 213 km/h (59 m/s) prescribed as the 100-year return period wind gust in the current design standard for the region (Standards Australia 2002) (Figure 7). Some recent research suggests this may be too low, because the oceanic and tropospheric climate of Darwin could possibly lead to more severe events than historically observed (Cook and Nicholls 2009). This notion is in its scientific infancy, though, and its validity as applicable to Darwin is hotly debated (C Arthur, pers. comm., 29 October 2009; J Holmes, pers. comm., 3 December 2009; G Walker, pers. comm., 28 October 2009).



Source: Standards Australia (2002).

Figure 7: Average recurrence interval (ARI) for gust wind speeds at a point location in Darwin The upper limit is the maximum estimated wind speed estimated to have occurred at some point in the cyclone life, even though it did not necessarily impact Darwin.

3.2 Building stock

In the early 1970s, Darwin consisted of approximately 8000 houses, 3000 flats and several hundred engineered non-residential and industrial structures. For government-built housing, three convenient structural categories could be applied (Department of Housing and Construction 1975):

1. pre-1968 – Old Traditional
2. 1968–72 – New Traditional, and
3. 1972–74 – Houses with cyclone provisions.

It is generally understood that private housing construction followed the trends of government homes, and therefore could be classified similarly (Department of Housing and Construction 1975). Moreover, many privately owned homes were originally government owned. Walker (2004) and Haas (1976) suggest that the percentage of government-owned homes was approximately 40 per cent of the residential building stock at the time of Tracy. Privately owned homes tended to be older and were largely located in the southern parts of Darwin (south of the airport), with the newer northern suburb homes predominantly being government-owned and built (McKay 2004).

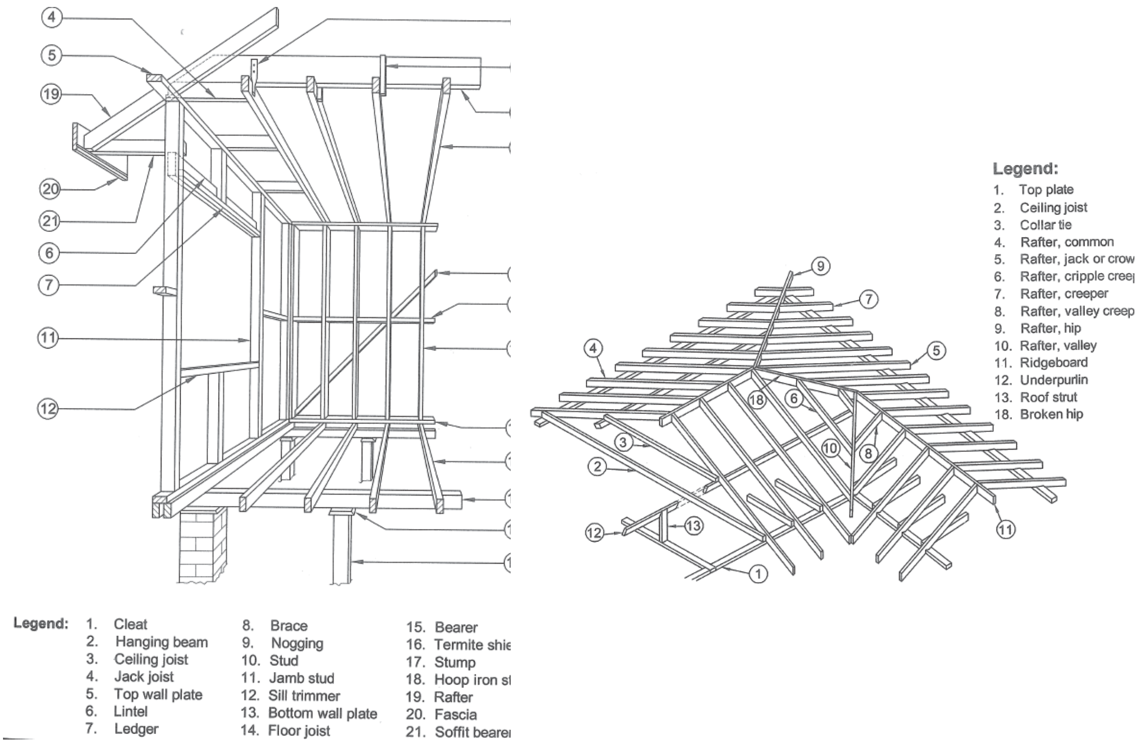
Old Traditional homes were timber framed (4" × 2") nail construction with studded walls and inset diagonal timber bracing (a nomenclature of common construction members is shown in Figure 8). Roofing was bolted truss or orthodox framing construction with galvanised-iron sheeting and diagonal timber bracing. In many cases (approximately 60 per cent), construction was on an elevated timber platform, but apart from this feature was consistent with housing throughout Australia. For low-set construction, many homes utilised a traditional 11” cavity brick wall with an anchored continuous reinforced concrete bond beam in place of the timber framing. New Traditional homes were structurally similar except for the use of gang-nails on trusses and triple-grips for the connection between purlin and truss (these strap type connectors replaced simple nail connections). Trusses became the dominant roofing system, but bracing between trusses was largely removed (Walker 1975), with roof sheeting assumed to resist this load. 3" × 2" studs replaced the larger 4" × 2" framing material previously used.

Under-housing steel posts were replaced with concrete, and the under-floor unreinforced block work laundry or storeroom was assumed to provide the stabilising characteristics of the previously used tie bracing (Department of Housing and Construction 1975). Low-set housing of this vintage represented a move away from the cavity brick design and relied upon a timber frame, brickwork veneer-type construction. About a year before Tracy, however, many builders moved back to a cavity brick type method, though they began to use smaller bricks and larger cavity widths. These two newer low-set housing types performed considerably worse than the traditional 11” cavity construction.

In 1971, Cyclone Althea went through Townsville in North Queensland. Investigation of damaged homes led to recommendations for increasing the cyclone resistance of houses, and these were scrupulously applied to homes built in Darwin after mid-1972. Some of the major recommendations from the Cyclone Althea damage assessment team were:

- more appropriate use of cyclone bolts from roof truss to floor joists
- use of screws in place of nails for fixing roofing material, with double fixings at eaves and ridges
- purlin straps replaced triple grip connectors, and
- timber bracing replaced by hoop-iron straps.

Many of the homes built in the newer northern suburbs incorporated these considerations into their design and construction, and it was expected that these homes would display greater resilience to cyclonic winds than the previous two categories. This proved not to be the case, however.



Source: Australian Building Codes Board (2009).

Figure 8: Nomenclature of common housing construction members

By and large, houses were clad with either fibrous asbestos cement (fibro), approximately 60 per cent, or brick, approximately 33 per cent. The remainder were a combination of fibro and brick, concrete or other specialised materials. Almost all elevated homes were externally clad with fibro, while brick was most popular cladding for low-set housing.

Non-residential, generally engineered, buildings can be categorised as:

- steel-framed (e.g. industrial buildings)
- reinforced concrete (e.g. hotels, office), or
- load-bearing brick (e.g. hotels, flats).

There were significantly fewer 'engineered' buildings than houses in Darwin, but unlike houses, these structures were required to be built to a regulated Standard to resist cyclonic wind loads and to be certified by a structural engineer (see Section 3.3). The prescribed design wind speed given in the code was, however, less than that experienced by several of these structures during Tracy.

Approximate dates of construction, on a suburb basis, are given in Figure 9. This figure graphically displays the general northward trend over time in development and, along with the data presented in this section, serves as an estimate proxy for the level of engineering input into the construction of homes in each particular area. Figure 10 shows the distribution of residential building types, with some indication of cladding material (e.g. fibrous asbestos cement or brick) where the information was available.

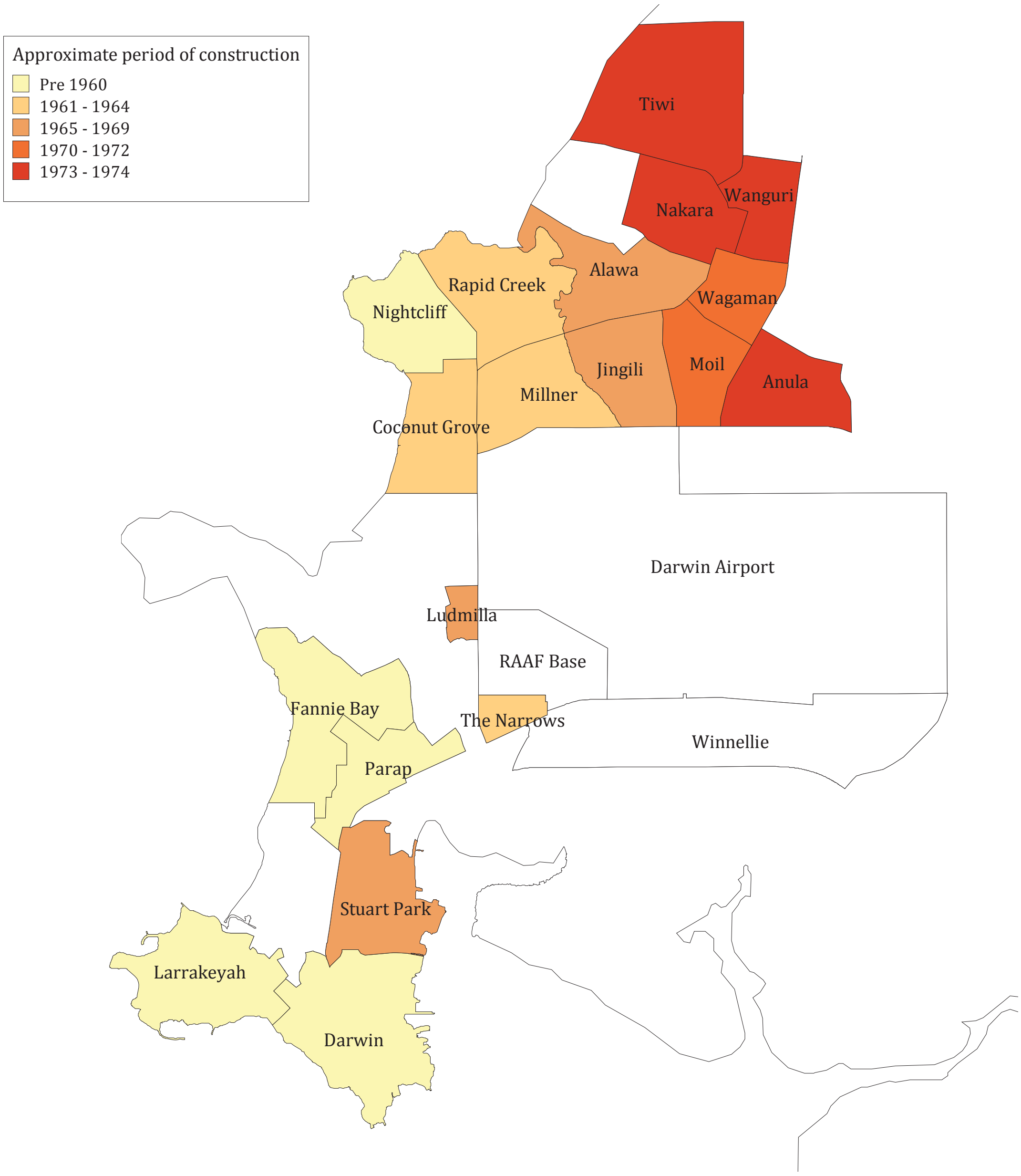
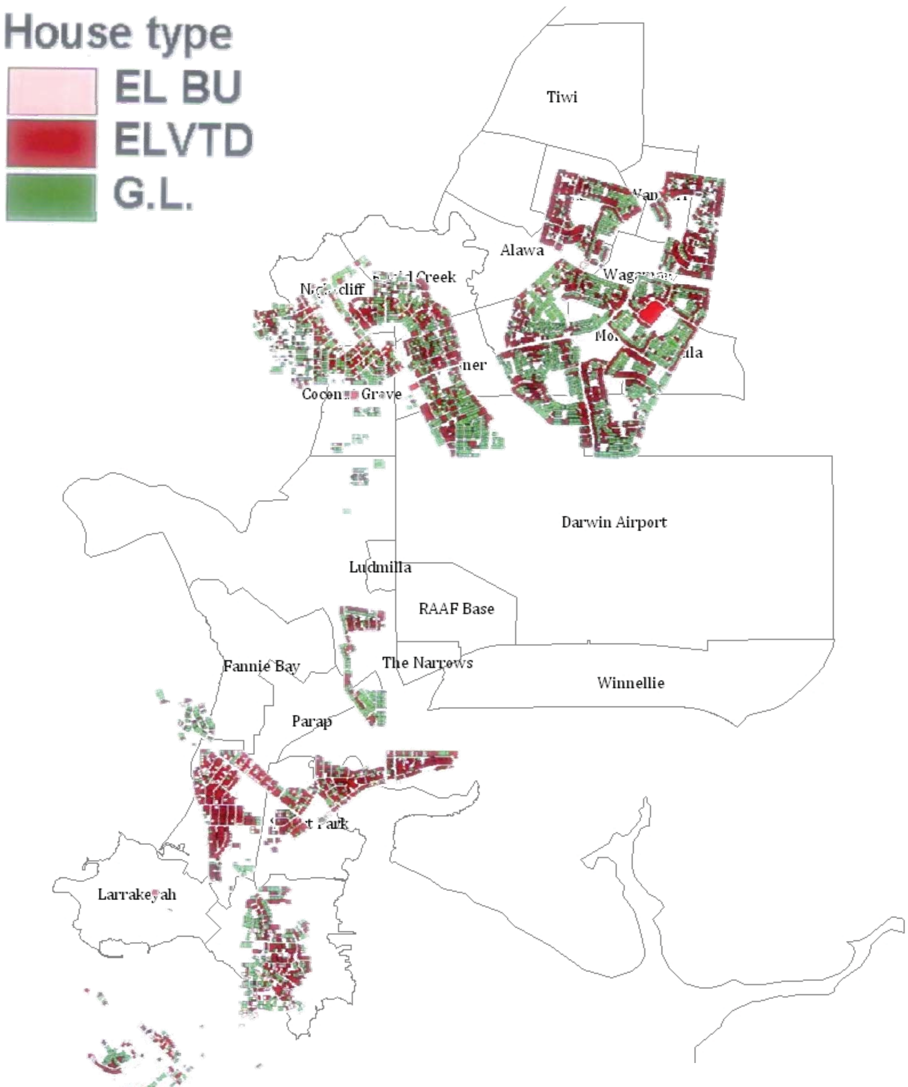


Figure 9: Approximate dates of construction for the suburbs of Darwin



Source: after Van der Sommen (2002).

Note: EL BU signifies elevated buildings with the underneath built out, ELVTD signifies an elevated home, while G.L. signifies low-set or ground-level homes.

Figure 10: Distribution of building type throughout Darwin

3.3 Building standards and regulations

Enforced building regulations can and are used as a disaster-mitigation tool by regulating bodies throughout Australia. By enforcing that structures be built to specified standards, a government, or its representative regulatory bodies, can ensure construction meets (to an acceptable level of risk) a series of life safety requirements. Prior to Tracy, design wind-loading specifications were prescribed by each of the state and territory building agencies through a set of statewide building regulations. Some states, however, passed over many of their regulatory powers to the municipal councils, allowing them to enact their own building regulations by way of council by-laws (Australian Building Codes Board 2009). Some, though not all, of these powers were retracted following World War II. In Darwin during the early 1970s, building regulations were embodied in the *Northern Territory Building Manual*, administered by the Northern Territory Building Board (Department of Housing and Construction 1975).

In 1952, Australia's first national wind loading standard was introduced, SAA Interim 350: *Minimum Design Loads on Buildings*, covering wind loading as a sub-section of the document. The introduction of this loading standard provided the first opportunity for regulatory bodies nationwide to reference a single document for their loading specifications (Pham 2007). This was done in Darwin through the *Building Manual* for structures *requiring engineering input* into their design and construction. Prior to this time, designers were reliant on specifications in an appendix of the 1939 version of SAA CA1, the steel structures code of the time (Walker & Reardon 1987). The design philosophy adopted by these standards was that of working stress. What this meant was that for a specified *design wind speed* a structure must behave as it would under normal working conditions not being stressed or deflected excessively. Under the working stress approach, the design wind speed was set as the maximum statistically expected (64 per cent chance of exceedance) wind speed over the life of a structure. Factors of safety were then applied to design calculations, thus giving the structure considerably greater strength to account for the occurrence of extreme events.

The specification of a design wind speed is an important step in the design process. This is the case for two reasons. First, the wind load is directly proportional to the square of the wind speed, thus any changes in this value can significantly influence the load a structure is designed to withstand. Second, it is through the design wind speed and its relationship with annual recurrence that governing bodies express the level of risk their constituents are expected to accept and finance.

In the Interim 350 wind code, design wind speeds of 110 mph (49 m/s) for inland areas, and 130 mph (58 m/s) for exposed regions of Darwin were given. These wind speeds were questioned as being too high by the Darwin branch of the Department of Housing and Construction, with the department's Head Office suggesting housing with an expected 50-year life be designed for a wind speed of 110 mph (49 m/s) or 105 mph (47 m/s) if the expected life was 30 years. An additional drop in design wind speed to 100 mph (45 m/s) was allowed if the house was less than 20 ft (6 m) tall. In 1969, however, based on a series of wind tunnel tests, it was proposed that all elevated homes be designed for a wind speed of 110 mph (49 m/s) (Department of Housing and Construction 1975). On top of these winds, a factor of safety (1.22) was applied (in most cases) to account for the increased wind speeds of extreme events.

Despite these specifications, it is apparent that – most likely due to the lack of legal obligation – none of the above criteria was actually used in the rational structural design of residential housing until the introduction of an updated Interim 350 in 1971 (Department of Housing and Construction 1975). This updated document was issued as Australian Standard CA34, and for the first time the document was divided into two parts with the wind loading standard published as an Australian Standard CA34 Part II – *Wind Forces*. This also signifies the introduction of 'expert' sub-committees for regulation of each of the loading hazards (e.g. wind, earthquake). In CA34, the design wind speed for Darwin was raised to 126 mph (56 m/s), but the inclusion of terrain category reduction factors (which purport to account for the reduction in near-surface wind speed due to the presence of trees or other momentum-absorbing surface features) allowed the design of homes in regions of wooded surrounds to be reduced by a factor of 0.7 to 88 mph (39 m/s). This is now known to be inappropriate given the level of defoliation intense winds instigate, but at the time this was not widely appreciated. Wind speeds specified in CA34 were directly related to the 50-year return period wind speed derived by a Gumbel analysis of historic records in a specific area. The limitations of using this approach, particularly in cyclone prone areas, were acknowledged, and a *cyclone factor* of 1.15 was introduced as a factor of safety in these regions (50 km inland, north of 27°S, Appendix A). CA34 was metricated in 1973 and released as AS1170 part 2, with only minor revisions.

Although 1972 saw the introduction of structural design *concepts* to residential housing, it was by necessity prescriptive and strictly the application of structural engineering ideas, not structural design. The same could be said for the recommendations made after Cyclone Althea (and applied in Darwin); these were engineering solutions to isolated problems but did not address the building as a whole, or develop a continual load path through the structure. In fact, up to the time of Tracy, the general practice in Darwin – and in fact the rest of Australia (and the world) – was for builders to construct homes based on skills obtained over years of experience and passed from builder to apprentice. No continued engineering of the house's structural system was required due to the relatively low cost of housing, the high complexity of its structural system, and the idea that homes possessed inherent strength beyond the understanding of structural engineers (Walker 2004).

The trial and error approach in itself is not unreasonable when designing for events that occur relatively frequently, but for infrequent events such as tropical cyclones there is no opportunity for feedback to take into account the actions of extreme events that may happen only once, if at all, during a builder's working life. Nonetheless, to say there was no engineering input into the design of houses is incorrect, as individual components (e.g. the fixing system for roofing material) were often tested by the manufacturer from which installation guidelines were developed and provided to a builder purchasing the product. There was, however, no regulation of these tests – or even a requirement for them to occur. Some local councils did have rudimentary requirements for approval of housing construction, but again these were based on the trial and error approach, and were by no means widely applied throughout the cyclonic regions of Australia.

With these comments in mind, there were some construction rules by which the majority of built homes abided; these were the specifications set out by lending institutions as provisions for obtaining a loan. An example of this was the Commonwealth Bank's *Blue Book*, which set out a series of prescriptive rules for all facets of housing construction with the concept of wind-resistant design being but one of them. A typical requirement for construction in cyclone regions such as Darwin was the provision of enhanced tie-down when compared with non-cyclonic regions. Many lending institutions had these types of rules, but they were only applied to those needing to borrow money, and the prescribed construction rules were not regulated by an engineering body.

3.3.1 Development of a national building regulation framework

Although not in use at the time, the Australian Model Uniform Building Code (AMUBC) was under development at the time of Tracy. The AMUBC was the first attempt to develop a nationwide building regulatory framework upon which all states could base their state and local building guidelines. This document was being written by the Interstate Standing Committee on Uniform Building Regulation (ISCUBR), a body created in 1965 for this purpose, and was in essence an agreement between the state administrations responsible for building regulatory matters to pool their resources for the benefit of all states (Australian Building Codes Board 2009). The AMUBC was not the same as a Standard, but called upon these documents, or provided technical and administrative guidelines (including inspections) as appropriate. At the time of Tracy, the AMUBC had no legal standing, but was the forerunner for the Building Code of Australia in use today, and was used as a building block for the *Darwin Area Building Manual* developed for Tracy's reconstruction.

3.3.2 Building certification

In theory, inspections were required at certain critical points throughout construction of a building and permission granted for construction to continue. For housing, this was to be done by local council certifiers who typically had a carpentry background. In practice however, the number of notifications made were few, and not enough critical stages were defined (Department of Housing and Construction 1975). Often only one inspection was made where, if cladding had been installed, no inspection of connections (the most vulnerable component of construction) could be made (L Pham, pers. comm., 3 December 2009). In Darwin, because the DHC was in charge of most housing construction, one would expect the inspection process to have been better than for the remainder of the country. The lack of strictly regulated certification, though, was an issue which meant that even if technical regulations had been in place for housing construction, there would have been great difficulty in ensuring compliance.

4. Wind damage to buildings during Tracy

The predominant cause of building failure in Darwin was through impact from the wind or objects propelled by the wind. The destruction in Darwin was then, and still is today, the worst meteorologically driven natural disaster to have impacted Australia (Crompton & McAneney 2008); this observation is based on insurance industry payouts since credible recording began in 1967.

Damage to buildings throughout Darwin was not uniform. Differences in building type, local topography and proximity to the cyclone eye played important roles in determining which buildings survived and which did not. Proximity to failed buildings was also an issue due to the domino effect that wind-borne debris can have on building damage.

The general conclusion drawn from the series of damage assessments performed in the wake of Cyclone Tracy was that engineered buildings performed adequately in spite of wind speeds exceeding design levels, but non-engineered buildings such as residential dwellings performed unacceptably poorly (Walker 1975; Leicester & Reardon 1976). It was also found that the non-engineered residential housing in the northern suburbs performed considerably worse than those in the southern and central areas of Darwin, to a degree that increased wind speed alone cannot explain. The justification for these conclusions is outlined in this section.

4.1 Damage surveys

Two large-scale damage surveys were conducted in the immediate aftermath of Cyclone Tracy. The most widely cited of these is that commissioned by the Department of Housing and Construction (DHC) and the Darwin Reconstruction Commission, led by Dr George Walker, then of the James Cook University, North Queensland. This survey was conducted by teams of engineers whose primary objective was to ascertain the amount of accommodation immediately available and the location of houses that could most quickly be repaired (Walker 1975). The survey was therefore, by necessity, relatively quick, with some questioning the validity of parts of the data set (Van der Sommen 2002). Notwithstanding this criticism, with more than 7300 of the estimated 8000 houses assessed in the survey, statistics from this work are extremely useful in assessing the performance of various categories of structures. The damage survey also assessed the performance of approximately 150 blocks of flats and a similar number of buildings with engineering input into their design. For each house, an assessment of the extent of damage to the roof, wall, floor and columns was made and recorded, along with the type of building, address and building ownership status. Based on this information, an overall assessment of the total percentage of buildings destroyed (presented as a ratio value termed here the *damage ratio*) was made. Damage ratios greater than approximately 0.6 meant the structure was effectively destroyed and would require complete rebuilding. Photos were taken of each building, and these are now stored at the Northern Territory Department of Infrastructure, Planning and the Environment.

A second damage survey was conducted by the Commonwealth Scientific and Research Organisation (CSIRO) along 38 selected routes uniformly distributed through the built-up areas of Darwin (Leicester & Reardon 1976, 2008). The survey produced damage repair index data for approximately 2800 buildings, of which 1486 were timber-framed elevated houses, 532 low-set brick houses, 127 fibrous asbestos cement sheet houses, approximately 300 non-residential buildings and 200 light steel industrial buildings. During the survey, each building was assigned a damage class based on the worst observable damage feature and building type. From this information, a *damage repair index*, Equation (0.1), was assigned to signify the approximate repair cost of the structure. To associate the worst observed damage feature (Table 11) with a repair cost, the assumption was made that each building type (e.g. elevated with asbestos cement cladding) would follow a specific collapse sequence, thus implying a series of predictable failures had occurred. A damage repair index value of 0 signifies no damage and a value of 1 signifies either complete destruction or that it is not feasible to repair. The method of assigning damage repair indices is outlined for each building type in Appendix 2. Throughout this report, damage class and not damage repair index is discussed, but the reader is directed to the tables in Appendix 2 to gain an appreciation of approximate repair costs. The routes followed by the CSIRO survey team are also given in Appendix 2. Although the extent of this survey is not as wide as the DHC survey, the choice of tracks ensured surveyed data was representative of the building stock as a whole, and maintenance of similar exposure over each track length, meant results could largely be viewed as such.

$$\text{Damage repair index} = \frac{\text{cost to repair damage}}{\text{initial cost of building}}$$

(0.1)

Table 1: CSIRO survey damage classes

Damage class	Worst damage feature (housing)	Worst damage feature (steel industrial)
1	Negligible	Negligible
2	Missile damage to cladding or windows	Loss of half wall or half roof sheeting
3	Loss of half roof sheeting	Loss of all wall or all roof sheeting
4	Loss of all roof sheeting	Failure of non-load-bearing gable end wall
5	Loss of roof structure	Loss of all wall and all roof sheeting
6	Loss of half walls	Failure of load bearing gable end wall
7	Loss of all walls	Failure of some secondary structural members
8	Loss of half floor (elevated only)	Failure of some primary structural members
9	Loss of all floor (elevated only)	Total collapse of primary structure
10	Collapse of floor support piers (elevated only)	-

4.2 Damage statistics and distributions

As ascertained from Section 4.1, damage indices for the two surveys were not identical, but in principal are based on the same information – that is, the extent of destruction of particular buildings. Damage statistics for the DHC survey are shown in Figure 11 for the housing and engineered structures (Figure 11(a) and (b) respectively). Damage ratio data from the survey was recorded at 0.2 intervals – that is, 0, 0.2, 0.4, 0.6, 0.8, 1.0 – with the addition of a 0.1 level for those structures suffering only minor damage. For the sake of plotting consistency, the 0.1 data is aggregated with the recorded 0.2 data.

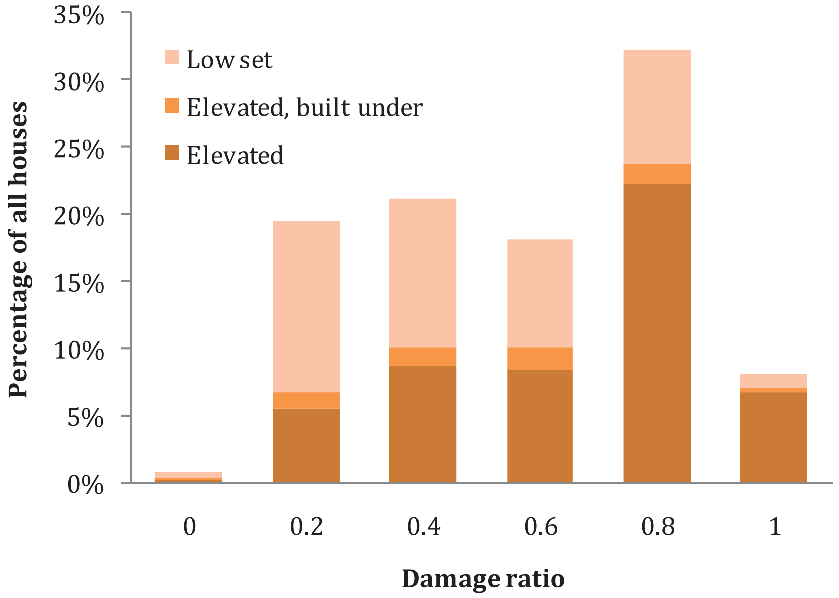
In Figure 11(a), housing is broken into three categories: elevated; elevated – built under (same as elevated but with the area under the home built out); and low-set. Survey results are shown as a damage ratio – that is, a percentage of the building destroyed as a fraction of total destruction (=1). What is immediately noticeable is that only about 1 per cent of housing escaped Tracy without some level of damage. Only about 6 per cent of homes (a subset of the 0.2 bar) were classified as intact except for minor damage to wall cladding or windows (Walker 2008). This meant that about 94 per cent of homes were considered uninhabitable in the immediate aftermath of Tracy, this being the catalyst that necessitated the large-scale evacuation of residents to other regions of the country.

A second point of significance is the spike in damaged homes shown at a level of 0.8. This spike is driven by the poor performance of elevated homes, with almost complete failure as the dominant damage subset. Inspection of the survey records show that for elevated houses a damage value of 0.8 corresponds to the destruction of almost the entire roofing and wall structure, with only the flooring and columns remaining. When considering this with those assigned a value of 1 – that is, damage to support columns as well as all roofing and walls – the general propensity for elevated homes to reach almost complete destruction once damage was initiated is clearly evident. More than 50 per cent of elevated homes lost almost all roofing and wall structure, with a further 15 per cent destroyed to such an extent that repair was considered unviable. This signifies a major failure of the home's structural system and a lack of redundancy in its design.

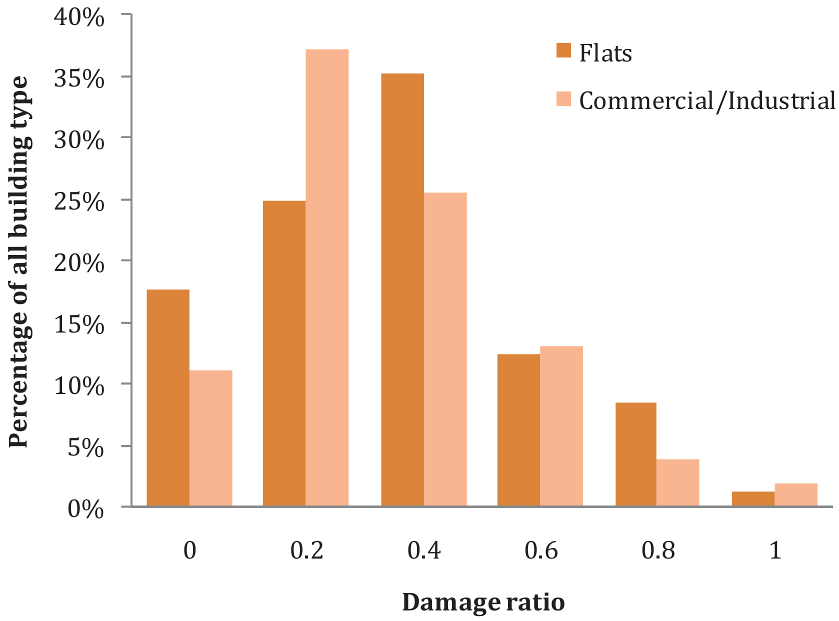
In comparison, low-set houses have a larger weighting of damage at the lower end of the damage scale, peaking at 0.2, and the relative frequency dropping off as the damage index increases. This trend was consistent for all low-set homes, irrespective of the cladding type. Approximately 40 per cent of low-set homes were, however, still considered destroyed – that is, ≥0.6 – but the larger proportion of homes at the lower end of the damage scale does suggest these structures may have exhibited greater resilience than the elevated homes. This comparison between (and within) housing types can only be strictly made after consideration of differences in terrain, topography, housing distribution or proximity to the cyclone eye, all of which will influence the true wind speed experienced by each individual home, a point to which we return in the following section. To a first approximation, though, the comparison made is considered reasonable.

Compared with housing, the overall damage to buildings whose structure had been engineered was light (Walker 1975). The level of damage for these buildings is shown in Figure 11(b), along with the distribution of damage to flats. Although not all blocks of flats were strictly engineered, it is expected that many of the larger apartment blocks would have had some engineering input into their design. In contrast to statistics for housing, Figure 11(b) shows that a larger percentage of both flats (18 per cent) and commercial/industrial buildings (11 per cent) sustained only very minor damage – that is, a destroyed level of 0. Note, statistics for flats only relate to the top floor, as all other levels generally had little if any structural damage – damage to glass due to flying debris was, however, noted. The increase in the number of buildings surviving with only minimal damage likely implies a stronger overall cladding system, and thus a greater resistance to the impact of flying debris. In reality, this could have simply meant a reduction in the window area, instead of any major increase in the impact resistance of the cladding used in these structures. In saying this, however, the load-bearing brick and sheet metal cladding used on many buildings did probably provide some enhanced protection.

The damage distribution for the two categories of building is weighted more to the lower end of the damage scale, with flats showing a peak at 0.4 and commercial/industrial at 0.2. Both distributions drop steadily with increased damage. Comparing the number of destroyed buildings, (i.e. damage scale ≥0.6), with that of housing (60 per cent), a significant reduction is noted, with the flats (22 per cent) and commercial/industrial buildings (19 per cent) – that is, approximately one–third the level of housing damage. This reduction suggests not only an increase in structural strength of these building types, but also an increase in redundancy whereby even though 80–90 per cent of these structures suffered some form of damage, the buildings exhibited enough strength to avoid total collapse. This was not always the case, though, with Baker and Walker (1976) describing some types of steel-framed structures that performed poorly due to a lack of redundancy in their design. On a more positive note, the comparatively low number of engineered structures that suffered complete failure is encouraging given that the wind speeds experienced by many of these buildings was higher than that used in their design (Baker & Walker 1976). It is also a justification of the use of engineering input, as opposed to intuition and experience alone, in the design and construction of buildings.



(a) Damage statistics for houses



(b) Damage statistics for flats and engineered buildings

Figure 11: Damage statistics for (a) residential houses and (b) flats and engineered buildings collected by the Department of Housing and Construction survey

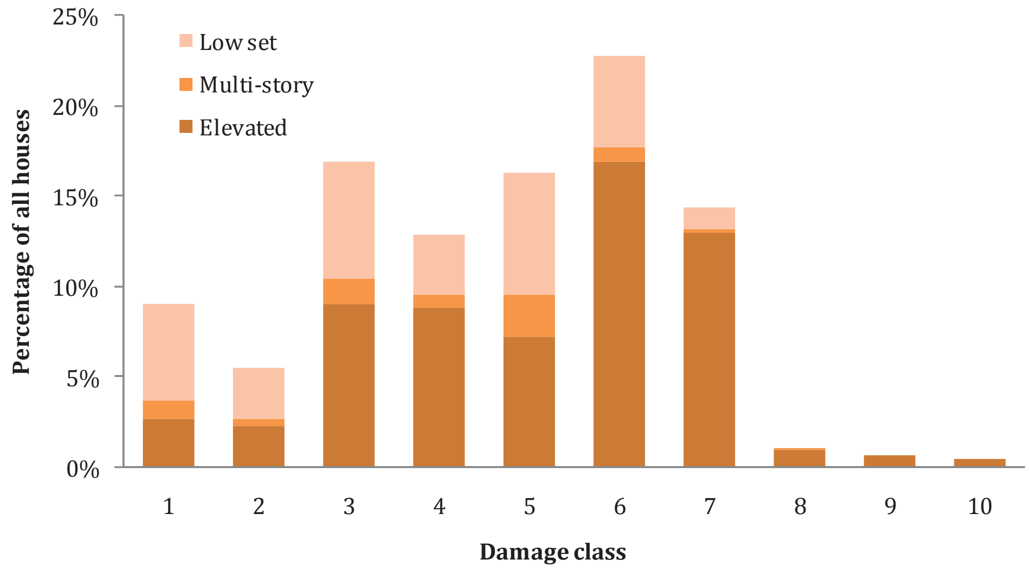
For the CSIRO survey, Figure 12(a) and (b) shows damage statistics for houses and industrial buildings respectively. Unlike the DHC survey, CSIRO damage classes specify the worst observed damage, not a percentage of overall destruction. The general concept, however, is that the higher the damage class, the greater the level of damage to a building. The assumption required for assigning damage classes is that the damage described for all lower classes has occurred, thus implying a general damage sequence. A tabulated description of damage classes for both housing and industrial structures was given earlier in Table 1, the designation between the two required due to differing failure sequences. Despite the differences between DHC and CSIRO data formats, an attempt to relate the overall damage percentage (DHC) to damage classes (CSIRO) is made in Table 2.

Table 2: Approximate relationship between DHC and CSIRO survey data

Damage class	Percentage destroyed (Housing)
1	0
2	0.1–0.2
3	0.2–0.4
4	0.4
5	0.4
6	0.6–0.8
7	0.8–1.0
8	1 (elevated)
9	1 (elevated)
10	1 (elevated)

Note: This comparison is only approximate and does not hold true in all cases. This is evidenced by DHC reports that parts of the wall system were often lost prior to failure of the entire roofing system.

This suggests that the most populous failure class was loss of all roofing and approximately half the wall structure. In general, this agrees with the DHC survey. One difference between the two surveys is the amount of housing that experienced negligible damage. Figure 12(a) shows about 9 per cent of homes in this category, while Figure 11 shows only about 1 per cent of homes. It is perhaps not surprising that differences would appear at the lower end of the damage spectrum, given that a negligible level is somewhat subjective. Class 0 may have also been applied to the CSIRO survey if only minor wind pressure damage (i.e. not due to wind borne debris impact) was evident in, say, the loss of a single roof sheet, whereas this could have drawn a damage percentage of 0.1 (aggregated with 0.2 here) in the DHC survey. Irrespective of these differences, single-digit percentages of negligible damage imply a poor performance from the housing stock.



(a) Damage statistics for houses

(b) Damage statistics for industrial (engineered) buildings

Figure 12: Damage statistics for (a) houses and (b) industrial (engineered) buildings collected by the CSIRO survey

The housing data from the CSIRO survey follow a similar trend to that presented for the DHC survey with a general increase in number of buildings per damage class up to a peak at class 6. Housing is again broken into several main groups: low-set, elevated and multi-storey. The two main groups – low set and elevated – correspond to those used in the DHC survey, and the multi-storey category is expected to roughly correspond with elevated, built under; however, where the line between housing types was drawn is unclear. Viewing only elevated homes, it is again shown that this housing type drives the total housing distribution of damage to the higher end of the scale (6, 7). A distinct peak in damage class is evident for values of 6 and 7, indicating that many homes lost their entire roof and more than half of their wall structure. The small values shown in classes 8 through 10 show that many of the sub-floor column systems remained upright despite the levels of destruction described above. This suggests that the sub-floor structure exhibited more strength than the wall/roofing system, though it is questionable whether as many would have survived if the above-floor structure had have maintained integrity to stronger wind speeds.

Data for low-set homes again displayed a distribution favouring less severe damage, with the peak occurring prior to the loss of any wall structure – that is, ≤ class 5. Multi-storey homes, as with the elevated built-under homes in the DHC survey, exhibited a relatively uniform distribution throughout the damage classes.

For engineered steel-framed industrial buildings (Figure 12(b)), a clear shift towards lower damage classes is seen when compared with the distribution of houses. Approximately 28 per cent of industrial buildings suffered negligible damage, again clearly showing the superior performance of structures incorporating engineering principles in their design. More than 30 per cent of structures suffered loss of significant levels of wall or roof sheeting, but relatively few, < 5 per cent, displayed a failure of primary structural members or total collapse. Baker and Walker (1976) suggest that despite the loss of sheeting on many structures, the cladding performance on industrial buildings outperformed cladding on residential housing.

In summary, results from both damage surveys show the following key points:

- Housing in general performed poorly, with approximately 60 per cent damaged to the extent that rebuilding was not feasible.
- Elevated homes performed significantly worse than low set housing.
- Buildings with engineering input into their design and construction performed considerably better than non-engineered housing despite wind speeds being greater than specified in the then current design standard.

4.3 Spatial distribution of damage

To determine the spatial distribution of damage throughout Darwin, the damage ratios for each residential structure, based on the DHC damage survey, are plotted in Figure 13. A distinct northern suburbs (and therefore north of the eye) bias is evident, with the northern most suburbs of Nakara, Tiwi and Wanguri being worst impacted. Arithmetic averaging of damage percentages over the suburbs to the north and south of the eye reveals average ratios of 0.62 and 0.42 to the north and south respectively. The increased basic wind speeds to the north, noted in Figure 3, in part defined this distribution, but this does not explain the near-complete destruction of the northernmost suburbs (Walker 1975).

Source: image courtesy of Geoscience Australia.

Figure 13: Distribution of damage percentage ratios based on the DHC damage survey

In Figure 14 we consider the average damage ratio at the suburb level. Comparison between the three northern most suburbs (Tiwi, Nakara and Wanguri) and the remaining northern suburbs, gives average (weighted by number of buildings) destruction ratios of 0.82 and 0.55 respectively. This compares homes built prior to 1972 (refer Figure 9) and those built incorporating lessons learnt from Cyclone Althea (i.e. the three northernmost suburbs). The significantly higher destruction ratios for the newer homes suggest that, despite additional design information and a presumed higher level of wind resistance, these homes performed significantly worse than the older homes. In fact, the destruction ratio of 0.55 for the older northern suburbs homes suggests these buildings performed only marginally worse than those to the south of the eye (0.42), a difference that could arguably be put down to increased wind speed alone.

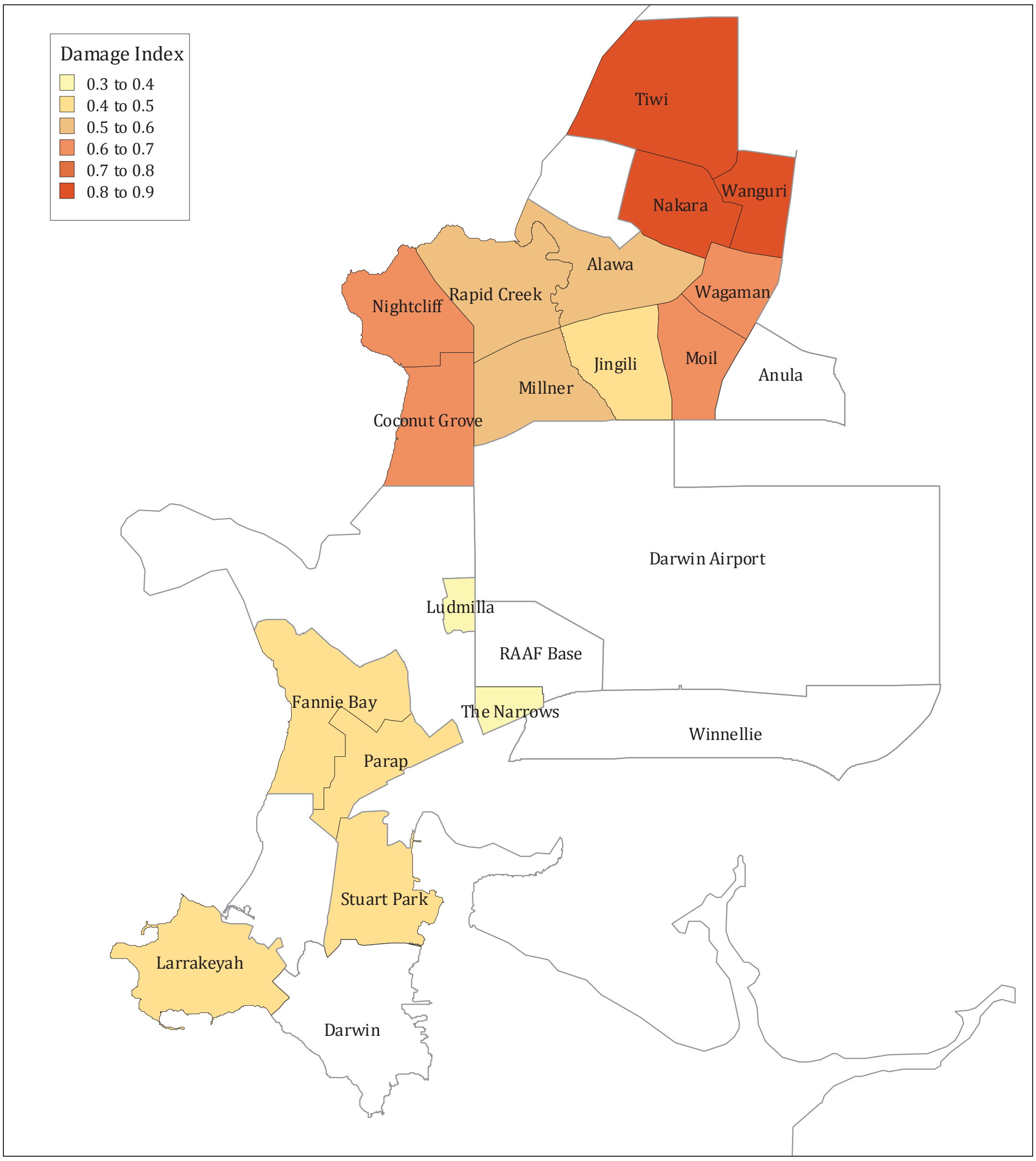


Figure 14: Distribution of damage percentage ratios by suburb

In addition to wind speed and housing type, several other issues influence the true wind loads felt by a given structure. These are discussed in more detail below.

The duration of high-velocity winds is important in determining the level and distribution of damage. Simply put, the longer a given structure is loaded by strong winds, the more likely it is to fail. Given Tracy's slow translational speed, much of Darwin felt sustained high winds for a considerable period of time. This was particularly the case for the northern suburbs, where no lull was felt during the passage of the *eye*. Walker (1975) suggests, however, that the difference in loading duration for different parts of Darwin – or, more strictly speaking, the change in structural response to the differing wind loading durations – was not substantial enough to cause noticeable changes in the distribution of damage.

Exposure can also play a vital role in determining the wind speed felt by a given building. Surface roughness significantly influences the structure of winds at or near the ground. In general, the rougher the surface – say, an area of high density housing compared with an open field – the more the surface will slow down winds near to it. This being the case, those buildings exposed directly to winds off the ocean will, all else being equal, experience higher wind loads than those several suburbs back from the beach. To investigate whether the poor performance of the newer homes in the northernmost suburbs was due to their relatively exposed location, their averaged destruction ratio is compared with that for the similarly exposed conglomerate of Nightcliff, Rapid Creek, Millner and Coconut Grove. This comparison puts side by side two areas of roughly equivalent exposure – that is, both regions were hit by winds directly off the ocean, and allows an assessment of the housing types within each. An averaged destruction ratio of 0.55 is found for the four suburbs around Nightcliff, again significantly less than the 0.82 for the newer northern suburbs. This finding further solidifies the concept that it is design/construction features of the newer homes that drove the higher destruction ratios.

Local topography also plays an important role in determining the wind load on individual buildings. When air moves over a surface that is not flat, wind speeds at a given height are either increased or decreased depending on the slope. In a broad sense, if the wind is blowing up an incline wind speed increases, while blowing down it decreases. In structural loading terms, a home sitting on the top of a hill will experience significantly higher wind loads than one in a valley. It is evident that a number of suburbs would be expected to have increased wind speeds due to their location. Nightcliff and Stuart Park to the north, and Larrakeyah and Darwin City to the south, for example, would have experienced intensified wind speeds due to the rapid increase in elevation with distance from the ocean. In contrast, suburbs such as The Narrows and Ludmilla, which suffered relatively low levels of damage (0.3 and 0.33), were for the most part in valleys to the lee of hills so would have been subject to reduced wind speeds. Walker (1975) suggests that the influence of topographic features may have contributed to the eyewitness reports of the *second* wind being stronger than the first in many of the southern suburbs.

A further factor to influence localised wind loading is the upwind shielding. In the same way that standing behind someone or something on a windy day provides relief from oncoming winds, trees and surrounding buildings can shield a given structure from oncoming winds and thus reduce the wind loads. At the time of Tracy, the newer suburbs to the north were significantly less vegetated than the more established suburbs to the south. This meant that the level of shielding afforded the homes in the north was less than those to the south. The lack of vegetation may also have reduced the debris shielding to downwind buildings when material was lost from upwind homes (i.e. a tree can *catch* flying debris). However, trees can also be a significant source of flying debris themselves, and thus may cause just as much damage as they prevent. To further complicate this issue, the level of shielding provided by vegetation is dependent on the duration and intensity of strong winds. If, as was the case in Tracy, high wind speeds exist for extended durations, leaves and branches are stripped from trees and their shielding capacity substantially reduced. This was not widely considered before Tracy, and led to restrictions as to how subsequent building standards should be applied with respect to selection of terrain categories.

4.4 Engineering explanations of structural failures

The two most conspicuous failures mechanisms observed during Cyclone Tracy were the widespread loss of roof cladding and the lack of structural integrity, particularly of homes, once this and other cladding was lost (Walker 1975). Discussion of these factors (which were common to all structures) and a description of the most prevalent failure modes for each type of building are summarised below. The structure and content of this section follows that of Walker (1975) relatively faithfully.

4.4.1 Loss of roof cladding

The loss of roof cladding was prevalent on both homes and engineered structures. Over 90 per cent of houses and up to 70 per cent of all other structures lost components of their roof cladding system (Walker 1975). In many cases, the loss of roofing meant a loss of rigidity, weakening the building's overall structural integrity. This loss occurred because cladding was often relied upon for bracing and load transfer. The two most significant factors contributing to the loss of roofing were:

1. fatigue failure of cladding in the vicinity of fasteners due to dynamic wind loading, and
2. a sudden increase in wind load on cladding due to a sudden increase in internal pressure following penetration of a windward wall by flying debris.

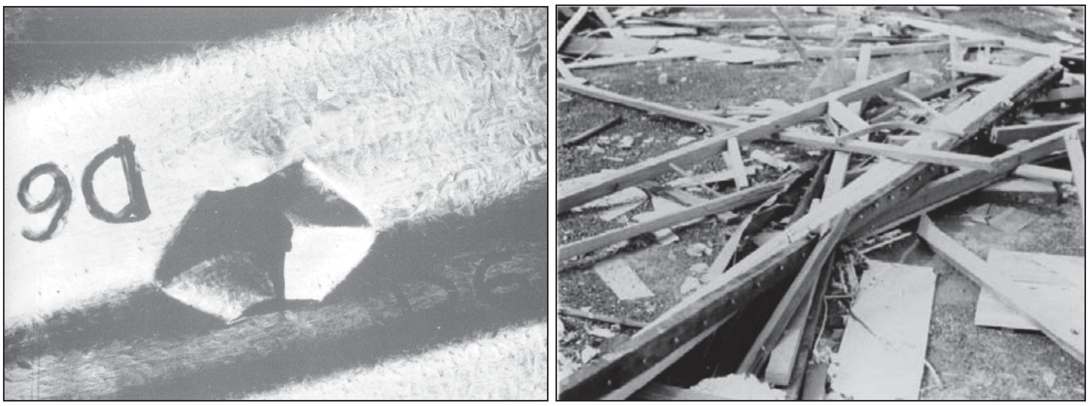
After the substantial loss of roof sheeting during Cyclone Althea in Townsville, connections were structurally tested to ensure their capacity. The issue with this testing regime was that it was conducted in a static manner, assuming this was representative – or at least suitable – for describing the loading due to wind. However, wind by its very nature is turbulent, characterised by rapid fluctuations in velocity; thus, so too is the loads on a structure. In engineering terms, wind loading is dynamic. In tests conducted shortly after Tracy (Morgan & Beck 1977), it was found that for the level of fluctuations estimated to have occurred, dynamic loading could reduce the ultimate strength of the fastening system to 15 per cent of that found with the static testing rig. This meant that roof sheeting would fail at much lower load than it was rated for. As evidenced by the extent of damage, this was a load well exceeded during Tracy. This failure mode was particularly prominent in the post-Althea homes.

The reason this failure mode had not been detected earlier was because in the early 1970s the housing industry shifted from using mild steel to thinner high-strength steel for roof sheeting. The static loading characteristics of these two materials are relatively similar, but dynamically they are very different. Under repeated loading conditions, mild steel – through its higher ductility – is able to deform repeatedly (in the vicinity of fastenings) without failing. High-strength steel, on the other hand, is much more brittle, and fails under substantially fewer load cycles (Figure 15(a)). Observations during the damage survey showed many instances of failure of the high-strength roof sheeting around fastenings, leaving these fastening attached to the roofing purlins (Figure 15(b)).

It was not only the newer, high-strength steel roofing that suffered significant failures. Although older homes had fewer fatigue problems, the use of nails rather than screws as cladding fasteners meant sheeting was lost more often by simply pulling the nail and the sheeting from the purlin. This failure mechanism had been observed during Althea, and was the reason newer homes used screws. However, the traditional approach of fixing the purlin to the rafter by way of a wooden cleat in the construction of some older homes was replaced by a simpler direct nail joint. In these homes, failed roofs were found with sheeting, nails and purlin still attached but separated from the truss or rafter. This was the weakest connection in these roofing systems, and it failed before the sheeting could be pulled from the purlin.

In analysing structural failures, it is useful to consider the old saying that *a chain is only as strong as its weakest link*. When a building is subject to extreme loading, the weakest component – typically a connection – will be exposed and will instigate failure.

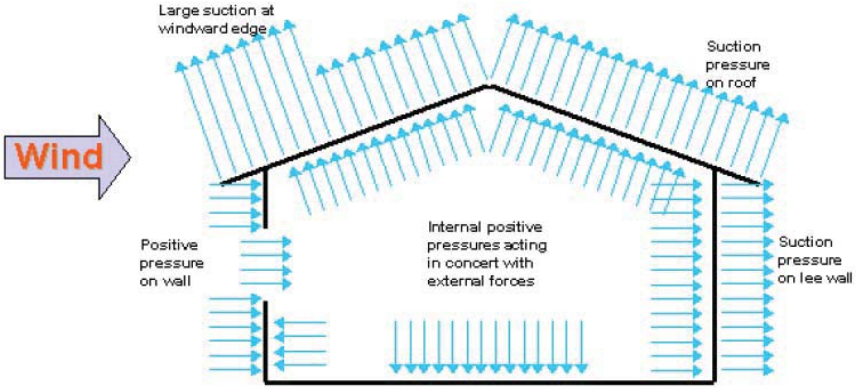
The force that must be restrained in order to keep the roof on is a combination of the external wind load trying to suck the roof off the home, and the internal pressure applied to the underside (inside) of the roof. Depending on the configuration of building openings – that is, doors, windows, and so on – the internal pressure could be positive (pushing the walls out and roof up) or negative (sucking the walls in and roof down). In the worst case, the internal pressure is positive acting to lift the roof off. To develop this loading scenario, an opening must exist on a windward wall, allowing air to be driven into the building and push outward on all surfaces. This process is shown schematically in Figure 16, and is conceptually analogous to blowing up a balloon. In cyclonic conditions, the most common cause of this loading scenario is when wind-borne debris penetrates the windward wall/window/door of a home.



(a) (b)

Source: Morgan and Beck (1977).

Figure 15: Failure of high-strength steel roof cladding over fastening screws in: (a) lab tests; and (b) as demonstrated by screws remain in a purlin after Tracy



Source: Henderson et al. (2006).

Figure 16: Wind forces with a dominant windward face opening

The issue of internal pressures was not new to engineers or builders, but the general practice throughout Australia was to assume that all potential openings would maintain their integrity and the building would remain sealed. This practice led to the calculation of relatively small internal pressure loads and an under-estimation of hold-down requirements on the roofing when an envelope breach occurred. In Tracy, windward wall breaches were common, and the significantly higher than anticipated loads on the roof system were a significant factor in the loss of the roof from many homes. Several eyewitness reports describe the breaking of a window by flying debris followed almost immediately by the failure of part or all of the roof (McKay 2004).

The roof cladding on larger buildings, despite having the same poor fastenings and absence of design for internal pressure, generally outperformed cladding on houses (Walker 1975). This occurred because of a reduction in the external suction pressures driven by differences in the building aerodynamics (i.e. differences in shape). Steeper roof pitches, removal of roof overhang, use of parapets and small height-to-span ratios all contributed to reductions in the roof loads and fewer failures. This behaviour was also noted for housing, where hip style roofing outperformed gable roofing due to inherent aerodynamic reductions in applied load and an increase in natural bracing.

4.4.2 Loss of wall cladding, windows and doors

As discussed in Section 3.2, the most common type of wall cladding for residential homes was asbestos fibrous cement (fibro) sheeting or brick. On larger buildings, corrugated iron and ribbed metal decking were standard.

Asbestos sheeting performed extremely poorly. Almost no home clad with this material escaped damage due to flying debris. This damage was so severe in many of the northern suburbs homes that, if still standing, houses showed a wall framing completely devoid of its cladding (Figure 17). Despite the capacity of asbestos cement as a shear resisting material (i.e. in the plane of the wall), it has an extremely low capacity to absorb impact, so as soon as any flying debris existed, these homes lost much of their rigidity.

The tacked fastening of the asbestos cement to the frame was also found to be relatively poor. In many cases, the cyclic loading of a home worked (racked) the tacked nails out of the frame because of an inability to transfer load from the frame to the sheeting. This in effect nullified the shearing strength of this material and was the primary contributing factor in the racking failure of homes, discussed below in Section 4.4.3.

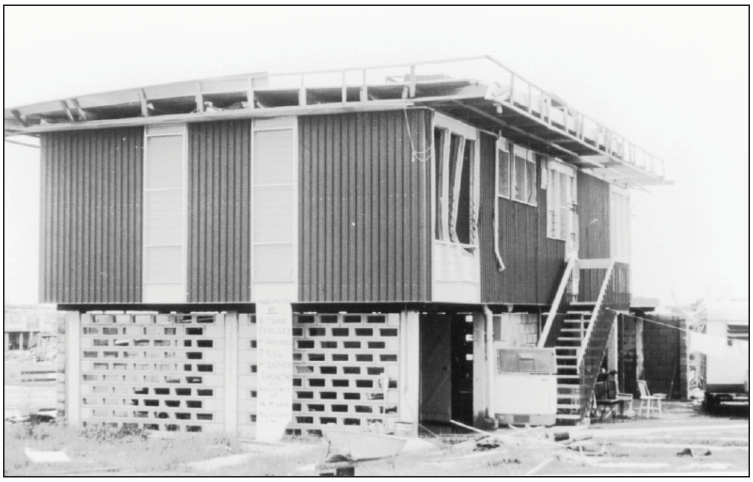
(a) (b)

Source: Walker (1975).

Figure 17: Failure of asbestos sheeting through (a) debris impact and (b) racking

When brick and concrete block masonry were used as non-structural veneers, they performed poorly under debris impact loads. Even when concrete masonry walls were infilled, their resistance to impact loading was poor unless reinforced. It is therefore clear that, irrespective of the cladding material, most houses were vulnerable to flying debris because of the veneer's inability to absorb sudden impact loads.

On larger buildings, and with a small number of homes, corrugated iron or ribbed metal was used for cladding and performed comparatively well. The reason for this was its ability to plastically deform when impacted by flying debris without tearing (Figure 18). This meant structures maintained their rigidity even when roofing was lost.



Source: Walker (1975).

Figure 18: Survival of a house clad in sheet metal

There were two predominant classes of window failure: the first was damage due to debris impact; the second involved the blowing out of complete window frames from walls. With the occurrence of so much wind-borne debris, the first of these is expected when non-impact-resistant glass is used. Some reductions in window failures were observed when sunshade systems were in place and afforded an extra layer of protection from debris. The second of these issues is more serious from an engineering perspective because it implies that window framing was blown out under direct wind pressure – something against which it *should* have been designed. During the post-disaster survey, it was reported that many of the windows that failed in this manner showed little sign of connection between the window frame and the housing structure. Walker (1975) points out that this was clearly the result of a systematic failure in the construction and supervision practices for the installation of these features, but he also questions the window manufacturers' role in not providing sufficient (if they even had it) information on fixing their products. The problem of both types of window failures was exacerbated with larger picture-type windows, as the surface area for impact and the direct wind pressure loading would have been greater.

Failure of doors was reported primarily on blocks of flats or hotels. Failure occurred because approximately half the load had to be taken up by the latch, which did not have sufficient strength. This problem can be fixed by having additional bolts or latches to distribute the load transfer from door to frame.

Large roller doors were a more severe problem, with almost 100 per cent of these failing. Failure of these doors had been observed during previous cyclones (James Cook University of North Queensland 1972), and is still an issue today (Henderson et al. 2006). The issue with roller doors was linked to their size and flexibility: when either strong winds or debris loaded a door, it would bow inward and pull the edges of the door from their guide rails. The larger the door, the greater the problem. Failure of a roller door itself was, however not the major issue: they typically failed on the windward face, thus allowing sudden internal pressurisation and enhanced loads on walls and roofing. In some instances, as with windows, failure to securely fasten door framing to the surrounding structure was observed. Despite the previous observation of roller doors as a problem, it is unclear that manufacturers or builders had addressed this issue.

4.4.3 Failure of housing

As previously discussed, older homes outperformed newer ones. This was true for both elevated and low-set housing.

For the Old Traditional elevated homes, the most common failure was the loss of roof cladding with or without the purlins, and serious debris damage to the asbestos cement wall cladding. In these homes, because diagonal timber bracing was used in walls and roofing, once roof sheeting was lost there was enough resilience in the structure to stop a total collapse of the frame. This was not the case for newer elevated homes, where roof bracing was removed, timber wall bracing was replaced by hoop iron straps, and cladding was supposed to provide a significant proportion of a home's bracing capacity. In these homes, the general failure sequence was for debris to penetrate windward wall cladding, roof cladding to be lost, then a total failure of the framing system. Alternately, if enough of the wall cladding was lost, the hoop iron wall bracing would fail and the house would undergo racking failure (Figure 17).

Older homes had considerably more bracing (roof and walls) and thus greater strength once cladding was lost. For the newer elevated homes, too much was required of the cladding system so that when it was removed, there was little remaining resistance in the structure and they fell down. Once the roof goes, there are many modes of failure for the rest of the structure. Walker (1975) therefore postulates that if the roof sheeting had remained on, homes would have maintained significant portions of their bracing ability, and the reduction in wind-borne debris would have meant less damage to wall cladding, the by-product of which would have been a further increase in bracing strength.

As with elevated homes, considerably more damage was done to newer low-set homes than older ones. This was perhaps even more prominent for low-set construction (Walker 1975), where a move from 11" cavity brick walls to either timber framed brick veneer or 300 mm masonry cavity (90 mm concrete block inner and brickwork outer leaf) significantly reduced the structure's capacity to resist impact loading and to perform as a unified resisting element. Only about 10 per cent of older low-set homes suffered total failure, with many suffering only minor damage. For the newer homes, however, complete destruction was common.

4.4.4 Failure of flats

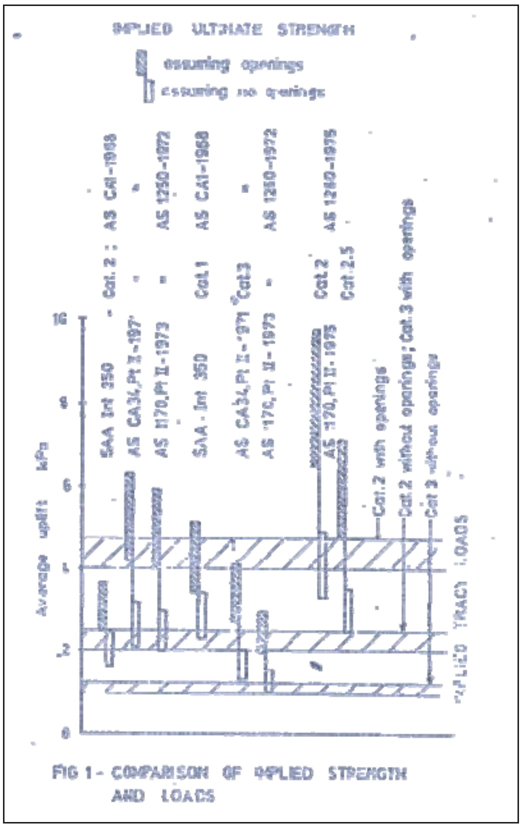
Damage most often observed to blocks of flats was to the roof and top storey (Figure 19). As with housing, loss of roof sheeting was due to inadequate fixing to the roofing purlins. Roof sheets were again expected to take up a significant proportion of the roof bracing, so once lost, failure of the roof system occurred. When failure of the end purlins occurred, end wall failure would generally follow because this purlin provided support for the top of the end wall. Insufficient tie-down of the roof structure to the remainder of the structural frame was also an issue noted as leading to failure of the roof, pulling down parts of the masonry walls.

4.4.5 Failure of engineered buildings

Structures that required an engineer to certify their structural capacity performed well (Section 0). Of those that did fail, more often than not this was ascribed to inappropriate application of design standard concepts. This generally came about because of inadequate explanation in the standard. A by-product of this was generally the application of a design wind speed well below the probable wind speeds experienced during Tracy. A prominent example was the use of terrain category 3 (well built up or vegetated areas) in regions that were severely de-vegetated by the extreme winds and more appropriately would have been classified as terrain category 2. A second example was the design of structures with large roller doors as nominally sealed buildings. Given the discussion in Section 0 on the poor performance of these doors, not clearly specifying that roller doors, unless designed to withstand wind and debris loading, as potential openings was inappropriate.

Source: Walker (1975).

Figure 19: Failure of the top level of a block of flats



Source: Baker & Walker (1976).

Figure 20: Comparison of implied strength and loads on a simple rectangular 'engineered' building

Figure 20 (Baker & Walker 1976) compares the implied loads on a simple rectangular 10 m high building due to the winds from Tracy and the range of design standards that would have been used throughout Darwin for engineered buildings that stood at the time. Ranges are given for implied terrain category 2 and 3, with and without design consideration for dominant openings. It is evident that for newer structures, if terrain category 2 and a dominant opening were considered (as was certainly the case for many buildings), the design of each building would most likely have been appropriate. However, if terrain category 3 and no dominant openings were used, the loads considered in design would have been significantly less than was experienced.

There were some cases of failure of members, particularly in light-gauge cold-formed steel structures, where instability in members led to unexpected failures. Some of these failures were again linked to the assumption that cladding would act to transmit load from one element to another. Others were due to deficiencies in understanding of these failure mechanisms, and were therefore not represented appropriately in the design standards.

4.4.6 The role of human error

It is often suggested that many engineering failures come about through errors caused by sloppy construction and/or supervision. Walker (1975) suggests that the damage observed during Tracy was largely an engineering failure, and although some human errors were found, they were not the predominant reason for the majority of failures. Leicester and Reardon (2008), on the other hand, suggest that human error played a significant role in the observed failures. This, they suggest, can be put down not specifically to builders and certifiers alone, but to a housing design concept not amenable to error-free construction or inspection. They suggest that cottage-type housing construction, where builders connect together several hundred elements according to a set of specifications, is intrinsically too prone to error, and thus is unable to ensure a reliable transfer of load to the ground in the case of extreme loading. The authors also suggest that it is extremely difficult to inspect many of the connections, implying that many of these errors would slip through unchecked, thus weakening the housing strength. The implication is also made that the absence of suitably trained engineers from the design and construction process meant that there was little scope for improving many of the design practices, as in general home builders were unable to appreciate many of the load-transfer and resistance mechanics required to make these changes.

With the extremely high wind speeds and extreme levels of destruction observed during Tracy, it is difficult to adjudicate upon the issue of human error. To justify their point, Leicester and Reardon (2008) use examples of pre- and post-Tracy building inspection surveys, as well as results from full-scale house testing at James Cook University, where construction errors were found in almost every home. Leicester suggests that even today errors are being built into houses, reducing their wind-resistant capacity. To overcome this, Leicester suggests a load bearing anchor type structure be incorporated into each home, upon which the remaining structure can be connected. What this concept essentially does is provide a relatively easily inspected structural load path that would ensure errors in the construction of the home's base structural system could be easily identified. This concept is discussed further in Section 5.1.3.

4.5 Building damage, loss of life and injury

Although not the primary focus of this work, a rudimentary analysis of how building damage contributed to death and injury is justified. As outlined in the Introduction, the official number of deaths for Cyclone Tracy was 71, of which 50 occurred on land and 21 at sea (i.e. drowning). This total number was increased from 65 in 2005 when, after 30 years, a Northern Territory Coronial Inquiry officially attributed the drowning deaths of six people 'lost at sea' to the event (Morgan 2005). Of the 50 land-based deaths, the Darwin Reconstruction Study Group (1975) classifies 46 as shown in Table 3. Crush asphyxia is clearly the primary cause, with the majority of these deaths occurring due to falling masonry. Unreinforced internal and external blockwork walls, as well as unreinforced brickwork veneers, were the main contributors to this statistic. The remainder of deaths were associated with injuries sustained from flying debris impact, with roof sheeting and glass being most fatal.

Table 3: Cause of land-based fatalities

Cause of fatality	Number
Crush asphyxia	31
Crush asphyxia and glass laceration	2
Crush asphyxia and iron (roof sheeting) laceration	5
Iron (roof sheeting) lacerations	5
Spearing or penetration by timber	3
Total (as reported on 10 January 1975)	46

Source: after Darwin Reconstruction Study Group (1975)

In addition to the 71 deaths, approximately 650 people suffered injuries severe enough to require medical treatment. Of these, approximately 500 were outpatients, the vast majority of whom suffered superficial lacerations from roof sheeting and glass. Approximately 140 patients were admitted to hospital, with 64 suffering severe lacerations and 74 suffering blunt object impact injuries (some patients suffered both and some injuries were not recorded) (Darwin Reconstruction Study Group 1975). Dr AF Bromwich, a Senior Surgical Specialist, suggests:

> It is my impression that a higher proportion of these more severe lacerations *[as compared with superficial lacerations]* could have been caused by fibro-asbestos as well as glass and corrugated iron. The blunt injuries were caused by flying objects such as timber, by falling object, again such as timber, or by crushing. In addition, a small number of fractures and contusions were caused by bodily impact – falls out of stilt houses, etc.

It is clear that, in order to reduce the number of deaths and injuries, falling masonry and flying debris must be minimised as a priority.

5. Post-event response, adaptation and lessons

5.1 Building construction and standards

It was abundantly clear in the aftermath of Tracy that the methods formerly used for design and construction of buildings –particularly housing – were inadequate and needed to be dealt with as a matter of urgency. The problem with this was that most engineers believed their construction methods were sound, particularly those incorporating changes made since Althea in 1971. In fact, only a few weeks before Tracy, the DHC lobbied the Commonwealth for funds to apply these changes to Darwin's older homes in an attempt to enhance their wind resistance (Walker 2008). In the aftermath, therefore, there was no immediate understanding of why so many buildings had failed, and research had to be undertaken to discover this. This section details the response of the building and construction industries to this deficit, and discusses how knowledge gained from this process has helped adaptation for extreme wind events to this day.

5.1.1 Immediate response

Within five days of Tracy striking Darwin, the Commonwealth government had decided to establish a statutory body to plan, coordinate and undertake the leadership role in the reconstruction of Darwin, referred to as the Darwin Reconstruction Commission (DRC) (Walters 1978). The aim of the body was to ensure housing and living standards were returned to a suitable level as quickly and economically as possible. The DRC was therefore the government's arm in Darwin, and had the skills of the DHC at its services.

The DRC's first role was to direct Housing Commission and DHC staff to survey house and flat accommodation to determine which of these could be repaired temporarily to provide shelter for those staying in Darwin. This information formed the basis of the damage statistics discussed in Section 4.1. Those buildings could be repaired were done so temporarily (650 structures were demolished or made safe and 4600 structures were re-roofed), but the decision was made that no reconstruction would occur until the cause of failures was identified and design practices changed to account for them. This view was vocalised by the federal government and personally espoused by the prime minister. Significant will for this goal also existed, at least initially, amongst the general population of Darwin and the country because of widespread horror at the level of destruction that had taken place. This will to learn from a disaster (and act upon it) seems to have been an important factor that monetarily equivalent, but outwardly less catastrophic, disasters since have lacked (e.g. the Newcastle earthquake). This has inhibited the ability of these events to impact accepted methods of design and construction in the same way that Tracy has done (G Reardon, pers. comm., 5 November 2009; G Walker, pers. comm., 28 October 2009).

Ownership was also a big issue. The Commonwealth owned 40 per cent of the housing in Darwin, and a significant proportion of those they didn't own had originally been built by the DHC before being sold on to private owners. The blame for any failures therefore rested squarely with the government, and it was its responsibility to ensure this didn't happen again, a responsibility that was taken seriously. The DHC's role as the body in charge of building meant it was responsible for delivering 'a cyclone resistant Darwin', as promised to the population by the government in the days following Tracy (Walker 2008). On top of this, the level of destruction clearly indicated that there was an issue with current practice, with no clearly defined solutions. Whether a moratorium such as that enforced after Tracy could be applied today is debatable. This is a point taken up in later discussion.

With a moratorium on reconstruction, the DHC, academic institutions, engineers and architects compiled damage documentation and determined the reasons for observed failures. Within less than a month, this information had been used to draft a new Darwin Area Building Code (Department of Housing and Construction 1975). The final report describing the impact of Cyclone Tracy on buildings was released within three months (Walker 1975), and the official *Darwin Area Building Manual* was released early in 1975. The major recommendations and implications of these changes are discussed in the following paragraphs.

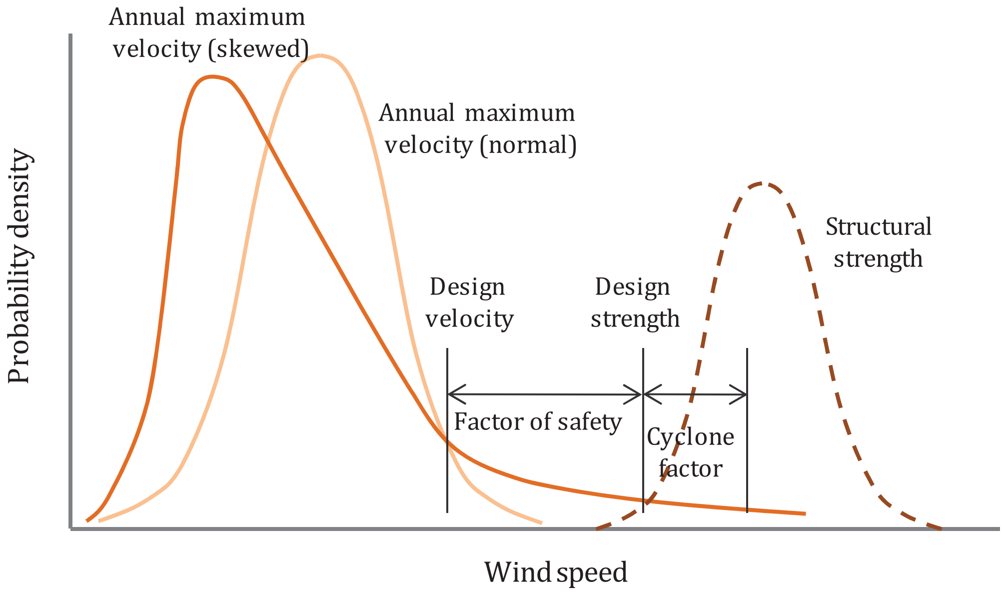
Housing to be engineered

A new approach to housing design had to be adopted in tropical cyclone regions. The level of destruction, and the peril to human safety Tracy had posed, clearly showed the traditional housing approach to be inadequate for high-impact, low-occurrence events. The recommendation made was that houses be considered to be on the same level as public, commercial and industrial buildings, with the requirement that structural strength be certified by an engineer prior to commencement of construction, and with adequate supervision provided throughout the construction period. This was a radical recommendation that had not previously been implemented anywhere in the world for wind-resistant design. New Zealand was the only country to enforce engineering design of housing, and this was for earthquake, not wind (G Walker, pers. comm., 28 October 2009). Historical opposition to this approach lay in the fact that the engineering costs were considered too high with respect to the cost of a single home. However, with newer homes increasingly being built from standardised plans, engineering becomes viable if the cost is spread over all housing built from a given plan.

Shift to limit state design philosophy for cyclone regions

Any enforced design philosophy for housing construction would be considered an improvement on what was in practice prior to Tracy, but even the design of engineered structures could be improved by the implementation of limit state design. This recommendation was not new. Standards Australia was already in the process of discussing a change to the limit state philosophy; Tracy, however, provided the impetus to hasten this change (J Holmes, pers. comm., 3 December 2009; G Walker, pers. comm., 28 October 2009).

Limit state design represented a shift in thinking more amenable to regions with long-tailed peak-wind gust distributions. The use of working stress design philosophy (and therefore its factors of safety) was largely developed in regions with less skewed velocity distributions (i.e. closer to a normal distribution), where the likelihood of extreme excursion was low. In practice, this meant the chance of the design velocity being exceeded by a significant amount was very small, even if distribution shape varied slightly between locations (see Figure 21). This scenario is suitably accounted for using a single factor of safety. In cyclone-prone regions, however, the wind speed distribution extends well past what would be set for the design wind speed (e.g. the 50-year return period gust) (see Figure 21). Therefore, simply applying a factors-of-safety derived based on a normal type distribution could not ensure that significant structural failures (i.e. design strength exceeded) would not occur during extreme events. This fact was realised by engineers, and an additional factor of safety – the cyclone factor – was applied in practice.



Source: after Walker (1975).

Figure 21: Interaction between wind speed and strength for normal and long-tailed distributions

The shift to a limit state design philosophy effectively meant the tail of the wind speed distribution had to be considered on a case-by-case basis with a second, ultimate limit wind speed identified. This ultimate limit was the wind speed up to which a building was required to remain safe, but to which localised failures (e.g. large deflections or cracking) were accepted. In effect, two wind speeds were now set for design of each structure, one at a return period level to ensure there would be no outward signs of structural distress over the lifetime of a structure, and a second, higher wind speed to ensure that in the event of a cyclone with, say, the 500-year return period wind gust, a structure would maintain its integrity so the occupants would remain safe. The limit state design approach was not implemented immediately, but after several years of research and development it was introduced into engineering practice in the late 1970s and early 1980s (G Walker, pers. comm., 28 October 2009), and officially into the wind standard in 1989.

The two recommendations discussed above required conceptual and philosophical changes to be made to the way buildings were designed and constructed. This process required considerable research and improvements in understanding, and as such could not be implemented immediately. Therefore, because the adoption of a suitable building code was deemed essential before reconstruction could proceed (Department of Housing and Construction 1975), it was recommended that new cyclone provisions be developed and incorporated into the Australian Model Uniform Building Code (AMUBC), with the ensuing document, the *Darwin Area Building Manual*, legally replacing the *Northern Territory Building Manual*. At this stage, there was still some subjectivity to the new cyclone wind provisions; however, it was felt they were conservative in nature, and could be adjusted as the required research was performed (Walker 1975). A continual review process of the code was recommended. In essence, this led to an overly conservative initial set of design specifications that in time would be wound back to a level that more appropriately represented an acceptable level of safety as well as cost-effective design.

The specific recommendations made to be implemented in the reconstruction of Darwin – some with reference to the entire cyclone-prone region of Australia – were:

- **The definition of cyclone areas.** Specific zones should be set so it was clear where cyclone provisions should be applied.

- **Update and amend the AMUBC.** It was important to update the AMUBC so that Darwin-specific regulations could be included. It was also required that the deficiencies in the standards called upon in this document were highlighted so new recommendations could be used. The recommendation also called upon Standards Australia to be notified of all deficiencies in their documents. The Standards most notably requiring changes were:

  – AS1170: Minimum Design Loads on Structures
  – CA 38-1971: Light timber framing Code
  – AS1562: Design and Installation of Self-supporting Metal Roofing, and
  – CA 32-1967: Concrete Block Masonry Code.

  The AMUBC, as with all other design codes of the time, was lacking in design specifications for housing. This information was developed as a set of deemed-to-comply standards for the AMUBC as a matter of urgency prior to reconstruction beginning in Darwin (Department of Housing and Construction 1975). This is the first such case anywhere in the world, so was not a trivial exercise.

- **All reconstructed housing to be designed by an engineer.** This was the initial application of the first conceptual recommendation above. Although there were only limited guidelines for housing construction in standards, the use of an engineer at the design phase would have ensured general engineering principals were satisfied in the design of new homes. It was expected that by using the design specifications currently set out for engineered structures, homes would have considerably more resilience that those built by the traditional method.

- **Increase in design wind speed:** The general good performance of engineered structures during Tracy suggests that the design wind speed was set at a reasonable level (when using factors of safety). However, given the short period of wind records, and the exceedance of the specified design wind speed, it was lifted from 49 m/s to 55 m/s. As discussed in Section 3.3, a cyclone factor of 1.15 was also applied to elevating the effective design wind speed further.

- In the current design standard, AS1170 part 2, 2002, the design wind speed for Darwin at a return period of 50 years is 52 m/s with a cyclone multiplier of 1.05, in effect roughly aligning with the pre-Tracy specification. This comparison, however, is only valid for engineered structures. The implementation of engineered design to housing and the assignment of enforceable design wind speeds to these structures represented a significant increase in required resilience and a step change their safety (G Reardon, pers. comm., 5 November 2009).

- **Specification of a minimum category reduction factors.** Minimum wind speed reduction factors to account for defoliation occurring during extreme wind events and acceleration over topography were set. The minimum allowable design wind speeds for structures embedded in suburban regions became 45 m/s, and for those on the top of cliffs, 65 m/s.

- **All housing to be designed for full internal pressurisation.** All housing required design for the additional loads that would occur through failure of a windward window or loss of cladding due to debris impact or high localised pressures. This scenario was generally neglected prior to Tracy, under the assumption that windows would not break under wind pressure, overlooking the threat of debris impact. The recommendation was not required for commercial or industrial buildings if measures were taken to stop debris impact failures. To justify debris impact ability, it was required that the ability to withstand a 4 kg piece of 100 mm x 50 mm travelling at 20 m/s could be demonstrated. Specification of this test in the *Darwin Area Building*

Manual was the first implementation of a standardised test for debris impact anywhere in the world (Minor 2005).

- **Improvements to cladding design.** Cladding was no longer allowed to be used for bracing the supporting frame of large structures, but could still be used to this end in housing design, provided provision was made for debris impact resistance, and the building was designed to a higher specification (i.e. to withstand a higher wind speed) than normal. Irrespective of the type of building, all roof cladding fixing systems were required to resist the newly developed fatigue tests to account for the cyclic nature of wind loading and reduce the number of failures observed with the high-strength steel sheeting (Section 4.4.1. These recommendations have the specific objective of keeping the roof on at all costs (Walker 1975). This was considered essential because of the enormous effect that loss of roofing had on the damage, through both production of flying debris and the loss of structural rigidity due to loss of the major bracing element. Keeping the roof on also maximises the safety of the internal occupants and minimises loss of contents.

- **Strengthened design of masonry walls.** Unreinforced masonry performed extremely poorly, causing structural failures and danger to life due to falling masonry. To minimise these effects, all masonry was to be designed using relevant design standards, which in essence meant much of it required reinforcement and bond beams (fixed to the roofing). Enhanced strength was required for internal masonry to minimise the danger this material posed when falling. Restricting masonry veneer to the ground level was also recommended to further reduce the risk of falling brickwork. On top of the structural benefits of strengthening masonry walls, stopping masonry from falling was of vital importance, given that the major cause of death during Tracy was asphyxiation caused by the collapse of these walls on to people (Section 4.5).

- **Design of windows and doors, and their connection to the wall frame.** Failure of windows and doors often initiated failure of a building. It was generally the case that, despite standards being available, the fixing of windows and doors to the remainder of the building structure was left to the builder. Recommendations were that designers utilise the available standards to specify connections to ensure resistance to wind pressures. Although this recommendation does not account for debris impact, ensuring the wind pressure load could be transferred to the main structural frame without failure was a significant improvement over what had existed previously. The issue with designing windows for debris impact is that it is not practical to use glass of suitable width to ensure its integrity under impact loading. From an overall structural safety point of view, debris failure of a windward window should not be an issue if the design recommendation for full internal pressurisation is applied. Failure of windows does, however, increase the potential for injury of occupants (e.g. lacerations due to glass, increased risk debris flying into the building), and increases the damage to contents. This second point may be significant for commercial and retail outlets. Shutters, sun-shading devices or similar window protection are suggested as a possible amelioration technique, but this was not enforced in the recommendations given the previous internal pressure recommendations. Where window protection is used, Walker (1975; pers. comm., 28 October 2009) cautions that this should not be done at the expense of design for full internal pressurisation, but recommends their use as an additional safety measure. He also cautions that unless window protection is implemented as a semi-permanent feature, the relatively low frequency of required use may present maintenance problems.

- **In residence shelters.** In tornado-prone regions of the United States, the presence of an internal *safe room*, where a resident can reside during a severe storm, is common. These safe rooms are designated areas within a building designed to withstand more severe wind and debris loading than the remainder of the structure, and provide a place for occupants to go during cyclones. It was recommended that research be performed to test the viability of this type of construction in cyclone regions, with the possible incorporation of this design into the laundry or bathroom of housing. Initial recommendations suggested a design wind speed of 80 m/s for these rooms. This recommendation would remove any danger from flying debris that enters a building, and also ensure occupant safety if, despite application of improved design methods, other parts of the building fail. Construction of a room such as this will, however, come at an increased cost to the home, and for regions prone to storm surge would not be suitable.

- **Strengthening of existing homes:** It was recommended that non-destroyed homes be modified, where possible, to incorporate the concepts embodied in the recommendations for new buildings. Generally, it would not be possible for the structural system to be modified, so methods such as overbattens were recommended. This recommendation does not afford the same level of protection as a new home, but does work to ensure the roof remains on the structure. Walker (1975) highlights that many other cities in cyclonic regions have significant levels of buildings constructed similarly to those in Darwin, and therefore would suffer comparable destruction if a storm equivalent to Tracy were to occur, unless some level of retrofit is conducted. J Holmes (pers. comm., 3 December 2009) suggests that this is even the case today, with Cairns being particularly vulnerable.

- **Education:** Those involved in the building of new homes in cyclone-prone regions must receive training on how and why changes to traditional methods are required. This service should be free.

- **Inspections:** Given that regulations cannot be ensured in the absence of inspections at critical stages of the construction process, it was recommended that stricter enforcement of building inspections at critical stages be applied. This necessitated a better definition of where the critical stages were, and required that a sufficient number of appropriately qualified inspectors were available. It was also recommended that a certificate be obtained prior to occupancy from an appropriate building authority.

These recommendations addressed all failings observed during the damage survey. To arrive at several of the recommendations, significant structural testing was required. This was achieved through use of local engineering consultants, DHC and other government personnel, in consultation with nationally respected academics in the field. The DHC completed the work of which it was capable, and outsourced that it couldn't do, or which could be done quicker/better by external consultants. The first new housing was started on 25 June 1975, and the first homes were completed in December of that year. This meant that it took less than six months for an existing building practice to be broken down and redeveloped in a manner more amenable to cyclone wind resistance. Within this period, builders and certifiers were trained in new methods of construction and educated on the new regulations to be implemented. From an engineering perspective, the quantity of work achieved in only a few months, and the ready acceptance of ideas and methods by a naturally conservative and often entrenched industry was remarkable.

The overall cost of implementing the cyclone-resistant recommendations to residential housing was approximately $5000 per home (Cole 1977). With a rebuilding cost of approximately $35 000 to $45 000 (Appendix 2), this value represents an increase in costs of the order of 10 per cent. For more recent construction, a value of 5 per cent is expected to be more appropriate when included at the time of construction, but increases to 15–50 per cent for retrofitting (G Reardon, pers. comm., 5 November 2009; Stewart 2003).

5.1.2 Adaptation and lessons

All major recommendations were implemented in the reconstruction of Darwin (Walker 2008). Walker suggests that this occurred in large part because of the control the federal government had in Darwin, and the significant role the DHC had in implementing its plans. To be sure, the DHC at the time of Tracy found itself in a unique position where the most suitable body to make the change (i.e. the DHC), was actually in a relatively unimpeded position to implement the changes deemed necessary.

Today, however, the DHC does not exist and the federal government no longer controls Darwin. So the question of whether the same type of response could be achieved if a Tracy-like event were to recur today must be asked. Throughout this section, the way Australia's wind-resistant design regulations, and the bodies responsible for governing design and construction, have adapted in light of Tracy are discussed, and an attempt made to answer the question posed in the previous sentence.

Over the years following the introduction of the *Darwin Area Building Manual*, the recommendations for the reconstruction of Darwin were gradually made more codified and introduced into national design standards. To a large extent, many of the recommendations have remained relatively unchanged, in principle if not in value, to the present day (Walker 2008).

In 1975, Standards Australia released a major revision to AS1170 Part 2, which began to address the shortcomings of relying solely on a Gumbel analysis of historic gust records to specify design wind speeds. Newly developed methods of probabilistic cyclone modelling began to be employed. Cyclone Tracy highlighted the inability of a local, short-record Gumbel analysis to, in all cases, predict wind speeds for extremely rare events. Probabilistic models, on the other hand, were able to (to a degree) account for these through a series of statistical averaging processes in their calculations. In combination, the two methods showed was that design wind speeds in many tropical cyclone regions were too low and should be increased. The 50-year return period design wind speed of 55 m/s recommended for the Darwin Area Building Manual (Section 0) was shown to be suitable for Darwin and was specified as such in AS1170.

The 1975 revision also saw the formalisation of the idea introduced in the 1971 version that the entire northern coast was susceptible to cyclonic winds, despite the absence of monitoring stations in some locations or the absence from records of cyclonic winds in others. To this end, a three-tier cyclone zoning system was introduced. The first zone was the strip within 50 km of the coast above 27°S (the same area to which the 1.15 cyclone factor was applied the 1971 standard) which, as for Darwin that sits within it, was assigned a design wind speed of 55 m/s. The remaining two zones were successive inland 10 km strips, with decreasing design wind speeds of 50 m/s and 45 m/s respectively (see Appendix 1). These latter two zones accommodated the decreasing wind speed displayed by a decaying cyclone as it moved inland.

Although there have been some changes to exact boundaries and designated wind speeds, the concept of coastal cyclone zones is still used today (Appendix 1). To determine the appropriate wind speeds for each zone, a mixture of the probabilistic and historic wind record analysis methods is used (J Holmes, pers. comm., 3 December 2009). In general, the higher wind speed for a particular area based on both methods is used in the standard. Cook and Nicholls (2009) have suggested a return to a more detailed wind speed contour-type map – for example, as shown in Figure A1.1, such as used in the United States. In reality, however, this attributes too much confidence in the ability of models to predict locally accurate wind speeds without recourse to significant validation.

More accurate contour-style zoning is possible in the United States because the number of surface wind speed monitoring stations is significantly higher than in Australia, and the need for more accurate location-specific estimates is greater given the population density on the cyclone-prone coastline. In the Australian context, the monitoring network for cyclonic winds around the coast is so sparse, and the vast majority of the coast unpopulated, that the need for a more precise velocity contour system seems unnecessary and the ability to validate one is unrealistic. Irrespective, the framework exists in the current cyclone zoning system to account for regions of intense cyclonic activity. Examples of this were the treatment of Onslo in the 1975 revision and the specification of Region D in the 2002 edition (to be discussed later in this section).

Cook and Nicholls (2009) also raise the issue of modern adaptations to the probabilistic approach of wind risk modelling, and improvements these can make to wind hazard prediction. In their paper, Cook and Nicholls use a numerical weather prediction-type model that couples the ocean–atmosphere interaction, as well as accounting for historic records of sea surface temperature and wind shear (Emanuel et al. 2006; Vickery et al. 2009). Compared with probabilistic models, such as those contributing to the current cyclonic design wind speeds, this analysis method utilises more contributing environmental factors into the calculations of cyclone behaviour, and reduces the need to rely solely on statistical models.

However, at this stage it is difficult to determine the validity of this modelling approach and the relatively untested nature of the science behind the predictions (Vickery et al. 2009). Given this, the authors' finding that the cyclone risk for Darwin was significantly higher than that accounted for in the current design standard was greeted with scepticism by the wind engineering community (J Holmes, pers. comm., 3 December 2009; L Pham, pers. comm., 3 December 2009; G Walker, pers. comm., 28 October 2009). Numerical weather prediction-type models will, however, most likely be used in the next generation of cyclone risk models (Vickery et al. 2009); however, it is felt that there is not significant evidence to justify applying their current findings to design standards, at least in the short term.

The adoption of the *Darwin Area Building Manual* for the reconstruction of Darwin led to the recognition that similar measures should be applied in other cyclonic regions of Australia of similar risk (Walker & Reardon 1987). This seemed particularly pertinent for the more highly populated eastern coast of Queensland. However, despite the recommendations made for the reconstruction of Darwin, the lack of legal obligation meant that relatively few areas applied the new testing measures, and most continued to build in the same manner as they had always done. In an attempt to resolve this issue, the Department of Construction (formally the DHC) agreed to host a workshop in 1977 to review and update the criteria adopted in Darwin and determine their applicability to other cyclone-prone regions of the country. The workshop was attended by representatives of a wide cross-section of the building industry, with academics, researchers, industry, Standards and government representatives, as well as consulting engineers, in attendance. The outcome of this workshop was a set of guidelines for the testing and evaluation of products intended for use in cyclone-prone regions of the country. The document was known as TR440 and rapidly became the 'bible' for construction in many areas (Walker 2004).

By and large, the conceptual principles of the *Darwin Area Building Manual* were accepted and embodied in TR440, with particular endorsement of the recommendations for:

- full engineering of housing, though acknowledging that this would be a gradual process (Department of Construction 1977)
- design for full internal pressurisation unless protective measures were taken
- the specification of a debris impact test, and
- the necessity for fatigue testing of roof cladding.

Some of the Darwin recommendations were, however, scaled back in TR440, with the magnitude of internal pressure required for design reduced in some cases, the impact velocity for debris impact tests dropping from 20 m/s to 15 m/s and the fatigue testing loads reduced. These reductions were a reflection of research findings conducted since and in light of Tracy. An additional recommendation by TR440 was that separate, less stringent (25-year return period) loading criteria be specified for serviceability (e.g. deflections and cracking of members) requirements. This is seemingly the first shift towards limit state type recommendations, reflecting the shift in the structural engineering community towards this design philosophy.

TR440, in its commentary section, highlights an important point, one that was a significant impediment to implementing structural engineering concepts in housing design. It states:

> In a large section of the housing industry, the control and supervision of housing design and construction is not in the hands of people with engineering training and consequently sophisticated codes of practice prepared by engineers for engineers are often not appropriate. The wind-loading code is a good example of this. Its use requires a considerable degree of engineering judgment particularly in relation to the choice of terrain category and internal pressure coefficients. In addition the degree of sophistication of the wind code is far greater than that exercised in the design and construction of housing.

For the reconstruction of Darwin, because it was specified that a structural engineer must be involved with the design of housing, the implications of the above statement were somewhat muted. For other regions of the country, though, engineers were not required, and judgement decisions were left to the builders. To minimise this problem, TR440 specified a simplified set of design and testing criteria for use by the housing industry. The TR440 commentary continues by suggesting that:

> It is inevitable that this approach will lead to some individual houses being overdesigned and perhaps others being underdesigned. The primary object, however, is to limit the impact of tropical cyclones on the community as a whole by reducing the total potential for damage, rather than guaranteeing the absolute security of every individual dwelling. This is not considered a serious objection, particularly as the variables and uncertainties inherent in the current design and construction of dwellings are probably of greater magnitude.

Although TR440 was widely accepted, its non-legal standing meant the penetration of its concepts and test methods was incomplete, and in practice varied from state to state. Queensland was the most receptive, with the 1981 inclusion of the Home Building Code of Queensland as an appendix in the state building regulations. The Home Building Code embodied many of the findings of TR440 and, due to its widespread use, ensured many of the principles were applied by designers. Use of TR440 was not as widespread in Western Australia, but the general awareness of tropical cyclones and their potential effects on buildings, and the relatively high frequency of occurrence, meant that traditional housing design methods were already quite well adapted to cyclonic loading conditions. In the Northern Territory, however, TR440 was not accepted, and the *Darwin Area Building Manual* continued to be used. Although these two documents were similar, the Northern Territory authorities were reluctant to reduce some of the loading criteria to TR440 levels, choosing in most cases to keep using the (generally) more conservative of the documents. The non-uniform take up of this document highlighted the need for a legal framework that would ensure cyclone resistance throughout cyclone-prone regions.

The next major step in improved resilience through codification came with the publication of the 1989 version of AS1170 Part 2. It was with this update that the recommendation of a shift to limit state design was realised. This was not just done for the wind standard, but was implemented throughout the suite of loading standards (i.e. wind, earthquake, snow). In reality, many practising engineers had moved to the limit state design philosophy prior to this time, largely driven by the DHC's decision to do so throughout the country shortly after Tracy. Given the DHC was such a big player in the construction industry, its transition ensured that many in the structural engineering profession would follow (Walker 2004). Irrespective, this was the first nationwide instance of a standardised limit state wind resistant design manual in this country. There were many other significant changes that occurred with this update. Some of the more significant, which can directly be linked to either Cyclone Tracy or the research performed because of Cyclone Tracy, were:

- the inclusion of many of the guidelines embodied in TR440, including specification of the cladding fatigue test not accepted by the Northern Territory
- specification of wind speeds for ultimate limit (1000-year return period), serviceability limit (25-year), and permissible stress (ultimate load/1.5, notionally equivalent to the 50-year return period) design
- removal of all contours from the design wind speed map, leaving zones exclusively to determine design wind speeds. Four wind zones were used, A, B, C and D, signifying regions where peak wind gusts are generated by thunderstorm or synoptic-scale storms, decaying tropical cyclones or thunderstorm wind gusts, tropical cyclones up to a mid-range category 4, or severe tropical cyclones respectively. Exact boundary locations changed somewhat from the 1975 edition, but the general concept embodied in the earlier standard continues here.
- development and inclusion of a simplified deemed-to-comply design procedure for housing construction, and
- development of a more rational approach to wind speed multiplier selection.

Therefore, the 1989 edition of AS1170 Part 2 completed the standardisation of all major recommendations set out in the post-Tracy report. That is, the two philosophical recommendations – engineering design of all housing and the move to a limit state design philosophy – were achieved, and most of the technical issues relating to, for example, internal pressures and fatigue loading were covered in specific clauses – at least for cyclone-prone regions.

One discrepancy that did remain was the Northern Territory's refusal to accept the fatiguing test outlined in AS1170 Part 2, and its continued requirement that the test specified in the *Darwin Area Building Manual* be performed. Given that the state/territory has the final say on regulations, this type of local anomaly was possible. Granted, the recommended test prescribed in TR440 and subsequently the 1989 version of the wind standard was derived based on a limited number of experiments (Walker & Reardon 1987). The Northern Territory building community was therefore justified in its insistence on application of a conservative test. In subsequent years, additional tests were performed and indeed showed, in some instances, that the specified TR440 test was not conservative, and thus required modification. The modified test is now incorporated into the wind standard, but this came about only after a period of many years and significant political roadblocks (Walker 2009).

During the move from working stress to limit state design, the necessity for the cyclone factor, 1.15, to be applied to the design wind speed was no longer considered necessary and was removed. What also occurred in the transition was that the 1.5 factor of safety applied to the wind loading, which in theory accounted for the higher wind speeds of extreme events – that is, the shift from the specified 50-year return period to the 1000-year return period – was no longer used. In essence, this meant that previous standards had assumed the ratio of ultimate to working stress design condition wind speeds was $\sqrt{1.5}$ instead of allowing the wind speed distribution to determine this value. The theoretical advantage of the limit state approach is that the actual limit state can be predicted. Of course, this assumes that there is enough data to make accurate predictions out to this return period. What this meant for Darwin was that the effective design wind speed in the 1989 standard dropped back to just above the pre-Tracy level. This was a winding in of what was perceived to be an over-reaction in the aftermath of Tracy, and was probably warranted given the engineered buildings utilising the pre-Tracy design wind speeds performed relatively well.

Outside the fatigue testing case, the 1989 standard represented the last time direct lessons from Cyclone Tracy have been used to directly change a building standard, though these lessons still run through these documents. This statement is true for cyclonic and non-cyclonic regions alike, because much of the research performed in light of Tracy provided information on wind resistance as a general principal, which is equally valid in all regions (Walker 2004).

At present, the 1989 standard has been superseded by a 2002 edition of AS1170 Part 2, which again has evolved based on research since the release of the previous edition. This edition was to be superseded during 2010, with further changes made. Although many changes exist in these documents, two are of significant importance to the current discussion. The first is that the wind loading standard no longer specifies a simplified design procedure for small structures. This process has been moved to a separate standard, AS4055 *Wind Loading for Housing* (first introduced in 1992 then superseded in 2006). This document is in principal based upon AS1170 Part 2 and is a simplified version of the information presented within that document for use by the housing industry. In practice, however, differences have emerged between the two documents, with simplifications and the acceptance of a higher level of risk often leading to lower design wind loads in the housing standard (J Holmes, pers. comm., 3 December 2009; L Pham, pers. comm., 3 December 2009).

Leitch et al. (2009) highlight specific differences between the two, specifically in the determination of topographic and shielding multipliers. Lack of communication between committees for the two standards is contributing to these differences and must be addressed by Standards Australia if uniformity is to be ensured (J Holmes, pers. comm., 3 December 2009). This problem is not helped by ever-diminishing funding for the development of new standards by Standards Australia and the diminishing willingness of companies/institutions for their staff to be involved at company expense. The perceived status that once existed for a member of these committees, and which contributed to the willingness of employers to release and fund employee involvement, is now also much diminished (L Pham, pers. comm., 3 December 2009; G Reardon, pers. comm., 5 November 2009). If these issues are not addressed, it is likely that, despite the best intentions of committees, the quality of standards will suffer.

The second change made in the 2002 edition, which was to be carried forward to the 2010 edition, is that AS1170 Part 2 no longer offers guidance on the appropriate design wind speed structures – that is, the standard no longer specifies that, say, ultimate design should be based on the 1000-year gust. It was viewed that the wind loading standard, a technical document, had no place in determining the acceptable public risk. This was considered a public policy issue, and thus a responsibility to be transferred to the state regulating authorities (Pham 2007). Instead, design wind speeds are now given for a range of return periods, and a designer must reference the Building Code of Australia (which is ratified by state governments, refer to the next sectionbelow) to determine the appropriate minimum value. The reasons for this change are discussed further in the following section, but in general what it has meant for the design of general structures is that the acceptable return period for ultimate limit design has changed from 1000 years to 500 years. This in effect reduced the design wind speed in the 2002 revision from its 1989 level. However, the reintroduction of cyclone factors – 1.05 for region C and 1.1 for region D – has meant that in practice there has been little change in the actual wind speed used for design.

Building Code of Australia

In all, the progression made by standards means little if these documents are not used by the building industry. It is the responsibility of state or territory governments to set building regulations (Section 3.3), and these bodies in general will ensure the use of standards by calling upon them in a deemed-to-satisfy manner in these (legal) regulations. The first attempt to nationally unify the way in which states and territories regulated their building practice was through the Australian Uniform Building Code, as introduced in Section 3.3. As discussed, this document set out technical and administrative guidelines upon which states and territories could develop their own regulations.

During the late 1970s, the AMUBC was implemented by state and territory governments, though many chose to vary quite considerably from the original format. Variation was particularly common on the way states chose to administer the regulations, but agreement on technical specifications was generally good (Australian Building Codes Board 2009). By the end of the 1970s, it was clear that national adoption of the AMUBC in its current format would not occur, primarily because a consensus on administrative regulations proved elusive. Thus, in 1980, the federal, state and territory governments created the Australian Uniform Building Regulations Co-ordinating Council (AUBRCC) to develop a national building code, focusing solely on the technical components in the AMUBC. This document was the Building Code of Australia (BCA), which was completed in 1990 and was the first technical building code usable across the nation. As with the AMUBC, states and territories were still given the opportunity to add local variations, such as, stricter cyclone provisions in the Northern Territory, but the aim was to keep these deviations to a minimum. It took several further years, but by the early 1990s all states and territories were calling upon the BCA in their primary building regulations for the construction of buildings, thus legally enforcing its use.

At about the same time, the agreement that led to the AUBRCC was undergoing a strengthening on the back of a COAG report that showed inefficiencies in current building practices were costing the nation up to a billion dollars annually (Australian Building Codes Board 2009). This process led to the creation of a national governing board, the Australian Building Code Board (ABCB), which was charged with the continual improvement of the BCA (Australian Building Codes Board 2009):

> In essence, the new agreement set in place a co-operative arrangement between the Commonwealth, state and territory Governments, Local Government and the various elements of the building industry to achieve nationally consistent performance-based building regulatory systems that w[ere] efficient and met community, industry and national needs.

The ABCB's first role was to develop the current BCA into a more performance-based code, so that designers had more flexibility to build more cost-effective structures than the 1990 edition allowed. This new version was released in 1996 and accepted by the regulatory bodies of all states and territories by early 1998. Revisions of the BCA were originally released biannually; they are now released annually.

With the introduction of the 2002 edition of AS1170, the responsibility of determining a suitable level of design risk was transferred from the standards committee to the ABCB. This transfer occurred because the level of risk assumed by the occupant of a building is a public policy decision, best determined by governments and not the technical committee that write standards (Pham 2007). The separation of policy and technical decisions, although not an issue for countries where standards are written by their government bodies, is an issue for Australia given that our standards are produced by a committee of volunteers for a corporate entity. The separation of risk levels from the standard is logical, and in theory represents a system where governing bodies can be held accountable by their constituents for lax levels of assigned risk.

Pham (2007) highlights a secondary role played by the BCA: the checking of standards. The role of referencing standards by the BCA is in effect the only independent checking mechanism available to ensure that standards do not breach any government policies, such as competition policy or the *Trade Practices Act*. This is an important role that has seemingly received little attention historically. Again, this is not an issue when standards are written by government authorities, and in the early days when standards were largely written by DHC employees a form of self-checking would seemingly have been in place. Today, however, with the dwindling funding that goes to standards committees, it is not too hard to imagine that vested interests may become an issue. It is also the role of the committee itself to self-regulate in order to ensure that these types of interests are not introduced. Pham (2007) suggests that the checking role of the ABCB will increase in the future, and that even today, some Standards Australia documents are being replaced in the BCA reference list by those written by competing organizations, provided they demonstrate their willingness to comply with regulations designed to protect the public interest.

The current BCA (Australian Building Codes Board 2009) calls upon AS1170 Part 2 and AS4055 for the specification of load calculations throughout the country. To determine the level of risk to which a given building should be designed, the building use and level of hazard to occupants and other buildings must be assessed. From this information, an importance level is assigned. Based on the importance level, a return period for design is determined. For general structures or housing, an importance level of 2 is obtained, which leads to the BCA recommending that a *minimum* return period of 500 years be used for ultimate wind loading.

Building Certification

As discussed in Section 3.3, pre-Tracy certification of housing was performed by certifiers from the local council. Generally, these inspectors were builders without a strict engineering background. For much of the period since Tracy, this remained the same – though in the immediate aftermath of Tracy the levels of inspection throughout Darwin would most likely have risen. In the late 1990s, citing potential improvements in speed and efficiency, the certification process was opened up to private enterprise and private certifiers who could compete with council certifiers for work. At this point, many council certifiers became private certifiers.

In general, the current practice for building certification, once a certifier is appointed, is:

- review and comment on plan
- issuance of building permits
- inspections, and
- issuance of occupancy certificate. (Lampert 1999)

The number and extent of inspections vary between states and territories, but in many cases multiple inspections are involved throughout the construction phase. Irrespective of whether certification is done through local council or private sector certifiers, reports are required to be submitted at each stage of the process so regulating authorities can ensure legality (Lampert 1999).

The process itself is relatively solid – the issues that arise are with ensuring certifiers actually do the job they're supposed to. With the introduction of private certification came the concept of 'project teams', where the certifier is included at the design phase of a project so their expertise can be utilised and redesign costs minimised (Lampert 1999). In theory, this is a good concept and is seemingly encouraged by authorities. However, the role of a certifier in the building process is one of an impartial third party, and this must be ensured in their assessments. As part of a team, this may be questioned. The issue of impartiality is further compromised by the reality that in many cases the certifier is engaged by the builder. With this scenario, builders are free to choose a certifier who is perceived as 'easy' (relying on their insurance if something goes wrong) and the opportunity for collusion can and does exist (L Pham, pers. comm., 3 December 2009).

As Lampert (1999) points out, the opportunity for corruption is not limited to the practice of building certification, and was already an issue before privatisation. Certifier audits are a measure used to minimise this practice. The current certification system is not ideal; however conceptually, if enforceable and if inspections are made at enough suitable times (this is important so that major structural elements and connections can be assessed), it is reasonable. In an attempt to clean up some of the perceived conflicts of interest, Lampert (1999) suggests:

> It should be a requirement that the building certifier be engaged (and paid) directly by the owner, not by an agent of the owner (such as the builder) … Such an arrangement would more clearly establish the role of the certifier in protecting the owner against poor building design or practice. This is not intended to detract from the important role of the certifier in the project team; however, the certifier should not be subservient to the team.

This suggestion would reduce some of the potential conflicts, but of course would not rule them out completely.

The issue of education of certifiers raised after Tracy has also improved with specified tertiary-level education required for all certifiers (Building Surveying). Specified periods of work experience are also enforced to obtain certification grades. The problem with certifiers not understanding all the complex structural responses or implications their inspections are in principle assessing is not entirely addressed with these educational provisions, but unless structural engineers start to become certifiers, it is likely that this will continue to be the case. Despite this, the importance of continued education of both certifiers and builders on this issue by structural engineers cannot be understated.

5.1.3 Reflection

Wind damage

Despite the number of positive adaptations made to wind-resistant design and construction methods since Tracy, there are still changes that can be made to help improve resilience of structures to cyclonic wind loading. A brief summary of some currently unresolved issues is provided in this section. Several items highlighted are conceptual issues without immediate solutions, while others have more practical responses.

- **Department of Housing and Construction.** Walker (2004) asks the question: Who would replace the DHC in the post-disaster adaptation process in the event of a disaster of Tracy's magnitude today? The DHC played a huge part in the immediate post-Tracy adaptation process, and, of significant importance, accepted responsibility for the disaster. This meant that a single organisation (although others were involved) was compelled, equipped and funded to determine the reasons why failures occurred, and then obliged by government promises to find solutions to these problems. Given its position in the construction industry, particularly in Darwin, the DHC had the power to implement these solutions.

  It is hard to imagine today that a group would – or probably should – accept responsibility for a disaster in the same way the DHC did. It is, however, important that a group of people is kept ready to react in a similar manner to the DHC's response after Tracy. For the initial damage assessment, organisations like the Cyclone Testing Station (CTS) at James Cook University (often with the backing of the Australian Building Code Board) and Geoscience Australia seem to be filling this role. The CTS, along with other academics and consultants throughout the country, also has the knowledge to perform analyses to address issues raised during the assessment. The numbers of academics/researchers in this area are, however, dwindling. To ensure implementation, the ABCB would be required to make changes to the BCA and have the state governments accept these amendments. Under normal circumstances, this process is long and time-consuming. It is, however, expected that in the aftermath of a disaster, pressure would exist for this process to be fast-tracked, particularly if the (political) decision had again been made to suspend reconstruction.

- **Decay of structural integrity.** Given that all processes are followed, a new home is certified to the fact that at the point in time of initial occupancy the home satisfies all regulations in regard to safety. What is not addressed, however, is whether the elements that have gone into constructing the home will survive the life of the structure. For example, a building will pass inspection if it designed for a notional life of 50 years but uses material that will only last 20 years. This becomes more of an issue in coastal regions, where corrosion further reduces the lifespan of elements. The reason that this scenario is currently acceptable is because the Building Code of Australia does not define durability in its regulations, based on the idea that it is a consumer choice issue (L Pham, pers. comm., 3 December 2009). The concept of lifetime inspections for housing should be considered – particularly in cyclone regions. There are significant issues with this concept, given the inaccessibility of most connections and members in a building once it has been constructed. This issue is, however, not considered insurmountable. The concept raised by Leicester and Reardon (2008) of an easily inspected anchor structure is particularly amenable to this concept. On this issue, it is also advisable that those doing probabilistic risk modelling of cyclonic winds incorporate decay in structural integrity into their vulnerability modelling.
- **Retrospective code enforcement.** It is the case that when changes are implemented into codes or standards, their application is only mandatory for buildings built after that point. This does not address the issue of weakness in those buildings constructed prior to that point in time. It is unlikely that in the foreseeable future retrospective codes will exist, so other measures are required to ensure the continual upgrade of structural strength to a level currently deemed suitable. One means of achieving this is through the use of banded insurance payments. In this type of scheme those who upgrade their buildings to current regulations will receive reductions in their insurance premiums. This provides an incentive for owners to upgrade. This scenario was at one time tabled (G Walker, pers. comm., 28 October 2009), to the extent that pricing guidelines were developed. The concept did not take off, however, because insurance companies feared they would lose business if the system were voluntary. It is felt that this issue still has merit and should be reinvestigated.
- **Compatibility of standards.** As discussed in this document, there are several differences between the governing wind loading standard and the housing wind loading standard. These should be streamlined so that performing the same calculation with each produces the same design result. To achieve this, there needs to be better communication between the two Standards committees.
- **Design wind speeds.** The wind speed specified by a wind loading standard is perhaps the most uncertain component of the entire design process (J Holmes, pers. comm., 3 December 2009). As such, continual reassessment of these values should be made. This should be done through analysis of historic wind speed records and through probabilistic risk modelling. The largest barrier to this systematically occurring is that there is no explicit funding provided for it to happen. If the most appropriate wind speeds are desired for design throughout the country, monies should be made available for this analysis to occur on a regular basis. At present, updates are generally only made when private practitioners or researchers provide their results to the standards committee free of charge.
- **Cyclonic wind speed measurement.** The sparse network of wind-monitoring stations around cyclone regions of the country should be improved. This would provide much-needed validation for probabilistic risk models attempting to determine accurate cyclone risk calculations, and would provide better guidance for the determination of wind speed multipliers in cyclone events (see below).

- **Wind speed multipliers.** In general, the wind speed multipliers prescribed in the standard were developed for large-scale synoptic type wind storms. These storms differ from tropical cyclone in structure; therefore, it is reasonable to assume that the effect on wind speed profiles (accounted for in the standard by multipliers) will also differ. Throughout the world, there is a lack of understanding of this area of wind engineering. Further research is recommended (J Holmes, pers. comm., 3 December 2009).
- **Internal pressures.** In cyclone regions, it is a requirement that all buildings be designed for full internal pressurisation. This is not the case for housing in non-cyclonic regions. However, the subsequent increase in loading that occurs when an envelope breach occurs is identical, irrespective of what type of wind storm induces it. The necessity for enforcement of design for full internal pressurisation in non-cyclonic regions should be investigated (Walker 2004; Leitch et al. 2009).
- **Roller doors.** In almost all post-wind event damage assessments, there are reported cases of roller door failure. Failure of a roller door often leads to the scenario where a dominant opening exists on a windward face that was not accounted for in the design of the building. The specifications for installation of domestic garage doors should be tested for their adequacy (Leitch et al. 2009).
- **Developing a strong envelope.** The main goal of many post-Tracy modifications to the wind standard was to ensure the roof was not lost from the building. The loss of roofing material that occurred during Tracy was a primary cause of progressive failures that occurred. In principle, the wind loading standard (AS1170 Part 2) sets out two acceptable scenarios for a building to effectively keep its roof on. First, it can be designed to withstand (or at least increase the chances of withstanding) any envelope penetration by designing potential openings to withstand impact from flying debris through use of, for example, impact-resistant glass or window protection. Second, a building can be designed for full internal pressurisation loading if the resilience of potential openings cannot be ensured (design for full internal pressure is a requirement for housing). The result of both design methods is that the roof stays on the building and structural integrity is maintained. However, the second case leaves a structure open to the elements where water ingress and the danger of flying debris entering the building are significantly amplified. This scenario potentially increases the losses to an occupant due to increased contents damage. With time, this is becoming more of an issue, given that the ratio of contents to home value is increasing. A cost-benefit analysis should be performed to assess the consequences of allowing envelope penetration. Innovative methods for window protection should also be investigated, and studies into the safety implications of allowing debris to enter buildings should be conducted.
- **Thunderstorm winds.** Though not discussed in this report, the wind standard requires further specification for design against thunderstorm wind gusts. At present in the Australian (and almost all worldwide) standard, atmospheric boundary layer wind characteristics are applied for the design of buildings in regions where thunderstorm wind gusts produce the design wind speed. This is generally the case because the wind engineering community does not understand these phenomena with enough certainty to include them in its standards. This should be rectified through further research, both in laboratories and at full scale.

Despite this list, it is still the case that the wind-resistant provisions developed and enforced in this country are among the best in the world. To ensure this continues, increased funding is required for research and innovation in a field that has received little over the last 20 years (Power & Pearce 2007).

It should also be remembered that even if compliance to the wind standard is achieved and the engineering performs to expectations, building failure may still result if wind speeds exceed design strength. The decision about the level of safety that is suitable is a public safety decision and must be made by a public body, in this case the Australian Building Codes Board. These decisions extend beyond the scope of this report, but we note that there is always a trade-off between building cost and likelihood of exceeding building design strength. More extreme wind speeds are certainly possible within the bounds of natural variability, and may in the future be aggravated by global climate change. At least for the immediate future, current wind standard specifications are considered acceptable.

Storm surge

Cyclone Tracy was a wind event. Despite the potential for storm surge and flooding accompanying tropical cyclones, these perils were not significant in Tracy. Given that this report is a case study on Cyclone Tracy and the specific lessons learnt from that event, we describe the impact of a single cyclonic event and the potential impact of similar (i.e. wind) events. This report does not attempt to deal with *all* cyclonic events and all hazards – speculating about lessons that *could* have been learnt had surge or flooding been an issue lies outside the scope of this study.

Notwithstanding these observations, the issue of water inundation (rainfall or surge) is extremely important and must be addressed by engineers designing homes to withstand the impact of climatic extremes, government agencies specifying appropriate land-use regulations and emergency managers determining appropriate disaster-management strategies.

Improving structural resistance to wind loading does not implicitly improve a structure's resistance to storm surge or wave action. Specification of wind resistance changes have, however, always been done in a way that does not *increase* the surge risk. For example, in-residence shelters are not widely mandated because although these rooms may ensure safety during high winds, they would be highly inappropriate if the building were located in a surge zone.

It is important that the difference between wind resistance and overall cyclonic resistance is understood by those living in cyclonic regions. Where surge is a risk, this hazard must be explicitly designed for (i.e. water and wave loading, appropriate floor levels) and appropriate evacuation procedures put in place if structural safety cannot be assured. Unlike wind loading, where a structure is almost immediately safely occupiable if it survives the passage of a storm, even if a structure withstands the impact of surge or flooding, it is likely to be unfit for occupation because of retained water and all the associated physical and biological hazards that go with this. This being the case, a home may not be a suitable refuge even if designed to withstand the physical storm loading. In these cases, life preservation can only be assured through evacuation.

A corollary to this is that the need for evacuations can largely be ignored outside of surge zones as long as the structural integrity of shelter (including housing) can be assured. It was the general consensus of those interviewed during this research that current wind resistant regulations ensure this, not for all possible events but to a level of risk deemed appropriate by state authorities.

6. The cost of Cyclone Tracy

6.1 Introduction

The first natural disaster event in Australia for which we have credible estimates of insurance industry losses is the 1967 Hobart bushfires. At the time, the insured loss from this event was $14 million. During the early 1970s, though, Cyclone Ada in the Whitsunday Islands caused an insured loss of $12 million, Althea led to $25 million in losses in Townsville, Madge caused $30 million in losses to parts of Queensland, the Northern Territory and Western Australia, and the 1974 Brisbane floods, caused by Cyclone Wanda, led to the largest loss to date with an insurance bill of $68 million.

Losses from the 1974 Brisbane floods were greater than the combined loss of the three cyclones that had occurred in the previous few years, so this event came as a significant shock to the insurance industry, leaving many questioning its capacity to deal with natural disasters (Walker 2009). Walker (2009) suggests that at the time there was little understanding of the true exposure, and that maximum estimated event losses were often calculated by simply taking the largest previous loss and multiplying it by a factor of two or three.

Despite the significance of the 1974 Brisbane floods, Cyclone Tracy would eclipse all previous events and set a new benchmark for the industry's perception of likely losses, not only in Australia but throughout much of the insured world. The following discusses the implications that this event has had on the insurance industry and its capacity to deal with events of this nature today. Much of what follows is taken from Walker (2009).

6.2 The cost of Tracy

According to the Insurance Council of Australia's (ICA) Natural Disaster Event List, Cyclone Tracy cost the insurance industry an estimated $200 million.[1] Of this cost, approximately 38% was borne by the insurance and reinsurance industries within Australia and the remainder by foreign reinsurance companies (Cole 1977). As reported in Section 6.2, this is the estimated cost to the insurance industry and does not reflect the overall economic cost of the event to Darwin, its people or to the Commonwealth.

At the time of Tracy, Darwin had some unique features that will have influenced the insured loss for the event. This issue was addressed in Section 6.1, but is further expanded here. The three significant factors germane to estimating the cost of Tracy are changes in building ownership that have occurred in Darwin since 1974, the issue of underinsurance and the role of post-disaster inflation (demand surge) at the time of the original event. These factors are discussed briefly below.

6.2.1 Change in ownership

When Tracy hit Darwin, a significant number of buildings were owned and occupied by the government. In 1974 the government owned approximately 40 per cent of all housing (the total number of houses was approximately 8000), and also owned about 20 per cent of apartments (total number approximately 3000). As is general practice, the government self-insured its buildings, and therefore did not utilise private insurance to cover its risk. This means that no losses to government buildings are accounted for in the $200 million insured loss figure.

Today, almost all housing is privately owned and only a small percentage of apartments are still owned by the government. In 1974, the government also owned and occupied a small percentage of commercial and industrial buildings (5 per cent), whereas today the government leases all the buildings it uses and so has almost zero ownership of the total building stock (Walker, pers. comm., 28 October 2009). What this means is that with the higher private ownership of buildings today, we must assume that the penetration of private insurance will be much greater and in the event of a recurrence insured losses would surely be greater. An attempt to quantitatively describe this change in ownership is made in the main document.

6.2.2 Under-insurance

An ASIC report (Australian Securities and Investments Commission 2005) suggests that building contents are systematically under-insured because of an ignorance of the true value of these items. This was the case during Tracy and remains true today. This said, it is unlikely to be a significant factor is deriving a normalised loss value for the event, but does highlight a problem that exists for building owners.

6.2.3 Post-disaster inflation

At the time of Tracy, buildings were insured for the cost of their replacement under normal working conditions. In the aftermath of disasters, however, this value may be significantly less than what the actual replacement costs will be. One reason for this is that the cost of materials and labour often rises because of the need for these to be brought in from other locations. The result is that there is a significant increase in the cost of reconstruction relative to the cost of labour and materials before the event. The isolated location of Darwin meant that post-disaster inflation was a significant issue for the reconstruction of the city, with house prices increasing by approximately 100 per cent to between $35 000 and $45 000 over the pre-Tracy cost of $20 000 to $25 000 (Darwin Reconstruction Study Group 1975; Cole 1977). Only part

[1] Emergency Management (2006) reports the insured loss of Tracy as $837 million. This appears to be a quasi-normalised figure to 1993 values.

of this jump (approximately $5000) can be attributed to the increased building cost imposed by more stringent wind-resistant design (G Reardon, pers. comm., 5 November 2009; Cole 1977).

Post-disaster inflation is variable between locations and different types of disasters. Inflation is also dependent upon the state of the building industry at the time. The inflation observed during Tracy, however, was much greater than could be expected in any other, more accessible location. Importantly, the increased strength of buildings in respect to wind loading, and thus the significantly lower expected damage, should mean that post-event inflation would be more constrained in the event of a repeat of a Tracy-like event. Walker (pers. comm., 28 October 2009) suggests a value of 20–30 per cent. If more people start taking out policies that account for post disaster inflation, however, insured losses will increase systematically.

With these points under consideration, Walker (2009) suggests that the true total cost of Cyclone Tracy was of the order of $500–$600 million (in 1974 dollars). This value includes $200 million paid out by the Commonwealth to rebuild government homes and pay assistance grants.

The Commonwealth Bureau of Transport Economics (BTE) also attempted to estimate the total economic cost of Cyclone Tracy in 2001 values, albeit with the caveat of significant approximation (Bureau of Transport Economics 2001). This report attempts to account for direct and indirect cost as well as attributing monetary values to the loss of life and injury (intangible cost). In doing this, it was found that the direct cost of Cyclone Tracy (1974 dollars) was approximately $330 million, the indirect cost approximately $80 million and the intangible cost approximately $27 million. The combined direct and indirect cost of $410 million is roughly comparable to Walker's estimate of $500–$600 million, again indicating a true cost of the event in excess of twice the insured losses. The BTE also attempts to normalise its loss data to predict the true cost of a recurrence today (1999 in this case). Unfortunately the approximately $1800 million value at which it arrived used CPI to update the estimated costs of both destroyed and damaged homes to 1999 and then assumed zero inflation for the years to 2001. In other words, considerable increases in wealth and population were neglected (Crompton & McAneney 2008). This being the case, it is difficult to have much confidence in the figures' normalised value.

6.3 Insurance response to Tracy

Much of this section is drawn reasonably faithfully from Walker (2009), who to the knowledge of the authors is one of the few to have commented on the insurance response to Tracy. However, we begin with Cole (1977) who reports: 'As far as I can determine, Insurance Companies rose to the occasion in the Darwin situation.'

Dawn Lawrie (in Cole 1977) suggests of the insurance companies:

> Some were very good and some were dreadful … the insurance companies hang out and hang out until you are desperate for the money and offer you half of your entitlement and because you are desperate you take it … after the cyclone some companies demonstrated their avaricious and wrong attitude by intensifying that type of activity.

The largest complaint seemed to be related to the effects of post-disaster inflation not being accounted for in insurance policies. This meant that even when insured homes were fully paid out, the home owner was left to cover approximately half the reconstruction costs. For uninsured home owners, the government passed the *Darwin Cyclone Damage Compensation Act* in May 1975, which allowed owners/occupants to claim 50 per cent of the pre-cyclone home and contents value up to respective limits of $25 000 and $5000 from the government purse. Although politically this was the right thing to do, it also provided a free form of insurance and a disincentive for people to cover their personal exposure to extreme events. There will, of course, always be those who cannot afford private insurance, but given that the government allocation was not means tested, those who could have afforded insurance but chose not to take it were not isolated.

Today, some insurance companies offer the option of insuring for post-disaster inflation. As an example, at the time of writing, several insurance companies (including some operating in

Darwin) were offering an optional extra to insure for coverage of up to 30 per cent higher than the insured cost of a home. Of course, this will be recouped through the additional charge to a customer's premium, but it clearly indicates the industry's acknowledgement of the risk.

Cyclone Tracy had an impact on both the local insurance industry and the international reinsurance industry. This occurred because the magnitude of losses experienced was far in excess of what either of these industries felt the probable maximum loss (PML) could be for a natural catastrophe in this country (Walker 2009). Although no major failures occurred, many insurance companies were stretched significantly, with reinsurance levels exceeded in some cases and reserves required to fulfil payments. For the reinsurance industry, the level of cyclone risk in Australia was increased significantly, and with it so too were reinsurance premiums paid by insurers. The increased premium, however, was not only to cover the increased level of risk, but – as was the practice at the time – for the reinsurance companies to recoup the money paid out to insurers over a period of several years.

Just prior to Tracy, and based on the run of insured losses during the early 1970s, the insurance industry declared that some of the hazards it was currently covering were, in effect, uninsurable (Walker 2008). To investigate this further, a committee was set up to explore the feasibility of developing a natural disaster insurance scheme backed by the Commonwealth. This investigation led to the realisation that under the current system of insurance, the risk of both flood and earthquakes meant the nation was uninsurable. Cyclones were a notable exception to this list. The investigation recommended that the Commonwealth set up a fund so that, in the event of a major disaster, any shortfall not covered by reinsurance would be picked up by government funds. Funding for the scheme was to be through a levy on all general insurance policies. The reasoning for a scheme such as this was to guarantee that, in the event of a major disaster, the insurance system as a whole remained solvent (Walker 2008). This recommendation was made in October 1974.

Walker (2009) reports:

> How much notice the government would have taken of the committee's suggestion if Cyclone Tracy had not occurred will never be known. In the aftermath of Cyclone Tracy, and its severe impacts on many insurance companies, the government took little convincing that it was not in the national interest to expect the private insurance industry to bear such risk and thus put the whole insurance industry at risk of insolvency.

So in the aftermath of Tracy, a working party was put together and several years of intense research across a wide range of industries ensued. This was an important period for disaster management in Australia because it alerted the insurance industry to the wealth of expertise in the country's universities and research organisations. To this point, the industry had been acting in isolation, but it rapidly became aware of what these researchers did and how they could help manage risk more efficiently. Since this time, the insurance industry's dependence on scientific and technical expertise to facilitate better financing of catastrophe risk has increased continuously (Walker 2008). Walker (pers. comm., 28 October 2009) does, however, suggest that this partnership is not as strong as it should be.

Despite all the good work, no natural disaster scheme eventuated. This seems to have occurred because in the six years following Tracy, the absence of any significant insurance losses allowed insurance companies to replenish their reserves, and allowed the general public to adjust to higher levels of premium charged by insurance companies to cover the increase in reinsurance costs (Walker 2008). The decision not to implement a national disaster scheme was aided by changes in government attitudes on its role in private industry (Leigh et al. 2009), with the then Treasurer, John Howard, citing reasons including that 'the scheme would be inappropriate on budgetary, technical and insurance grounds' (Howard 1979) and that

> such a scheme would be inconsistent with a basic tenet in [the government's] political philosophy – namely that governments and government authorities should … avoid intervention in matters that can be left to the private sector.

Governments have come and gone since then, but the 'hands-off' approach remains and there is still no nationally uniform approach to natural disaster insurance. This, in effect, has meant that the insurance industry has had to deal with the issue itself – and has felt that it could.

6.4 Insurance today

As discussed in the previous section, the insurance industry has become increasingly dependent on science and modelling to better manage its exposure to natural catastrophes. In essence, what science has done is allow the insurance industry to make more rational decisions about its exposure to risk and the methods it uses to manage this risk through reserves and reinsurance.

The first major improvement came with the development of the zone accumulation method in the late 1970s. This method took scientific information about a specific hazard to determine zones that could be impacted by a single catastrophic event. Within each zone, an estimate of the PML could be calculated for a given level of event and be presented as a PML factor – which is simply the ratio of the event PML to the total insured value of the zone. Using this information, insurance companies could assess their risk in a particular area and purchase reinsurance based on this information. This method also allowed premiums paid to insurance companies to be aligned with the risk at a specific location, meaning that individuals began to pay more appropriate prices for their exposure to hazards. This was in contrast to the historical approach, where all people over large areas paid identical insurance premiums, with those in relatively unexposed areas covering some of the risk of those in more exposed locales (G Walker, pers. comm., 28 October 2009). For over 20 years, the zone accumulation method was the mainstay of insurance company catastrophe loss risk management in Australia, and is still used in many countries around the world (Walker 2008).

The next improvement came in the early 1990s, when GIS-based catastrophe risk models began to be used widely. These models use statistical information about hazard events and mathematically simulate long-duration synthetic data sets. These models are ever evolving, and with the advent of faster computing systems continually allow more detailed scientific information to be included in their calculations. The advantage of using catastrophe models over simply analysing historic data sets, such as in the zone accumulation approach, is that whole-of-portfolio losses can be suitably determined, leading to more appropriate levels of reinsurance purchase and less fluctuation in reinsurance premiums. Another product of the introduction of catastrophe models is, in theory, a more precise estimate of localised risk and the ability to price exposure as such.

In very recent times, alternative risk-transfer products have been developed to complement reinsurance in high-risk concentration regions where reinsurance is prohibitively expensive (e.g. hurricane- and tornado-prone areas of the United States). For Australia, however, Walker (pers. comm., 28 October 2009) suggests that reinsurance is a suitable mechanism to cover most catastrophe scenarios, given that on a global scale our PML is relatively small.

Walker (2008, 2009) concludes by saying:

> One consequence of Cyclone Tracy is that Australians began paying a much larger amount of money each year for protection from damage from catastrophic events through insurance premiums … Australians began paying a more realistic price in relation to the risk.

with the further observation:

> Had Cyclone Tracy not occurred the Australian insurance industry would by now have been using technical expertise, but instead of being a worldwide leader it is more likely that it would have been a follower.

7. Tracy today

In this section, we review two studies that attempt to estimate the impact on Darwin if Cyclone Tracy were to recur in Darwin today. The first, a study by Crompton and McAneney (2008) of natural disaster losses since 1967, involves the normalisation of insured loss data from the Insurance Council of Australia's Natural Disaster List (Insurance Council of Australia 2009). The process attempts to normalise the insured monetary losses of the day with what the expected loss would be given present societal conditions.

The second study, Arthur et al. (2008), employs the Geoscience Australia statistical tropical cyclone loss model to recreate Tracy's path. Using current building stock information and estimated wind speed/damage relationships, the extent of building damage under a repeat event is predicted. This study focuses on building losses and reports results as a change in damage ratios (Section 4.1), as for the DHC damage survey.

7.1 Normalised insurance loss

The Insurance Council of Australia's (ICA) Natural Disaster Event List puts the insured loss from Cyclone Tracy at $200 million. This nicely rounded number is an estimation based on reported insurance losses, but is not a representation of the total economic cost of the event (many of the buildings were government owned and would have been included in this figure). In the following analysis, the assumption is made that insurance companies paid out to the limit of the policies rather than fully addressing the effect of demand surge that, in effect, almost doubled the cost of rebuilding.

The objective of Crompton and McAneney (2008) was to normalise insurance industry losses due to meteorological disasters since the beginning of the ICA database, 1967. By doing this, they estimate what a repeat event would inflict given 2006 societal conditions. As such, Cyclone Tracy was only one of 156 weather-related hazard events in the database and, as the authors were aiming for a standard simple-to-apply methodology for all of these, they deliberately did not seek event-specific adjustments. Nonetheless, given the iconic status of Tracy and its importance in terms of historical losses, some re-evaluation of this event is relevant here.

The normalisation procedure begins with the ICA loss value and applies factors to account for changes in the number of occupied dwellings ($N_{i,j}$) and in the average nominal value of new dwellings ($D_{i,k}$, on a state basis) since the time when each event occurred. In the case of tropical cyclones, a further adjustment, B_{tc}, was applied to account for increases in structural resilience due to changes adopted in the Australian wind loading standard. This tropical cyclone adjustment is based on the proportion of the losses attributable to wind loading, the maximum event gust wind speed, the proportion of structures in the given area that utilise post-Tracy wind-resistant design and the relationship between wind speed and the proportion of destruction derived by Walker (1995). In the original work, a blanket assumption was made that wind-resistant design was introduced across all cyclone-prone regions in 1981. As discussed already, this does not apply to Darwin, where implementation began during the reconstruction efforts.

The normalised loss value for a given event is calculated using:

$$L_{06} = L_i \text{ x } N_{i,j} \text{ x } D_{i,k} \text{ x } B_{t,o}$$

(2)

where L_{06} is the normalised insured loss in the year 2006, and L_i is the insured loss at the time of the event (1974 in the case of Tracy). Results for Cyclone Tracy are given in Table 4:4 and show a normalised value in 2006 of $3650 million. Table 4 also shows that if we were to ignore the additional tropical cyclone adjustment, the estimated loss is roughly doubled to $7140 million. This highlights the significant improvements made by the introduction of wind resistant provisions in the Australian Standard.

Table 4: Normalised losses for Cyclone Tracy

Wind damage	100%
Pre-1981 residential building distribution	
1974	100%
2006	44%
Notional maximum gust speed at landfall	61 m/s
Residential building loss ratio	
Pre-1981	78%
Post-1981	10%
Original loss (1974)	AUD$200 million
Normalised loss (2006, excluding B_{tc})	AUD$7140 million
Normalised loss (2006)	AUD$3650 million

Source: Crompton & McAneney (2008).

Given the previous discussion, an attempt is made to improve upon the Crompton and McAneney (2008) estimate for a repeat of Tracy by making some of the broad assumptions made by the authors more Darwin-specific (refer to Appendix 2 for a wider discussion of the following points). There are still some significant simplifications in the updated approach, but it is felt that this new analysis is more representative for this given case.

First, since 1974 the extent of government ownership of housing in Darwin has changed significantly. As discussed in Section 3.2, in 1974 approximately 40 per cent of homes and 20 per cent of flats were government owned and therefore not insured through private insurance. Thus insurers were spared significant losses as the government self-insured its assets against catastrophe losses.

To get a rough idea of how much more this event might have cost insurers had the government not been such a significant player in the building market (as it isn't today), the original $200 million can be adjusted and the normalisation of Crompton and McAneney done on this updated value. In particular, we know that the government paid out some $310 million in total to cover the cost of rebuilding government-owned buildings (about $250 million) and also in special payouts for those without insurance (about $60 million) (Cole 1977). The former would have included the effect of demand surge via an increase in the costs of goods and materials, which has been estimated by Walker (2009) to be around 100 per cent. Payouts to non-insured were capped at 50 per cent of the pre-Tracy home and contents values, however, so would not have been inflated by demand surge. In an attempt to bring these values to equivalent insured values (i.e. value of building without demand surge), crudely using the 100 per cent inflation value, the $250 million is reduced by half to $125 million, while the $60 million is doubled to $120 million to account for the 50 per cent cap on government payout (this now assumes 100 per cent of property owners have taken out insurance). Summing these two and combining with the original $200 million insured loss, a rough combined figure of $445 million is found for a notional insurance property loss assuming dominance of the private sector. This is a very coarse assumption, but given all the other uncertainties inherent in this kind of calculation it is not unwarranted.

A second issue that will influence the normalised loss is that a significant proportion of Darwin's housing population was rebuilt in the period between 1975 and 1981 (the latter being the threshold year used by Crompton and McAneney (2009) for the 'national' implementation of wind-resistant design); thus the percentage of buildings utilising the wind-resistant standard in the original analysis will be severely under-estimated. According to Arthur et al. (2008), the percentage of current housing in Darwin *not* utilising cyclone wind-resistant design is approximately 1 per cent. The 'pre-1981' percentage given in Table 4:4 is therefore updated to represent this.

A third issue that we do not address here is that of the vulnerability curves used by the authors. The use of a single curve for this analysis is another approximation, given that retrofit homes, those constructed between 1975 and 1980, and those built to the Australian wind standard will all have differing vulnerability curves, so are not strictly represented by the single curve used in the analysis (not to mention buildings of different design and material). However, for current purposes, use of a single curve is considered acceptable given that it is probably a reasonable middle ground for the comparatively weaker retrofit homes and stronger 1975–80 homes.

In an attempt to incorporate some of the Darwin-specific modifications, with the aid of R Crompton (pers. comm., 25 January 2010), the Cyclone Tracy figures were reanalysed with the updated insured loss and the earlier introduction of wind-resistant design considered. From this reanalysis, an insured loss of approximately $2250 million (2006 value) is calculated. The reduction from the originally estimated $3650 million is primarily attributed to the enhanced building standards being implemented in Darwin much earlier than originally considered. Comparing the modified normalised value with $7140 million estimated in the absence of any changes to the wind standard, an approximate 72 per cent reduction in potential losses is found, all of which can be attributed to the improvements in wind-resistant design introduced since Tracy.

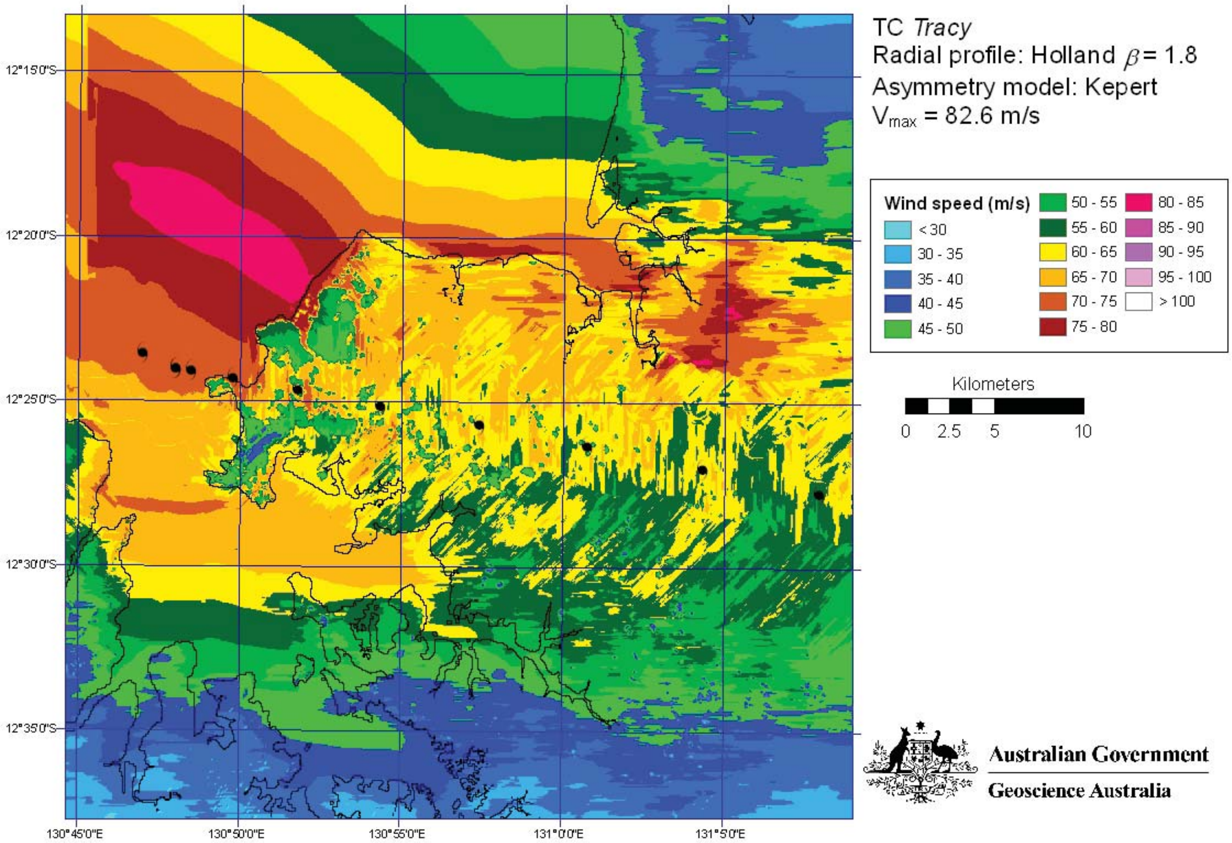
7.2 Scenario loss model

Arthur et al. (2008) used GeoScience Australia's Tropical Cyclone Risk Model (TCRM) to simulate the impacts of Cyclone Tracy on Darwin under current societal conditions. TCRM was developed to run as a statistical loss model using historic cyclone observations to develop estimates of cyclonic risk around the Australian coast (Arthur et al. 2008). Using the model in a deterministic mode, individual storm data can be input and estimates of resulting damage obtained for an individual scenario.

The TCRM follows a two-step procedure to determine the estimated wind field for the recurrence of Tracy. Using the Bureau of Meteorology's 'best track' geospatial and meteorological data for the event, the near surface wind field was developed using a two-dimensional gradient wind model along with a boundary layer wind field model to introduce asymmetry (Holland 1980; Kepert 2001). These calculations were performed on a grid of approximately 1 km resolution. Wind field multipliers were introduced into calculations at each specific location in order to incorporate the influence of terrain, topography and shielding. These multipliers serve to speed up or slow down ground-level wind speeds based on the local surface characteristics (Section 4.3), with multipliers calculated at a 25 m resolution based on the Australian wind loading standard (Standards Australia 2002). Use of engineering multipliers is not an ideal approach, as the natural conservatism written into standards leads to an over-estimation of the impact of specific features. This shortcoming is acknowledged by the authors and is in the process of being improved (C Arthur, pers. comm., 29 October 2009).

When running the model with 1974 societal conditions, Figure 22 displays the predicted maximum near-ground wind field for the duration of the event. Comparing predicted peak wind speed at the airport anemometer site with that estimated from the partial anemograph (Section 0), the prediction of 72 m/s aligns well. This is an encouraging validation for the wind field model. Assessing the remainder of the wind field, wind speeds are seen to the north of the eye track (small black symbols) to be greater than to the south, and to slow significantly as they transition to flow over a rougher surface after landfall. There are however, still areas of Darwin's northern suburbs that show wind speeds over 75 m/s, as north-westerly winds off the ocean meet relatively open land upwind of the housing. Lower wind speeds are shown to the south of the eye with several of Darwin's southern suburbs predicted to have peak wind speeds as low as 40 – 45 m/s. The influence of shielding, particularly by housing, is a prominent feature that reduces the modelled maximum wind speeds in areas of dense housing. This effect is clear in Figure 22, where localised peak velocity minima are evident in these regions.

In general, the predicted wind speeds shown in Figure 22 are as expected. However, there are some minor points that may influence localised wind speeds, and therefore – via the building vulnerability curves – damage prediction. First and foremost is the fact that a two-dimensional statistical model, and not an appropriately forced three-dimensional atmospheric model, is used to predict the wind field. What this means is that localised changes in the storm structure (e.g. deviations from the mean storm path and eye intensity, non-uniformity in the wind field around the eye) that may influence patterns of damage are unable to be represented. This is inconsequential when running a long-term risk model to estimate exceedance loss statistics; however, when attempting to recreate patterns of loss from a particular historical event, this may be a significant problem. In effect, the wind field model could miss 'pockets' of either high or low winds that were actually present during the real event.



Source: C Arthur, pers. comm., 29 October 2009.

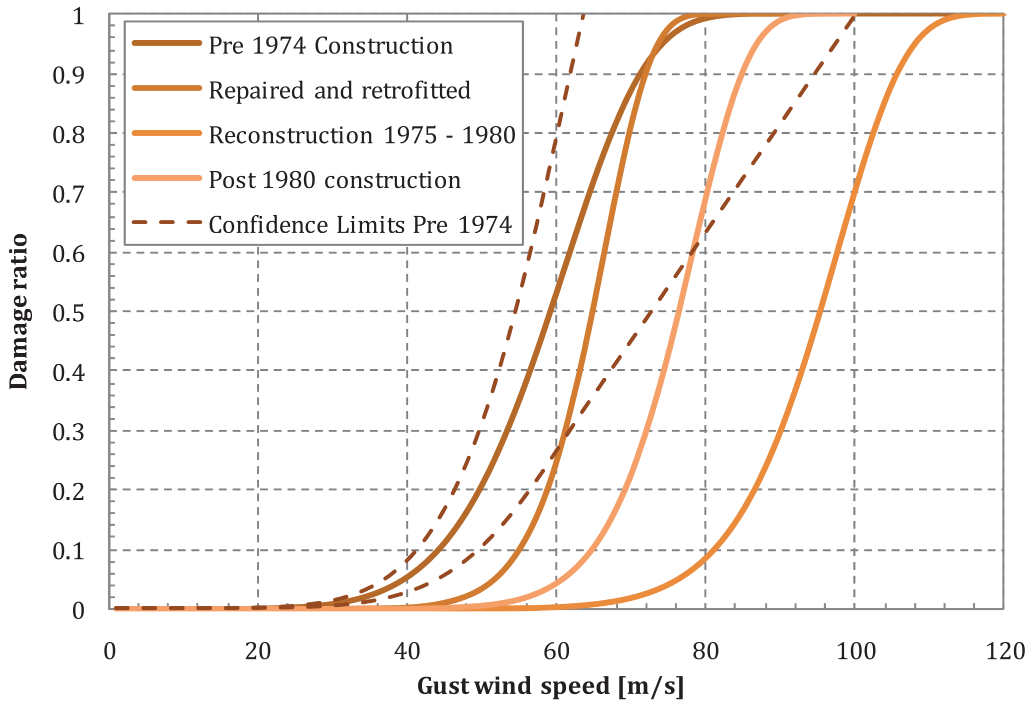
Figure 22: Estimated maximum wind speeds for Tracy under 1974 conditions using the Geoscience Australia TCRM

A second possible issue is the method used to select peak wind speeds. The approach taken was to obtain the maximum near-ground wind speed and direction for each location prior to the implementation of any of the multipliers (i.e. shielding, topography, terrain) (C Arthur, pers. comm., 29 October 2009). This means that where a non-uniformity exists in the circumferential distribution of these factors, there is the potential for an under-estimation of peak wind speeds if the chosen direction does not align with the direction of the maximum wind speed based on the combined parent wind speed and multipliers.

A third factor is the model's handling of shielding. This is a particular problem with intense cyclones where strong winds defoliate or destroy vegetation, and in the most severe cases, destroy buildings. During Cyclone Tracy, both trees and buildings suffered extreme destruction and therefore reductions in numbers. The shielding characteristics of Darwin's suburbs therefore changed significantly throughout the passage of the cyclone. The TCRM cannot allow for this temporal change in shielding, and because of this may underestimate the building damage.

The model also does not explicitly account for the impact of flying debris; however, this will to a certain extent be moderated for the fact that the vulnerability curves were based on observed damage. An issue with debris impact is that the often localised domino style destruction is effectively spread over an entire population of buildings. Again, this may not be an issue when running a statistical loss model, but for scenario modelling it means that the true spatial distribution of the damage is not reproduced accurately. When running the model for present societal conditions, the reduced level of building destruction means the effect of this, and the previous issue, will be reduced significantly.

As in the normalisation method discussed in Section 7.1, wind speed is related to building damage through vulnerability curves (Figure 23). For the 1974 scenario, only a single loss curve is applied, but given the significant changes made to building design and construction since that time, a suite of curves are utilised for the 2008 scenario.



Source: Arthur et al. (2008).

Figure 23: Vulnerability curves used for the scenario loss model. Only the average curves were used in the scenario analysis discussed in the text.

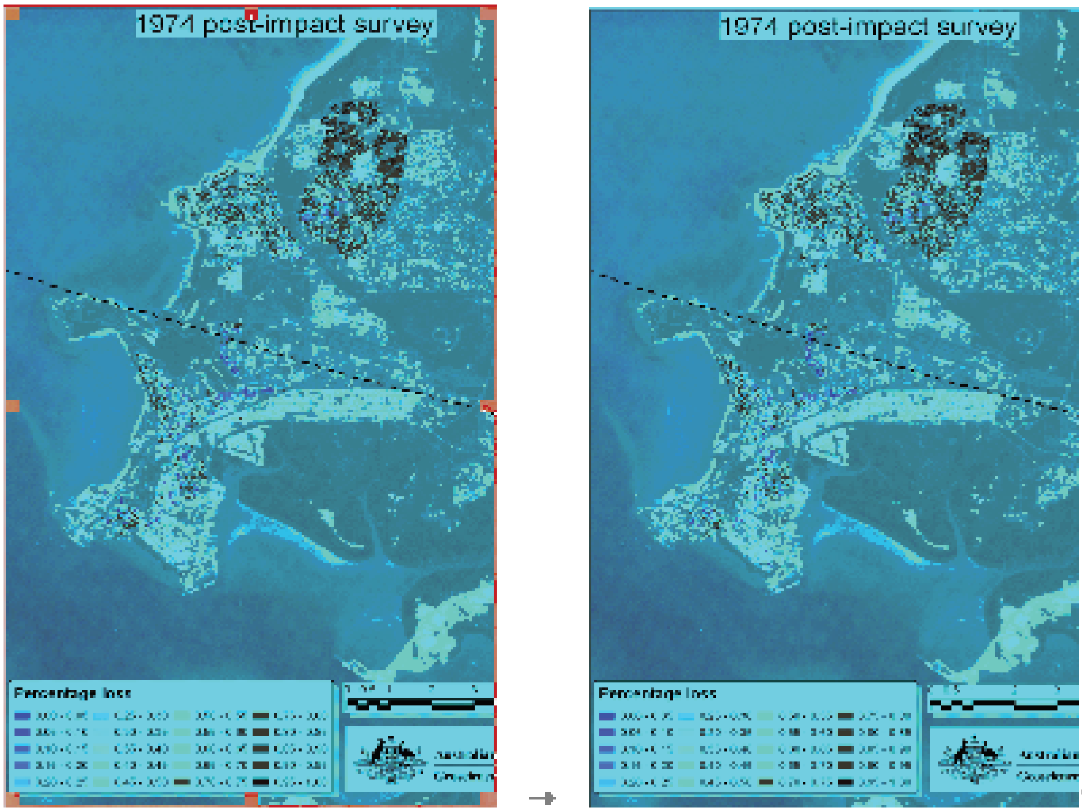
The following categories were used for describing the different building types:

1. pre-1974 construction
2. repaired and retrofitted
3. reconstructed 1975–1980, and
4. post-1980 construction.

The appropriate assignment of vulnerability curve to an individual structure for the 2008 scenario was done based on GeoScience Australia's National Exposure Information System (NEXIS), which holds information on building location and age throughout much of the country. No sub-category classifications were made (e.g. differing façade or framing systems), with age being the single discriminating factor. There are some inherent problems with this approach, but generally, once building standards were in place, all constructed buildings – if built to those standards – should have been built to essentially fail at a similar threshold wind speed, irrespective of the construction type.

All curves were developed by a panel of wind engineers during a series vulnerability workshops run by GeoScience Australia. Due to the dearth of information relating damage to wind speed for all types of building, much of the curve development is based on the engineering judgement by the panel, particularly for the damage levels at higher wind speeds. This also means there is a high degree of subjectivity, and for this reason upper and lower confidence limits were also set for each curve. These are shown in Figure 23 for the pre-1974 curve.

Performing the scenario loss calculation for 1974 societal conditions, Figure 24(a) displays the predicted damage ratio for each building throughout Darwin. Figure 24(b) is a repeat of Figure 12, to facilitate easy comparison between the model prediction and post-disaster damage survey. Some distinct differences are noted. First, the level of damage predicted for Nightcliff and Rapid Creek is significantly over-estimated by the loss model. Arthur et al. (2008) suggest that the reason for the high values in this area is proximity to the coastline and hence high wind speeds coming off the ocean. This is physically reasonable, but does not explain the difference between the two figures. Comparing results for the northernmost suburbs (Nakara, Tiwi, Wanguri), the model under-predicts the actual damage. To the south of the eye, the loss model generally predicts lower damage values than to the north, but in several localised areas over-estimations are observed.

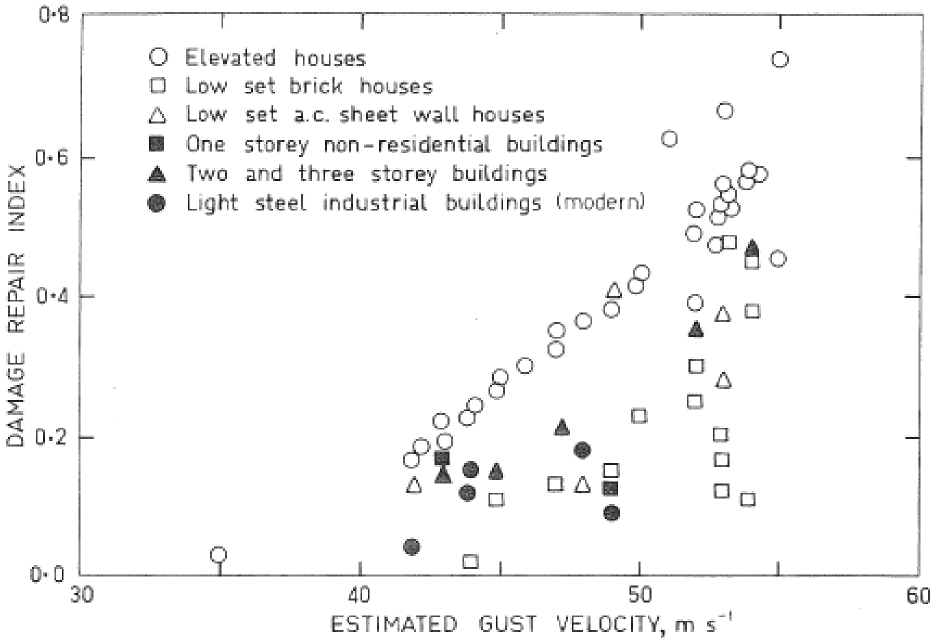


(a) (b)

Source: C. Arthur, pers. comm., 29 October 2009.

Figure 24: (a) Scenario loss prediction for damage ratios at each building location under 1974 societal conditions, and (b) post-Tracy damage survey results

Several reasons may explain the observed difference between the predicted and observed damage ratios; however, the most likely contributing factor is the use of a single vulnerability curve for all pre-1974 buildings. Just as with post-Tracy buildings, not all these structures were identical, and based on the discussion in Section 3.2, this will have influence their behaviour under wind loading (e.g. low-set brick homes performed better than elevated housing). A single vulnerability curve will systematically over-estimate damage to the more resilient structures and under-estimate losses to those less resilient. This is exemplified in Figure 25, where the results of Leicester and Reardon (1976) show the relationship between their damage repair index and maximum gust wind speed at a location. A distinct separation is seen between elevated and low-set homes.



Source: Leicester & Reardon (1976).

Figure 25: Relationship between damage repair index and gust velocity at building eaves height of a low rise building

Given the discussion in the previous paragraph, it is perhaps more appropriate to consider the scenario loss results from an average point of view, hoping that the model's over- and under-predictions will even out. There remain issues with taking this approach – for example, it assumes that the distribution of housing type is evenly distributed spatially, which is known to be untrue. Averaging the damage index over the entire building stock, the model predicts a value of 0.35. Taking the same approach to the survey data, a value of 0.56 is obtained. It is therefore clear that the loss model under-estimates the true damage.

Arthur et al. (2008) suggest one of the primary reasons for the model's overall under-prediction is the fact that the shielding multiplier does not change with time, thus allowing destroyed buildings to continue shielding those downwind. Arthur (pers. comm., 29 October 2009) also explains that the vulnerability curves used only account for the impact of small-sized debris, not larger, roof-sized debris, which caused significant damage during Tracy, but is perhaps less likely to occur on newer structures. However, the inability of the model to capture the structural characteristics of all types of buildings, and also the distribution of these, must also play a role. Issues such as loading duration and building orientation are also factors that in reality will impact the extent of damage to a given structure but will not be captured by the scenario loss model. Moreover, it is unlikely that the loss distribution for a given wind speed is symmetrical about the mean curves, and this non-linearity would weight losses towards higher values unless the sample size is large enough to recover the mean. In defence of the model, it should be reiterated that these scenario loss calculations were not the primary objective for developing TCRM, and few loss models would fare much better.

Performing the scenario loss analysis for 2008 societal conditions, the Darwin averaged damage ratio is calculated as 0.035, with a spatial distribution shown in Figure 26. A simple damage ratio comparison shows a drop in averaged damage ratio of 90 per cent. Given that the number of buildings and average building value is much greater in 2008, this value *does not* represent a 90 per cent reduction in monetary losses. Arthur et al. (2008) also highlight that because of Tracy's small size and Darwin's inland spread, many of the newer suburbs would not have experienced the full force of the wind. Therefore, to isolate the influence improved building standards have had on resilience, only damage ratios for the 1974 footprint were compared with damage survey results. In doing this, the averaged damage ratio becomes 0.052, a reduction of 85 per cent from the 1974 results. These reductions are significant, once again suggesting that the improvements made to the wind loading standard would significantly improve the structural performance in the event of a recurrence.

Source: C. Arthur, pers. comm., 29 October 2009.

Figure 26: Damage ratios for 2008 societal conditions

7.3 Implications for evacuation and safety

Despite some of the counter points concluding the previous section, Walker (G Walker, pers. comm., 28 October 2009) agrees that the improvements in building standards since Tracy would lead to significant improvements in damage ratios, and considers the 85–90 per cent reduction in average damage ratio reasonable. However, Leicester (pers. comm., 3 December 2009), while agreeing improvements would exist, believes this level of improvement too high, attributing this to the continued incorporation of human error in the construction of buildings. Irrespective of the value, all interviewees, reports and scholastic material suggest that significantly less damage to buildings would occur if Tracy were to recur today. From an emergency management perspective, the improvement in structural resilience is all-important, given that one of the primary reasons for evacuating 35 000 residents in the aftermath of Tracy was because housing for those who had lost homes could not be provided. However, if damage was largely restricted to minor failures, as the predicted 2008 average damage ratios shown in Figure 26 suggest (or even if it were doubled or tripled), the majority of housing would remain liveable and evacuation would become unnecessary. This statement is made on the proviso that power and sanitation could be ensured.

In relation to life safety and the prevention of injuries, reduced building damage through improved standards will also be highly beneficial in minimising the social impact of a recurrence of Tracy. Given the discussion in Section 4.5, two of the major causes of injury or death during Tracy were asphyxiation due to falling masonry and lacerations from roof sheeting as flying debris. In the immediate aftermath, the *Darwin Area Building Manual* was updated to reduce both the loss of roof sheeting (e.g. houses to be designed for full internal pressure loading and improved dynamically specified sheet fastenings) and to reduce the risk from falling masonry (e.g. internal and external walls to be designed to standards and much increased use of reinforced masonry). It can therefore be surmised that if people were to shelter in stronger homes, there would be less masonry fall and proportionally fewer deaths/injuries due to this and the greater resilience of cladding connections, and the specification of full internal pressure loads should proportionally reduce the amount of flying debris available for injuring those outside of buildings. Although not directly comparable, the more recent occurrence of Cyclone Larry – a marginally weaker event (peak gust at landfall estimated at up to 230 km/h (63 m/s)), which impacted an area where at least one-third of homes were built using some form of post-Tracy wind-resistant design specification (Henderson et al. 2006) – resulted in no fatalities and only approximately 30 reported injuries (Emergency Management Australia 2006), which suggests that stronger homes can increase life safety.

7.4 Will structures stand up to a repeat of Tracy?

This report demonstrates that the wind performance of structures – particularly housing – has been significantly improved as a result of building regulations introduced following Cyclone Tracy. Geoscience Australia's scenario analysis (Arthur et al. 2008) suggests an average per home reduction in structural damage of approximately 85 per cent from levels observed after Tracy. Although this result is gratifying, in the absence of a recurrence of a similar-strength event, it is difficult to validate this assertion, and thus far Darwin has been spared such a test. However, while the estimated improvement was considered reasonable by experts interviewed for the case study, it was acknowledged that human error in construction, degradation of structural components over time and the level of certifier efficacy may act to reduce this value somewhat.

Nonetheless, the history of cyclonic impacts from other parts of the country provides some confidence in the performance of new construction standards and, in this respect, we compare the levels and patterns of damage observed in the Townsville-Innisfail region after cyclones Althea in 1971, Winifred in 1986 and Larry in 2006.[2] Although these comparisons do not include structures built to the standards of the strict post-Tracy *Darwin Area Building Manual*, they provide a conservative estimate of the improvements made in Darwin – that is, construction improvements in Darwin are expected to be better because of the large number of structures built during the Darwin reconstruction.

Of these events, Cyclone Althea made landfall prior to any stringent regulation of cyclone or building provisions for housing construction; Cyclone Winifred made landfall approximately five years after wind-resistant housing regulations were mandated in Queensland; and Cyclone Larry occurred another 20 years later. Peak three-second gust wind speeds for Cyclones Althea and Winifred were approximately 55 m/s, while Larry is estimated at 65 m/s.

Comparing the area-wide proportion of structures that suffered 'significant damage' during Althea and Winifred, James Cook University (1972) and Reardon et al. (1986) found a

[2] Further examples for Western Australia can be found in Boughton & Falck (2007) and Reardon et al. (1999) for Cyclones George and Vance and for the Northern Territory in Henderson & Leitch (2005) for Cyclone Ingrid.

reduction from approximately 15 per cent to 5 per cent. Reardon et al. (1986) highlight the structural improvement to both modern (1982–86, after the introduction of cyclone resistant specification in the Queensland building code) and old buildings (pre-1982) during Winifred, and suggests:

> This [improvement in wind resistance] can be attributed to improvements in the fastening of the roof cladding of older buildings undertaken since Althea and the much better performance of houses built in accordance with the new cyclone resistant building regulations.

Reardon et al. (1986) continues,

> An obvious example of the difference in performance of modern and older houses was evident at Kurrimine Beach where, within approximately one kilometre, there are a group of houses 15 to 20 years old and another group of modern houses. It is estimated that significant damage occurred to 20–30% of those older houses whereas the modern ones had damage restricted to failure of attachments such as guttering, awnings, etc. – i.e. structural damage to the main fabric of the houses was almost non-existent.

The impact of the use of an engineering-based housing wind standard is clearly evident. The almost nil structural damage to modern housing is a major improvement, and its performance is in line with expectation given the predicted peak wind gust was 10–15 m/s below the wind speed these homes were built to withstand.

Similar improvements in structural performance were seen during Larry, where approximately 17 per cent of pre-1985 housing (some of which had been renovated) suffered significant damage, whereas only approximately 7 per cent of post-1985 structures did so (Henderson et al. 2006). For the newer buildings, Henderson et al. (2006) concludes that in the cases where significant damage occurred, it was generally through inappropriate application of wind standard specifications and not a technical deficiency in the standard itself. This again points to the fact that the wind standard is doing its job.

For older buildings affected by Larry, degradation/corrosion of members and joints, as well as roof cladding and structural issues observed during Tracy (Mason and Haynes 2010), were causative factors in failure. While the repeat of structural/cladding failures in non-renovated housing is unsurprising, the significance of corrosion highlights the importance of considering structural decay over time, and not just considering strength at the time of construction.

Avoiding decay types of failures can only be achieved through smart material choices at the time of construction, and regular inspection and maintenance activities throughout the life of a structure. It is our recommendation that serious consideration be given to the implementation of a lifetime inspection and maintenance program for buildings in cyclone regions. A program such as this should require compulsory participation, given that the implications of structural failure are not localised, but dispersed to surrounding buildings due to the cascading effect of flying debris. These are public safety issues, and should be dealt with accordingly. Mandated structural inspection at the point of sale may go some way towards achieving this result.

One positive solution to structural degradation is renovation and retrofit. Henderson (2006) highlights the positive influence retrofitting had on the structural performance of roofing during Larry. In this event, roofing on pre-1965 houses outperformed those on structures built between 1965 and 1985. This improvement occurred because of the higher number of renovated roofs – often done for aesthetic or general maintenance reasons – on these homes. Since renovations were built to comply with current structural design standards, they provided greater structural resilience than older roofing construction on newer homes.

It would be wrong, however, to rely solely on this natural approach to renewal, given that renovation often only addresses the weakness in one part of the structural system – say the roof – and does not imply an upgrade of the entire structural load path. In strong events, such an oversight may have the effect of simply moving the failure point further along the structural resistance chain.

The result of allowing structures to degrade has public safety ramifications. Mandated lifetime inspections would address this point, and could be used to identify homes that require substantial retrofit or renovation. The financing of any such works would be an issue that will require further analysis and debate.

So will structures stand up to a repeat of Tracy? In short, yes. Wind-resistant standards have significantly improved since Tracy, and the application of these standards to housing construction has led to a step change in the level of safety these structures provide. All housing constructed since Tracy should maintain structural integrity in the event of a cyclone of the same strength *if built and maintained to current standards*. Evacuation therefore becomes a secondary consideration and, provided surge is not an issue, the primary focus during cyclonic events should be to ensure people are safely inside their homes or workplaces.

8. Climate change, tropical cyclones and adaptation

Thus far, we have considered the success (or otherwise) of the adaptive response to Cyclone Tracy in the context of an 'unchanged' climate. But moving forward, adaptive responses and subsequent measures will need to consider the risks associated with a changing climate. In this section, we consider the evidence that indicates the risk of increased or changed cyclone activity in the future as well as the trade-off between risks and costs that will need to be included in developing adaptation responses to climate change predictions.

8.1 Cyclone risk under climate change

A significant signal-to-noise problem exists for detection of an anthropogenic signal against large-amplitude variations in the background activity of tropical cyclones, so it should come as no surprise that modelling studies have struggled to find an unequivocal signal with the results varying between basins and models (Knutson et al. 2010). The most recent down-scaling studies, based on the ensemble mean of 18 global climate change projections (Bender et al. 2010), point to an increase in the strength of the most intense cyclones and a decrease in frequency overall by the end of the twenty-first century. The CSIRO's document *Climate Change in Australia: Technical Report 2007* (<http://www.climatechangeinaustralia.gov.au>) takes a similar view for Australia; however, as has been shown by Bender et al. (2010), projections of future cyclone activity vary widely according to the Global Climate Model used to set the boundary conditions under enhanced CO_2 conditions. We certainly expect the incidence of meteorological hazards to change with increasing global temperatures, but the exact manner in which these changes may play out in terms of cyclonic activity for Australia is currently speculative.

Despite uncertainty as to the future impact of climate change on wind speed, increasing weather-related natural disaster losses have been well documented (e.g. Munich Re 2007; Swiss Re 2010). This result is unequivocal. A recent focus of research has been the question as to whether or not an anthropogenic climate change signal is manifest in these records. After adjusting for various changes (population, wealth, inflation and building codes) known to have influenced the loss records, a process called loss normalisation, no study has yet been able to detect an anthropogenic signal across a range of natural perils including tropical cyclones and different jurisdictions (e.g. Pielke & Landsea, 1998; Pielke et al. 2008; Crompton & McAneney 2008; Crompton et al. 2010; Barredo 2009 and 2010).

Bender et al. (2010) suggest that it may be 60 or more years before any significant climate change signal is manifested in terms of cyclone activity, and thus we would expect that it might take significantly longer than this before any similar signal becomes evident in disaster losses. This being the case, the most appropriate means for reducing losses due to natural hazards come firmly back to the choices society makes about where people build and how homes are constructed. From a public policy perspective, if we are serious about reducing disaster losses, then we need better risk-informed land planning decisions and strong building codes. Any gains achieved in these areas significantly improve our position for both future extreme weather arising from climate change and natural causes. This point highlights why the improved construction standards that emerged from the experience of Cyclone Tracy are so important, and why these have been the primary focus of this report.

8.2 Trade-off between cost and risk

The issue of appropriate design wind speeds is a joint engineering/public policy issue, and should be dealt with (and funded) as such. The most appropriate people to determine suitable return periods (recurrence intervals) for specific wind speeds are engineers and meteorologists. However, societal impacts of what wind speed to use for design are an issue that has public implications and must be addressed in the public domain. At present, this responsibility is upheld by the working committee for the wind standard, determining recurrence intervals, and the Australian Building Codes Board, determining the recurrence interval to use for design.

Given the public implications of inappropriately determining the wind speed–recurrence interval relationship, it seems sensible for at least some funding for its determination and update to come from the public purse. Funding of a five-yearly review of cyclonic wind speed utilising up-to-date observational data and modelling techniques seems appropriate. A detailed peer review of analysis and prediction techniques should be required, with publication in international journals recommended.

A further issue of importance is that the return period quoted in the wind standard or the Building Code of Australia is the return period for a gust wind speed measured *at a single point*. This is quite different from the return period of a given wind speed *for an area*, such as a city. It is the latter that is of more interest to emergency planners developing disaster plans for a particular area. Homeowners are concerned primarily with the probability of their homes being affected, whereas the State Emergency Services are interested in the risk to the community. This is a consideration for all natural hazards, with the most relevant risk measure depending upon perspective and responsibilities; the likelihood of a certain level of property damage by bushfire to Marysville is different from the risk to the whole of Victoria and different again to the risk to the nation.

To pursue this line of argument, let's examine, for example, the hypothetical case of cyclones impacting a given town. If on average a cyclone impacts the town every ten years, but only affects half the town each time it hits, then the return period for cyclones *impacting the town* is ten years. If the impact location within the town were randomly distributed, then the return period of the impact *at any given location* would be 20 years – that is, assuming on average only every second cyclone impacts a given point.

It is therefore evident that the risk of the peak winds within a cyclone hitting any part of a city is greater than the risk that it will hit a given structure within that city. The risk relationship between a point in space and area is non-trivial and dependent on the area under consideration, local topography, land cover, and regional cyclone frequency and structure. Which wind speed on the wind speed–return period curve is most appropriate is again a public policy issue and must be considered by state and local authorities. A continued review and publishing of area-wide return period information, as with the point risk, should be pursued for at-risk areas of the country. This could be done relatively simply by those who conduct the former (point risk) work.

In our view, building codes and more risk-informed decision-making in relation to land planning are among the key adaptation policy options available to government under scenarios of climate change, if this country is serious about reducing losses from natural disasters. Such adaptations will also provide community resilience in respect of any aggravation of cyclones arising from the uncertain impacts of global climate change. In this respect, the Tracy case study is important in illustrating just how effective the engineering response was and how this response will avoid the need for a future evacuation of Darwin, given the recurrence of a cyclone of similar intensity. There are precious few examples in this country where we can claim to have learnt from a disaster in a similar manner.

Glossary

Report-specific terms

Average recurrence interval. *See* Return period.

Cyclone factor. Factors of safety applied to the design wind speed in modern wind standards to account for uncertainty in the calculation of these wind gusts at long return periods.

Extreme value analysis. Statistical method for describing extreme geophysical variables based on one or more of the three extreme value distributions identified by Fisher and Tippett (1928).

Eye (in relation to eye of the cyclone). Roughly circular region of predominantly calm weather at the centre of a tropical cyclone.

Gust wind speed. The greatest expected (or measured) three-second average wind speed over a predefined period.

Limit state design approach. A rational approach to the design of structures where the ultimate and serviceability limits are defined (after Holmes 2001). The serviceability limit is the level beyond which a structure, while maintaining structural integrity, will be unfit for occupation. Ultimate limit refers to the level beyond which a structure is structurally unsound.

Normalised insurance loss. Reported insured losses adjusted to account for current societal conditions. Factors included in the adjustment are, changes to the number of occupied dwellings, changes in the average value of dwellings and changes to the strength of structures due to improvements in building standards.

Permissible stress design. Engineering design approach where stresses due to the application of working loads, including factors of safety, are designed to remain below a limit that would cause permanent deformity of a structure or system.

Racking failure. Failure that occurs in walls parallel to the wind direction due to lack of in-plane bracing.

Retrofit/retrofitting. Repairing or upgrading of an existing structure to increase its resistance to a specific loading.

Return period. The average time period between exceedances of a given intensity threshold (e.g. average time between gust wind speeds exceeding a specific value at a given location). Mathematically, the return period is the inverse of the probability that a threshold will be exceeded within a given time period. For design wind speeds, return periods are generally given in years; thus an event that has a probability of exceedance of 0.01 in any one year has a corresponding return period of 100 years. Return period is interchangeable with average recurrence interval (ARI).

Saffir-Simpson scale. A tropical cyclone scale used in some regions to describe the intensity of the sustained winds within a storm. The scale was developed to provide a sliding scale of damage potential for hurricanes, including that arising from storm surge (<http://cawcr.gov.au/bmrc/pubs/tcguide/ch9/ch9_5.htm>).

Shielding (in regards to shielding characteristics and shielding multiplier). The phenomenon where an object (e.g. a true or a building) ‘shields’ a downwind building from the full force of the wind. This process is accounted for in design practice by the application of shielding multipliers that reduce required design loads when shielding objects that exist upwind of a building.

Translational speed. The forward speed of a cyclone, the speed at which a cyclone or other system moves.

Zone accumulation method. Method used by insurance companies for determining the maximum loss for a given area (e.g. Darwin) for which coverage should be bought.

General adaptation-related terms

Adaptation. Actions taken to avoid actual or anticipated impacts from climate change, or to attain potential benefits arising from climate change. Action taken in light of an event or the emergence of new information to avoid an undesirable outcome.

Adaptive capacity. The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities or to cope with the consequences. This is also applicable in the case where 'extreme' is redefined by the occurrence of a previously unexpected event.

Resilience. The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation and the capacity to adapt to stress and change.This statement is equally applicable to buildings – but of course a building can't change on its own.

Vulnerability. The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity and its adaptive capacity. This is also true for buildings, but climate change is not the only reason buildings and communities are vulnerable. Poor construction, building standards, council regulation and lifetime decay (to name a few issues) also contribute to the built environment.

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Appendix 1: Wind maps

This appendix displays the different wind maps used in successive wind loading standards for determination of design wind speeds at a point location within Australia. Wind speeds given in Figures A1.1 to A1.3 are 50-year return period three-second gusts at an elevation of 10 m, while those given in Figure A1.4 are 1000-year return period winds. Compilation and supply of all figures was by Dr John Holmes (J Holmes, pers. comm., 20 January 2010).

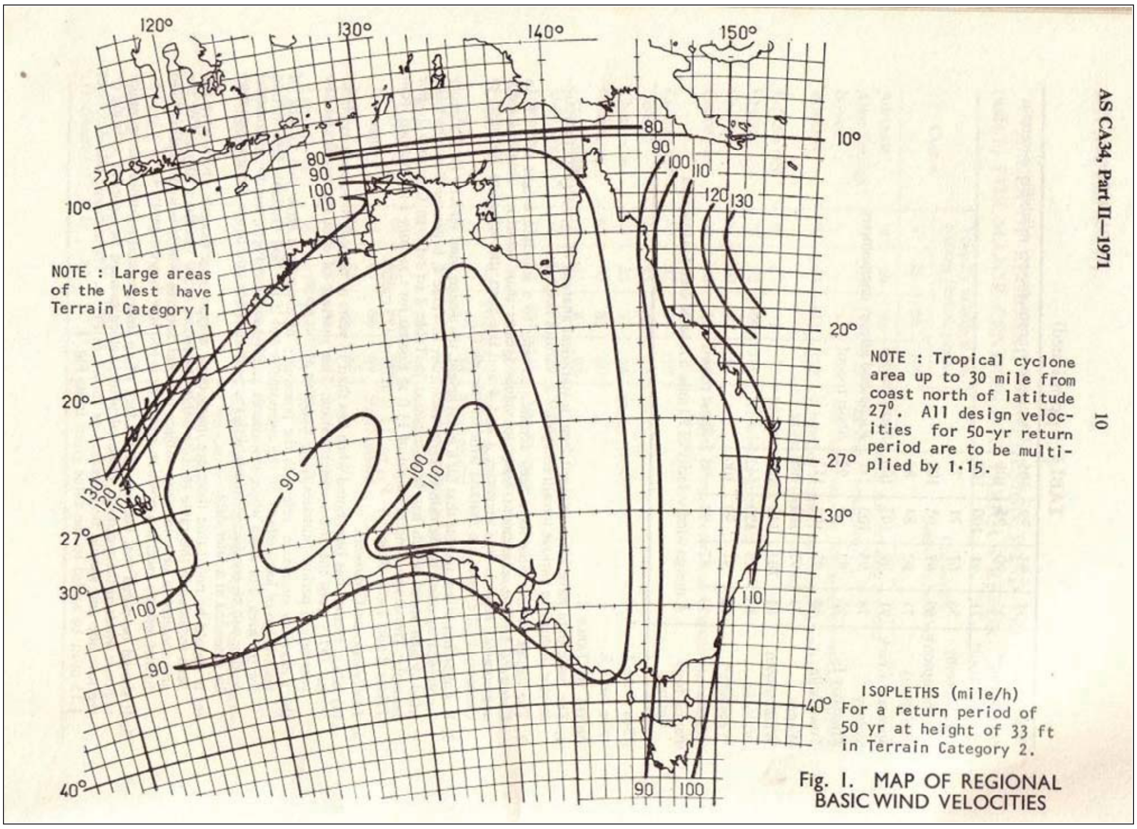


Figure A1.1: AS CA34 Part 2, 1971

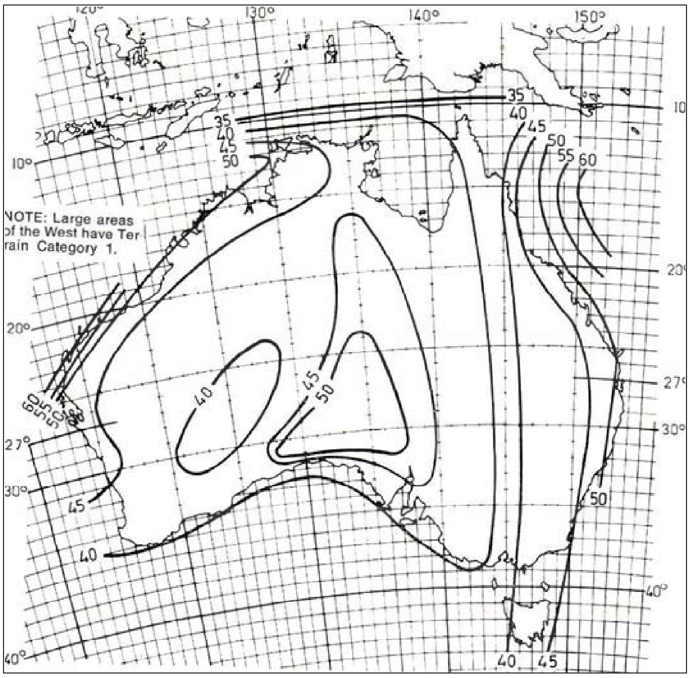


Figure A1.2: AS1170 Part 2, 1973

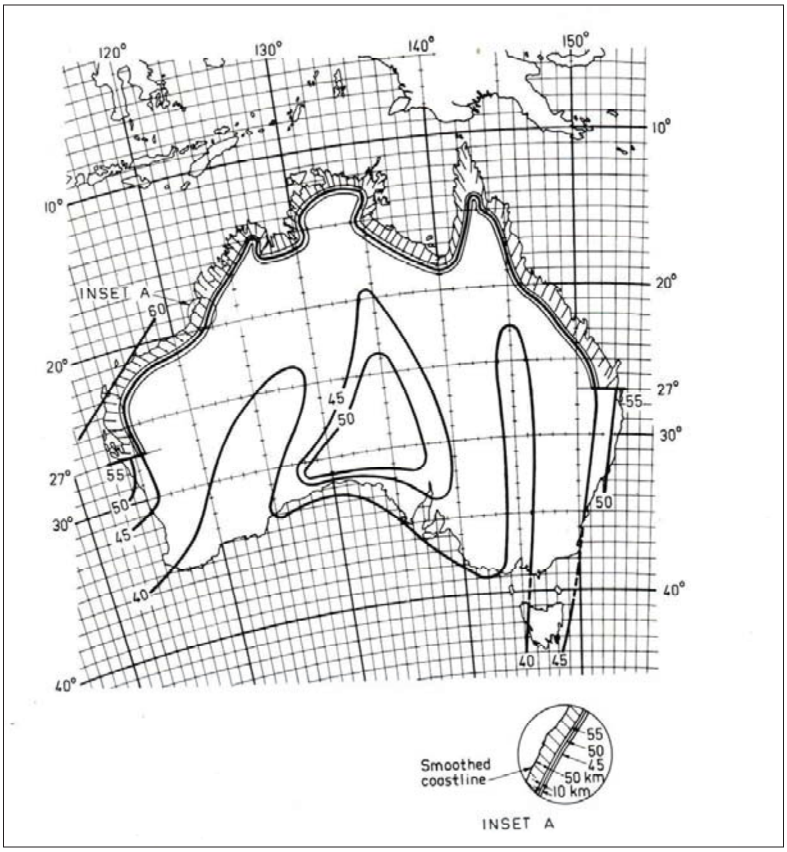
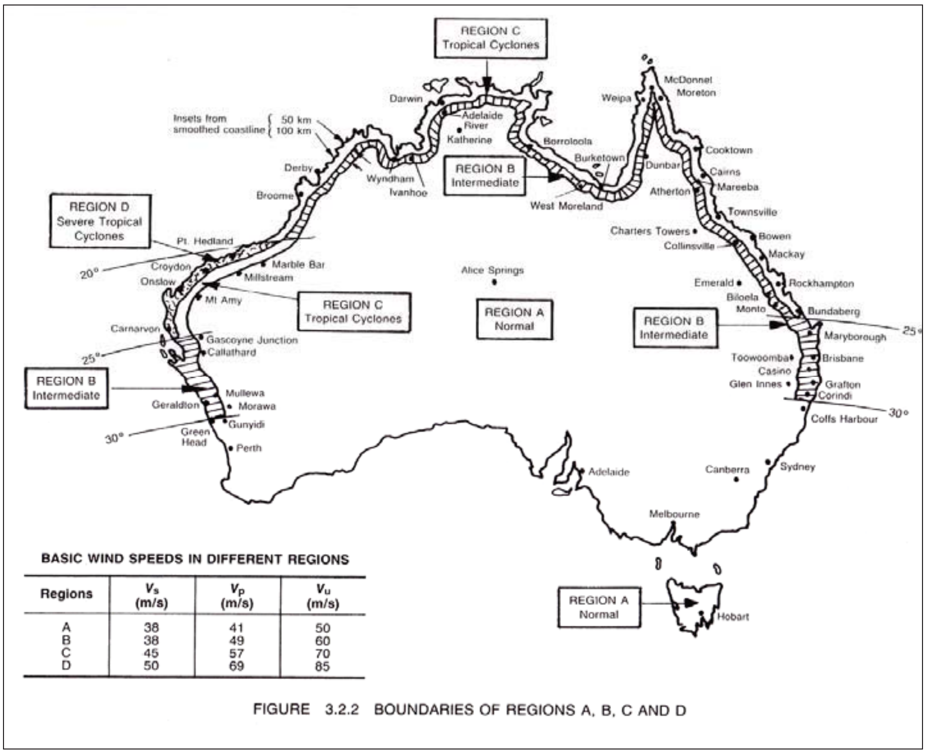


Figure A1.3: AS1170 Part 2, 1975 (remained the same for 1981 revision)



Regions	V_s (m/s)	V_p (m/s)	V_u (m/s)
A	38	41	50
B	38	49	60
C	45	57	70
D	50	69	85

FIGURE 3.2.2 BOUNDARIES OF REGIONS A, B, C AND D

Figure A1.4: AS1170 Part 2, 1989

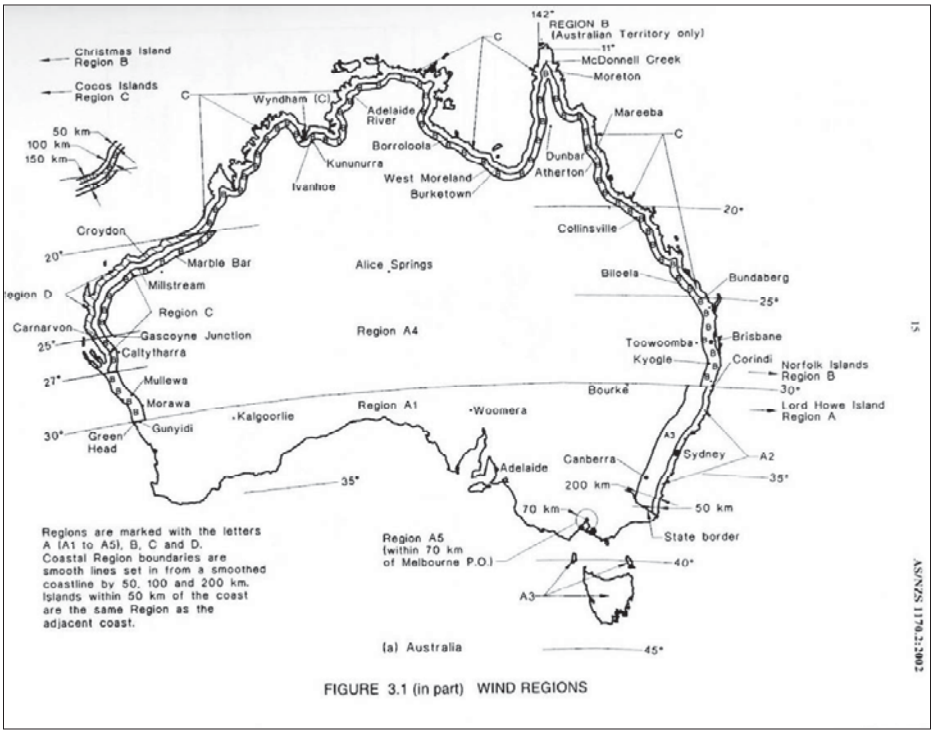


FIGURE 3.1 (in part) WIND REGIONS

Figure A1.5: AS1170 Part 2, 2002

Appendix 2: CSIRO damage survey information

This appendix outlines some the information used to determine damage repair indices for the CSIRO damage survey analysis, Table A2.1 and A2.2. The routes through Darwin used by the survey team are also shown in the figures below (B Leicester, pers. comm., 2 December 2009).

Table A2.1: Damage definitions for residential buildings

Damage class	Worst damage feature	Damage repair index*				
		Elevated houses	Low-set houses		One-storey non-residential buildings	Top floor of multi-storey buildings
			Brick walls	Asbestos cement walls		
1	Negligible	0.00	0.00	0.00	0.00	0.00
2	Missile damage to cladding or windows	0.05	0.05	0.05	0.05	0.05
3	Loss of half roof sheeting	0.10	0.10	0.10	0.10	0.10
4	Loss of all roof sheeting	0.20	0.20	0.15	0.15	0.20
5	Loss of roof structure	0.25	0.25	0.20	0.20	0.25
6	Loss of half walls	0.50	0.65	0.60	0.60	0.55
7	Loss of all walls	0.75	0.90	0.90	0.90	0.80
8	Loss of half floor	0.85	—	—	—	—
9	Loss of all floor	0.95	—	—	—	—
10	Collapse of floor support piers	1.00	—	—	—	—

$$\text{*Damage repair index} = \frac{\text{cost to repair damage}}{\text{initial cost of building}}$$

Source: Leicester & Reardon (1976).

Table A2.2: Damage definitions for steel industrial buildings

Damage class	Worst damage feature	Damage repair index*
1	Negligible	0.00
2	Loss of half wall or half roof sheeting	0.05
3	Loss of all wall or all roof sheeting	0.15
4	Failure of non-load bearing gable end wall	0.20
5	Loss of all wall and all roof sheeting	0.30
6	Failure of load bearing gable end wall	0.40
7	Failure of some secondary structural members	0.60
8	Failure of some primary structural members	0.80
9	Total collapse of primary structure	1.00

Source: Leicester & Reardon (1976).

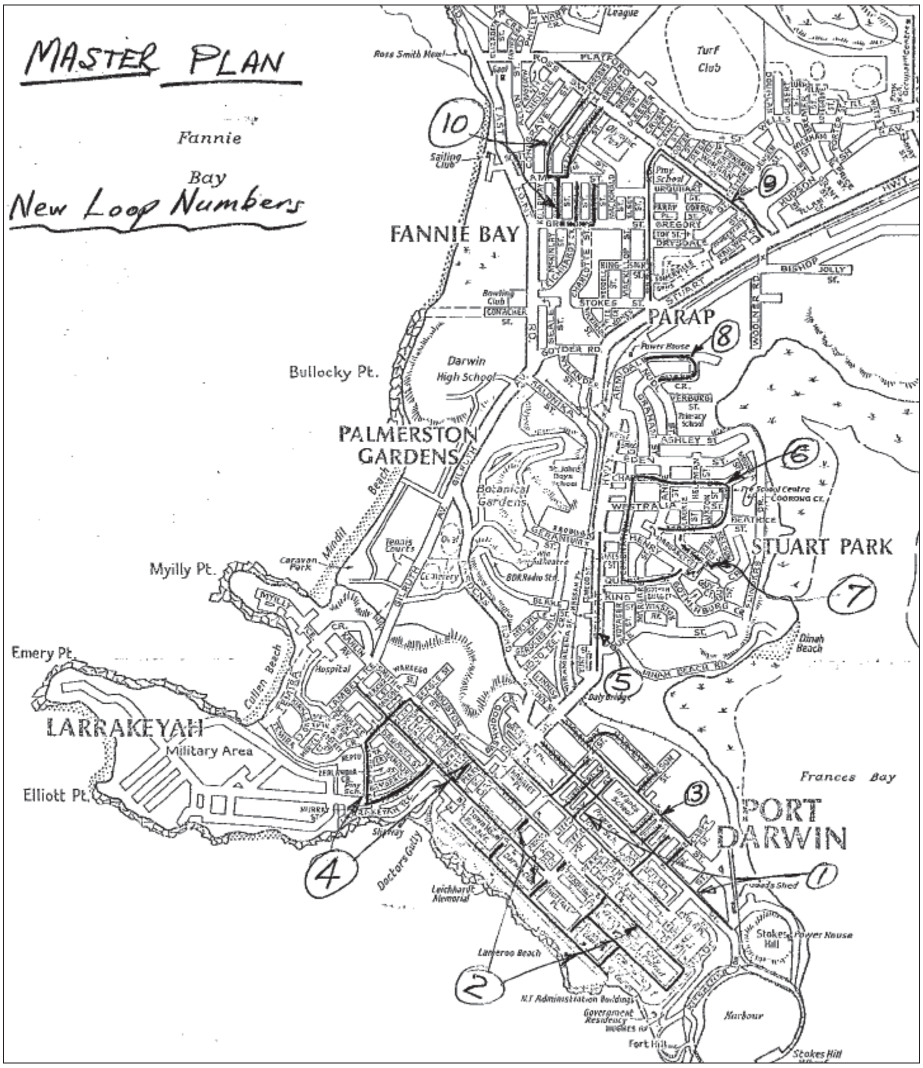


Figure A2.1: Survey routes through the southern suburbs of Darwin

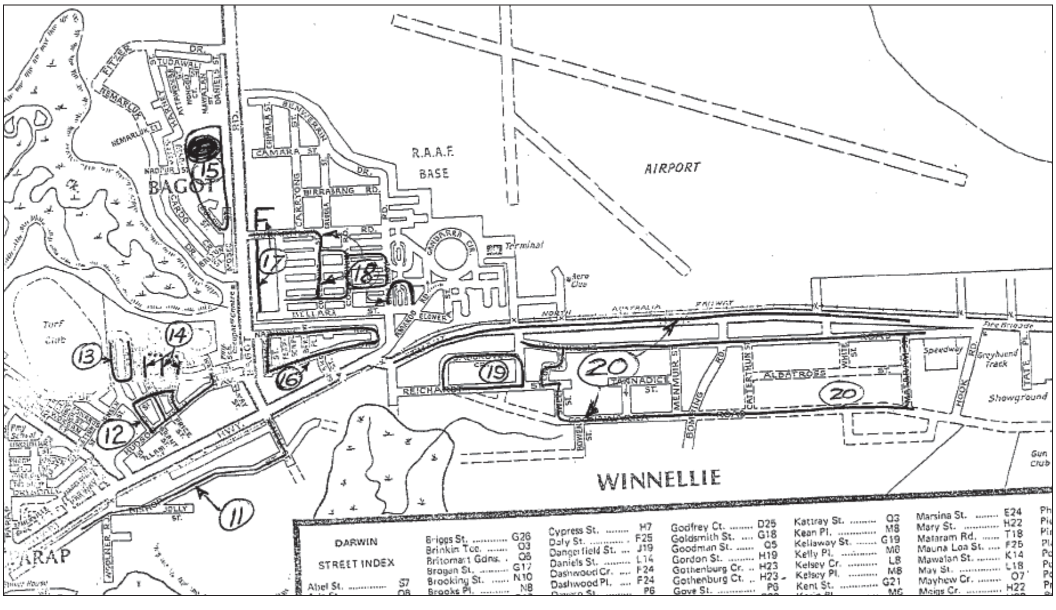


Figure A2.2: Survey routes through the central suburbs of Darwin

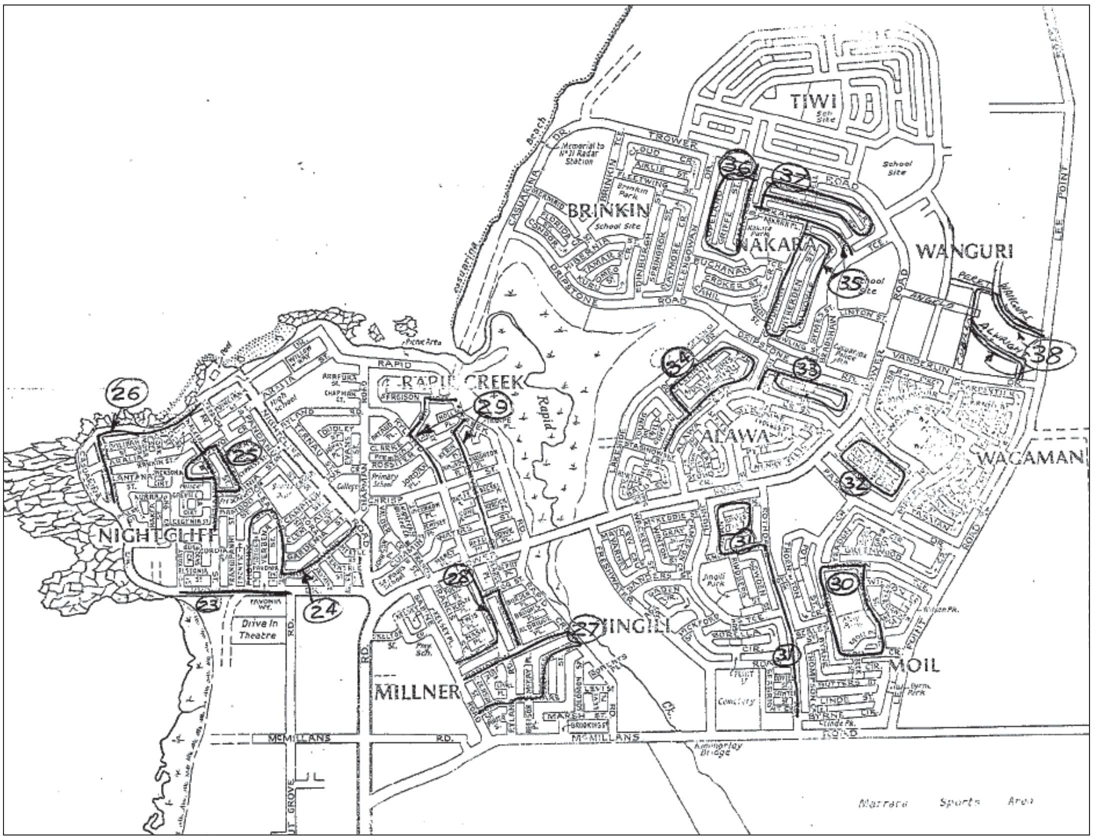


Figure A2.3: Survey routes through the northern suburbs of Darwin

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THE UNIVERSITY OF NEWCASTLE AUSTRALIA