DEPARTMENT OF HOUSING AND CONSTRUCTION

REPORT ON CYCLONE
“TRACY”

- Effect On Buildings -

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Volume 1

BY

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The writer would like to particularly acknowledge the support of Professor D. H. Trollope, Pro-Vice-Chancellor and Professor of Civil Engineering at the James Cook University of North Queensland whose initiative and encouragement in the development of tropical cyclone studies at this University following cyclone “Althea” in December, 1971, has been a primary factor in the writer’s own involvement in this work.

The ready and willing co-operation of the Director of the Department of Housing and Construction in Darwin, Mr G. Redmond, and his staff, in particular the Principal Structural Engineer, Mr J. Gamble, is gratefully acknowledged. Much assistance was also gained from members of the Department’s Darwin Reconstruction Study Group. The willing co-operation of Mr D. Green of the Northern Territory Housing Commission was also appreciated.

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In an investigation such as this a great deal can be learnt from the experiences of those who were in Darwin at the time of the cyclone, and the readiness of Darwin residents from all walks of life to share this information with the writer was greatly appreciated.

Appreciation is also due to the staff of the James Cook University who produced the interim report in a short space of time, in particular Mrs S. Hobson who typed the report and arranged its production.

Finally the writer would like to thank the Department of Housing and Construction for giving him the opportunity to undertake this investigation and in particular, its Chief Structural Engineer, Mr N. Sneath under whose general direction he has worked, and who organised the review of the interim report. The discussion and comments of the members of this review group, who are named elsewhere, were greatly appreciated. Appreciation is also due to all those who helped in the production of this report.

CHAPTER 1

INTRODUCTION

1.1 COMMISSION

On 25th December, 1974, tropical cyclone “Tracy” passed across the city of Darwin causing severe damage to the extent that the major proportion of the population had to be evacuated and the life of the community was completely dislocated.

The Australian Department of Housing and Construction subsequently commissioned the writer to prepare a report on the damage to buildings along the lines of the report prepared by the James Cook University of North Queensland for the Queensland Government following the damage to Townsville by tropical cyclone “Althea” in December, 1971.

This report represents the final outcome of this commission. It follows a reasonably comprehensive review by a group of wind engineering specialists and members of the Department of Housing and Construction of the main sections of the interim report produced by the writer after a detailed inspection of the damage.

The commission followed a preliminary study of the structural damage for the Department of Housing and Construction by a small group of engineers under the direction of its Chief Structural Engineer, Mr N. Sneath

1.2 SCOPE OF THE REPORT

Chapter 2 presents a brief summary of the findings and recommendations arising out of the study.

Chapter 3 presents a brief description of the physical characteristics of tropical cyclone “Tracy”.

Chapter 4 presents a description and interpretation of the overall pattern of damage which occurred in Darwin.

Chapter 5 presents a detailed discussion of the structural aspects of the failure of buildings.

Chapter 6 presents the implications for the design and construction of buildings in tropical cyclone prone areas arising from the study of the damage.

A bibliography of relevant reports and papers completes the main body of the report.

To supplement the work of the writer, who concentrated his field work mainly on traditional housing construction, a firm of consulting engineers, Halpern Glick Pty. Ltd. were commissioned to prepare reports of the following aspects:

(1) Indications of wind velocity from the behaviour of simple structures.

(2) Investigation of the performance of major buildings.

(3) Investigation of the behaviour of systems type housing.

These reports are presented as Appendices.

Also presented as Appendices are the following:-

1. A report prepared by Mr V. Beck of the Department of Housing and Construction following an investigation of the behaviour of metal roof cladding under dynamic wind loading.

2. The preliminary report on the damage prepared for the Department of Housing and Construction under the direction of Mr N. Sneath.

3. A report prepared by Mr F.L. Wilkinson of the Department of Housing and Construction following an investigation of the storm surge associated with cyclone “Tracy”.

4. A report prepared by Dr R. H. Leicester and Mr G. F. Reardon of C.S.I.R.O. following their investigation of the damage.

5. A report prepared by the Darwin Local Group of the Institution of Engineers, Australia, during 1974. This report is presented for the information it contains on the previous history of tropical cyclones in the Darwin area, and also to indicate the concern that was being felt within the engineering profession in Darwin prior to “Tracy” regarding the ability of Darwin to cope with a serious tropical cyclone.

6. The draft Building Regulations for Darwin submitted to the Darwin Reconstruction Commission by the Department of Housing and Construction.

The main body of the report is contained in Volume 1 and the Appendices are contained in Volumes 2 and 3.

1.3 REVIEW GROUP

Members of the Group which reviewed the interim report were:

Mr N. Sneath	- Department of Housing and Construction
Dr W. Melbourne	- Monash University
Prof L. K. Stevens	- University of Melbourne
Prof B. J. Vickery	- University of Sydney
Prof D. H. Trollope	- James Cook University
Dr R. D. Marshall	- National Bureau of Standards U.S.A.
Dr J. Minor	- Texas Tech University, U.S.A.

Mr J. Fowler - Irwin Johnston and Partners
Dr L. Blakey - Department of Housing and Construction
Mr K. Jack - Department of Housing and Construction
Mr R M. Ure - Department of Housing and Construction
Mr C. Bubb - Department of Housing and Construction
Mr J. Gamble - Department of Housing and Construction
Mr A. Muffatti - Bureau of Meteorology
Mr D. Brooks - Bureau of Meteorology
Dr G. R. Walker - James Cook University

1.4 OBJECT OF REPORT

This report is written with the sole purpose of discovering the lessons that are to be learned from observing the damage caused by cyclone “Tracy”, so that a disaster of such magnitude might be prevented in the future. It is the hope of the writer that it will be accepted in this spirit by all concerned and that the willing co-operation of all sections of the building industry will be obtained to put these lessons into practice.

CHAPTER 2

SUMMARY

1. Tropical Cyclone 'Tracy' was a small but very intense tropical cyclone which produced extremely high wind speeds with the maximum gust velocities estimated to have been of the order of 130-140 knots.

2. Cyclone 'Tracy' highlighted a number of features regarding construction in tropical cyclone prone areas which had not previously been generally appreciated. Among these were:

   (i) The magnitude and duration of the winds were significantly greater than was generally anticipated from previous Australian records.

   (ii) Wind induced repeated loads can significantly reduce the strength of roof fixings.

   (iii) The structural integrity of housing is as important as the structural integrity of larger buildings.

3. Buildings whose structural strength had been certified by a structural engineer before construction performed reasonably well even though the maximum wind speeds exceeded the design wind velocities in general.

4. Traditional housing performed extremely badly particularly in the more recently built northern suburbs of Darwin. Overall between 50 and 60 per cent of houses were damaged beyond repair and in some of the northern suburbs the destruction was nearly 100 per cent.

5. Topography had an influence on the pattern of damage but would not account for the degree of damage which occurred.

6. A major factor in the extreme damage to housing appeared to be the loss of roof cladding which led to

   (i) a significant loss of strength in many structures which led to their structural collapse.

   (ii) The production of a large amount of wind blown debris which became a major agent in the further damage to buildings, thereby creating a chain reaction effect. Over 90 per cent of all houses in Darwin had significant loss of roofing and approximately 70 per cent of all other structures. The fixing of all types of roof cladding proved inadequate and it appeared that a reduction in strength due to fatigue under repeated loads played a significant part in this.

7. Important factors in the failure of houses, particularly among those of more recent construction were:-

(i) dependence on cladding which was removed by the wind or wind born debris for much of the bracing in framed construction;

(i) the poor performance of concrete masonry and of the detailing and tying down of the bond beams in masonry construction

(ii) a general lack of structural integrity through inadequate tying together of the main structural elements of houses.

8. Wind blown roof cladding and falling masonry was a major danger to personal safety and caused a number of deaths and many injuries.

9. Although Cyclone “Tracy” produced the most extreme velocities recorded in a major centre of population in recent years, there is reason to believe that other tropical cyclones of similar intensity may cross the tropical cyclone prone coast of Australia in the foreseeable future.

10. If a disaster such as occurred in Darwin is to be prevented in the future, there will need to be a radical change in the approach to housing construction in tropical cyclone prone areas. The adoption of a rational structural design procedure for houses is required.

11. In order to achieve the required improvement in housing strength it is recommended that houses constructed in tropical cyclone prone regions of Australia be required to have their structural design certified by a structural engineer and to have their construction adequately supervised.

12. Interim measures are recommended for the design of buildings, particularly housing, in tropical cyclone prone regions. These would be revised and updated in the light of research and experience.

13. It is regarded as a matter of urgency that improved methods of fixing roof cladding be developed as soon as possible. It is considered that the roof cladding should be capable of remaining in place up to basic gust velocities of the order of 80 m/s. taking due account of any reduction in strength due to the repeated loads experienced in strong winds. The development of an appropriate method of testing roofing systems is of prime importance in this regard.

14. It is recommended that procedures based on limit state design philosophy be evolved for structural design in tropical cyclone prone regions by which structures would be designed to –

    (i) satisfy requirements of normal codes of practice for winds of magnitudes having a relatively high probability of occurrence during the lifetime of the structure;

    (ii) satisfy a collapse limit approach to design for extreme winds having a relatively low probability of occurrence during the lifetime of the structure.

15. Some changes are recommended for steel construction to ensure greater reserves of strength as current code requirements would appear to produce some structures relatively sensitive to extreme winds.

16. It is recommended that more anemometers be placed in tropical cyclone prone regions and that studies be undertaken of the effect of local topography on wind velocities in these areas.

17. More information should be obtained on tropical cyclones when they occur by the use of aircraft flying into the cyclones to obtain data on barometric pressures and wind velocities.

18. Research into the ultimate strength of housing, in particular under repeated loadings of the type experiences under strong winds, should be developed as a matter of urgency.

19. It is recommended that studies concerned with the probabilities of occurrence of cyclonic winds and of the interaction of wind and low rise structures from a point of view of both loads on the structures and the probabilities of damage, be continued.

20. The strength of existing buildings, particularly houses, in tropical cyclone prone areas should be investigated. The strengthening of existing houses by the provision of battens over the top of the roof cladding where considered necessary should be seriously considered.

21. In tropical cyclone prone regions, serious thought should be given to the provision of ‘inresidence shelters’ in houses not likely to be affected by a storm surge, and the provision of public shelters to which persons living in storm surge prone areas could be evacuated.

22. It is recommended that serious thought be given to the protection of windows by the use of screens which could be used both to provide sun shading and debris protection.

23. It is recommended that positive steps be taken to educate builders on the details of construction required in tropical cyclone areas and the reason for them.

CHAPTER 3

CHARACTERISTICS OF CYCLONE "TRACY"

3.1 INTRODUCTION

In this chapter a brief account of the physical characteristics such as size, central pressure and wind velocities for cyclone "Tracy" is given. The information is largely based on the preliminary report on "Tracy" prepared by the Bureau of Meteorology in Darwin.

A more detailed account can be expected to be published in due course by the Bureau of Meteorology.

A summary of the main characteristics of "Tracy" when over Darwin is as follows:

Central pressure	940-950 mb
Size of eye	8 KM
Diameter of destructive winds	20-30 km
Forward speed	5 knots
Maximum wind velocities	65-70 m/s (130-140 knots)
Rainfall	Not known
Direction of travel	South-east

3.2 PATH

Tropical cyclone "Tracy" developed from a tropical low which was observed to have formed 700 km North-east of Darwin at 9 a.m. on Friday, 20th December, 1974. This low moved slowly South-west and had intensified into a tropical cyclone by 10 p.m. on Saturday 21st December.

During the next two and half days it continued to move very slowly South-west to be off the western end of Bathurst Island early on the morning of Tuesday, 24th December, when it proceeded to curve round to a direction of East-south-east on a track heading directly for Darwin. It continued slowly along this path passing almost directly over Darwin in the early hours of Wednesday, 25th December before moving across Southern Arnhem Land into the Gulf country of Queensland.

Figure 3.1 is a map of the approximate path of cyclone "Tracy" from its formation until it had passed Darwin. Figure 3.2 shows the approach to Darwin in more detail including an indication of the size of the cyclone. Figure 3.3 is a map of Darwin itself showing the layout of the suburbs and the approximate path of the centre of the eye.

3.3 BAROMETRIC PRESSURES

Figure 3.4 is a copy of the barometric pressure record obtained at the Bureau of Meteorology's office in Darwin, which was located in the city area just to the South of the passage of the eye.

A reliable estimate of the central pressure of "Tracy" is not available to the writer at the time of writing but it is believed to have been in the region of 940 mb representing a pressure drop of the order of 50 mb across the tropical cyclone. For comparison the lowest pressure in "Althea" was estimated to be 952 mb.

It was reported that in the hour immediately preceding the lowest reading the pressure dropped 23 mb at the Bureau of Meteorology office, rising the same amount in the following hour.

3.4 FORWARD SPEED

The forward speed of "Tracy" was noted for its extreme slowness throughout its history until well after it passed Darwin. During its passage across Darwin its speed has been assessed at approximately 5 knots. By comparison the speed of cyclone "Althea" was of the order of 10-12 knots.

3.5 SIZE OF THE EYE

The size of the eye of cyclone "Tracy" was noted for its very small diameter and its tendency to decrease in size as it approached Darwin. At 6 p.m. on 24th December when "Tracy" was of the order of 50-60 km from Darwin the diameter of the eye was reported to be 14 km, while at 4 p.m. when the eye was over Darwin it was reported as having a diameter of 8 km. These estimates are based on radar pictures and would represent the diameter of the inner band of rain.

Reports by individuals in the path of the eye indicate a maximum calm period of approximately one hour which for a forward speed of 5 knots would indicate an eye diameter of the order of 8-9 km, confirming the radar estimate.

3.6 WIND

"Tracy" was characterised by a relatively narrow band of extremely strong winds around the eye which because of the very slow movement of the eye tended to have rather a long duration for points in the path of them.

Unfortunately the anemometer operated by the Bureau of Meteorology in Darwin was struck by debris and ceased to function during the passage of the cyclone. This was particularly unfortunate as the anemometer was located in the path of the eye. Figure 3.5 is a copy of the record obtained from the anemometer before it failed.

The time of failure was 3.05 a.m. which would have been shortly before the leading edge of the eye arrived.

The record shows the wind gusting up to 115 knots just prior to the failure, the excursion off the scale being regarded as a malfunction due to the failure.

From verbal reports and observation of debris it seems fairly definite that where the eye or a lull in the wind was experienced, the wind after the lull was much stronger that the wind before the lull.

On this basis it does not seem unreasonable to postulate that the maximum gusts may have been of the order of 130 to 140 knots, which would be well in excess of the previous maximum recorded wind gust velocity in Australia of 125 knots which was recorded at Onslow in North-west Australia on 7th February, 1963. These figures, of course, refer to a 3 second gust at an elevation of 10 metres in open country (category 2 in the Australian Wind Loading Code). The maximum recorded gust velocity in Townsville during cyclone “Althea” was 106 knots.

It should be possible to obtain a reasonable estimate of the maximum basic gust velocity from the barometric pressure record and knowing the forward speed of the cyclone. Theories relating wind velocities to pressure changes are available and it is possible that the Bureau of Meteorology will be able to give a reasonable estimate of maximum gust velocities when the appropriate analyses have been performed.

The phenomenon of the second wind being stronger that the first could be explained in two ways –

(1) The geography of Darwin is such that for the central and southern parts of Darwin the initial winds would have been coming off the land and therefore have been slowed down in the boundary layer, whereas because of the penetration of the harbour and the path of the cyclone to the north of it, second winds would have been coming more off the sea which offers less resistance to the wind.

(2) The decreasing of the diameter of the eye which appeared to be taking place may have been associated with a deepening of the pressure and intensification of the winds, which may have been significant enough to be noticed in the time it took the eye to pass.

The writer tends to the opinion that the first of these probably played a much bigger part than the second.

It is interesting to note that the same phenomenon was noted in the 1897 Darwin cyclone which appears to have been of similar intensity.

Regarding the size of the extreme wind field, reports of residents tended to indicate that the destructive winds lasted approximately an hour both before and after the passage of the eye. This might be regarded as the period in which the mean velocity exceeded about 50 knots with gusting in excess of 75 knots. Assuming a forward speed of 5 knots this would give a radial width of the zone of destructive winds of the order of 8-9 km.

Because of the slow forward speed of the cyclone it would not be anticipated that wind speeds on the northern edge of the eye would have been significantly greater than elsewhere around the eye.

Appendix 1 contains a report by Halpern Glick Pty. Ltd. on estimated upper and lower bounds of wind velocities based on the performance of simple cantilever structures such as signs and lamp posts. Although these figures cannot be directly related to the basic wind velocity because of differences in elevation, effective gust averaging time and dynamic interaction between the signs and the wind they are nevertheless considered to give an indication of order of wind velocities experienced. It will be seen that these are not inconsistent with the maximum wind velocities postulated above.

3.7 RAINFALL

At the time of writing a definite figure for rainfall is not available. An unofficial estimate of 10 to 12 inches was reported.

3.8 COMPARISON WITH OTHER TROPICAL CYCLONES

Tropical cyclone “Tracy” was without doubt the most destructive cyclone in recent times to strike a populated part of the Australian coast. A number of other tropical cyclones within historical times may have been as severe or worse, but no reliable estimates of wind velocity are available. Examples of these are the cyclones occurring in Darwin in 1897, Bathurst Bay in 1899 and Mackay in 1918.

On the basis of past history it would seem reasonable to assume that an event of the magnitude of “Tracy” would have a return period between 100 and 200 years in Darwin.

Comparing it with United States hurricanes, there appears to be a strong similarity between “Tracy” and hurricane “Celia” which struck the Corpus Christi coast of Texas in 1970. The two hurricanes had the following in common –

(i) wind velocities were extremely high;
(ii) storm surge was not significant in terms of damage;
(iii) the eye decreased in size as it approached the coast;
(iv) a similar magnitude of damage was produced.

Although “Tracy” was an extreme event there seems no grounds for believing that a major city or town in the tropical cyclone prone region will not be struck by a cyclone of similar intensity within the foreseeable future.

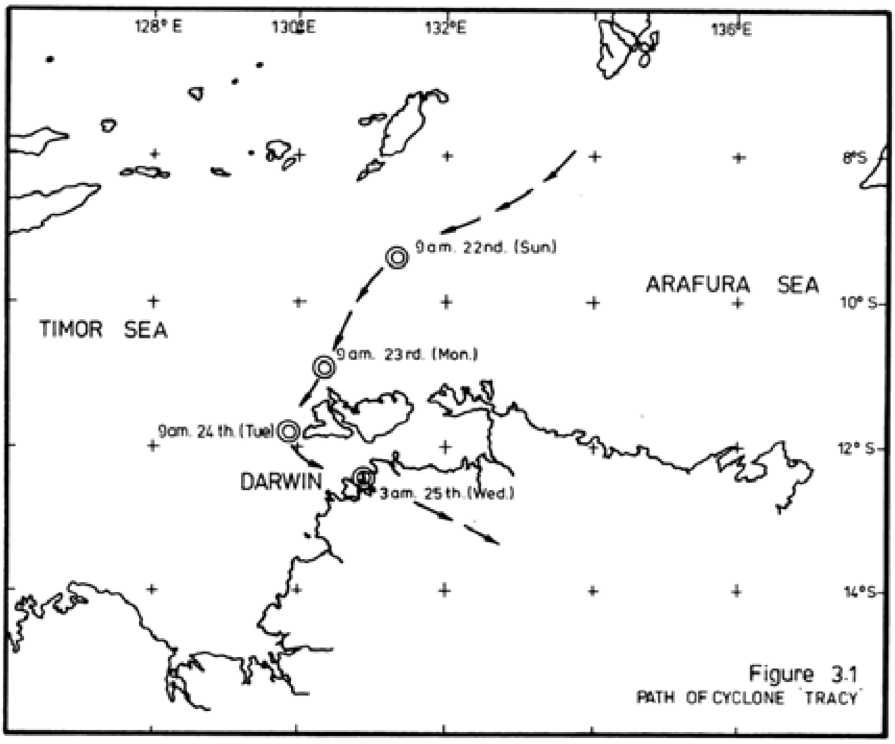


Figure 3.1
PATH OF CYCLONE 'TRACY'

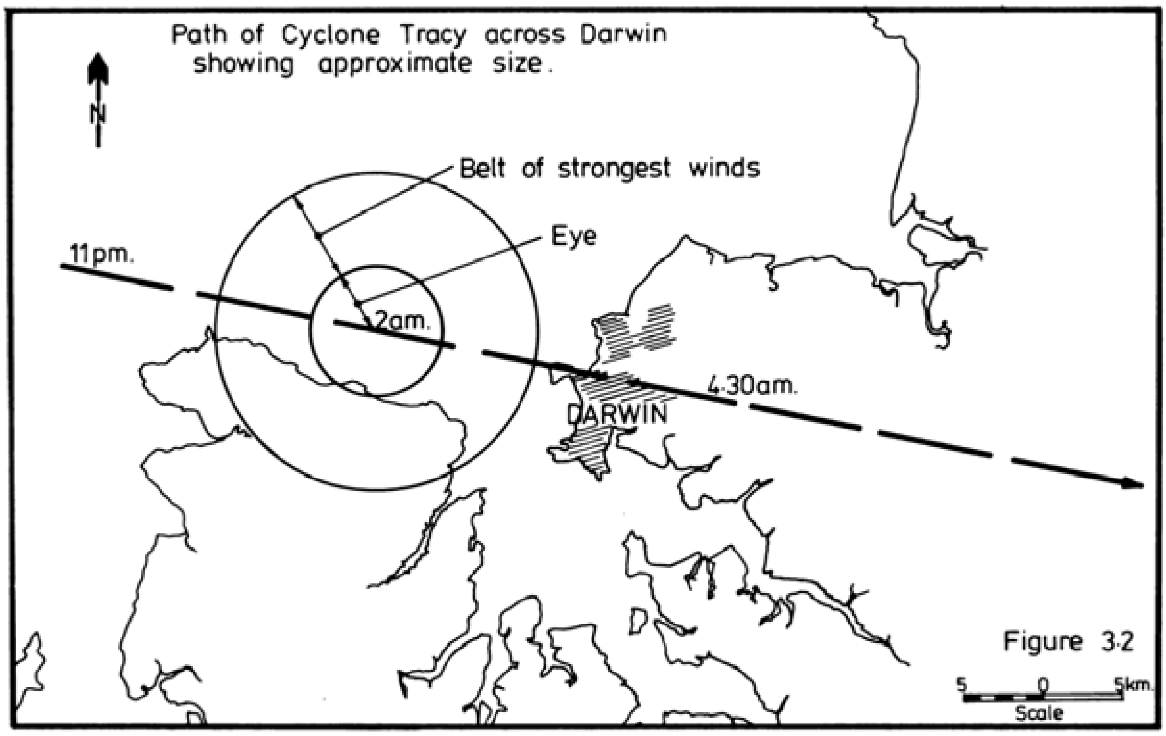

Path of Cyclone Tracy across Darwin showing approximate size.

Figure 3.2

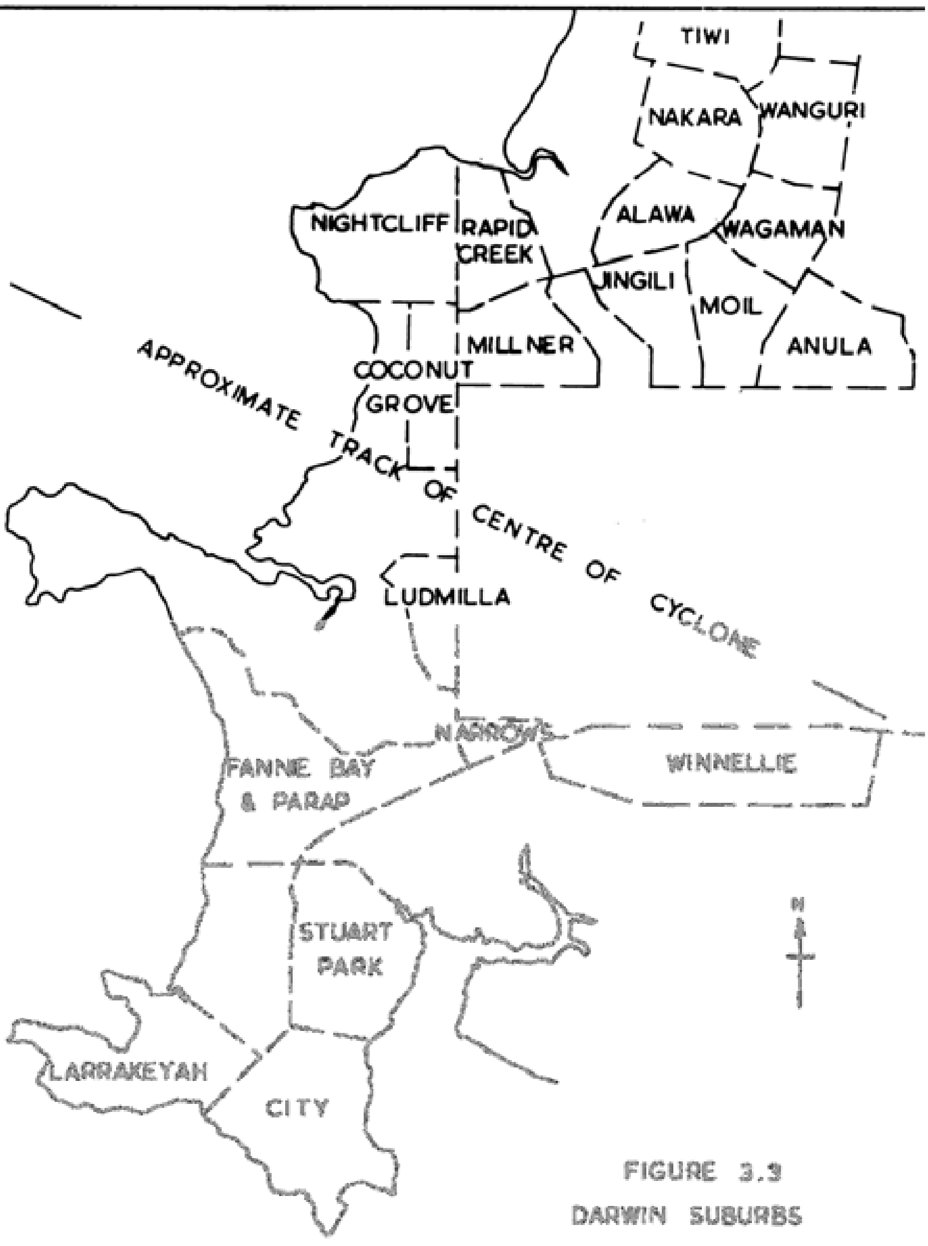


FIGURE 3.3
DARWIN SUBURBS

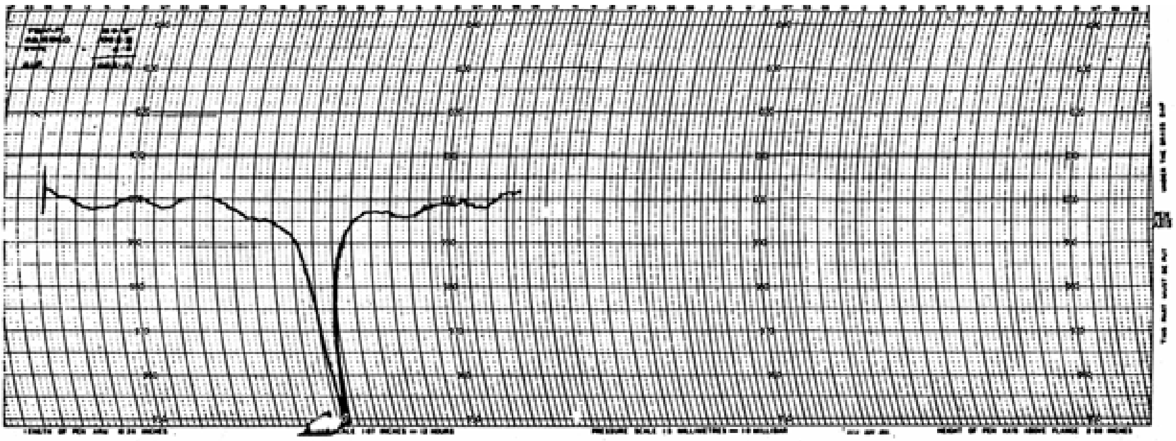


FIGURE 3.4 BAROGRAPH RECORD FROM DARWIN OFFICE OF BUREAU OF METEOROLOGY
(By courtesy of the Bureau of Meteorology)

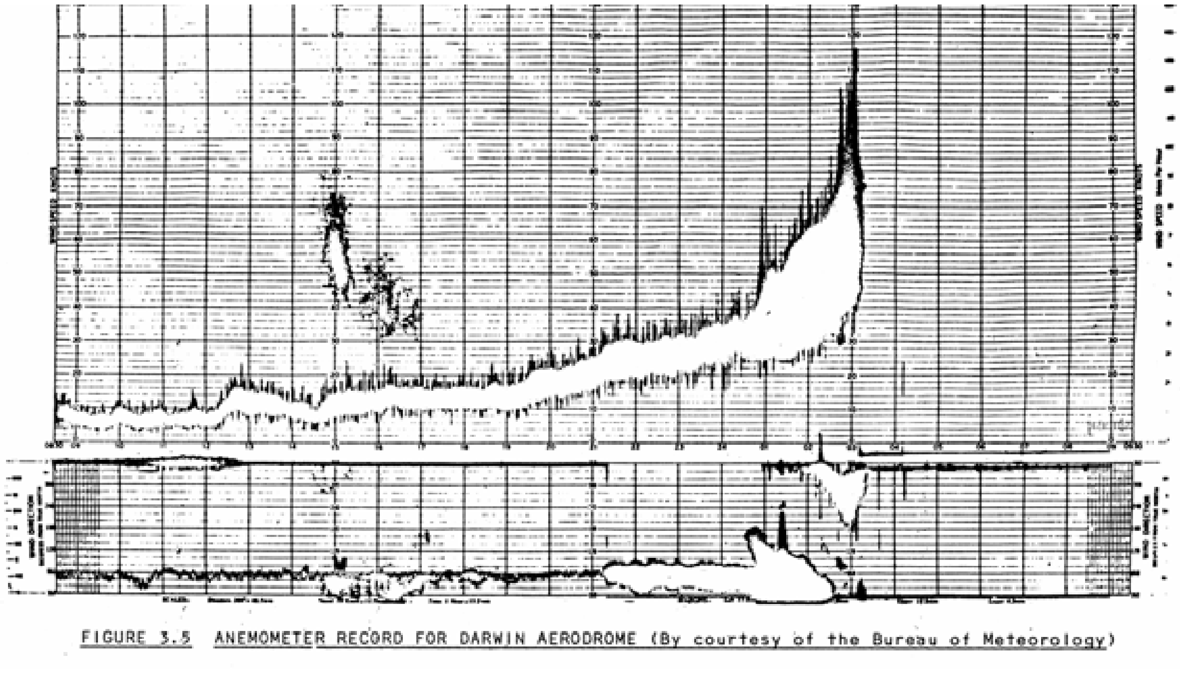


FIGURE 3.5 ANEMOMETER RECORD FOR DARWIN AERODROME (By courtesy of the Bureau of Meteorology)

CHAPTER 4

GENERAL PATTERN OF DAMAGE

4.1 INTRODUCTION

The destruction caused in Darwin by cyclone “Tracy” was the worst suffered by an Australian city in any disaster.

The destruction was not uniform but varied considerably as a function of both location and type of construction – see figures 4.1 to 4.8.

The dominant features of the damage were: -

(1) The major disaster was in the performance of traditional housing, the performance of engineered structures being in general adequate in view of the wind velocities experienced, with some minor exceptions.

(2) The northern suburbs fared considerably worse than the southern suburbs and central city area.

In assessing the pattern of damage the three major factors which must be considered are: -

(i) wind field of cyclone,
(ii) topography,
(iii) variation in building strength.

The object of this chapter is to present the overall picture of the damage and a general assessment of it in terms of the above three factors.

The detailed assessment of the structural behaviour is presented in Chapter 5.

4.2 GENERAL DAMAGE STATISTICS

4.2.1 Houses

Immediately following cyclone “Tracy” a survey of the damage to houses was carried out. Although the immediate objective of this survey was to ascertain the amount of accommodation immediately available, and the location of houses which could most quickly be repaired, the survey provided a very good base for the examination of the pattern of damage. The survey is being continually updated, with the information being stored on magnetic tape, so that ultimately a very detailed statistical analysis of the pattern of damage will be able to be obtained.

At the time of writing only the results of the preliminary survey of houses is available but these are quite sufficient to highlight the overall picture.

From the preliminary survey of houses which covered all the main residential suburbs with the exception of the very new suburbs of Tiwi and Anula, and the Defence Services homes, the following overall picture was obtained:

Number surveyed	6,981 (out of a total number of houses in Darwin of approx. 8,000
Destroyed	3,675 i.e. approx. 53%
Declared intact other than minor damage to wall cladding or windows	408 i.e. approx. 6%
Declared repairable	
(a) roof damage only	
(i) less than 10% roof damaged	200 i.e. approx. 3%
(ii) over 10% roof damaged	1,530 i.e. approx 22%
(b) roof and walls damaged	1,168 i.e. approx 16%

It is believed that when the final results are available the picture will look even worse because –

(i) the suburbs of Tiwi and Anula suffered extreme damage and Defence Service homes suffered serious damage;

(ii) follow up studies tended to indicate that many structures initially declared repairable may in fact have to be completely rebuilt owing to walls being more seriously damaged than initially realised.

It will be seen that these figures represent a disaster of major proportions as far as housing is concerned.

4.2.2 Flats

From a structural point of view flats in general performed somewhat better than houses. Although flats are being included in the Housing Commission Survey no information was available to the writer from this source at the time of writing.

From observation and some preliminary data of flat accommodation available immediately after the cyclone the following approximate estimates of damage have been made –

Destroyed	10%
Intact	10%
Repairable	
(i) roofing damage only	40%
(ii) damage to top floor, walls and roof	40%

4.2.3 Engineered Buildings

Overall the damage to buildings whose structure had been engineered was light compared with the damage to housing and flats.

At the time of writing no detailed statistics of performance are available but from observation of those structures built in the last 20 years or so the following approximate estimates of damage have been made: -

Structural collapse	3%
Serious loss of roofing and/or wall cladding	20%
Small loss of roof cladding	40%
Building intact other than damage to windows and/or wall cladding	40%

4.3 GEOGRAPHICAL PATTERN OF DAMAGE

From the preliminary results of the housing survey obtained for each suburb an indication of the geographic pattern of damage has been obtained as shown in figure 4.9. It will be seen that the Narrows is an exception to the general trend showing a relatively small percentage of buildings which will need to be completely rebuilt and that the far northern suburbs suffered by far the worst damage, particularly the most northerly suburbs of Nakara and Wanguri where the destruction was close to 100%. From observation it can be expected that the intensity of destruction in Tiwi and Anula will be found to be similar.

Figure 4.10 shows the same trends in a different manner where the population of each suburb approximately two and a half weeks after “Tracy” is expressed as a percentage of the estimated population as at the end of June, 1974. This gives an indication of the proportion of the total accommodation habitable immediately after the cyclone. The relatively high values for the City and Larrakeyah areas are partly due to the greater amount of high density accommodation such as hotels, motels, hostels and flats, which suffered significantly less damage than houses, in this area.

4.4 ASSESSMENT OF DAMAGE PATTERN

4.4.1 Wind Field of Cyclone

The characteristics of the cyclone have been discussed in Chapter 3 where details are given of the path, size of eye, wind velocities, etc.

In figure 4.11 an approximate basic wind field for cyclone “Tracy” is presented, where the basic wind velocity is defined as that velocity corresponding to a height of 10 metres in open country (Category 2 in the Australian Wind Loading Code.) This is based on the information presented in Chapter 3 and must only be considered as indicative of the real situation.

One uncharacteristic feature of this postulated basic wind field is that the winds on the northern edge of the path are not assigned significantly greater velocities than those in the path of the eye or to the south of the eye. The reason for this, as previously explained, is that the forward velocity was so slow relative to the circulating wind velocities that in this case the difference would not have been significantly marked.

This wind field indicates that the basic wind velocities were probably high in all parts of Darwin. The difference between the southern and northern suburbs would account for some of the increase in damage in the northern suburbs but is unlikely to have been the reason for the almost complete destruction in the far northern suburbs.

In addition to the magnitude of the wind velocity a major contributing factor to the damage was the duration of the high winds. Because of the slow forward motion of “Tracy” all areas in the path of the cyclone sustained high winds for a considerable period of time, despite the small size of the wind field. Those areas on the edge of the eye would have had to suffer the maximum duration of strong winds but it does not appear that the relative differences would have been enough to have had a significant effect on the pattern of the damage.

4.4.2 Topography

The basic wind velocity can be markedly affected by the effect of the topography on the velocity distribution of the wind in the boundary layer of air which roughly occupies the first 500 feet or so above the earth’s surface. The effect of this is clearly demonstrated in the Australian Wind Loading Code where factors are presented for modifying the basic wind speed as a function of terrain and relief. In general the rougher the surface of the earth the slower the wind in the lower regions of the boundary layer.

The sea offers the least resistance to the wind so that over the sea the wind velocities tend to be highest at any particular height in the boundary layer, the effect being more marked the closer one is to the earth’s surface. As a result areas exposed to wind coming off the sea tend to be prone to higher velocities than those exposed to wind coming off the land. The most exposed buildings will be those along the sea front, or on the top of ridges facing the sea.

Figure 4.12 shows the approximate contour lines for the 50 feet and 100 feet levels for the Darwin area and the directions of the principal damaging winds based on observation of debris and reported observances.

From figure 4.12 it will be seen that there are a number of areas where it would be expected that velocities would be high due to this effect such as the coastal high points of Nightcliff, Fannie Bay, Larrakeyah, Stuart Park and City areas, and the industrial area of Winnellie. With the exception of the latter, damage was intense in these exposed areas. As a complement to this effect one would expect velocities to be less in areas sheltered from the wind by being in depressions normal to the direction of the main wind or on slopes facing away from the wind. This is probably a significant factor in the relatively low figures for damage in the Narrows area where most of the houses are in such a depression, and for the pockets of reasonably undamaged buildings to be found in a number of similarly sheltered depressions in Larrakeyah, Stuart Park, Fannie Bay, Rapid Creek and Millner which helped to reduce the damage statistics in these areas. This was also probably a significant factor in the general reports of the second wind being stronger than the first in the southern half of the city.

The Northern suburbs beyond Rapid Creek and Millner are on a gentle slope rising from the sea in the direction from which the maximum winds occurred. Although the slope is considered too gentle to have given rise to severe exposure, the uniformity of this topography throughout the area may have been a contributing factor to the high degree of damage in these suburbs, as they lacked the sheltered pockets found in the other suburbs.

Two other factors contributing significantly to the topographical effect are the vegetation, and the size and spacing of the buildings.

Both vegetation and buildings, by increasing the roughness of the earth’s surface, tend to slow down the wind in the boundary layer and vegetation also plays a significant part in reducing damage due to debris by acting as a debris screen.

It may be of some significance that the older areas of the city where vegetation was much better established suffered considerably less damage than the newer areas of the far northern suburbs, which in addition to their exposure to the sea as previously described had been practically cleared of all vegetation before development, and sufficient time had not taken place for it to become re-established.

The effect of size of buildings also appeared to be reflected in the pattern of damage. Large buildings have a much more significant effect than small buildings and this undoubtedly contributed to a lessening of velocities generally in the central city area and a consequent lessening of damage relative to other areas to smaller buildings in this area in general.

The effect was also quite marked in the suburban areas in comparing damage to high and low set houses. Although other factors clearly also played a significant part it seems, by comparing roof damage alone, that low set houses suffered less damage in general because they experienced lower wind velocities by virtue of being –

(1) closer to the ground where velocities are likely to be less because of the boundary layer effects;

(2) protected by adjacent high set houses;

(3) protected by vegetation.

Buildings facing wind coming off open land such as parkland would be expected to suffer greater velocities than those surrounded by other buildings. However, this effect was not observed to have had a very significant effect on the damage pattern, being observed in some places but not in others.

It is probable that these structures started to fail earlier than the others behind them, but the effect of houses behind being exposed to greater amounts of debris than the frontline structures combined with the duration of the strong winds probably masked this, and in some cases produced a situation where the frontline structures were in better condition after the cyclone than the structures behind them.

4.4.3 Building Strength

If, after allowing for the wind field of the cyclone and topographical effects, buildings of varying strengths are subjected to the same velocities then it is to be expected that the weaker buildings would suffer significantly more damage than stronger ones. The fact that traditional housing suffered such extensive damage compared with the relatively small amount suffered by larger commercial and industrial buildings and schools, points to a significant difference in the structural strength of the two types of buildings.

It is significant that the structural strength of larger buildings is required by law to have been analysed and deemed satisfactory by a structural engineer, whereas no such requirement is demanded for traditional housing construction. Traditional housing has evolved from experience. It depends on changes to traditional practice being slow and experiences of maximum likely loads being frequent enough for corrections to be made before any serious disaster occurs. In a world where changes in building practice have been reasonably rapid and in an area where extreme events are likely to occur only very infrequently such an approach may well lead to a sense of false security and produce a disaster prone situation. In the writer's opinion this is the real underlying cause of the magnitude of the disaster caused by cyclone "Tracy". It is true that since cyclone "Althea" hit Townsville in December, 1971, there had been a significant engineering input into traditional housing in Darwin but even so it was along the traditional approach, through the correction of weaknesses exposed in Townsville traditional construction by "Althea", rather than by an analysis of structural strength from the foundations up, in terms of the engineering design codes of practice, which is the hall mark of an engineered building.

Turning to more detailed explanations of the damage pattern it is necessary to determine why the overall performance of traditional construction was so poor. In winds of the magnitude experienced in "Tracy", if for example 3% - 5% of the houses had been damaged to the extent of being declared totally destroyed, some useful lessons would presumably have been learned from the failure, but the level of damage would have probably been regarded as acceptable in overall terms, and, although still a disaster for those concerned, the community could have coped with it as did Townsville after "Althea". But with the exception of the Narrows, every suburb suffered well in excess of 25% of houses destroyed which in spite of the strong winds is well above acceptable limits. Furthermore, although some explanations based on wind field and topography have already been advanced, the question must be asked whether variations in construction from one suburb to another could also be a significant contributing factor to the variations in degree of damage from one suburb to another.

Traditional housing has undergone changes over the years and these changes may have influenced the damage pattern. Figure 4.13 shows the approximate date of construction of each suburb and comparison of this with the damage pattern shown in figure 4.9 shows that there appears to be considerable correlation between damage and age, with the degree of damage increasing the more modern the suburb.

It will be left to the next chapter to discuss this aspect of building strength in more detail.

Fig. 4.1 - Severe Damage

Fig. 4.2 - Severe Damage

Fig. 4.3 - Moderate Damage

Fig 4.4 - Moderate Damage

Fig. 4.5 - Debris

Fig. 4.6 - Exposed Location

Fig 4.7 - Housing Damage from the Air

Fig 4.8 - Central City Area

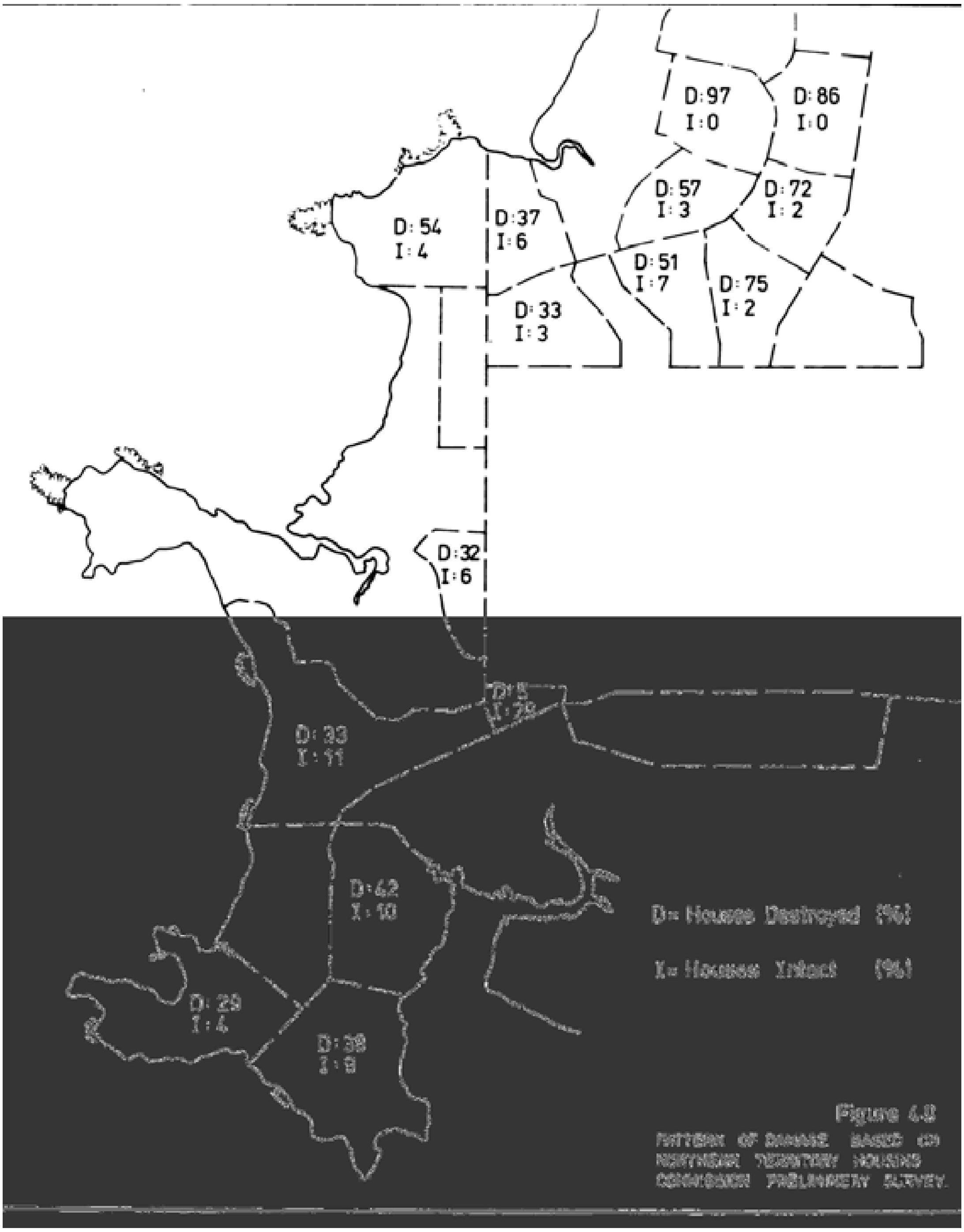
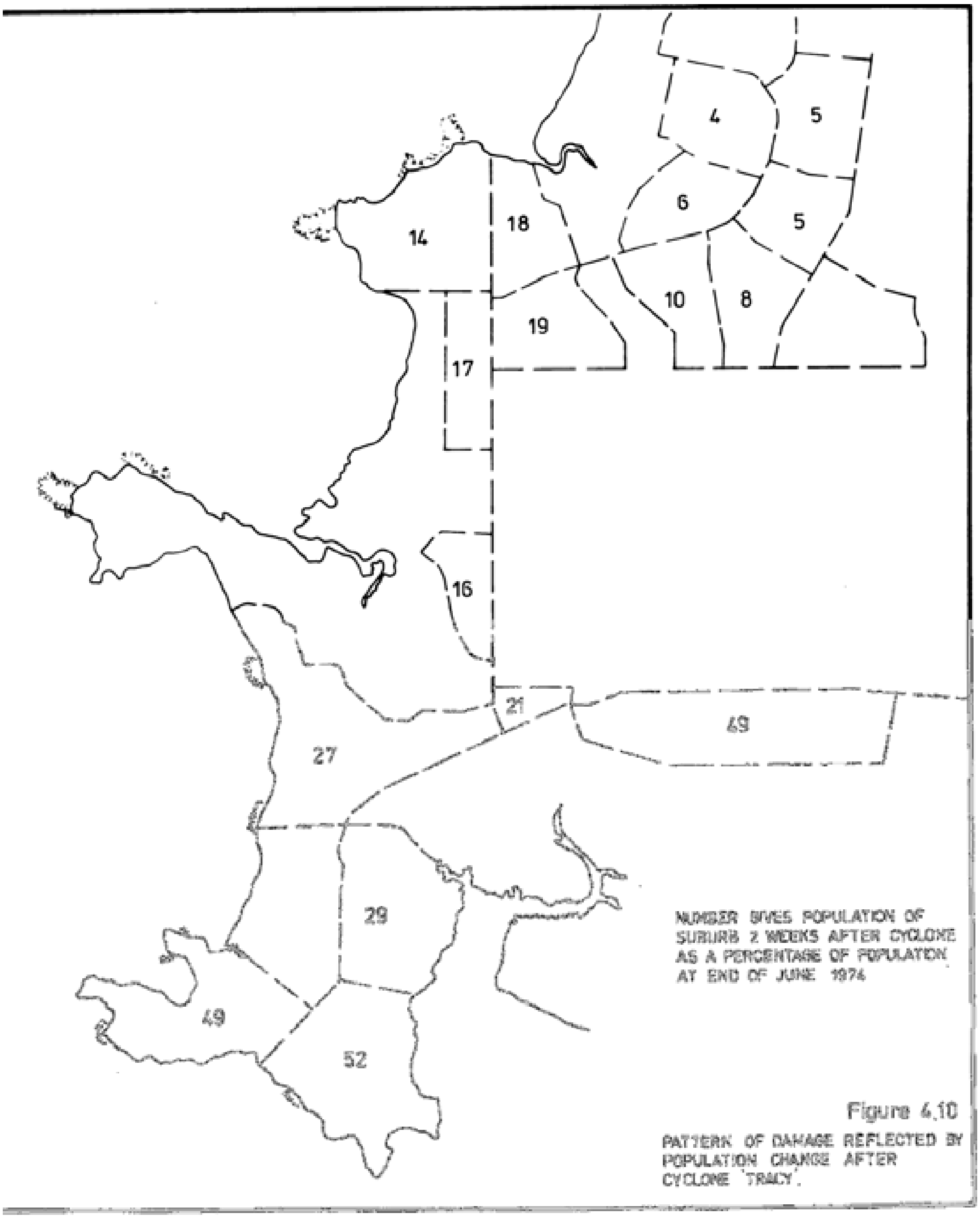


Figure 4.8
PATTERN OF DAMAGE BASED ON NORTHERN TERRITORY HOUSING COMMISSION PRELIMINARY SURVEY.



NUMBER GIVES POPULATION OF SUBURB 2 WEEKS AFTER CYCLONE AS A PERCENTAGE OF POPULATION AT END OF JUNE 1974

Figure 4.10

PATTERN OF DAMAGE REFLECTED BY POPULATION CHANGE AFTER CYCLONE 'TRACY'.

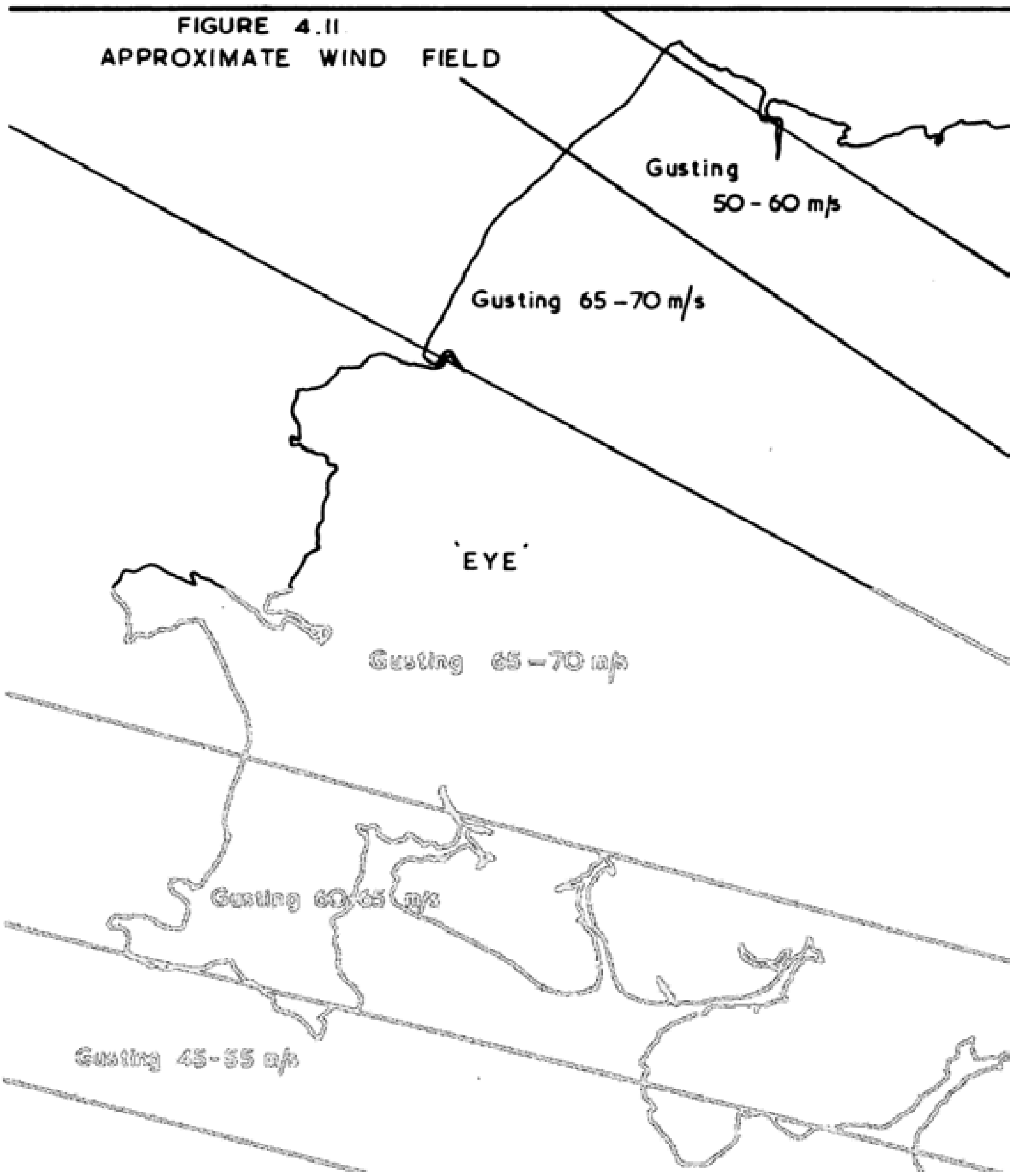


FIGURE 4.11
APPROXIMATE WIND FIELD

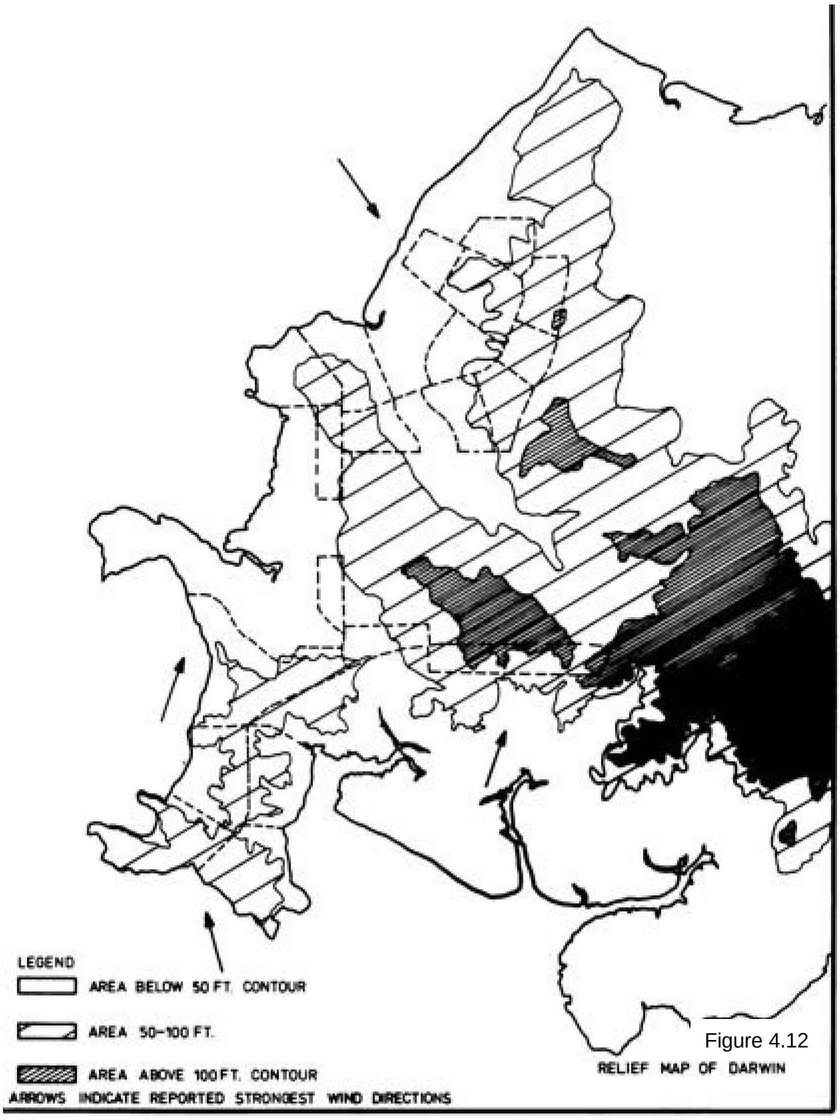


Figure 4.12

RELIEF MAP OF DARWIN

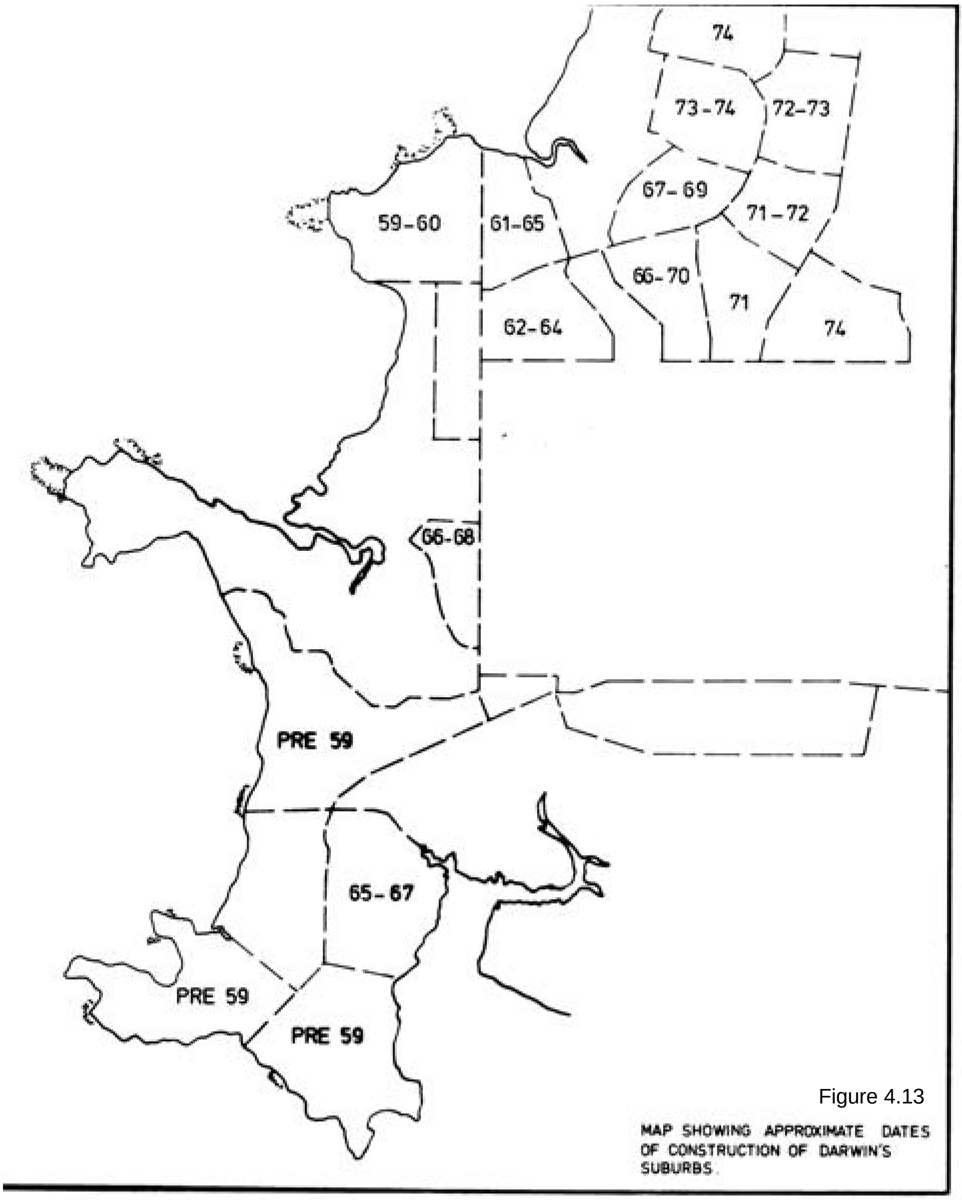


Figure 4.13

MAP SHOWING APPROXIMATE DATES OF CONSTRUCTION OF DARWIN'S SUBURBS.

CHAPTER 5

STRUCTURAL BEHAVIOUR

5.1 INTRODUCTION

The most conspicuous aspects of the structural behaviour of building were: -

(i) The widespread loss of roof cladding

(ii) The poor behaviour generally of traditional housing construction due to a lack of structural integrity, particularly after the cladding had been removed.

In this chapter the loss of roof cladding is discussed followed by a discussion of the structural behaviour of the various types of structures in Darwin.

5.2 FAILURE OF ROOF CLADDING

5.2.1 General

The most conspicuous type of failure arising from cyclone "Tracy" was the failure of roof cladding. Over 90% of houses and of the order of 70% of all other structures suffered a significant loss of roofing.

The loss of this cladding had two significant effects: -

(i) once removed from a structure the roof cladding became a source of wind borne debris and a potential danger to other structures as well as persons, in the vicinity;

(ii) the loss of roof cladding led to a significant weakening of many structures which were relying on it for their strength.

These two effects were probably major factors in the very high proportion of damage caused by "Tracy".

Significant factors in the loss of cladding appear to have been: -

(i) progressive deterioration of the strength of the fasteners due to the cyclic nature of the wind loading

(ii) sudden increase in the wind load on the cladding as a result of internal pressures generated following an opening being formed on the windward wall of houses.

Since the most common cause of the latter situation was wind borne debris, it can be seen that the loss of cladding caused something of a chain reaction effect.

5.2.2 Cladding on Housing

The most common form of roofing on houses was corrugated iron fixed to purlins or battens, which in turn were fixed to rafters or roof trusses. These in turn were fixed to the walls. The manner of the fixing varied considerable and this influenced the form of the failure – but not it would seem the magnitude of the failure.

Figure 5.1 shows a typically older style roof failure where sheeting was nailed on to the purlins which were fastened to the rafters with wooden cleats, the rafters being presumably skew nailed to the wall. Here the weakest link was obviously the nailing of the iron and the sheeting has gone with the nails.

In later construction the wooden cleats appear to have been abandoned and direct nailing of purlins to rafters or trusses, or use of a metal strap nailed into the top of the rafters or trusses was used. Combined with relatively large spacings between the rafters or trusses this joint appears to have become critical and for this class of construction there were many examples of purlins having been carried away with the roofing iron as shown in figure 5.2.

In more recent years spacings of rafters and trusses have become less and particularly since cyclone “Althea” far more attention has been given to the fixing down of the roof, the sheeting being screwed on to the purlins at every second corrugation along the eaves and ends, and every third corrugation elsewhere, and in many cases stronger fixing of purlins to trusses and of trusses to walls and floor have been employed. This construction was to be found in the worst hit suburbs of Nakara, Wanguri and Tiwi. The effect on keeping the roof on of these measures appear to have been negligible with just a change in failure mode occurring. In those structures where the roof structure was well tied down the sheeting pulled off over the screws leaving the screws intact – see figure 5.3 – or where no effective tying down of the roof structure was made the entire roof was lifted off – see figure 5.4. The second of these was more common with low set houses.

An investigation by Mr V. Beck of the Department of Housing and Construction of the failure due to sheeting pulling over the screws has shown that repeated loads arising from the interaction between the wind and buildings can cause a significant reduction in the strength of this connection, and that failures characteristic of this mode of failure were observed following cyclone “Tracy”. A report on this investigation will be found in the Appendices. This phenomenon of fatigue weakening was not generally appreciated before cyclone “Tracy”, and it has cast considerable doubt on design information based on static tests which has been the normal approach to date.

Other types of cladding used in house and flat construction – metal decking, concrete, clay and steel tiles, and precast concrete slabs – performed no better than corrugated iron.

It is clear that the general fixing of roof cladding in domestic construction was totally inadequate, in spite of modifications made since "Althea". It is difficult to be precise but in the writer's opinion had the roof cladding stayed in place the degree of destruction would have been much less.

If there was any type of domestic roof where cladding appeared to stay on better than elsewhere it was the hip roof. Reasons for this could be –

(i) better aerodynamic performance;

(ii) majority of hip roofs were on low set houses where velocities were probably lower for reasons previously discussed;

(iii) hip roofs were often associated with open eaves which would relieve pressures under the cladding and thus lower the total wind load on it.

5.2.3 Cladding on Larger Structures

On large buildings the performance of roof cladding appeared to be markedly better than on small buildings such as houses, flats and small shops, despite the fact that the fastening in many cases did not appear to be any better – see figures 5.5 and 5.6.

The significantly better performance of roof cladding on larger structures merits some attention particularly as the actual fixing was in many cases probably no better than that on domestic construction and indeed in many cases was probably much worse. It was noted that the better performance appeared to be associated with one or more of the following factors: -

(i) steeper roof pitches;

(ii) no eaves overhang;

(iii) protection of edges by parapets or flashing;

(iv) ventilated eaves;

(v) height small relative to width and length of building.

All these factors are related to aerodynamic considerations which have been observed in wind tunnel studies.

In view of the importance of holding on the cladding these features will need to be investigated with respect to domestic construction.

5.3 FAILURE OF HOUSES

Houses in Darwin fall into two major groupings: -

(i) 2-story or high set homes,

(ii) single storey or low set homes.

Two different authorities were responsible for the greatest majority of the houses and since one concentrated on high set houses and the other on low set houses within each of these groupings where is a strong uniformity of design, the proportion of privately built houses within each group being relatively small.

A further subdivision can be made between traditional construction and system built houses with traditional construction being by far the most dominant.

In surveying the damage it is convenient to group the houses into three categories: -

(i) traditional high set construction,

(ii) traditional low set construction,

(iii) systems built construction.

5.3.1 Traditional High Set Construction

Of the three groupings traditional high set construction undoubtedly suffered the most severely.

These houses consist of a timber framed structure, with asbestos wall cladding and corrugated iron roof cladding, on a timber floor mounted on concrete or steel piers approximately 8 feet high. The general style is common throughout the tropical regions of Australia.

In Darwin there had been some significant changes in the details of the designs over the years.

Early designs tend to be mounted on steel piers often braced by diagonal ties in the transverse direction. Over the last 5 or 6 years reinforced concrete piers have been used with bracing being provided by infilled concrete masonry walls – generally 4" thick and unreinforced – between some of the piers to provide a laundry and storeroom, and some screening of the downstairs area.

For framing, the older designs generally had 4 inch x 2 inch stud walls supporting a framed roof system of rafter and ceiling joists with diagonal timer bracing in the walls and roof to provide resistance against horizontal racking. With the passing of time studs have been reduced to 3 inch x 2 inch members, the roof bracing appears to have been eliminated, and trusses replaced the tradition timber framing in the roof.

At a later date still, following concern that the notching of the 3 inch x 2 inch studs to take the timber bracing was seriously weakening the bending strength of walls in relation to likely wind pressures, the timber bracing was eliminated with galvanised iron strapping being used to brace the frame during construction and the wall cladding being expected to provide the wind bracing.

Following cyclone “:Althea” in Townsville and the recommendations which followed in the reports on the subsequent investigations, the tying down of the structure was significantly improved by the inclusion of cyclone bolts, with the intention being that each truss be bolted down to the underside of the floor, with the purlins being securely tied to the trusses by galvanised iron strapping. In addition the corrugated iron was screwed down to the purlins instead of being nailed, using screws at every second corrugation along the eaves and every third corrugation elsewhere.

In general the overall impression was that the older houses held together better than the more recent houses with a significantly great proportion of the older houses being repairable.

The general pattern of behaviour among older houses was loss of cladding, with or without the purlins, and sometimes with the timber roof framing as well. In roughly half the cases the remainder of the structure remained intact although often suffering serious debris damage to the asbestos wall cladding. Of the remainder, where structural failure of the wall occurred it appears to have been generally by blowing out of one of the walls of the main living room area which generally occupied one end of the house – see figure 5.7. Progressive failure of the remainder of the house then followed. There were numerous examples among all high set construction of a demolished living room area with the more rigid bedroom and bathroom area still standing – see figure 5.8. Failure of the piers was rare although occasional example of total collapse of the piers occurred – see figure 5.9.

Among the later houses the failure was much more dramatic with a much higher proportion of them suffering total collapse. The general sequence of failure appears to have been loss of sheeting, following a hit by debris on the windward wall, leaving the roof and longitudinal walls relatively unsupported, so that they have collapsed soon afterwards. Alternatively the wall sheeting has been shed and the galvanised iron bracing in the wall has failed and allowed the structure to fail by racking – see figure 5.10. By and large the piers performed reasonably well but in a significant number of cases the block walls between them collapsed. In some cases this has led to failure of the piers in bending or at foundation level – see figure 5.11. Cracking of the piers is common in situations where these walls did fail but in most cases there is little sign of permanent deformation. There was also evidence of floors having moved horizontally on top of the piers in some instances.

The basic cause of the failures appeared to be a lack of structural integrity in the houses particularly with respect to the following: -

(i) the connections between walls which were often ineffective

(ii) lateral support of the top of walls by bracing in the plane of the roof which was generally minimal after the roof cladding had been lost, particularly on more recent houses

(iii) tying down of roof structure to walls and floor, which had been significantly improved in the most recent construction, although some deficiencies in the design of the connections were still apparent

(iv) in-plane bracing of the walls which was inherently poor due to the incorporation of a large number of floor to near-ceiling windows in the longitudinal walls, leaving only short lengths of wall between them

(v) tying down of floor to piers

(vi) bracing of piers-

The most disturbing aspect is that those structures in which the most consideration appears to have been given to wind effects, namely those built in the last two years incorporating cyclone bolts and other tie down features, are the structures which have suffered the greatest destruction with almost 100% likely to require complete rebuilding. It appears that in general they have failed in spite of the tying down, and not because of inadequacies or faults in the construction, though some were apparent, of the tying down system.

From inspection of semi-damaged structures it appears that the primary mode of structural failure was racking or inwards or outwards collapse of the walls due primarily to a lack of bracing following loss of roof and wall cladding.

Older structures had considerably more bracing both in the roof and in the walls due to the use of timber diagonal braces and masonite internal linings on the walls and ceilings which continued to provide resistance after the loss of the external cladding.

In more recent construction much greater reliance was placed on the external cladding for bracing and when this blew off, in the case of the roof cladding, or was shattered by debris or racked off, in the case of the asbestos wall cladding, there was little remaining resistance in the structure and it fell down – see figure 5.12.

The net result of these inherent weaknesses was that if the roof cladding had stayed on thus providing bracing to the structures and limiting the debris, the houses stood a good chance of survival, but once the roof cladding went it was almost certain that structural collapse would follow. The writer believes that this was the major factor in accounting for the extremely high proportion of destruction of this type of construction in the far northern suburbs.

The relatively good performance of hip roofs on high set buildings was probably largely due to the inherent bracing which a hip roof structure provides.

The relatively poor performance of asbestos wall cladding on more recent houses is considered to be due to the inability of the connections of the sheets to the wall framing to transfer the racking loads into the asbestos sheets, resulting in the sheets; being racked off the wall.

The behaviour of the floor support system of the high set houses also left much to be desired although the complete collapse of the piers was rare.

Where steel cross bracing of piers had been used – generally with older style construction – no problems were observed despite the fact that the cross bracing generally was only in the transverse direction. It would appear that stairs provided a large measure of the bracing in the longitudinal direction.

The value of stairs as bracing in the longitudinal direction was also apparent in the new houses on concrete piers where despite the failure of the infill walls underneath which were intended to provide the bracing no serious longitudinal movement was observed. However, in these situations considerable transverse movement was observed to have taken place. Although some complete failures were observed, the general result was either piers out of line due to permanent deformation in bending or foundation failure or more commonly cracking of the piers due to considerable bending stresses having been imposed upon them.

The failure of infill walls which generally formed a laundry and screen walls appeared to arise from lack of bending resistance under transverse wind pressures. Factors associated with their failure appeared to be: -

(i) poor bond between mortar and concrete;

(ii) lack of reinforcement in the walls which were generally of 4 inch or 90 mm concrete block;

(iii) inadequate tying into piers to ensure integral action between piers and walls;

(iv) poor workmanship and lack of supervision in that the walls did not appear to be built according to the specifications, particularly as they related to the inclusion of a bond beam in more recent construction;

(v) shrinkage of block walls away from the piers.

5.3.2 Traditional Low Set Construction

Like the high set houses, low set houses have also undergone changes in design in recent years, and the greatest damage was done to the more recently built houses, the effect being much more marked with the low set construction.

Until the early 1970's the most common low set house comprised a traditional 11 inch cavity brick walled house on a concrete floor and surmounted by a continuous reinforced concrete bond beam which supported a timber framed hip roof clad with corrugated iron. The bond beam was anchored down to the cavity walls at the corners to approximately four feet of brickwork.

These houses performed very well in cyclone “Tracy” and formed a significant proportion of the undamaged and repairable homes – see figure 5.13. The most common failure was loss of roof cladding, quite often with the purlins as well. Lifting of the bond beam with subsequent damage to brickwork where it was anchored down at the corners was the most common form of more serious damage but overall it would appear that less than 10% of the homes in this group were damaged beyond repair.

A small group of precast concrete homes built to almost identical design except that the brickwork was replaced by hollow concrete panels performed equally well.

This basic design was eventually replaced by a quite different construction consisting of a timber framed structure with brick veneer on the end walls. These homes did not perform very well. The brick veneer generally collapsed and the timber framed structure behaved very similarly to the timber framed high set homes.

This design was superseded about a year before the cyclone by another design which represented a return to the masonry construction but with significant differences from that used previously. Concrete bricks and blocks, 90 mm wide, were used almost exclusively, and the cavity was increased to approximately 120 mm, (i.e. an increase from 2 inches to approximately 4 ½ inches) to fit in with the new metric module of 300 mm.

Blocks were used for the inner leaf and bricks for the outer leaf. Gable roofs tended to be substituted for the hip roofs and bond beams supporting them were placed along the two sides of the house only on which these roofs rested. In addition the bond beams were made from precast u shaped blocks infilled with concrete and reinforcing steel and simply sat on top of the walls without any tying down.

These houses performed very poorly being virtually 100% destroyed – see figure 5.14. Roofs tended to be lifted off taking the bond beams with them and the walls blew down, the 300 mm concrete cavity masonry walls displaying very poor behaviour.

The reasons for the relatively good performance of the earlier cavity brick houses were probably –

(i) integrated construction of traditional 11 inch cavity brick walls in relatively small houses with interlocking of internal and external walls providing a strong boxlike structure resistant to both debris and wind loads;

(ii) a continuous bond beam of reinforced concrete round the top of the walls which tended to hold all the walls together;

(iii) the hip roofs which provided a well braced roof system capable of bracing the walls after the loss of roof cladding;

(iv) the relatively weak connection of the roof sheeting and purlins to the rest of the structure, as a result of which no significant uplift forces were required to be transmitted from the roof to the walls in the majority of cases, which was probably just as well for the integrity of the walls. The bond beam to which the roof was attached was only tied down at the corners where it was tied by about 4 foot long anchors to the cavity walls. Where failure of these structures occurred it was inevitably by lifting of this bond beam with the ties tending to fail the walls – see figure 5.15. Had the roof sheeting and battens been more firmly fixed it is almost certain that the damage to these structures would have been far more severe.

The precast concrete panel wall low set houses performed very similarly to these cavity brick structures for probably much the same reasons.

The timber framed brick veneer construction which replaced the cavity brick construction as the standard lowset house performed poorly for much the same reasons as the high set timber framed construction. The brick veneer was used to clad the end walls only and performed poorly, generally being demolished, presumably by a combination of wind and debris. The inadequacy of the connection of the wall to the timer frame is shown in figure 5.16 where ties hooked over a staple had just pulled out without it would seem meeting much resistance.

The most recent standard design of low set houses suffered as severely as its high set counterpart. The design was a reversion to the masonry construction of earlier years but with significant differences. The roof sheeting appeared to be better attached to the roof structure which was tied down to the bond beams. Gable roofs were used more frequently than hipped roofs and where they were used the bond beam only ran along the top of each of the side walls. The bond beam was a concrete infill masonry block type which sat on top of the walls without any tying down whatsoever. This provided the weakest link to the uplift forces. A common form of failure appeared to be the lifting of the roof complete with bond beam off the structure – see figure 5.15. This left the walls inadequately supported and the majority failed to varying degrees.

The poor performance of these walls relative to those in the earlier designs appeared to be due to: -

(i) increased size of rooms and windows over earlier designs which combined with the loss of the roof left the walls with much less support;

(ii) the bond strength between the concrete blocks, which were generally used in this later construction for the inner leaf, and the mortar appeared to be very poor. This factor has already been noted in respect of the infill masonry walls between the piers of the high set houses and appeared to be a common factor in the failure of concrete masonry walls in a wide range of situations;

(iii) the walls themselves appeared to behave poorly as a unit due to having a different geometry. Following metrication brick sizes have decreased to 90 mm but the overall thickness of the cavity walls has been increased to 300 mm. The result is thinner leaves with a cavity twice the previous size. It appeared that the ties between the walls were inadequate to assure composite action so that each leaf tended to act independently.

Thus a situation involving two major changes from long established tradition in building had developed – the substitution of block for brick and the change in wall geometry – both of which appear to have led to a weakening effect and played a significant part in practically the whole of this class of building being destroyed.

A failure which highlighted another problem of concrete masonry construction is illustrated in figure 5.17. This construction differs from most other masonry buildings in that hollow block masonry had been used. There was a complete absence of any horizontal reinforcement and apart from the corners a complete absence of vertical reinforcement – yet without this reinforcing this type of construction has virtually no strength at all.

The same weakness was observed in many industrial buildings where similar masonry construction had been used for infill walls.

The collapse of this latter house also highlighted the danger of falling masonry, it being reported that four people had been killed in its collapse. It appeared from reports that wind borne roof material and collapsing masonry were the two most common causes of deaths arising from the failure of buildings.

5.3.3 System Built Houses

During recent years a number of different types of system built homes have been built in Darwin.

Overall these appear to have performed significantly better than traditional housing, although there were some exceptions to this.

Like traditional housing they suffered extensive loss of roofing in many cases but generally the walls stood up better and the great majority will be repairable.

A detailed investigation of the behaviour of most of the types of system build houses was made by Halpern Glick Pty. Ltd., the report of which will be found in Appendix 3.

Where these systems were developed from the foundations up, with the structure engineered for the materials used, behaviour was generally good as far as structure was concerned. Where, however, they represented a grafting on to traditional construction of a different material or style of construction then they tended to possess similar deficiencies to traditional construction and behaved no better.

5.4 FAILURE OF APARTMENT BUILDINGS

The typical block of flats in Darwin is two to four stories high with masonry load bearing walls, concrete floors and a steel or timber framed roof supporting metal deck roof cladding.

A detailed description of the behaviour of a typical block of flats may be found in Appendix 2.14.

The characteristic feature of the damage to flats and motels was loss of the roof and top story – see figure 5.18. The reasons for this appear to be –

(1) The inadequate fastening of roof cladding, generally steel decking, to purlins which were usually of either timber or cold formed light gauge steel section and which were often at rather larger spacings than is usual in housing.

(2) The dependence on cladding to brace end purlins which were expected to support the top of the end walls which were generally of masonry. Once the cladding had gone the compressive strength of the purlins was considerably reduced so that they tended to buckle allowing the wall to collapse. Since the windward end walls required the most support and the cladding was likely to go from the windward end first, because that is where the uplift loads are greatest on the cladding, this type of failure tended to be rather common.

(3) The lack of sufficient tying down of the roof for the loads experienced. A common practice in masonry construction appeared to be to tie the roof down to a limited number of courses of masonry. In some cases this appeared to be the weakest link and the roof had pulled the masonry wall over.

Problems pertaining to cavity wall concrete brick and block construction previously described were also noted with respect to the performance of flats.

Flats constructed using precast concrete wall panels generally showed no significant structural damage other than to the roof. The performance of one such system is described in Appendix 3.3.

A block of flats incorporating an insitu concrete roof was conspicuous by its good performance – see figure 5.19.

5.5 FAILURE OF ENGINEERED BUILDINGS

The term “engineered buildings” refers to buildings for which the structural strength is required to be certified by a structural engineer.

Overall the number of structural failures among engineered buildings was small.

The generally good performance, structurally, of these buildings indicated that in general the engineering codes of practice are adequate to cover extreme events such as “Tracy” whose maximum velocities were probably considerably in excess of the design velocities for many of the buildings.

The exceptions to this general statement were a number of structures where instability of steel members had taken place resulting in partial destruction of the building, and a group of four identical prefabricated buildings which had suffered complete frame collapse – see figures 5.20 and 5.21.

Details of the performance of a range of typical larger structures, including those in which structural failure occurred, is given in a report prepared by Halpern Glick Pty. Ltd. and presented in Appendix 2.

For the group of four identical steel structures which suffered total frame collapse, the structural strength was plainly inadequate for the wind loads sustained. These structures were designed for a design velocity of approximately 40 m/s based on a category 3 terrain. The minimum load factor permitted for framed structures in the current Australian Steel Design Code is 1.30 which would give for these structures an ultimate velocity of approximately 45 m/s. This is significantly less that the maximum velocities probably experienced in the area where the buildings were located, particularly as it is questionable whether they were protected to the extent envisaged by the category 3 terrain factors in the Wind Loading Code.

Although there are little reserves of strength over that given by the load factor in steel frames because of their basic simplicity of structural action and the uniformity of the yield strength, most structures even though nominally designed for the load factors specified in the code end up with considerably greater load factors in practice because of –

(i) the choice of available sizes of sections generally means using a larger section than really necessary;

(ii) the cladding of structures generally provides additional bracing to frames not taken into account in design;

(iii) the natural conservatism of many engineers and the simplified methods of analysis used in design generally provides an extra factor of safety.

Where there is an incentive for fine design, however, as there would have been for the structures in question, then these extra reserves of strength over those required by the code may not be present.

It would seem therefore that the main reason for the collapse of these frames may have been the combination of the significant reduction in design velocities permitted in suburban areas combined with the low load factors specified for steel design. In other words it appears that the failures may have been primarily due to inadequacies in the codes rather than in the actual design.

However, there were some factors about the design which did raise questions and which could have contributed to premature failure. These were: -

(1) Lateral torsional buckling of the main rafter members appeared to have occurred due to lack of effective lacing together of the two individual members to provide composite action in regard to stability;

(2) Failures in the connections of column members to the rafter members which raised questions as to whether the eccentricities in the connections had been accounted for in the design

The other structural failures, with the exception of purlins failing under uplift, involved failure of roof members in buckling. In the majority of these cases the significant loading causing failure appeared to be the forces on the windward end wall which were required to be supported by the roof members in compression. This produced buckling failures in purlins and, in the case of the saw tooth trusses described in Appendix 2.9 a buckling of the trusses.

As far as the purlin failures are concerned it appears that these may not have been designed to transmit the compression loads with the roof cladding gone, which was a general feature of these failures. The same failing has been noted with roof failures of flats as well.

In the case of the truss failure it is possible it may have been due to inadequate reserves of strength being available from the code design rules although inadequate bracing of the truss may have contributed to it.

The failure of the bottom member of the roof trusses in the collapse of the Community College building described in Appendix 2.18 appeared to be due primarily to compressive forces induced by uplift on the roof, although horizontal forces from the windward wall may have also contributed to these, and inadequate lateral restraint being provided by way of bracing to this member.

5.6 WALL CLADDING, WINDOWS AND DOORS

5.6.1 Wall Claddings

The most common wall cladding on timber framed houses was asbestos sheeting and this suffered very badly. Hardly a house using this form of cladding escaped some damage to it from debris, and in the most damaged areas, walls, if still standing, tended to be completely devoid of it – see figures 5.22 and 5.23.

A more recent innovation has been the use of ribbed metal decking screwed on to the timber or metal framing and this cladding appeared to perform very well showing considerable capacity to absorb the impact of debris – see figure 5.24.

The good performance of steel cladding relative to asbestos sheeting is probably directly related to its ability to deform locally and absorb the energy of impact by plastic yielding without actual tearing of the sheeting. Where it did fail it was generally due to inadequate fixing. However, failure of fixings of steel wall cladding was generally nowhere near as bad as it was for roof claddings. This was probably due to –

(i) forces on the wall cladding being less than on roof cladding;

(ii) wall cladding being often much more securely fixed than roof cladding. This was particularly noticeable on the steel clad houses.

A sandwich panel type of wall cladding using asbestos sheets enclosing a polyurethane core also showed reasonably good behaviour against debris.

Where masonry was used as a non structural infill wall on both industrial buildings and domestic construction, it generally performed poorly especially if made of concrete blocks. As mentioned previously brick veneer also performed poorly.

The poor performance of infill concrete masonry walls was probably partly due to poor construction but also probably due to the poor ability of this type of construction generally to absorb impact loads unless reinforced.

On large industrial buildings corrugated iron and ribbed metal decking was widely used as wall cladding and performed reasonably well with some exceptions.

On a number of larger buildings, in the city area in particular, a considerable amount of sun screening had been incorporated. Light gauge metal louvre types performed relatively poorly where exposed on the windward face, but well constructed screen block and expanded metal cladding was observed to perform comparatively well, providing considerable protection to the windows in so doing – see figure 5.25.

The relatively good performance of much sun shade cladding in protecting windows was probably largely due to its ability to resist debris but there was also an impression that wind pressures on windows may have been lessened by its presence as well.

5.6.2 Windows

Window glass suffered severe damage particularly in areas where debris was intense.

A more serious type of failure from a structural point of view was the blowing out of complete window frames from walls, especially in the northern suburbs – see figure 5.23. Many of these showed few signs of attachment to the structure of the house.

An exception to this was the behaviour in some precast concrete system built housing where despite obvious severe impact due to debris, the frames had stayed in place – see figure 5.26.

Louvre windows generally performed better than others, but a common problem reported by inhabitants was that it was difficult to keep them open on the leeward side during the cyclone. In view of the importance of keeping some leeward windows open during strong winds this is considered a serious problem.

The poor performance of many window frames in being blown out of walls due to inadequate attachment was directly due to poor workmanship and supervision.

Indirectly, in view of the prevalence of the defect, it raises questions as to whether sufficient thought has really been given to this problem by the manufacturers of windows and the designers of the houses, with the builder being faced with a difficulty for which the easiest way out is to do nothing.

It is significant, in the writer's opinion, that the windows on the precast concrete houses were better fixed. Here it would have been obvious to the designer that there was a problem and deliberate procedures had been developed to solve it.

The problem with the louvres would appear to be due to the position of the pivot. By alteration of the pivot point it should be possible to obtain a situation where unless locked, louvres would tend to close if on the windward side and would tend to open if on the leeward side. This type of behaviour would be very desirable in cyclonic winds. Since the tropical cyclone prone regions must provide a significant share of the market for this type of window, this improvement should be seriously considered by the manufacturers.

5.6.3 Doors

A significant number of door failures were reported as having occurred particularly in flat, motel and hotel types of buildings. They were generally attributed to failure of the latches.

The problem of doors is that the catch is required to take half the load on the door. The solution to this would appear to be to have additional bolts fitted top and bottom for use during cyclonic winds.

Large roller doors on industrial buildings appeared to have suffered almost 100% failure.

Roller doors are a difficult problem during high winds as poor performance in both "Althea" and "Ada" also showed. The main problem with these doors is their flexibility, the doors bowing inwards to such an extent that the edges come out of their guides.

A secondary problem is that often the guides are insecurely attached to the structure of the building and pull off.

Fig. 5.1 - Roof cladding loss – timber cleated purlins

Fig. 5.2 - Roof cladding lost with purlins

Fig. 5.3 - Screw fastenings remaining in purlin

Fig. 5.4 - Failure of roof structure as a whole

Fig. 5.5 - Darwin High School

Fig. 5.6 - Typical industrial buildings

Fig. 5.7 - End wall blown out

Fig. 5.8 - Typical half demolished house

Fig. 5.9 - Pier collapse

Fig. 5.10 - Failure by racking

Fig. 5.11 - Failed pier

Fig. 512 - Collapse due to racking

Fig, 5.13 - Low set cavity brick construction

Fig. 5.14 - Failure of recent low set masonry home

Fig. 5.15 - Lifting of bond beam

Failure of tie in brick veneer

Fig 5.17 - Collapse of hollow block home

Fig 5.18 - Typical damage to flats

Fig 5.19 – Flats which performed well

Fig. 5.20 - Buckled purlins on industrial building

Fig. 5.21 - Collapsed steel building

Fig. 5.22 - Battered wall cladding

Fig, 5.23 - Having lost wall cladding

Fig. 5.24 - Metal clad house

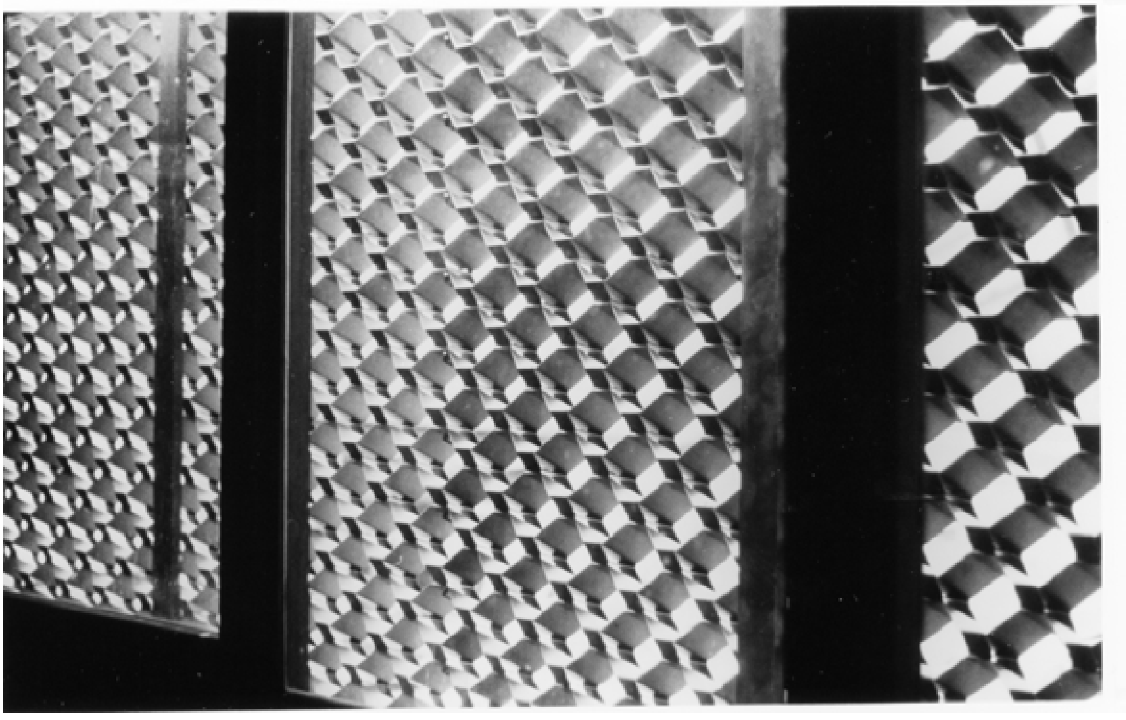


Fig. 5.25 - Sunscreen protected windows

Fig. 5.26 - Battered window frame in concrete house

CHAPTER 6

IMPLICATIONS OF DISASTER

6.1 INTRODUCTION

In this chapter an attempt is made to formulate a response to the effect of cyclone "Tracy's" effect on buildings in Darwin by outlining some of the implications for design, construction and maintenance of buildings in tropical cyclone prone areas which in the writer's opinion follow from a study of the damage.

The intensity of the winds was greater than has been recorded in closely populated areas in the past forty years or so, this being about the length of time for which reliable wind speed information is available, but the velocities were not outside the known bounds of possibility and were within the limits such that most structures, if reasonably designed, should have been able to withstand the forces without a significant number of failures, but showing signs of overstressing. The performance of engineered structures in general testified to this, but the poor performance of traditional construction points to the need for some radical rethinking in this area.

6.2 GENERAL APPROACH TO HOUSING DESIGN AND CONSTRUCTION

In the previous chapter it was noted that the basic cause of the destruction lay in the inadequacy of the traditional approach to house design and construction to cope with occasional extreme events such as cyclone "Tracy".

It seems clear that if such a disaster is to be reduced to acceptable limits in the future then a radically new approach to housing must be adopted in tropical cyclone prone regions. It is the opinion of the writer that housing needs to be put on the same level as large commercial, industrial and public buildings whereby the structural strength is certified by a structural engineer before construction takes place and adequate supervision of construction is provided. The structural integrity of homes is just as important as the structural integrity of the larger buildings as cyclone "Tracy" has revealed. Also in economic terms the investment in houses is of a similar order to the investment in the larger buildings.

It is interesting to note that in the private company developed mining towns which have been built in tropical cyclone prone areas it is common practice to treat housing in the same way as other buildings in respect of design and construction of the structure.

Quite apart from economics the human suffering involved in the mass destruction of homes provides a strong moral argument for requiring the same attention to structural strength in house construction as in larger buildings.

It is also interesting to note that systems built housing often requires an engineer's certificate before being accepted by many authorities.

The argument against the engineering of houses has been largely based on the fact that the structural behaviour of a house is just as complex, maybe even more so in many cases, as the structural behaviour of larger buildings and hence the design costs are large relative to the cost of a single building. Structural engineers, themselves, have probably been reluctant to become involved in this work in the past, as have architects and home owners been reluctant to seek their services, for this reason.

But the vast majority of home building today is not one-off production. Most homes today are built to standard plans with large numbers of each type being built and when viewed in the light of the cost of all the homes built to a particular plan the cost of a structural engineer's services would in general not be unreasonable. It would appear that in Darwin for instance, housing was being built in contracts which were approaching the order of a million dollars with no more than three or four basic designs involved. In such circumstances there does not seem to be any economic justification for not performing a full structural analysis as would be required for a large building of similar value.

The alternative of trying to produce a set of building by-laws or rules which will cover every possible situation with new ideas always coming in, is in the writer's opinion impossible to achieve. It is the way authorities have tried to cope with the design problems in traditional building in the past and has been shown by both "Althea" and now "Tracy" to be unworkable.

There will be problems involved in changing from the traditional approach but they will be resolved in due time if society is prepared to make the change.

It will involve, for instance, the development of a new relationship between builder, architect and structural engineer in house construction with the structural engineer playing a much more significant role than in the past, which will inevitably give rise to problems of adjustment for all involved.

It will involve structural engineers in an area in which most have had little experience and in which few ground rules have been determined. The type of structure and the materials involved are different from those with which most structural engineers are familiar and it will take time to develop this experience. New methods of analysis and modifications to design codes may be required as present methods of analysis and design are the result of years of experience of designing the types of structures most commonly used in larger buildings and these may not be appropriate to house design. However the structural engineer is equipped by his training to cope with this problem and given time and the sharing of the experience of the small number of structural engineers who have been involved in this field already it will be overcome.

Requiring the structure to be engineered will also alter the cost structure of housing in tropical cyclone prone areas.

The influence of design costs on standard type housing should be minimal since it will be shared over a large number of units but it will inevitably add to the cost of individual one-off houses. As a result it may well inhibit, to some extent individuality of style in tropical cyclone prone areas except for those who can afford the extra cost. It would seem that this will be art of the price of living in such an area.

The implementation of such a change would of necessity have to come about by an ordinance decreeing it being included in the building regulations for each city and town in areas subject to tropical cyclones, and the deletion from the regulations of all arbitrary rules and by-laws relating to the structural integrity of houses. There is no point, for instance, in specifying the number of cyclone bolts, or size and spacing of rafters and their fixings, etc., etc., if the responsibility for design is passed over to a structural engineer, though for purposes of standardisation it may be necessary to recommend certain common features. A mixture of engineered components and traditional building practice can be quite disastrous as was shown in cyclone “Tracy”.

Such a change could not come about overnight but would need to have a transitional period which may take some years during which it would be hoped the large house construction organizations would be encouraged to give a lead in implementing the changes, with a date being set after which all houses built must comply with the change.

6.3 CYCLONE DESIGN PHILOSPHY

Having decided that the structure of houses should be engineered the next question to ask is – What should be the design philosophy? This question is most commonly expressed as – What should be the design velocity?

It is clear that there is a great deal of misunderstanding, especially by the public, but also by many engineers, about what is meant by the term “design velocity”. Many people seem to think that the design velocity is the maximum wind velocity which the structure is designed to withstand. This is not true. The design velocity is the velocity for which structures are designed to behave as they would under ordinary working loads without stresses and deflections exceeding the permissible values stated in the codes of practice, or to provide a specified minimum load factor against collapse, depending on the method of design. Since these structures embody in them factors of safety which should give them a strength well in excess of the design value it follows that structures designed for a certain design velocity should be capable of withstanding considerably greater velocities without failing.

The present approach has been developed largely in areas not subject to occasional very extreme winds such as are experienced in tropical cyclone prone areas. In such areas the probabilities of the design wind velocity being exceeded by a significant amount is very small and factors of safety implied in the codes of practice are generally sufficient to easily cope with this – see figure 6.1. As a result misunderstanding of the meaning of the design velocity does not lead to any serious problems in design in these areas.

When areas subject to tropical cyclones are considered however, it becomes very important to understand the significance of design velocity. Figure 6.2 illustrates the interaction between the probability distribution of wind velocity where the probabilities of extreme events are much greater than in figure 6.1 and two different strength distributions, one where the coefficient of variation is small, and one where the coefficient of variation is large, with the same design strengths. It must be remembered that the design strength is not the mean strength but some minimum strength that has only a very small probability of not being exceeded by the actual strength of the structure. It will be seen that notwithstanding that the design velocity has been accounted for, one must also consider the possibilities of higher velocities and the effect these are likely to have. For instance if a velocity V2 in figure 6.2 has a reasonable possibility of occurrence then it could cause the collapse of the great majority of class A structures with the small coefficient of variation of strength but would be expected to have a much lesser effect on class B structures. A philosophy based entirely on design velocity is therefore inadequate.

This has been recognised to some extent in the wind code by the introduction of the cyclone factor whereby design velocities are increased 15% but this strictly only needs to be applied to class A type structures as the writer has shown in recent statistical interaction studies. Generally in housing design we are dealing with class B type structures – that is structures with a large coefficient of variation of strength with a design strength significantly less than the likely mean strength of the population so that we would expect average factors of safety to be quite high – although as design of them gets more refined and construction gets more sophisticated they are likely to tend towards class A type. Some figures on this are given in the report by R. H. Leicester and G. F. Reardon contained in the Appendices.

Since the extreme winds only occur very infrequently in cyclone prone areas and bearing in mind the inherent factors of safety in structural design, it is unreasonable to make the design velocity equal to its highest likely value, but it is important that this highest likely value be borne in mind in design.

The same problem faced the earthquake engineers a few years ago when it was realised that forces exerted on a structure by an earthquake could be far greater than those for which it was designed, but notwithstanding this many so designed did survive large earthquakes due to inherent factors of safety and ductility. As a result a new philosophy was developed which involved a two phase approach. Structures continued to be designed for similar design loads as in the past in accordance with the codes so that they would safely resist small earthquakes but in addition designers were required to ensure that the structures were designed in such a way that in a large earthquake they would retain their integrity, even though severely overstressed, and perhaps showing considerable signs of distress and failure, this latter procedure becoming known as providing ductility. It seems to the writer that an analogous two phase approach is required in designing for wind in tropical cyclone prone areas. Severe tropical cyclones are rare events and some overstressing or even signs of failure are acceptable providing structures retain their integrity and the roof cladding is kept on by one means or another.

Such a design philosophy might be along the following limit state lines:

The structure and roof cladding of buildings in tropical cyclone prone areas must be designed to provide for each of the following two situations –

(1) To satisfy the normal design code regulations for the maximum 50 years return period wind velocity based on annual maximum gust velocities. This would ensure no damage at all under these conditions.

(2) To provide sufficient reserves of strength within the structure of the building to ensure that it has a high probability of retaining its overall integrity, though local failure may have occurred, under a basic wind speed of the code of 80 m/s, which may be modified for terrain effects bearing in mind that vegetation may be stripped of leaves, and assuming large openings may have occurred in estimating the wind loads of the building.

If such a philosophy were accepted it would of course be necessary to determine by research and development appropriate design rules and details for the various materials and styles of construction in much the same way as has been done in the earthquake engineering field in regard to providing ductility.

In effect what this does is to apply a limit state collapse approach to design for tropical cyclones.

Satisfaction of the first criterion would ensure safe behaviour under winds that can reasonably be expected to occur during the life of the structure and satisfaction of the second would ensure that the majority of structures would at least hold together in the most severe tropical cyclone.

Roof cladding is included because it seems essential that it be retained in position, primarily to restrict the debris problem and its consequent danger to life and property, but also to ensure that homes remain habitable even if significant local damage within the building has occurred.

As with the change in building practice the implementation of this philosophy would take some time as considerable research on the ultimate behaviour of typical residential type structures would be necessary, but such research is required anyway, and the adoption of this philosophy would provide a rational framework within which to conduct this research.

6.4 INTERIM DESIGN RULES FOR CYCLONIC AREAS

Assuming the proposed cyclone design philosophy is adopted it will take some time for the appropriate design rules to evolve. It is therefore necessary to have some interim guidelines to tide designers over this period.

It is inevitable that such rules will be considerably subjective and will require some modification after sufficient time for a more rational approach to develop has elapsed. The writer offers them on the basis of his personal experience in design for tropical cyclones and observation of the damage in Darwin due to cyclone “Tracy”.

6.4.1 Design Wind Speeds

6.4.1.1 Larger Buildings

Recommendation: Design according to present codes with the following amendments: -

(i) basic wind velocity for 50 year return period of 55 m/s

(ii) minimum category reduction factor of 0.7

Comment: Generally the performance of engineered buildings was such that no great increase in design velocities would seem to be justified. However, the mere occurrence of velocities of the magnitude estimated to have occurred during "Tracy" raised the value of the expected maximum for a given return period and due account needs to be taken of this. Doubt about the effectiveness of obtaining full category 3 protection during high winds is the reason for specifying the minimum category reduction factor.

6.4.1.2 Housing

Recommendation: The design wind velocity for single dwelling buildings shall generally be 55 m/s inclusive of allowances for terrain category and cyclone factor. For houses in exceptionally exposed locations, e.g. on a cliff near the sea, this speed shall be increased to 65 m/s. For individual houses, to be built or restored in an embedded location in an established suburb, i.e. where total shielding is secured, the design wind may be reduced to 45 m/s.

Comment: Because of the standardised nature of most housing, difficulties of assessing possible terrains, and the debris factor, it does not seem practical to impose a detailed terrain evaluation factor on house design. In particular since the debris tends to increase in proportion to the density of housing it would seem reasonable to assume that it cancels out the increased sheltering effect thereby attained.

The general recommendation of a design velocity of 55 m/s is consistent with that given for other buildings assuming a terrain more closely approximating category 2 than category 3 in the Wind Loading Code.

6.4.2 Wind Loads

Recommendation: The wind loads on structures and their components shall be derived from the design velocity using the pressure coefficients specified in the code with the added requirement that in determining internal pressures, the maximum possible coefficient of 0.8 for a dominant opening on the leeward or side walls or the roof shall be used in determining the maximum internal negative pressure or suction. This requirement may be waived in commercial and industrial buildings where specific measures have been taken to reduce the possible occurrence of a dominant opening through the provision of protection for windows and doors against wind pressure and debris.

Comment: The purpose of the recommendation is to ensure that the structure can take the additional internal pressure loads which may be imposed on it following the formation of a large opening by window failure or local loss of cladding as a result of debris impact or localised wind effects not accounted for in the design.

6.4.3 Structural Design

Recommendation: Unless otherwise specified in these rules the design of all structural members and connections shall be in accordance with normal engineering design codes of practice with the following amendment: -

In the design of steel structures no increase in permissible stresses (or decrease in load factor) shall be permitted for design against the worst combination of dead loads and wind loads.

Comment: The failure of a small number of steel structures suggests that current practice does not provide adequate reserves of strength in all cases for extreme winds of the magnitude likely to be experienced in severe tropical cyclones. This amendment is designed to improve this situation.

With respect to the design of houses in the traditional materials of timber and masonry, current design rules in conjunction with the recommended design velocities are expected to yield conservative designs in general because of the large factor of safety generally associated with these rules. It is anticipated that with the development of a greater knowledge of the ultimate strength characteristics of housing structures through load testing, and of the statistical interaction between likely wind velocities and structural strength through probabilistic studies, that there may be some relaxation of the design rules in these materials for cyclonic winds. As recommended the rules will produce houses which will generally be several times stronger in the critical regions than they have been with traditional construction, and this could well cause a psychological problem for both designers and builders when first faced with the implications of these new design rules.

6.4.4 Cladding

Recommendation: Cladding shall generally be designed in accordance with the principles laid down in the previous sections 6.4.1 and 6.4.2 with the following additional criteria regarding roof cladding: -

(1) In larger buildings designed according to the rules specified in 6.4.1.1, the roof cladding shall not be permitted to be taken into account in the prime bracing of the supporting frame members.

(2) The fixing of all roof cladding shall be such that it will have a high probability of being retained on the structure even if showing signs of distress or failure, for wind velocities up to 80 mm/s.

(3) The fixing of all roof cladding where over-battens are not used, and of wall cladding which is used as bracing, shall be required to be deemed

satisfactory for 10,000 cycles of repeated loading from zero to the design load based on the criteria specified in 6.4.1 and 6.4.2.

(4) In houses cladding shall be permitted to be taken into account in the bracing of the structure, but in such cases the connections between the cladding and the frame shall be designed with normal factors of safety to transmit one and a half times the load calculated from the criteria specified in 6.4.1 and 6.4.2, and the designer shall also be required to assess the effect of debris impact.

Comment: The enormous effect which loss of roof cladding had on the magnitude of damage in Darwin is considered sufficient justification for the above restrictions. The object of design of roof cladding must be to keep it on at all costs, but the clauses do not rule out the use of secondary fixing such as over-battens which may not be sufficiently rigid or extensive to prevent serious deformations and even local failures of cladding but will be sufficient to prevent propagation of the failure and retain the cladding on the roof in very extreme winds.

The significant number of failures of supporting framework, generally purlins, under the compressive loads induced from supporting windward end walls, following the removal of the roof cladding adjacent to the windward edge, warrants the first of these restrictions.

The large reduction in strength of corrugated iron screw fastenings under repeated loads which was observed by Mr Beck (see Appendix 4) is considered sufficient justification for the third requirement. It is possible that other systems of roof claddings and fixings may not be so sensitive to fatigue effects but this will need to be demonstrated by testing and cannot be assumed.

The case of housing structures employing the cladding as part of their bracing is considered a special case in view of the fact that such structures will tend to have lower reserves of strength than those independently braced and also because of the virtual complete loss of strength, and hence inevitable destruction that is likely to result if failure of the cladding does take place, as exemplified by “Tracy” in the northern suburbs of Darwin.

Where cladding is being used to brace a structure it is obviously important that the cladding is not too severely damaged by wind born debris.

6.4.5 Masonry Construction

Recommendation:

(1) All masonry required to resist wind loads as part of the structure of the building shall be designed in accordance to the relevant engineering design codes of practice. Internal masonry walls which can be subjected to internal pressures shall be designed to withstand at least 50% of the maximum nett design pressures on external walls.

(2) All masonry walls shall be surmounted by a continuous reinforced concrete bond beam to which the roof shall be attached, and which shall be tied down directly by steel rods to the wall footings, and which shall be designed to transfer in addition to the above forces, the horizontal reactions from the tops of walls under transverse pressure to the transverse walls which shall be designed to resist the resulting racking loads.

(3) Cavity wall construction shall be limited to brick construction and the cavity shall not exceed 50 mm (2 inches).

(4) Concrete blocks may only be used in reinforced blockwork as defined by the design codes.

(5) Brick veneer shall not be regarded as having any load carrying ability and shall not be permitted other than between the ground floor and first floor levels.

Comment: These are regarded very much as interim measures and further research and development may well enable a relaxation of these rules.

Two factors which stood out strongly in the investigation of the damage in Darwin form the main background to these recommendations. These are the poor performance of unreinforced concrete masonry and the danger to life of falling masonry. This latter factor is the reason for requiring internal walls to be designed for differential pressures and for brick veneer to be limited to ground floor levels where its failure, which it is assumed may occur without structural damage to the house, will not endanger life.

The restriction of cavity size arises from apparent difficulties of walls with larger cavities to cope with the lateral wind pressures.

6.4.6 Connections of Walls, Windows and Doors

Recommendation: The interconnection of walls and the connections of doors and windows to the structure of buildings shall be designed in accordance with established engineering procedures for the criteria specified in sections 6.4.1 and 6.4.2.

Comment: It is clear that in many cases these connections are left to the builder to decide how it should be done. The performance of these is an important factor in the overall performance and safety of the building during extreme winds and accordingly they should be designed with the same degree of care as the structure itself.

6.4.7 Window Glass

Recommendation: Window glass shall be designed in accordance to the appropriate code of practice for the design criteria specified in sections 6.4.1 and 6.4.2.

Comment: Failure of windows is a common factor in the initiation of failure in a house. It is not practicable to design the window glass for debris but by ensuring the window glass is designed for wind pressure it allows the use of window protection directed solely at restricting debris. This allows much more flexibility in the design of window protection.

6.5 WINDOW PROTECTION

Internal pressurisation following an opening being made on the windward wall of a house is the most common first step in the failure of a house under wind. The most common cause of a windward wall opening is failure of a window, often due to debris.

While it is practical to design the thickness of the glass to resist the wind pressures, it is not practical to design it against debris impact. To reduce the possibility of windows being broken by debris it is therefore necessary to provide some form of protection in front of the window.

The apparent success of sunscreening on large commercial buildings in protecting windows suggests that the development of something similar for houses could considerably assist the performance of houses during cyclonic winds.

One of the main problems of window protection is its maintenance over long periods between use, but if it were also used for sun protection, which would provide a constant use, this problem would be largely overcome.

From a design point of view it would be necessary to specify some criteria regarding size, type and velocity of design debris and also the criteria of satisfactory performance against such loadings. This clearly would require some research.

Because it would be difficult to guarantee the performance of window protection for all possible circumstances that could arise during a tropical cyclone, the writer is of the firm opinion that the provision of shutters should not be taken into account in the design of the structure and roof cladding, particularly for houses. Rather it should be regarded as providing added safety to the occupants and improving the overall performance of the building during a tropical cyclone.

The writer is also of the opinion that window protection should be considered advisable but not obligatory.

6.6 IN-RESIDENCE SHELTERS

It is clear from the investigation of the effects of cyclone “Tracy” and the reports of those who endured it with their homes falling down around them that there is a real need for an extra safe area accessible from within the house to which residents can retreat with reasonable confidence for their ultimate safety during an extreme wind.

The term “in-residence” shelters has been coined by researchers at Texas Tech University for such refuges where use is made of an existing small room in the house, such as a bathroom, for this purpose. Walls, roof, windows and doors of this room are designed to cope with much more extreme events than the general house itself with the intention that it stays intact even if the rest of the house goes.

It may be argued that if the houses generally are designed as recommended in previous sections so that their chances of survival is very high then there is no need for these extra measures.

The arguments against this are: -

(1) Some houses will still fail for a variety of reasons but mainly because it is not possible to design for every conceivable eventuality or to ensure that every one is constructed exactly as the designer intended.

(2) For psychological reasons residents will feel much less fearful during a cyclone if they have a "safe place" to go to.

Criteria need to be developed for the design of these but it is suggested that it should provide for the safe resistance to wind velocities of the order of 80 m/s and for reasonable resistance to debris penetration under these conditions.

The work of Professor Keisling at Texas Tech University should provide a useful guideline to the design of these refuges.

In houses which may be subject to flooding, particularly by the storm surge, such shelters may not be a good idea and in fact could well become a death-trap. In these cases the provision of public shelters on nearby high ground warrants consideration, along with evacuation plans with which the residents of the homes likely to be affected are well informed.

6.7 AREA OF APPLICATION

The writer believes the recommendations regarding design for tropical cyclones which have been made in this report should be regarded as being equally applicable to all buildings in the presently defined tropical cyclone prone regions with the possible exception of isolated farm buildings whose failure would not endanger life or other property.

6.8 THE PROBLEM OF EXISTING BUILDINGS

Throughout the centres of population in tropical cyclone prone areas there are large numbers of houses whose ability to withstand winds of the magnitude and duration experienced in cyclone "Tracy" is unlikely to be significantly better than Darwin's houses.

Since several of these centres have populations of similar size or greater than that of Darwin when "Tracy" struck, these all must be regarded as potential disaster situations of similar magnitude to that which occurred in Darwin. This is a very frightening thought.

It is probably not practical to do much to the existing internal structure but one improvement is practical which could reduce the potential magnitude of disaster by an order of magnitude. This is to tie down the roof cladding more securely by the use of external roof battens placed over the cladding, the battens themselves being tied down by external means to floor or foundation level. It may not look nice but if it averts a tragedy of the magnitude of Darwin this price will be worthwhile.

Figure 6.3 shows a house in Darwin which had been modified in this way and which testified to the usefulness of the method. Houses in the immediate vicinity suffered considerable damage and destruction and as figure 6.4 shows this house was severely holed in the end wall producing a very critical situation for the roof. It seems fairly certain that the owner can thank the battening for still having a house with a roof on – even it is a little distorted. It is interesting to note that proposals were in hand in Darwin for strengthening a large number of residences of this type by a similar method at the time of the cyclone.

As with other proposals a potential disaster will only be mitigated if everyone adopts the changes and the question may well be asked how this may be made effective.

Ultimately the only way of getting everyone to comply is by a council ordinance through changes to the building regulations but this can take time as changes tend to be slow due to the inherent conservatism of local body politics and the strong influence of vested interests in resisting change.

Other incentives may therefore be necessary such as those provided by tax deductions and the cost of insurance.

Another aid to better performance would be the protection of windows, particularly against debris, as described in section 6.5.

6.9 THE ROLE OF INSURANCE COMPANIES

As has been pointed out in previous sections the only way the proposals put forward in this report can ultimately be implemented fully is by changes in the building regulations in tropical cyclone prone areas, a procedure generally fraught with delays and compromise and unlikely to produce the desired effect very quickly other than in Darwin. It is unfortunate, but true that one generally has to experience a disaster to be really convinced of the need to avoid one.

However there is one group which has a very vested interest in the situation and who could provide a strong incentive to bring the proposals to fruition much more rapidly, and this is the insurance companies.

In Australia insurance companies in providing storm and tempest cover do not differentiate between houses, providing insurance at the same rate for all types irrespective of their likely resistance to cyclonic winds. After cyclone “Althea” this policy was maintained but it was found necessary to triple the existing rate this being considered more acceptable than facing up to the problems which would be involved in classifying buildings.

But after “Tracy” the insurance companies must be giving serious thought to changing to a system of classification and if they should do this it will provide a powerful spur for the rapid implementation of the proposals.

This system of cyclone rating of structures is followed by insurance companies in Guam if reports received by the writer are correct.

In Guam four classes of structures are specified ranging from Class 1 which are fully reinforced concrete structures, both walls and roof, to Class 4 which would be structures having little or no protection against failure in cyclonic winds. Insurance rates are lowest for Class 1 and increase with class, Class 4 having the highest rate or not being insurable.

Such a system is only workable where certification of structural soundness by structural engineers can be obtained at the time of construction and can somehow be retained for the benefit of future owners, as once a structure is complete it is generally not possible for a structural engineer to perform a reliable assessment, but such problems must have been overcome in Guam.

As far as existing buildings are concerned it would seem that only two classes are possible, those employing an approved external strengthening system and those which do not. A significantly cheaper rate of insurance for the former over the latter could act as a very good incentive to owners to have the modifications carried out and consequently provide much greater protection for the insurance companies themselves.

6.10 RESEARCH NEEDS

For the proposed design philosophy to be implemented in a rational manner it will be necessary for research to be continued or initiated in a number of areas, particularly in relation to the probabilities associated with extreme wind speeds, the ultimate strength characteristics of low rise structures and the interaction between them, and the fixing of cladding.

6.10.1 Wind Velocities

In order to gain confidence in design it is important that as much information as is possible be obtained about the statistical and geographical characteristics of the occurrence of extreme winds in the main populated areas of the cyclone region. To this end it is recommended that: -

(1) Research be continued on the modelling of tropical cyclones and their occurrence around the Australian coastline with a view to obtaining a better understanding of the probabilities associated with their occurrence in terms of their magnitude and resulting wind field.

(2) The number of anemometers in tropical cyclone prone areas be greatly increased. The instruments should be capable of measuring gust velocities up to 90 m/s (200 mph) and be located so that the chance of debris damage is small. In each town with a population of 20,000 or more it would be preferable to have at least 3 such anemometers.

(3) Instrumented aircraft be flown into tropical cyclones when they occur to obtain data on barometric pressures and wind velocities, as is done in the United States of America.

(4) A portable set of anemometers and masts be developed along the lines perhaps of those developed at the National Bureau of Standards in the U.S.A. or the Building Research Station in the United Kingdom to obtain field measurements of velocity profiles up to 20 metres above the earth's surface in various locations within the major towns of cyclone prone regions so that information on local terrain and topographical features can be obtained.

(5) Wind tunnel studies of the effect of local topography on wind velocities in cyclone regions be carried out and related if possible to the field studies.

6.10.2 Wind Loads

In order to learn more about the actual loads exerted by winds on low rise buildings it is recommended that –

(1) Current interest in wind tunnel studies of the effect of wind on groups of low rise buildings be fostered.

(2) A programme involving full scale instrumentation of structures in windy locations along the lines of similar studies undertaken by the National Bureau of Standards, U.S.W., and the Building Research Station, England, be encouraged.

6.10.3 Structural Behaviour

6.10.3.1 General

In order to gain a better understanding of the structural behaviour of houses, particularly as regards the statistical relationship between real strength and design strength it is recommended that continued research be encouraged on the ultimate strength behaviour of all types of structures used in housing under the type of loading imposed by wind loads, including the effect of repeated loads.

6.10.3.2 Masonry

In view of the poor behaviour of concrete masonry in general and also of masonry walls with large cavities designed to fit the new metric recommendations it is recommended that studies aimed at overcoming these problems be instituted as a matter of some urgency.

6.10.3.3 Cladding

In view of the very poor behaviour of roof cladding of all types it is recommended that research and development work aimed at obtaining a better understanding of the reason for its failure and at developing methods of fastening and design of it that will prove adequate for wind velocities up to 80 m/s be instigated immediately as a matter of great urgency. Included in this is a need to develop more realistic methods of testing roof cladding bearing in mind the sustained dynamic characteristics of the wind pressures.

6.10.3.4 Debris Protection

In order to provide information required for developing criteria for the design of in-residence shelters and debris protection for windows, it is recommended that studies be instituted of the likely debris characteristics and its effect on various types of cladding and protection.

6.10.4 Wind-Structure Interaction

In order to obtain a better understanding of the interaction between extreme winds and damage as a function of design strength so that a more rational approach can be adopted for the determination of appropriate design velocities it is recommended that current probabilistic studies of this interaction be maintained.

6.10.5 Wind Damage Studies

In order to continue to learn the lessons that each example of wind damage provides it is recommended that field studies by engineers and architects experienced in wind engineering be undertaken wherever significant wind damage occurs.

6.11 EDUCATION AND SUPERVISION OF BUILDERS

There has been considerable comment regarding the effect of poor workmanship on the failure of houses in Darwin and attributing this to poor supervision.

While it is apparent that poor workmanship was apparent in many instances, particularly in regard to brickwork and blockwork, the fixing of window frames, and some of the cyclone bolting, and that this was a contributing factor to failure particularly of the masonry construction, the writer does not believe that more intense supervision is the most significant factor in the correction of this situation, although it will help.

Of much greater importance in overcoming poor workmanship is the proper education of builders by architects and engineers on how to construct the various details which they specify. Too often architects and engineers leave it to the builder to decide how to do a thing, when it is they and not the builder who has been trained to provide this guidance, albeit generally in consultation with the builder.

If the changes outlined in this report are to take place then this will be doubly important because by and large builders do things the way they have been taught to do them and if things are to be done differently they need to be shown how they are to be done.

Much more detail on plans and specifications will be a help in this respect but seminars and the like provide a much better environment for this learning process to be initiated.

A lead in this area has already been given in Townsville by the Cyclone Building Research Committee, a group comprising representatives of the Institution of Engineers, Australia, the Royal Australian Institute of Architects and the Queensland Master Builders Association, who through Cyclone Construction Seminars have sought to pass on to tradesmen the practical outcome following the application of the lessons learnt from the investigation of damage following cyclone “Althea”.

It is recommended that similar groups be set up in other centres throughout the tropical cyclone prone areas utilising the experience gained by this Townsville group and that Government support be given to these groups as part of its contribution towards continuing technical education.

The importance of this educational aspect in ensuring good workmanship cannot be underestimated in the opinion of the writer and will lead thereby to a significant reduction in the level of supervision which would otherwise be required. Failure to do this will inevitably mean that the supervisors or inspectors will be required to do the teaching on the job in an atmosphere not very conducive to a successful outcome.

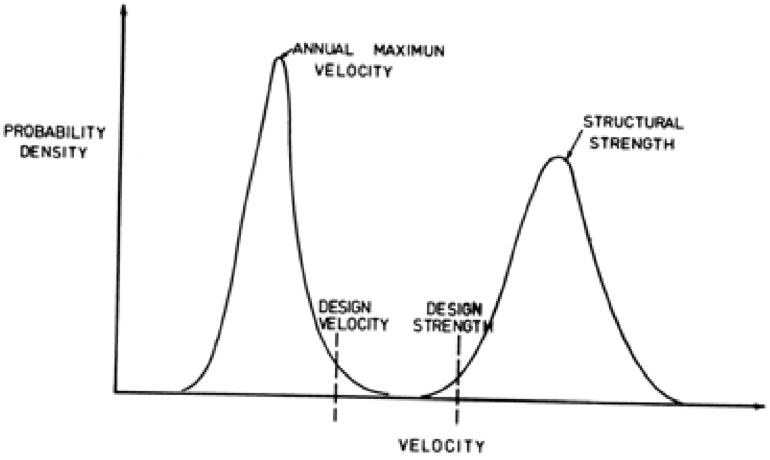


Figure 6·1

INTERACTION BETWEEN VELOCITY & STRENGTH FOR SMALL COEFFICIENTS OF VARIATION OF EACH.

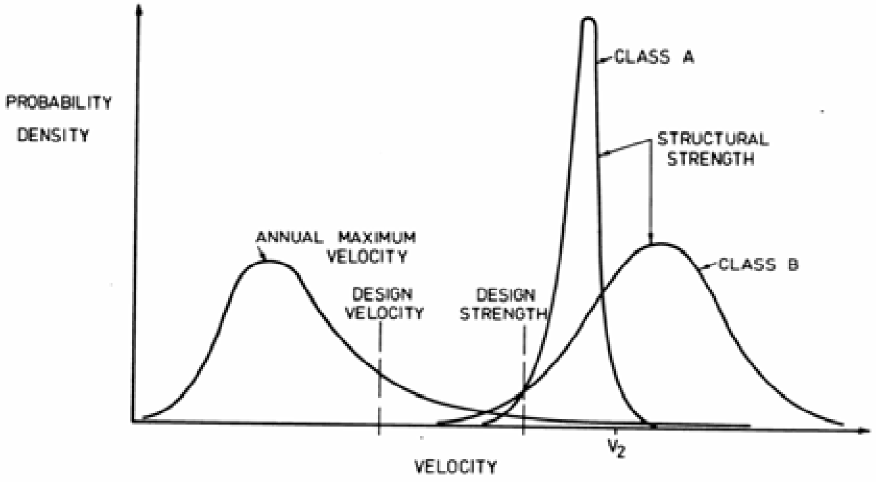


Figure 6·2

INTERACTION BETWEEN VELOCITY & STRENGTH WHERE COEFFICIENT OF VARIATION OF VELOCITY IS LARGE.

Fig. 6.3 - Performance of house strengthened with battens over the top of the roof

Fig. 6.4 - Damage to windward wall of house in Figure 6.3

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Postscript to 2007 Electronic Version

George Walker

Only a limited number of copies of report on Cyclone Tracy were printed and distributed by the Commonwealth Department of Housing and Construction in 1975, and it was never published as a formal Government publication by the Government printing office. With the demise of the Department many years ago, the only public source of the document has been libraries which obtained copies. For more recent generations of engineers it has effectively become unavailable. As the principal author of the report this has concerned me, as I believe much of the information in it still has value from an educational point of view. To be readily accessible to today's engineers it needed to be in electronic form.

The alternatives for achieving this were to either scan the original report into the computer or reproduce it by typing up a new electronic version. The original was typed on an electric typewriter in Courier script and directly reproduced from the typed script which didn't auger well for reproduction by scanning. The photographs were also photocopy versions. Consequently it was decided to retype the report in a modern computer typescript, and reproduce the diagrams and photographs from the originals. Apart from this every effort was made to keep the format as close to the original as possible. The occasional typing errors in the original were corrected, but no other changes made to the text. Because of the change in typescript the pagination changed.

I had originally hoped to have this electronic version available in time for the 30th anniversary of the occurrence of Tracy, but like a lot of good intentions this didn't eventuate. I owe a great deal to my wife, Mary, who typed up the manuscript on the computer, leaving me to be concerned only with formatting and diagrams. She finished her part in April 2004, but it has taken me until now to finalise my part, a spur for this being the appeal by Peter Miller in his regular column in the magazine of Engineers Australia for electronic copies of historical reports on major engineering failures.

Only Volume 1 has been reproduced at this stage. It was accompanied by 2 volumes of Appendices. These were individual reports produced by a wide range of investigators of specific aspects of Cyclone Tracy, on which the main report drew. Together with the main report they represent the most comprehensive collection of published material on any engineering disaster in Australia. Some day hopefully they will also be reproduced in electronic form. The complete set of reports was put together within a period of 2 months following Cyclone Tracy, without any help from the electronic aids now available, a remarkable effort that has never been bettered since in Australia following a major disaster.

The 2004 annual workshop of the Australian Wind Engineering Society was held in Darwin to mark the 30th anniversary of Cyclone Tracy. At this workshop I presented a paper reviewing the impact of Cyclone Tracy on building design in Australia, including the degree to which the recommendations made in the report were adopted. A copy of this paper is attached. Considering the very short time frame within which the report was formulated its impact has indeed been very significant, and the effectiveness of its recommendations was nowhere better demonstrated than in the Innisfail region when Cyclone Larry hit it in 2006.

AWES Workshop, Darwin, 28-29 June 2004

The Impact of Cyclone Tracy on Building Design in Australia

George R Walker

Introduction

When Cyclone Tracy hit Darwin in the early hours of Christmas Day 1974, Darwin was a Commonwealth Government city. The entire infrastructure was the responsibility of the Commonwealth Government and a large proportion of its houses were built and owned by the Commonwealth Government. Overseeing the associated construction and maintenance activities was the Commonwealth Department of Housing and Construction (DHC), at that time the largest engineering organisation in the country, employing many of Australia's finest engineers. Their own Darwin headquarters at the port end of Mitchell Street were little affected, but most of the houses they had built and owned were destroyed, particularly the more recent ones designed in the light of the knowledge gained from damage to housing in Townsville from Cyclone Althea three years earlier. Their structural engineers had been responsible for the design, and believed them to be cyclone resistant.

It was the worst disaster due to building failure in Australian history, and it was an engineering failure. The Chief Structural Engineer of DHC at the time, Norm Sneath, was quick to recognise this. Until the causes of the failure were identified and design practices changed to take these into account there would be no reconstruction of the houses. An investigation of the damage was organised. The author, then a Senior Lecturer at James Cook University of North Queensland in Townsville, was privileged to lead it. The reconstruction of Darwin was based on the recommendations of the resulting report. Today every house built in Australia embodies the major lessons learnt from the investigation in respect of wind resistance.

At the time the population of Darwin was about 40,000 living in about 8,000 houses. After the cyclone 50-60% of these were classified as being destroyed, and only 6% were classified as intact other than minor damage to wall cladding or windows. Most of the rest were regarded as uninhabitable without major repairs. The resulting evacuation of most of the population was the largest such operation ever conducted in Australia. It had long lasting social effects on many of those who experienced it, but although still the subject of controversy, it is difficult to see how they could have been looked after if they had stayed in Darwin. It was the real tragedy of Cyclone Tracy, and the Government resolved that it was never to happen again. Without this resolve it is questionable whether the impact on building design and construction would have been as great as it was.

The Event

Cyclone Tracy was a small but very intense tropical cyclone that produced extremely high wind speeds with maximum gusts estimated to have been of the order of 70 m/s. Although small with an eye diameter of about 8 km, its slow forward speed of less than 10 km/h meant that destructive winds were experienced for several hours.

Apart from housing, buildings whose structural strength had been certified by a structural engineer before construction performed reasonably well structurally, despite the estimated maximum wind speeds being in excess of the design wind speeds in many cases. A dominant feature of the damage was the loss of roof cladding, with over 90% of houses and approximately 70% of all other structures suffering significant loss of roofing. The other dominant feature, particularly in the northern suburbs, was the loss of wall cladding accompanied by gross racking distortion of the houses. There was also some spectacular roof tie down failures.

In the Northern suburbs the destruction of houses was almost 100 percent despite these being the newest houses and incorporating lessons learnt from Cyclone Althea. Although the wind speeds were also larger in this area, they were less than the wind speeds corresponding to the assumed ultimate strength of the cladding based on testing of roof cladding and design wind pressure coefficients.

Results of Investigation

In Cyclone Althea the major failure in housing was of roof cladding and of roof tie down systems. At that time such systems were not engineered but largely based on so called common practice embodied in housing standards such as the ‘Blue Book’ published by the Commonwealth Bank. Design at the time was still largely based on working stress analysis under design working loads. The investigation of damage from Cyclone Althea recommended that roof cladding should be tested to ultimate loads of the order of twice the working loads, and that tie down of the roof structure should meet engineering design requirements. No mention was made of racking strength as no significant racking failures had occurred.

These lessons were rigorously applied by the structural engineers in DHC in Darwin, led by their Principal Structural Engineer, Jack Gamble. Most of the houses in the northern suburbs had been built incorporating this approach. No other houses in Australia incorporated such a high level of engineering in regard to their wind resistance. The main concern of Darwin structural engineers was the weakness of the earlier construction. Only a few weeks before Cyclone Tracy they had lobbied the Commonwealth Government for funds to strengthen the older houses in Darwin. Those living in the older houses, such as Jack Gamble, would have been much more concerned as Tracy bore down on them than those in the newer houses in the northern suburbs. On Christmas Day, Jack’s house was damaged but still standing, like many others around it, but in the northern suburbs it was total devastation. What had gone wrong? This was the big unanswered question that faced Jack and his team on Christmas Day.

The investigation showed that three factors had contributed to most of the damage:

- Fatigue failure of cladding fasteners
- Internal pressures not allowed for in design
- Lack of design for racking forces.

The testing of roof cladding after Cyclone Althea was based on static tests. This was over the objections of Bill Melbourne, who warned that wind loads were dynamic not static. Before Cyclone Tracy the warning fell on deaf ears, but DHC soon heard it after Tracy and organised an investigation of the fatigue strength of the common cladding systems in place in

Darwin, and its significance in relation to the observed damage. In a brilliant study undertaken by Vaughan Beck and John Morgan under conditions of extreme urgency they showed that under the level of fluctuating loading which Bill estimated was likely to have occurred, the ultimate strength of the fastening systems could be reduced to 15% of the static fatigue strength, and recommended a testing procedure that is still the requirement for roof cladding design in Darwin.

If the effect was so dramatic, why had it not been observed previously? Until after Cyclone Althea steel roofing was primarily made from mild steel. Not long after there was a major change to the use of thinner high strength steel. Mild steel is more ductile than high strength steel, and less susceptible to fatigue failure. The report of Tracy recommended that fatigue testing of roof cladding be mandatory in cyclone regions.

However there was also another factor at work. At that time general practice throughout Australia was to base internal pressures used in design on the assumption that there were no significant wall openings. This led to rather small internal pressures which after subtraction of self weight loads often led to even smaller design loads with the factor of safety only applying to the difference. When windows failed on the windward side, often as a result of debris impact, the resulting large increase in internal pressures would have produced much higher loads than those assumed in design. This had particularly severe consequences for roof tie down systems where the effect of self-weight meant that working stress design tie-down forces were often very small. Such failures were common where cladding failure had not occurred. This damage highlighted the limitations of working stress design as well as design practice regarding internal pressures. The report recommended the speedy adoption of the limit state approach to design and the use of full internal pressures in design in cyclone areas unless the integrity of potential wall openings such as windows and doors could be ensured.

Even if all these changes had been made prior to Tracy, significant damage would still have occurred as a result of racking failures. At that time the most common external wall material used in timber framed housing in Darwin was asbestos cement sheeting or ‘fibro’. Internally the walls were lined with hardboard. Both of these materials were relatively strong in shear, but this strength cannot be utilised unless the sheets are fastened very securely to the timber frame. Unfortunately the latter was not the case with the sheets being only tacked to the frame. Resistance to racking was assumed to come from diagonal steel straps that had replaced the more traditional diagonal timber braces. The construction was typical of much housing construction in northern Australia at the time. It had a certain amount of strength. In Cyclone Althea the wind loads had not been sufficient to exceed the strength, but in Cyclone Tracy they well exceeded it.

Because such failures did not occur in Cyclone Althea no consideration had been given to racking strength in the recommendations that followed. It had been a case of the following the traditional approach to housing with design based on trial and error, not engineering in its full sense. In Althea there had been problems with cladding and tie-down, so an attempt was made to fix it. No racking failures occurred so it was assumed that traditional construction was OK in this respect. Houses were assumed to have inherent strength that was beyond the understanding of structural engineers, and not worth investigating because of the relatively low cost of housing. Cyclone Tracy put paid to this assumption. The result was the most radical recommendation of all. Henceforth all buildings in tropical cyclone prone areas including houses should be engineered to resist wind loads. This meant that wall systems would need to be tested for racking strength, not just assumed to have it. But it also meant that the complete load path would need to be checked out and no assumption made about the inherent strength of housing.

Implementation of Recommendations

All the major recommendations of the investigation were implemented in the reconstruction of Darwin. That this occurred is probably almost entirely due to role of the Commonwealth Government in Darwin, and the large part played by DHC in exercising this role. The Government had promised the residents of Darwin it would reconstruct a cyclone resistant city, and it was the responsibility of DHC to ensure this happened. It was a responsibility taken seriously by DHC from the top down. Once it had the report DHC had the resources and expertise within its ranks to make its recommendations happen. A comprehensive programme of testing housing components and systems was developed and undertaken, wind tunnel studies commissioned to obtain a better understanding of wind loads on housing, probabilistic modelling of cyclonic wind speeds using newly emerging GIS technology initiated, and specifications for reconstruction drafted.

Just under a year after Cyclone Tracy the first reconstructed house was handed over, to be followed by hundreds, which became thousands, over the ensuing two or three years. The criteria became more codified with time, but otherwise have remained largely unchanged to the present day. Most of the surviving buildings have been upgraded and those that have not are becoming an increasingly small proportion of the total building stock in Darwin – probably of the order of 2%. As a consequence Darwin can probably claim to be the strongest city in the world in respect of wind resistance.

Impact Beyond Darwin

Cyclone Tracy did not just have an effect on building construction in Darwin.

Its most immediate influence was on design in other cyclone prone areas of Australia. Fatigue testing of roof cladding and allowance for full internal pressures became a standard requirement in these areas, particularly in Queensland. In 1977 a workshop was held at the Experimental Building Station in Sydney (then part of the Department of Housing and Construction and now the North Ryde Laboratory of CSIRO Building Construction and Engineering). The object of this workshop was to review the criteria adopted in Darwin after Cyclone Tracy and make recommendations on its application to other Cyclone areas. The resulting publication known as TR440 was the bible for wind resistant construction in cyclone areas apart from Darwin for several years before its recommendations became incorporated in normal standards and codes. The fatigue testing criteria adopted at that time is still used for cyclone areas other than Darwin.

But the impact has not been limited to cyclone areas. When DHC adopted the recommendation to use limit state design, it did not restrict it to Darwin. Norm Sneath’s deputy at the time, and later successor, Charles Bubb, ensured it was applied throughout Australia. And DHC was such a big player in the construction scene in Australia, this ensured it was rapidly taken up by the structural engineering profession generally. The adoption of an engineering approach to the design of houses in cyclone areas led to knowledge on the structural performance of houses under wind loads that was equally applicable to non-cyclone regions. Although fatigue testing of cladding and the assumption of full internal pressurisation is still restricted to cyclone areas, most houses built in Australia today incorporate an engineered solution in their structural design for wind, generally implemented in the form of tables and charts. Shear walls to provide racking strength are now part of normal house design everywhere – a direct consequence of the lessons learned from Cyclone Tracy.

Current Issues

Despite the passage of 30 years there are still unresolved issues regarding the wind resistant design of buildings that can be traced back to Cyclone Tracy.

The most significant for cyclone regions is the fatigue test criteria. The TR440 test was never accepted in Darwin, partly because it led to the acceptance of fastening systems that seemed little different to those which failed in Darwin. An extensive 6 year programme of research at James Cook University in the mid-1980's confirmed these doubts, indicating that at least in respect of corrugated iron the test was unconservative. A test more representative of the sequence of wind loads experienced by cladding during a cyclone was recommended by Mahen Mahendren, but politically it was not welcome. Legislators did not want to know that a test they had been specifying for many years was inadequate, and neither did the cladding manufacturers. However lately there seems to have been some relaxation of these attitudes, driven by a recognition that the differences between Darwin and the rest of Australia on the issue need to be resolved for efficiency of manufacturing.

The lack of recognition outside of cyclone areas of the role of internal pressures is also an anomaly. The total uplift forces on a roof can more than double when openings occur on the windward face during extreme winds. This type of failure is a common feature of wind damage in non-cyclone areas, but it also seems that it is something neither the legislators nor the building industry want to know about. It is easier to blame shoddy building practices.

Another issue is the effect of private certification. After Cyclone Tracy a high level of building control was exercised in most cyclone prone areas in relation to wind resistant construction details. Private certification is not as transparent a process as public certification and the jury is still out on its effectiveness. Perhaps the next big cyclone will enlighten us.

The other big issue is who would replace the Commonwealth Department of Housing and Construction in the event of another event like Cyclone Tracy!

[Note: Since this paper was presented the issue of fatigue criteria has been addressed]