CYCLONE TESTING STATION

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Technical Report No. 21

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SUMMARY

Tropical cyclone 'Kathy' crossed the coast and passed close to the town of Borroloola on March 23, 1984. Although the maximum wind speeds had been reduced by the cyclone's progress over land, the winds of up to 190 kph damaged many buildings. This report details an investigation to determine the maximum wind speed in the town, the damage to buildings and the steps taken by the local counter disaster organisation to minimise injury to the townspeople. The benefit of recent building regulations and building supervision could be seen in the damage pattern. Most of the failures observed were due to inadequate connection details between structural elements that were able to carry the wind loads themselves. Conclusions are also drawn on the effect of internal pressures on the performance of structures, and on the lack of tie down provisions for boats, caravans and temporary structures.

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1. INTRODUCTION

Between 8 am and 3 pm on 23 March 1984 the Northern Territory town of Borroloola was buffetted by high winds associated with cyclone 'Kathy'. The story of the damage to buildings made headlines over the two days following the passage of the cyclone as it was the first time that significant damage to a Northern Territory community had been associated with a tropical cyclone since Cyclone 'Tracy' devasted Darwin in 1974.

Very significant changes have been made to many building codes since the time of cyclone 'Tracy' so the damage at Borroloola was of particular significance in that it provided a real assessment of the success of the new standards in minimising damage. A tour of inspection was arranged by the James Cook University Centre for Diasaster Studies and undertaken by two structural engineers (the authors of this work), an engineering student with a special interest in aboriginal housing and two behavioural scientists who were interested in assessing counter disaster organisation. The researchers visited Borroloola on March 27 but because of lack of overnight accommodation and nine hours total flying time from Townsville, only about six hours were available for the assessment. The tour of inspection was greatly assisted by the co-operation of the Northern Territory Emergency Service and by the townspeople who were keen to discuss their losses and lend help wherever possible.

Borroloola has a population of only about 400, and has about 140 houses, (including all Aboriginal dwellings), two shops, a hotel, a service station, a primary school and a kindergarten. A sketch plan of the town is given in Figure 1 and shows the spread out nature of the town and the location of most main buildings. The community is approximately 40 km from the south west corner of the Gulf of Carpenteria and enjoys holiday patronage from surrounding inland areas. It also supports a number of Aboriginal communities that live in or near the town. There are also quite a few permanent European residents and some government serviced buildings and residences that add up to give the town a varied cross section of buildings. Many of the buildings were of a temporary nature, and the absence of general building regulation enforcement in the town meant that often the termporary buildings were of a design and construction that were not at all suitable for resisting high winds. The variety of the buildings in the town and the presence of some 'post-Tracy' buildings gave the inspection significance to the Australian building industry.

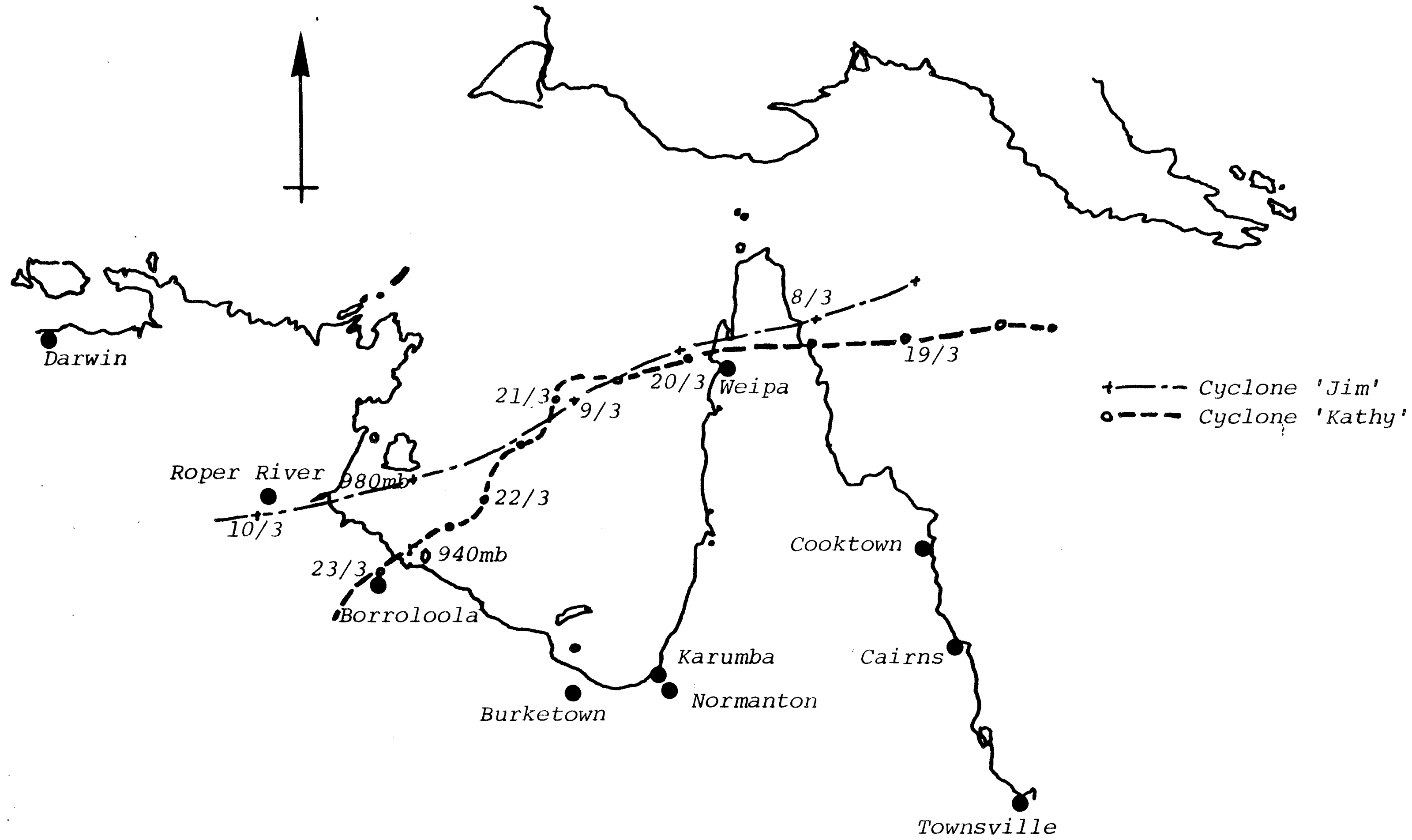

Figure 1 Tracks of paths of Cyclones 'Jim' (7/3 to 10/3) and 'Kathy' (18/3 to 23/3).

2. PRELIMINARY METEOROLOGICAL INFORMATION ON CYCLONE 'KATHY'

This section contains preliminary information derived from conversations with townspeople, observations of and calculations on damaged simple structures and vegetation and discussions with officers of the Darwin Meteorological Office soon after the event. A detailed meteorological report on the event will be issued later in the year which will largely supersede this information.

2.1 Cyclone 'Jim'

Cyclone 'Jim' developed in the Coral Sea on 7 March and crossed the Cape York Peninsula north of Weipa, on 8 March. It then regenerated in the Gulf of Carpentaria and appeared to threaten communities on Groote Eylandt. It crossed the coast south of those communities with very little wind damage, but caused flooding in the Daly River. This caused the settlement of Daly River to be evacuated and accommodated in Northern Territory Emergency Service tents. This reduced the number of tents available for temporary shelter in Borroloola immediately after cyclone 'Kathy'. The town of Borroloola was placed on alert for a short time along with other Gulf Communities while cyclone 'Jim' posed a threat.

2.2 Cyclone 'Kathy'

This cyclone followed a very similar pattern to cyclone 'Jim'. It was first declared a cyclone at 1 pm on 18 March having developed from a tropical low in the north Coral Sea. Its progress took it on a similar path to 'Jim', crossing the Cape York Peninsular and then regenerating in the Gulf of Carpentaria. The regeneration in the Gulf was quite rapid. The estimated path of tropical cyclones 'Jim' and 'Kathy' are shown in Figure 2 together with some estimated central pressures. As the cyclone approached the coast its development accelerated with the central pressure falling rapidly to its estimated 938 millibar minimum, and estimated maximum wind speeds increasing from just over 100 kph to 280 kph in less than 48 hours.

The eye of the cyclone crossed Centre Island in the Sir Edward Pellew Group where meteorological observations were regularly taken. The central pressure was recorded there and the anemometer failed prior to the arrival of the eye but had shown speeds of 125 knots or 225 kph. This recorded speed was just less than that estimated as the peak gust speed in cyclone 'Tracy'. The total

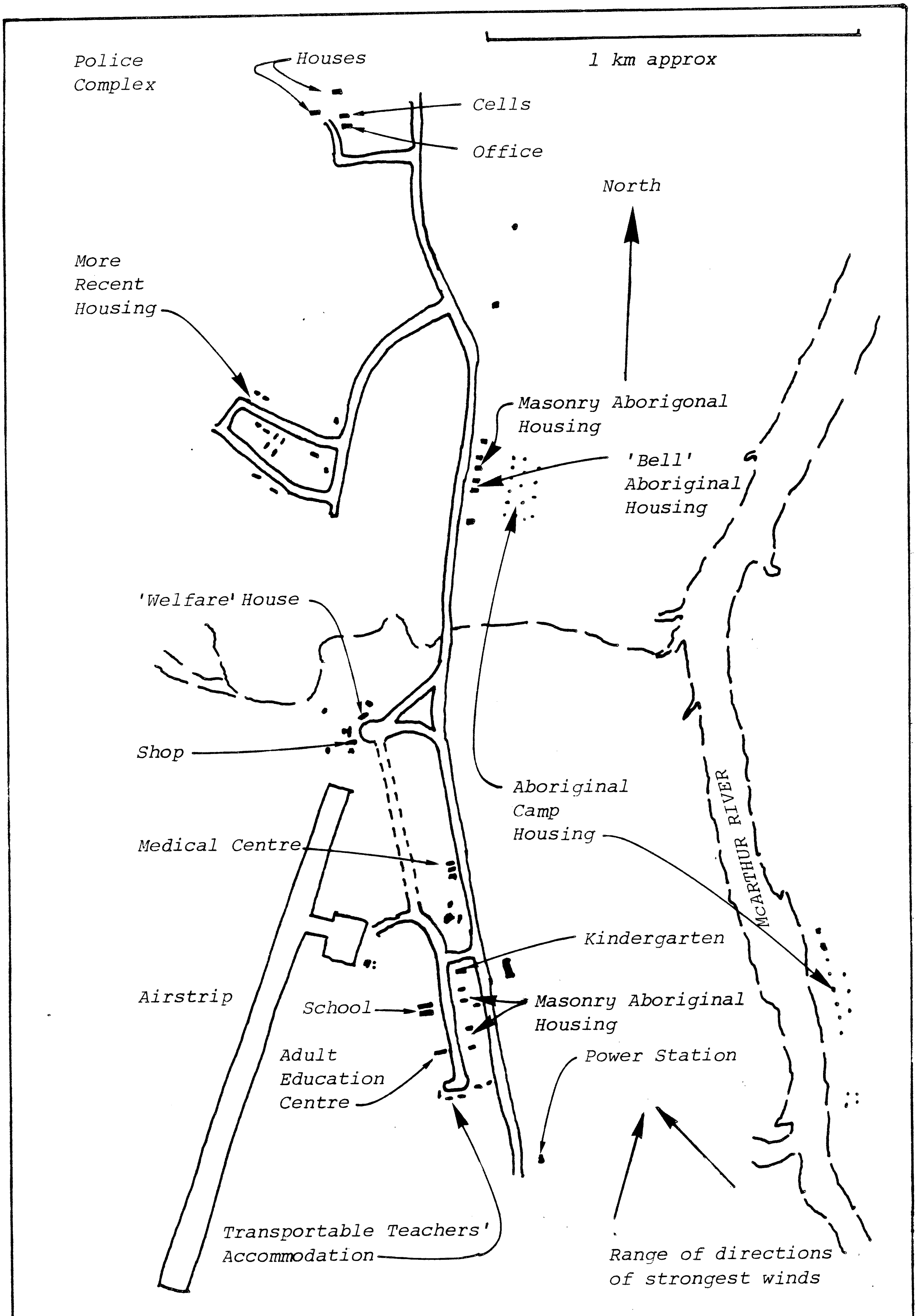

Figure 2 Sketch Map of Borroloola

defoliation of trees in the islands in the Sir Edward Pellew Group also supported the comparison of the cyclone's intensity as approximately that of Cyclone 'Tracy's'. The eye diameter was estimated at 32 km at this point.

The minimum central pressure was also estimated by the skipper of a prawn trawler at 938 millibars by extrapolation below the lowest calibration on his aneroid barameter. The reading on Centre Island was 940 millibars and these two estimates also compare well with estimates of Cyclone 'Tracy's' central pressure. The rapid development in the Gulf of Carpenteria still permitted approximately 24 hours warning of the severity of the cyclone to be given to Borroloola.

Once cyclone 'Kathy' crossed the coast which is rather poorly defined at this part of the coastline, it travelled over approximately 10 km of coastal tidal flats and 30 km of flat sparsly wooded terrain before reaching the township of Borroloola. The maximum windspeeds had decreased considerably in its transit over the land, and the vegetation in the vicinity of the township was damaged but still supported leaf growth. The number of fallen trees was significantly less than that on Centre Island. From the tree damage pattern, officers of the Meteorological Bureau, Darwin, estimated the wind speed at 180 kph or 50 ms^{-1}. In a totally independent study of damage to simple structures the authors estimated the peak gust velocity of 10 m in terrain category 2 to be between 46 ms^{-1} and 52 ms^{-1}, a range in very good agreement with the meteorologist's estimates.

The details of the calculations will not be presented here, but the methodology involved selecting some simple structures - in this case caravans. An upper bound was determined by calculating the wind velocity that would have been required to overturn a van that had remained in place throughout the cyclone, and a lower bound by determining the wind velocity required to overturn a van that had been overturned during the periods of high winds. Both vans presented their largest face nearly normal to the direction of strongest winds. Roy (1983) provided information on the winds required to give specific overturning moments and also indicated that the moment was largely independent of wind direction over a range of 30° each side of normal to the long face of the van. Figure 3 shows one of the caravans used in the analysis.

This range of wind speeds is much less than the speed of 62 ms^{-1} recorded at the coast, and also than the current design windspeed for cyclone prone areas

Figure 3 The force required to overturn this caravan was used to find a lower bound on the maximum wind gust.

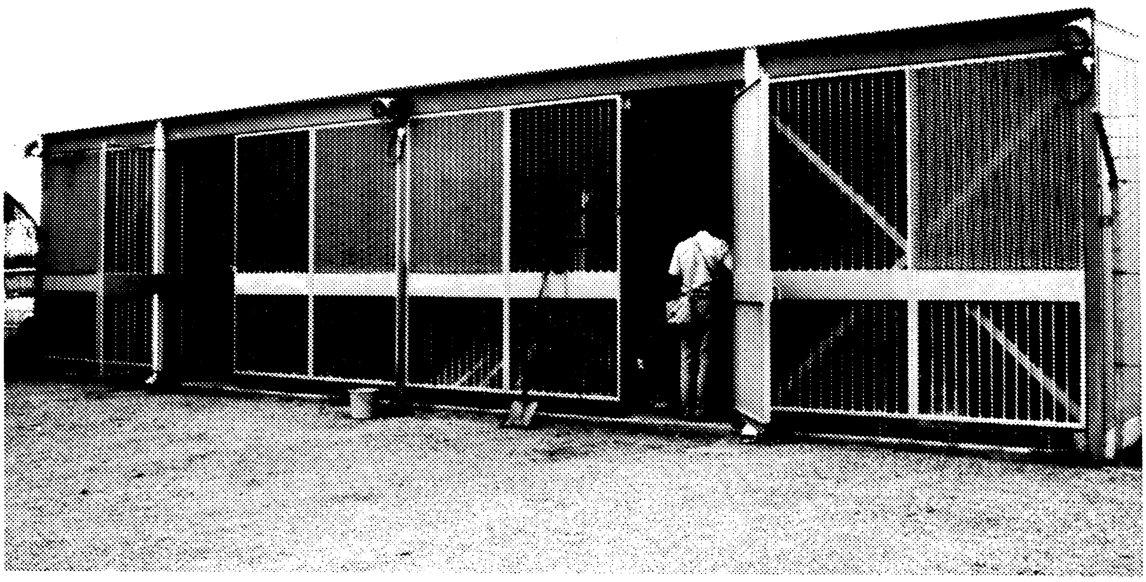

Figure 4 The cell block that accommodated people during the cyclone. Maximum winds normal to bars.

of 63 ms^{-1} (after use of the cyclone modification factor). Thus although the cyclone had windspeeds at the coast similar to design wind speeds, its passage over land had reduced the wind speed and loads significantly.

	Estimated Wind Speed	% of design load AS 1170 - II (1983)
Design cyclone windspeed	63 ms^{-1}	100%
Cyclone 'Kathy' at Centre Island	62 ms^{-1}	97%
Upper bound cyclone 'Kathy' at Borroloola	52 ms^{-1}	68%
Lower bound cyclone 'Kathy' at Borroloola	46 ms^{-1}	53%
Recorded speed - Cyclone 'Althea' Townsville	57 ms^{-1}	83%

Table 1: Comparison of Wind Speeds and Wind Loads

The wind loads had been reduced by 30 to 45% by the cyclone's passage overland which reduced its potential for damage at Borroloola to less than that of cyclone 'Althea' in 1971 at Townsville.

3. DISASTER CONTINGENCY PLAN AND COMMUNITY REACTION

This section consists of a brief description of events immediately prior to and during the impact of the cyclone on the communities at Borroloola, as detailed by Mr M. Van Heythuysen, the senior constable at the town and Local Counter Disaster Controller.

It has little structural significance, but nevertheless is included, as the co-operation and organisation of the townspeople did much to lessen the magnitude of a potential disaster.

3.1 Disaster Contingency Plan

A disaster contingency plant for Borroloola as drawn up by the Northern Territory Emergency Service (NTES) is currently being processed, and by coincidence the Unit Officer of the NTES Borroloola Volunteer Unit, was in Darwin for training at the time of the cyclone. However the operation of the local group of the NTES, had been assisted by two incidents in the weeks prior to the occurrence of cyclone 'Kathy'.

The first of these was cyclone 'Jim' whose track was similar to the course of cyclone 'Kathy' within the Gulf. It caused the community of Borroloola to be alerted on 10 March, some 2 weeks prior to 'Kathy'. At that time a public meeting of the whole town was held and each family alerted to the possible dangers of the event, and a course of action to be pursued in the event of an emergency. Shortly after that incident the town was taken off alert as cyclone 'Jim' had ceased to be a threat, but a light aircraft crash near the town gave the local counter disaster organisation an opportunity to work together in a co-ordinated activity.

Both the community and the local Northern Territory Emergency Service Unit had a degree of preparedness for the events associated with cyclone 'Kathy'.

3.2 Immediate Community Reaction to Cyclone 'Kathy'

This section takes the form of an abbreviated diary of events as indicated by Senior Constable Van Heythuysen who supervised the pre-cyclone preparations and the early stages of the counter disaster operation.

Thursday 22 March, 1984

8.30 am: Northern Territory Emergency Service advised via radio VJY, the outpost radio network, that the cyclone may head towards Borroloola. Aboriginal communities in the area were notified by an aboriginal police aid and Aboriginal Council officers.

2 pm: Cyclone was still heading towards Borroloola. All Europeans were notified by personal contact and Aborigines through Council officers.

5 pm: Central pressure and estimated wind speeds made it clear that 'Kathy'

was very severe. All vehicles in the town were filled with fuel and usual precautions taken with radios, flashlights and emergency rations.

8 pm: 'Kathy' still moving very slowly - notified of possible 3.5 m storm surge.

11 pm: 'Kathy' still heading to Borroloola, still very severe. An Aboriginal camp on east side of the McArthur River was evacuated as the ford was still passable. The entire population of the camp plus any others that felt anxious were accommodated in the Adult Education Centre - a large portal framed building with an enclosed workshop approximately 15 m x 6 m. It had been selected in prior local planning as a strong and reliable shelter, and was prepared prior to the evacuation by cleaning up around the building to minimize debris, and placing heavy desks against windows to maximise space and minimize danger due to window glass failure.

Also at this stage some townspeople were anxious about staying, but were advised not to leave. Two European families left with caravans in tow, one of which was subsequently wrecked on the road south from the town.

Friday 23 March, 1984

3 am: Cyclone 'Kathy' estimated just north of Vanderlin Island (approximately 100 km away from town) and still heading towards Borroloola. All residents were woken and advised to eat a meal, gather some personal belongings and report to the designated cyclone shelters. These were:

(i) Police station complex of cells and office block
(ii) Adult Education Centre

Figure 4 shows the cell block, necessarily a very strong building.

At this stage those who had been left at the Adult Education Centre overnight were fed with food requisitioned from the local government store.

5.30 am: Strong winds and driving rain were being experienced in the town and people were starting to arrive at the designated shelters. Tarpaulins had been placed across the front of the open cells to shelter those housed there from the rain. Some Europeans had opted to stay with their businesses but all Aborigines with the exception of one old man who refused to leave his house and the Aboriginal Pastor who stayed in the church, sought refuge in the designated shelters.

The estimated numbers of the shelters were:

173 Aborigines in adult education centre.
194 Aborigines in the cells.
65 Europeans in the police station offices.

All of these shelters would have been very crowded with insufficient room for everyone to lie down.

8 am: Winds were strong enough to blow the overhead electric power wires together, so the power station was shut down. Also, more food was distributed to all the shelters.

High winds continued from the south east and south until approximately 11 am. During this time, the Europeans who had previously chosen not to join the shelters left their premises and joined other townsfolk at the Police Station. A continual radio contact was available on Police frequencies throughout the cyclone, and radio checks were made every 15 minutes by the NTES Northern Divisional Officer in Darwin. The winds were predominantly from the southern quarter and were described as severe constant buffetting for approximately 3½ to 4 hours. A short lull of no more than 2 or 3 minutes was experienced near midday and the wind then swung through east to the northern quarter for approximately 2 hours of less severe activity. During these hours there were occasional very strong gusts, but generally the winds were not as severe or constant as those that preceded the lull.

3.00 pm: The winds had reduced sufficiently for people to start returning to their homes. Those whose houses had been destroyed were established in temporary accommodation in the school where a temporary generator had been set up with cooking and lighting facilities. However there was little dry bedding left in the town or dry places to sleep.

6.30 pm: The police aircraft arrived bringing limited supplies and the NTES Counter Disaster Regional Controller. This was followed by an Air Force Carribou carrying a few tents, food and other essential supplies.

3.3 Restoration of Services

The power house was operational by 8.00 am on 24 March, 1984. It had been shut down for under 24 hours and the reticulation received minimal damage. All services were disconnected and power generation recommenced with power being restored to premises progressively as electrical installations were checked.

Sufficient Water Storage in the tank was retained to enable the watersupply to continue through the cyclone and remain operative after the event.

Minimal damage was sustained by many buildings used to provide government services. This enabled little disruption to health services, effective shelter to be obtained during the cyclone in the Police Station complex and Adult Education Centre, and effective post cyclone shelter in the school buildings.

The airstrip was well drained and remained free of debris so that it was operational within hours of the cyclone. This enabled emergency supplies to be landed in the town very quickly after the cyclone. The supply of tents and tarpaulins for temporary shelter for the homeless was hampered by the prior utilisation of much of the NTES supplies in rehousing an evacuated community at Daly River following flooding.

3.4 Implication of the Community Reaction to Cyclone 'Kathy'

The efficient and effective discharge of the locally conceived contingency plan significantly contributed to the reduction of interruption to community life and the total lack of injury to people within the town. Sen. Const. Van Heythuysen is to be complemented on his care of the community preceding and during the cyclone. He was considerably aided by the co-operative spirit of the 430 people within his care and by those who so quickly restored essential services to the town after the cyclone.

The existence of buildings within the town that were strong enough to resist damage during the cyclone contributed to the safety of the townspeople. The rapid restoration of essential services by people from outside the community enabled homeowners to be free to work on the restoration of their own homes after the cyclone.

Whilst the community was fortunate to have endured the cyclone with no human injury, all premises sustained considerable water damage to contents and most sustained some structural damage ranging from loss of guttering to total demolition. All townspeople missed at least two consecutive nights sleep and will be involved in assessment, restoration and replacement of damaged items for many months.

4. EFFECT OF CYCLONE 'KATHY' ON BUILDINGS

In the time available for an inspection of the town, it was not possible to perform a detailed examination of every building or even to quantify the total damage. Rather, a brief inspection was made with due attention to personal privacy of the occupants of approximately 20 buildings. In 8 of these a detailed examination was warranted and permitted, in some cases even encouraged by the occupants. For some of the buildings, the cause of damage was possible to determine without gaining entry and with others a detailed examination of sections of the house that had been blown away from the main structure gave useful information about the failure sequence of the structure.

In all cases where damage was encountered, inadequate structural details that gave rise to the damage could be pinpointed. However the examination of some buildings that had sustained minimal structural damage provided some very useful information which will also be reported.

4.1 Police Station Complex - Offices, Cell Block, Residences

These buildings sustained superficial damage only and were completely functional after the event, however water ingress did cause some damage to their contents. The police station offices and cell block were used as a cyclone shelter for townspeople and the only damage to them was the loss of a fascia gutter from the office block.

The cell block was of steel framed construction with concrete infill and had a completely open face presented to the dominant windward direction as shown in Figure 3. Tarpaulins were used to limited effect, but the lack of openings in leeward and side walls would have led to a net positive internal pressure. The roof had a very low pitch and was clad with corrugated steel sheeting fastened using screws and cyclone washers. These were evident at every second corrugation throughout most of the roof, but at every corrugation along the eaves purlin and in each end sheet. The purlins were at 800 mm centres although the eaves purlin was 400 mm from the leading edge of the sheeting. The Northern Territory Cyclonic Areas Deemed to Comply Standards allow a maximum purlin spacing of 900 mm and maximum sheet overhang of 200 mm. Thus the main area of the roof was fastened more than adequately, but the overhang was longer than permitted in the Standards. At higher wind speeds or in the event of loss of the guttering this may have presented a problem

The police station office block was also of steel framed construction with a low pitched corrugated steel roof, but did not have the same dominant windward opening. It did however had an unlined verandah approximately 1.2 m wide all the way around the building. Its roof sheeting was fixed in a similar manner to that on the cell block. Both the offices and the cell block then had maximum uplift on the roof sheeting due to opening configureations and verandahs, but sustained no obvious damage to the roof sheeting or structure.

The dwellings were high set houses presenting the longest walls as the windward face. The external cladding was metal sheeting screwed to girts at approximately 900 mm spacings. The roof was fixed to battens on 10° pitch trusses using screws with cyclone washers. The fastening configuration was similar to that employed on the police station buildings except that every corrugation was fastened on the lowest two purlins and the purlin closest to the crest. The piers were 200 mm square reinforced conrete with 4 concrete block infill panels providing racking resistance. The house was well tied into a large steel chassis that was firmly bolted to the pier tops. The only visible damage to the house inspected, was the loss of the fascia guttering as shown in Figure 5. There were no signs of distress to the plasterboard internal walls or to any of the masonry panels underneath.

A feature of all of these buildings was the lack of debris damage to them. A wooded area separated them from other parts of the town and seemed to protect those buildings from airborne building materials. No louvres were damaged and even the external fly screens appeared free from tears. These buildings were well designed for a cyclone-prone environment, possibly for a post disaster function, and erected under government supervision. The structural integrity of these buildings that were used as a cyclone shelter undoubtedly contributed to the safety of the townspeople during the cyclone.

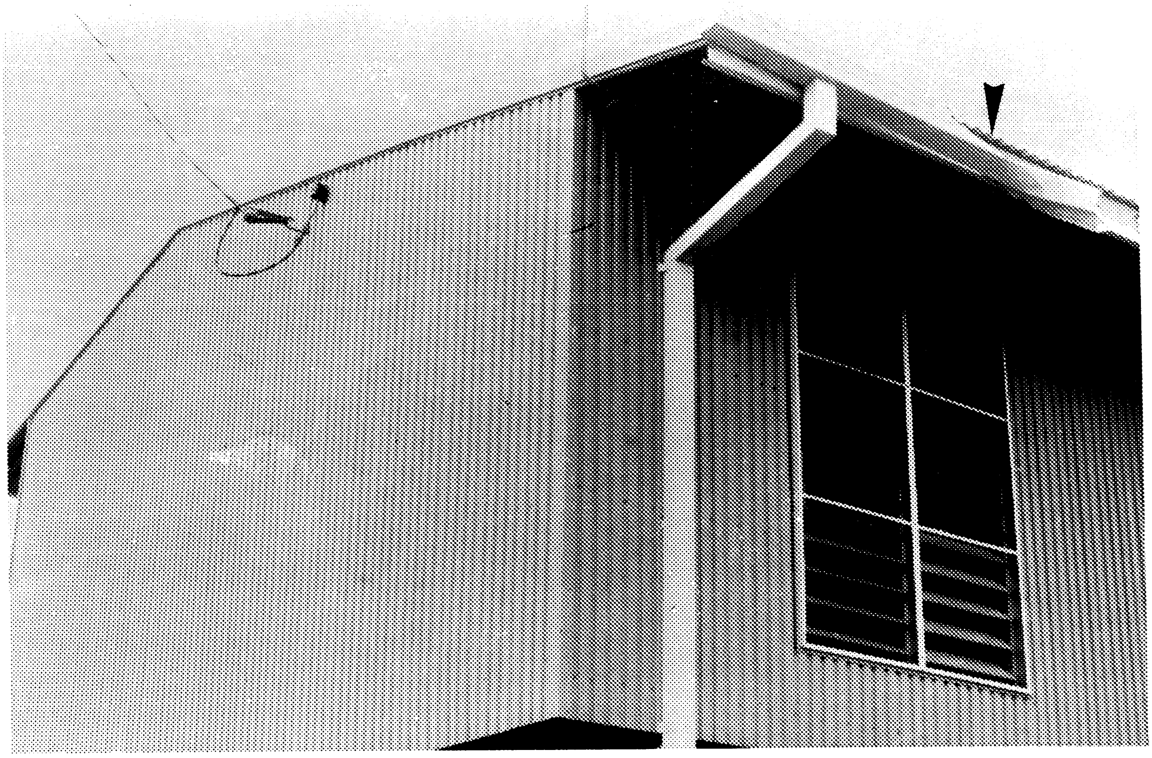

Figure 5 Police House showing damage to guttering, but screens and walls free from debris.

Figure 6 Adult Education Centre - viewed from direction of maximum winds.

4.2 Adult Education Centre

Again, this partially enclosed building was used as a cyclone shelter during the event and its good performance was due to the attention to detail during the design and construction of the building. Its basic frame consisted of portal frames bolted at knee and apex joints, and was braced in both directions and in the plane of the roof. Two thirds of the plan area of the building was open and could not have sustained positive internal pressures, however the highest velocity winds were normal to the dominant openings of the enclosed section. Again no damage to cladding was apparent, although the barge trim had been lifted off. The roof was screwed to Z section purlins at every corrugation for the bottom two purlins and at the crest of the roof, and proved adequate to resist the uplift loads. It is again likely that good supervision was used on the construction of this building and adequate fastening, good bracing and sufficient tie down ensured the safety of the building's occupants during the cyclone. The design and construction appeared to have complied with the Northern Territory Cyclone Areas Deemed to Comply Standards.

4.3 Houses that Sustained Primarily Roofing Damage

Five buildings which sustained varying degrees of roofing damage will be discussed here. Though many more buildings suffered roofing loss and damage, these are typical of the patterns of damage observed.

(i) A high set factory built home with attached carport: In this case the factory built home performed well with no visible external damage. Ingress of water had affected much of the house contents but the house structure had remained largely intact. However a site constructed carport had been added to the side of the house subsequently and was inadequately tied down. It was torn away from the house and complete with battens moved 50 metres, luckily without penetrating the skin of the house or causing damage to other buildings. Figure 7 shows the carport in relation to the house after the event. Poor attention to an on-site addition to a well engineered structure had created a large and potentially dangerous item of airborne debris.

(ii) A house that showed lifting of roof sheeting near the corners: This was typical of quite a few houses with roofs at 10° to 25° pitch where

Figure 7 This carport was removed from the otherwise undamaged house in the background.

Figure 8 Roof damage near corners.

the fastening was uniform over the entire roof with no special precautions taken at corners and edges. In this case the eaves were either unlined or the eaves lining had been broken away. The strong winds had been predominatly normal to the ridge line, and the sheeting in the corners on the windward side had been lifted as shown in Figure 8. The fasteners on the edge batten and the next one up the roof (over the external wall) had pulled through the sheeting, but the sheeting was still secured at the edge batten plus two.

This degree of damage was confined to the two sheets closest to the gable but the next two sheets in showed some damage at the edge batten too. Similar damage patterns were observed on a number of buildings, and some houses that had had new sheets of roofing steel fitted appeared to have suffered similar damage. Most of the houses that suffered this type of damage had battens at 900 mm centres in accordance with the Deemed to Comply Standards, but employed nails or screws with small or no washers at every second crest over the entire roof as a fastening system. This connection detail was not in accordance with the above Standard, and was shown to be ineffective even at the loads applied by the cyclone. Mention has already been made of the police housing which did have additional fasteners at edges and corners and suffered no observable damage to roof sheeting.

(iii) A house that had lost a large section of roofing complete with battens: Figure 9 shows a view of the section of roofing removed. This house had a verandah on the windward side which probably led to high upward loads on the roof sheeting on the windward side of the building. The roof sheeting had been adequately fastened to the battens, but the battens had only been connected to the trusses with a single nail through the top of the batten into the truss, and a thin metal strap held to the truss with one nail on each side as shown in Figure 10. Tests on a full scale house with many more nails per strap have shown that these nails tend to be pulled out progressively under cyclic loads unless the load per nail is quite low (Boughton and Reardon 1984b). This type of failure early in the cyclone allowed significant ingress of water and also removed an effective diaphragm for transferring lateral loads. This can lead to further degradation of the structure as other diaphragms are overloaded and lateral failure of walls occurs, however in this case the ceiling diaphragm was able to sustain the load the prevent structural damage due to lateral loads.

Figure 9 Roof panel removed with sheeting still attached to battens.

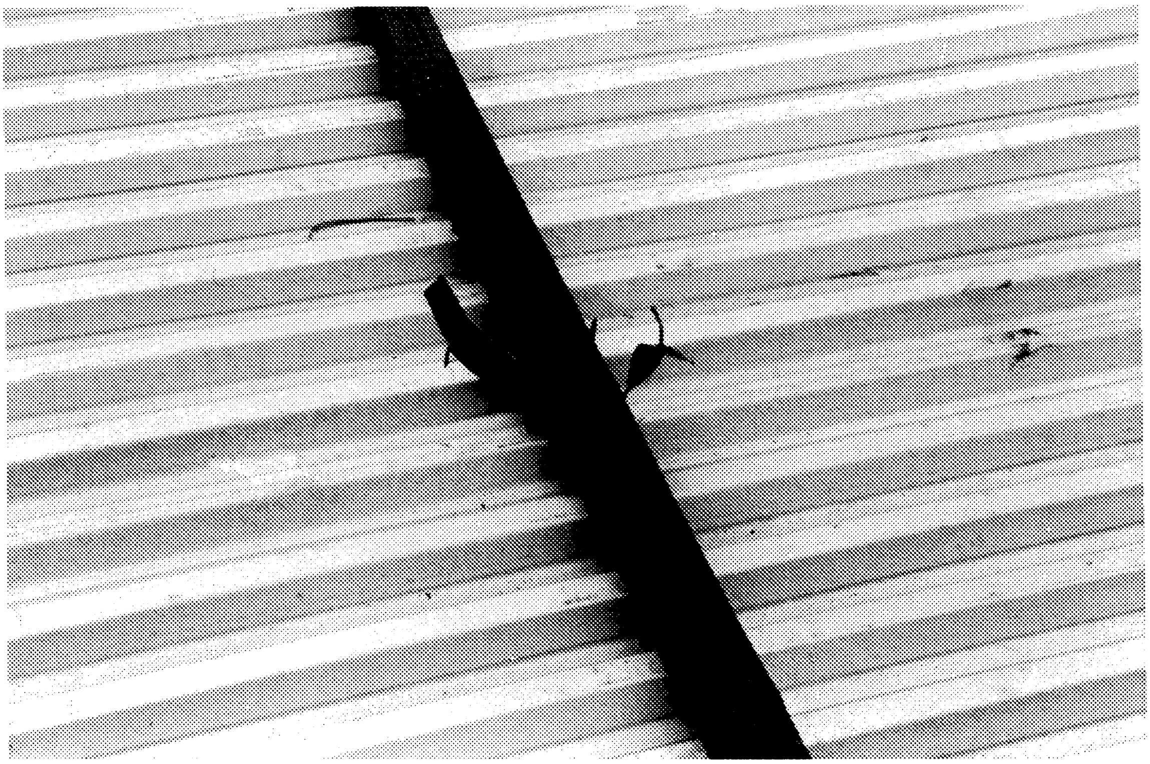

Figure 10 Detail of same panel showing one nail through batten and only one nail in each end of the strap.

(iv) A house with a rafter and brace type roof whose structure had been blown off as a single unit: This house had been imported from another town outside the cyclone zone and had only just been assembled on its new site. The owner was aware that the roof needed extra tie down provisions for the new location, but had not had the opportunity to effect these. The rafters were removed complete with battens and roof sheeting and carried for approximately 100 metres. It is probable that this happened early in the first part of the cyclone as a large amount of water had penetrated the ceiling and stained walls, contents and carpets. The wall and ceiling hardboard panelling allowed water to seep through joints and prevented ponding that would have brought the ceiling down and removed all diaphragms in the roof plane. The integrity of the ceiling braced the walls and prevented major structural damage to the walls. In spite of this structural integrity, the degree of water penetration will make the repair bill very high. Figure 11 shows this house with a tarpaulin over the roof preventing further ingress of water.

(v) A house whose roof had been removed and whose walls had then collapsed: This house may have been in the course of construction, but in any event showed that generally insufficient fasteners had been used throughout the roof structure. Generally the roof sheeting had been fastened to the purlins adequately, but the purlins had been fastened to steel trusses at 3 m spacings using gutter bolts. These did not have enough strength to carry the uplift loads. Some trusses remained attached to the roof but separated from the walls. The entire roof lay in two large sections approximately 30 m from the house, and the roof sheeting was torn underneath the fasteners along the top joints indicating that it had carried large shear forces. The roofing screws which incorporated large cyclone washers had not pulled through the sheeting. Once the roof structure had gone, there was nothing to resist the shear forces that had previously been carried by the roof sheeting and many of the walls had collapsed. Again, this is a failure mode that was typical of up to ten houses and sheds within the town.

4.4 Buildings that Sustained Damage Relating Primarily to Overturning

Five groups of structures will be discussed here as illustrating the types of damage due to lateral forces. Again it does not represent an exhaustive

Figure 11 Recently transported house from outside cyclone area lost its roof structure.

Figure 12 This complete roof structure was removed from its house causing almost total loss of walls.

coverage of the damage, but a typical sample.

(i) A group of transportable homes adequately restrained against over turning: These ATCO units of which Figure 13 is a typical example, consisted of transportable complete buildings. The buildings used as teachers' accommodation incorporated a heavy steel chassis of universal beam sections which was clamped in place on large concrete blocks. Metal lugs were held against the bottom flanges of the chassis by bolts cast into the concrete blocks. Fresh minor spalling of the concrete near the chassis support gave evidence to the effectiveness of this restraint to overturning. The spalling indicated that movement and force transfer had indeed taken place at this point, but overturning had been effectively resisted. We were told of some failures of large glass doors and damage to internal partitions to the teachers' residences although speedy repair work to these premises meant that most damage had been remedied within four days of the cyclone's occurrence.

(ii) A transportable house inadequately restrained against overturning: This house had been transported to Borroloola recently and positioned on site with no tie down provision at all. The roof on the module was profiled aluminium sheeting that had been pop rivetted to battens. The roof sheeting had torn over the pop rivets, but the small room sizes within the module and the rigidity of the walls had prevented significant distortion of the remainder of the module. Rather the lateral forces on the building had caused it to overturn so that one wall was lying on the ground with the roof and the chassis in a near vertical plane as shown in Figure 14. The position of the building indicated that winds primarily from the north had caused the overturning. The building had just been towed into position and no attempt had been made to tie it down. The robust and transportable nature of the building means that it should not have sustained much structural damage inspite of its spectacular position.

By contrast another house that had the same type of transportable unit as its structural basis, but had been adequately restrained against overturning and had a well secured roof placed over its original roofing, fared well with no visible external damage. It indicated that with relatively inexpensive modifications to a structurally

Figure 13 The tie down facility of this ATCO transportable prevented overturning.

Figure 14 This transportable had no restraint against overturning - it had only just been positioned on site.

unreliable building, significant reductions in damage could be achieved.

(iii) Unsecured Boats and Caravans: The proximity of the town to the good fishing waters of the Southern Gulf, the Edward Pellew Group of Islands and the Vanderlin Island, meant that a large number of small boats were kept in the town. Many of these were lightweight aluminium dinghies and proved to be easily moved by the high winds. Some boats were overturned but others were moved up to 30 m from their original storage positions. These would have been dangerous items of airborne debris as most were stored in close proximity to housing as shown in Figure 15.

Caravans too generally fared poorly. Generally the very light construction proved susceptible to debris damage, and where the strongest winds were presented to the side of the caravan, overturning occurred. There was little evidence of caravans being tied down in preparation for the cyclone. Some caravans were totally demolished, but none were free of damage. Figure 16 shows typical damage. Of the two caravans that had been towed from Borroloola 9 hours before the cyclone's arrival, one was blown over not far from the town. Unfortunately the road took them right into the path of the eye of the cyclone.

(iv) Caravans being used as permanent accommodation with covers erected for their protection: In two instances the covers had been blown away leaving the supporting columns in place, and these had prevented the overturning of the caravan. Again the loss of the cover freed a large and potentially dangerous piece of debris. It was observed that the blocks of land that had 'permanent' caravan accommodation on them supported more potential debris than the other blocks as there was insufficient covered storage available.

(v) Light weight steel sheds: The town also contained a number of light weight steel sheds, some of them owned by absentee land holders for storing holiday equipment. Some of these were not tied down at all, others were tied inadequately to concrete slabs and some had been constructed with close attention to details that secured the shed and contents through the high winds. Those that were not secured were

Figure 15 The house on this site was a total loss - The boat was also badly damaged.

Figure 16 Few caravans were adequately tied down - This was one casualty.

rolled over many times and broken up by a combination of wind pressure and impact due to overturning. One such shed had wall sheeting over 300 metres from its original site. Most of the panels of which the sheds were made did not disintergrate, but separated from other panels as shown in Figure 17.

4.5 Aboriginal Housing

The types of housing used by the Aboriginal communities varied considerably within the town. It will be categorized broadly on the basis of type of construction. Masonry housing and Bell kit homes were similar in styles to the European housing and will each be treated separately. The camp style accommodation which frequently consisted of light gauge steel sheeting fastened to steel or timber frames will also be discussed.

(i) Masonry construction Aboriginal Housing: These houses were of concrete brick construction and there seemed to be about ten identical such houses in the town. They showed very little sign of wind damage. Some louvres may have been lost due to debris damage and certainly some sheets of corrugated steel roofing were lost during the cyclone. Most of the roofing damage occurred near the ends of the roof where no extra fastening had been employed. At least four of the houses were damaged in this way indicating that the problem was systematic. The roof structure, however was quite intact so repair work could be easily affected, and in fact all of these houses were quite servicable within four days of the cyclone as shown in Figure 18.

(ii) Bell Kit Homes for Aboriginal Housing: These houses were of light gauge steel frame with fibre cement sheeting glued to it. The roof sheeting was screwed to graded Z section purlins which in turn were bolted to the top of the wall mullions using angle brackets. The houses had minimal eaves but large open verandahs at the back which also corresponded to the windward side of the houses. On one building, the verandah had been completely removed as shown in Figure 19, while on an identical building next door the verandah was quite intact. The verandah was supported on the open end by a steel RHS portal, which at the bottom was tied to a concrete slab. On the house which had lost the verandah, the site was quite level and the verandah floor was concrete which at the corners was less than 80 mm thick and

Figure 17 This light steel shed and its contents were a total loss.

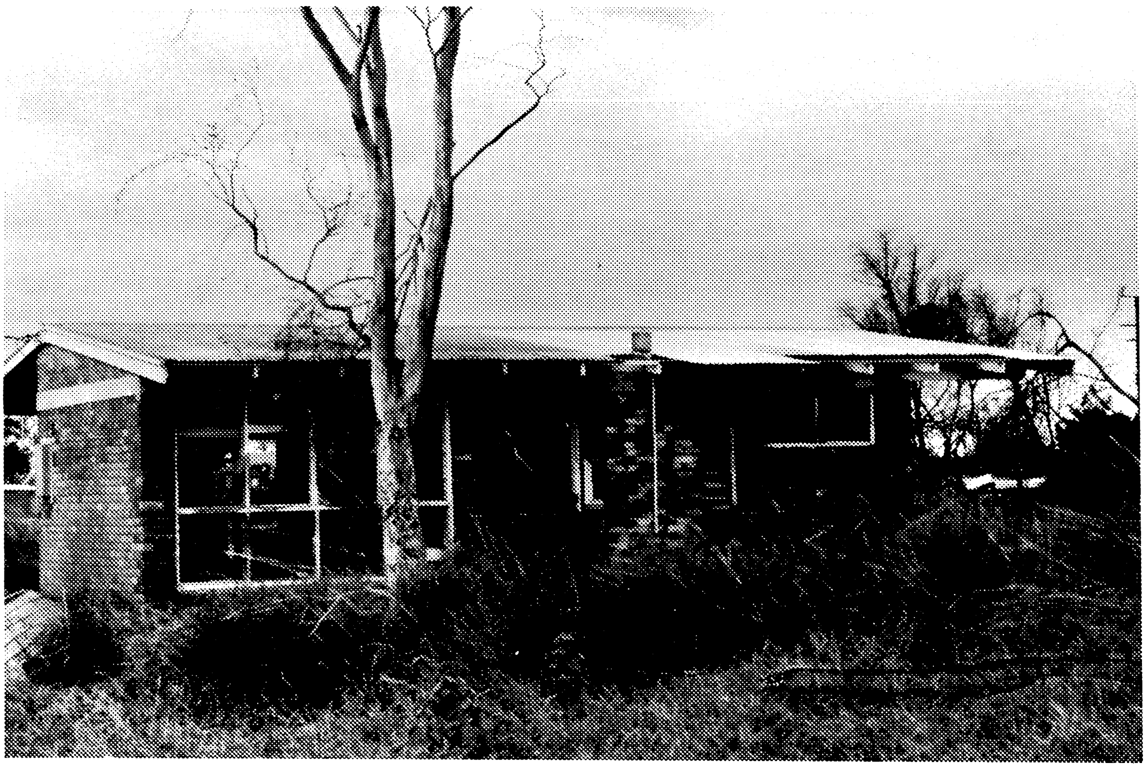

Figure 18 This masonry aboriginal housing lost some roof sheeting but could be quickly repaired.

Figure 19 This steel framed aboriginal house lost some external cladding, and a large open verandah.

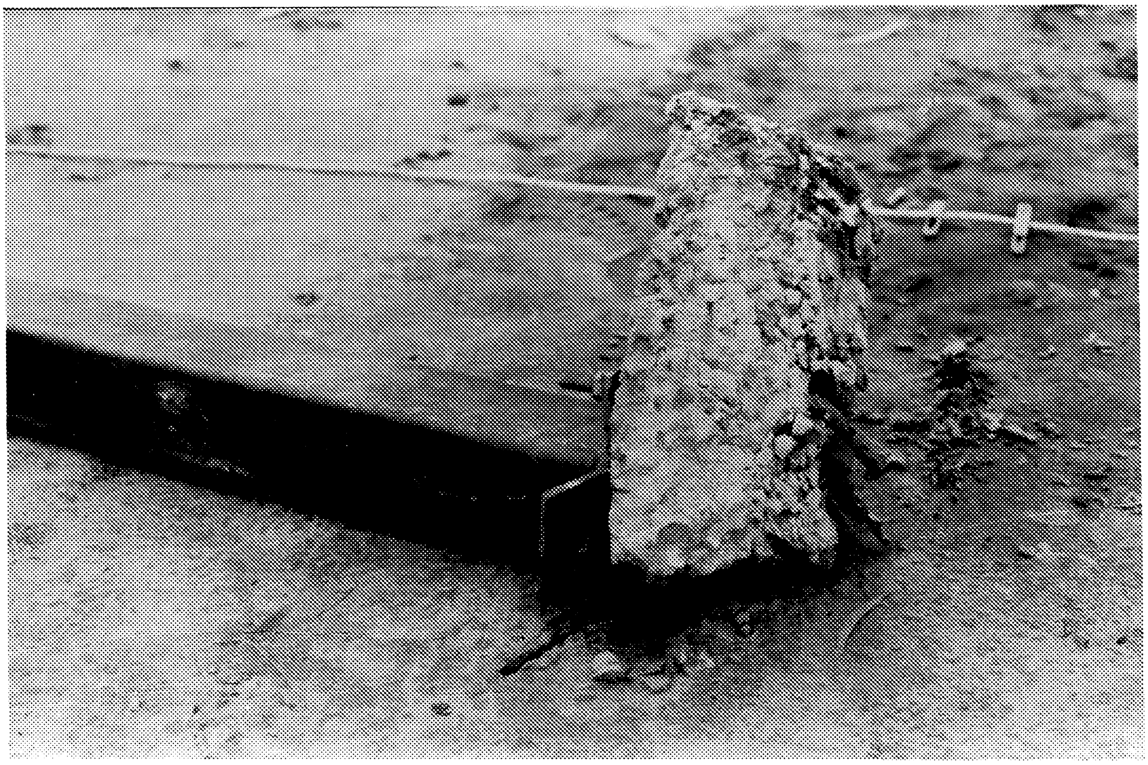

Figure 20 Detail showing failure of concrete slab at tie down column.

unreinforced. Bolts adequately secured the RHS verandah posts to the concrete floor, but the concrete had failed in shear adjacent to the column, and a small plug was still attached to each of the verandah posts as shown in Figure 20. The house next door with the undamaged verandah had thicker concrete at the edges due to its sloping site and this may well have increased the shear strength of the floor so that it could adequately transfer the uplift forces to the floor mass.

These houses also had some damage to the fibre cement wall sheeting on the windward wall. This could well have been due to debris damage as apparently much debris had been removed from the area prior to the inspection. Both houses had a 1 metre return on the verandah which would have experienced a high pressure differential during the highest velocity winds. On both there was some damage to both the wall cladding and the light gauge steel frame of the return, which could have been caused by wind pressures or equally by debris impact. It was the only flexural failure of a wall due to bending about a horizontal axis, sighted in the tour of inspection. Aside from the loss of the roof over the verandah, major structural damage to these houses was again minimal.

(iii) Small Steel Sheeted Homes of the Camps: There were parts of the town that were structured camp areas. They had reticulated electricity and water and the accommodation was mainly small shed type structures consisting of a frame with corrugated steel fastened to it. The size of these dwellings varied from 3 m x 3 m to 3 m x 6 m. One such camp area was visited and inspected. Most of the buildings in the camp that was inspected consisted of angle frames complete with bracing that had been welded together and had then had the corrugated cladding screwed onto it. A sketch of a typical section through one such dwelling is shown in Figure 21. In the camp examined, the buildings were of two main orientations - with the verandah on the windward side and with the verandah on the leeward side. The buildings with the verandah on the leeward side had little structural damage as shown in Figure 22. The dominant openings were on the leeward side so the net internal pressure would have been predominately negative. This would have helped to hold the roof down. However most of the buildings that had verandahs facing the direction from which the strongest winds came suffered major roofing damage. In nearly all of these cases the

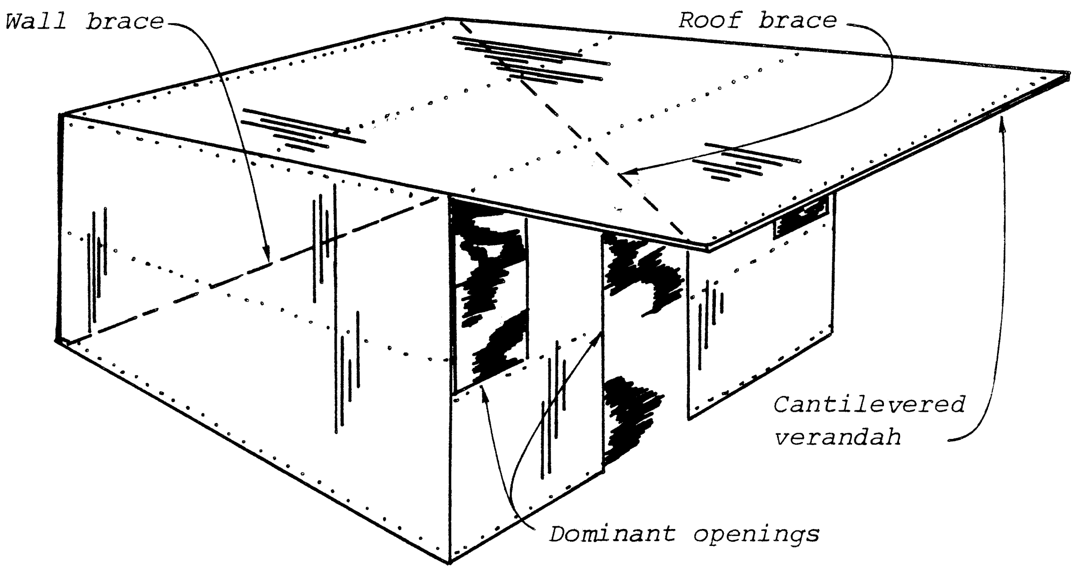

Figure 21 Sketch of Typical Aboriginal Camp Housing

sheeting had been blown off the cantilevered verandah leaving the frame behind, and in some cases, the roof sheeting had lifted off the enclosed part of the building too, as shown in Figure 23. The major openings in the enclosed space faced the verandah, so in the event of a door being left or blown open, significant positive pressures could be developed within the house and would have assisted in the removal of the roof which was fastened to frame members that were approximately 1200 mm apart. It appeared that internal pressures had played a big part in determining the fate of these buildings.

Although we did not inspect the other camps, one of which was on the other side of the river, we were told that they did not fare as well as the one we inspected, and the view from the aircraft tended to support this. Many of the houses in those camps employed timber frames from salvaged material and nailing of the sheeting. Most buildings in the camp on the eastern bank of the river had been totally destroyed.

4.6 Four Buildings that Warrant Special Discussion

These four buildings warrant special discussion because they either could not be classified readily in one of the other subheadings or the construction details were individual enough to be examined independently.

Figure 22 Aboriginal camp housing looking into direction of maximum winds - Little damage.

Figure 23 An almost identical building totally destroyed - Verandah and dominant openings on windward side.

(i) Two steel clad flat roofed buildings used as homes: These houses, built after the style of light industrial buildings suffered minimal structural damage. One had sustained some debris damage to a wall and the other had lost one sheet of roofing, but the overall performance of each was very much better than that suggested by their construction details. Neither building had any separate structural bracing and both were unlined as illustrated in Figure 24. This meant that all bracing resistance to the lateral forces on the buildings had to be provided by the external skin. Laboratory tests have shown profiled steel cladding to be a very stiff diaphragm (Nash and Boughton 1982) and the experience of both of these buildings bears that out. One building used light gauge steel C sections for purlins and girts spanning approximately 5 metres, and spacing of 1200 mm. The other employed 75 x 50 mm timber battens and girts spanning approximately 4 metres and spaced at 1200 mm. The fastening of the roof sheeting to battens and purlins was at approximately 150 mm centres throughout the entire roof, but the purlins and battens were secured to the frame with very light fasteners. The building that utilized the steel purlins had four pop-rivets at each end of the 5 m span securing the purlin to the portal frames as shown in Figure 25. They showed no sign of distress at all inspite of the fact that the average area of roof held down each pop rivet was 1.5 m^2! Certainly the failures of other roofing systems indicate that the performance of the pop-rivets was quite extraordinary. Each of the walls of the four buildings had quite large openings some of which had louvre windows, which were left open by the owners during the evacuation. Thus the net internal pressure was again probably negative, assisting the fasteners in restraining the roof. The owner of one of the sheds assured us that it was approved by a tertiary education institution, but its good performance was largely due to the precautions taken by the owners rather than to the design of the members and connections.

(ii) A House in the Early Stages of Construction: On this site vertical posts had been erected and concreted into the ground, and the purlins and beams erected to carry the roof. The corrugated steel roofing had been installed and screwed down at every second crest throughout the entire roof, and one external wall had been clad with fibre cement sheeting. Some temporary braces had been employed to keep the posts vertical during construction. While it is recognised that the house

Figure 24 View inside light gauge steel building showing total lack of bracing members.

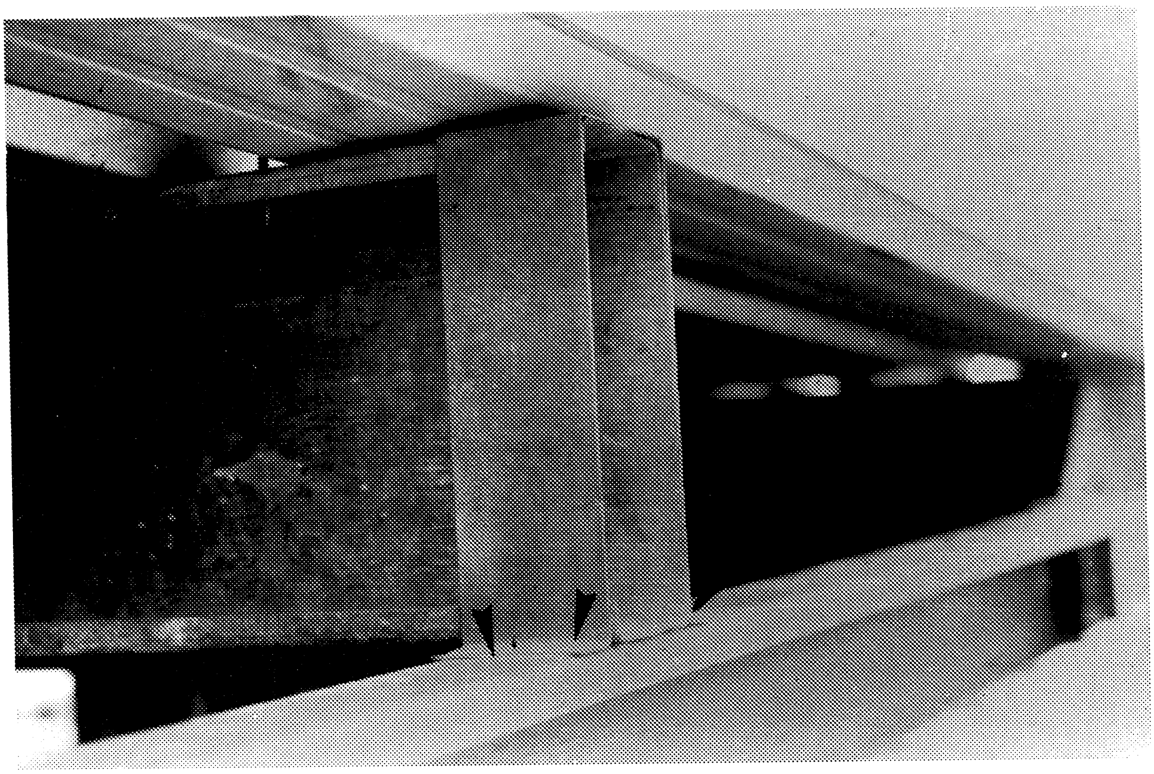

Figure 25 Another view in same house showing fastening of purlin - 4 pop rivets only between strap and frame.

was not complete, it certainly was unable to carry the wind loads placed on it. The roof sheeting had pulled over the screw heads near the corners as detailed for other buildings in Section 4.3. The purlins had been skew nailed to the roof beams in some locations and this detail had not proved adequate to carry the applied wind loads. Both these failures may have manifested themselves had the house been complete when the cyclone struck. However the building frame had racked significantly under the lateral loads attracted by the bare frame and roof as shown in Figure 26. The temporary braces were held in place at each post with nails that had not been driven home and as a result the brace could move away from the posts and bending of the nails then rendered the connection ineffective. The one wall that had been clad lost its sheeting when the wind blew through the open house onto the internal face of the cladding lifting it over the nail heads. The house in that condition was essentially unbraced and the racking failure was therefore inevitable. By contrasting this structure with the previous one where bracing was achieved only by using ribbed steel sheeting, the steel skin on the previous house can be seen to be a very effective bracing element.

Another type of failure observed on this house, but not elsewhere in the town was the lifting out of the ground of the concrete pads on the end of the posts as shown in Figure 27. Some of these had been lifted over 50 mm in the course of the cyclone but had dropped back in much the same location as the winds abated. Soil filling the space vacated by the concrete prevented them from returning to their original position. This illustrated the severity of the uplift forces on the upper surface of the roof as the internal pressure would have been effectively zero due to the complete lack of walls.

(iii) The Kindergarten Building: This had obviously been assembled on site from four prefabricated sections placed side by side and is illustrated in Figure 28. The lines separating each of the modules ran at right angles to the ridge line of the low pitched roof. Each module was built complete with floor walls and roof and butted up to each other on site. The roof structure consisted of two trusses each of which spanned approximately 9 m and were placed at each side of the 3 m module. Plywood webbed deep purlins then spanned between the trusses and supported the corrugated roof sheeting, and each truss was tied to

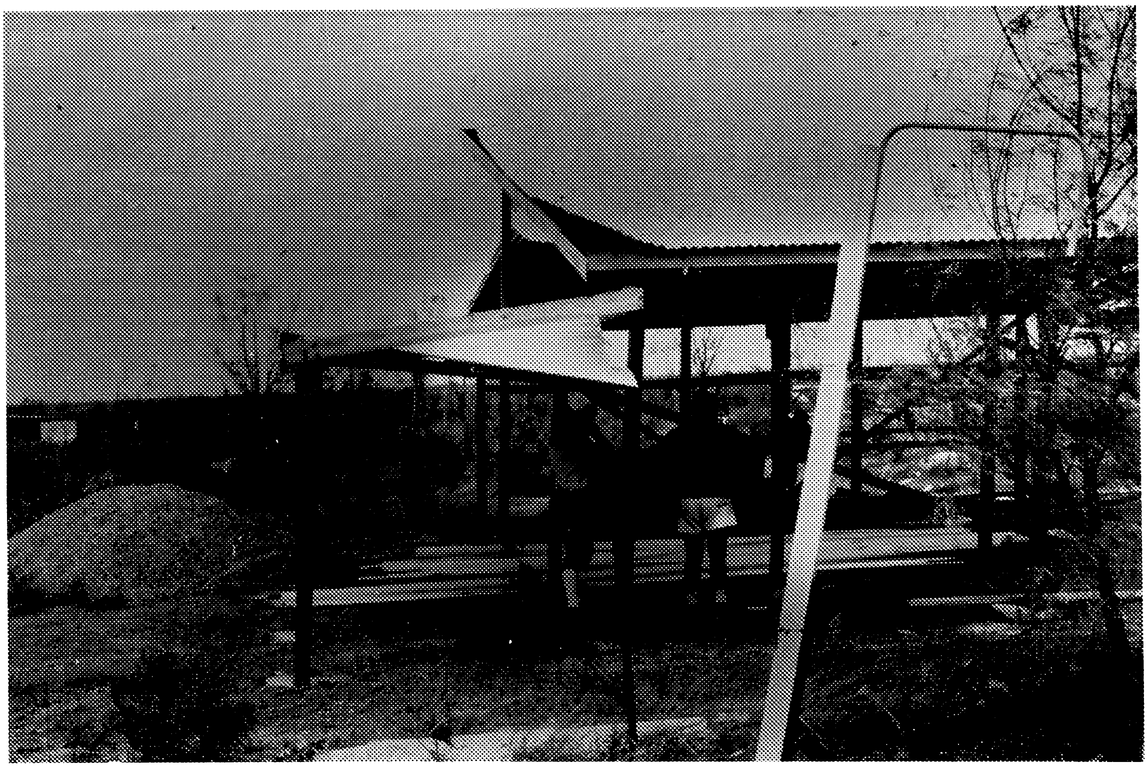

Figure 26 Partially completed house showing racking of the frame

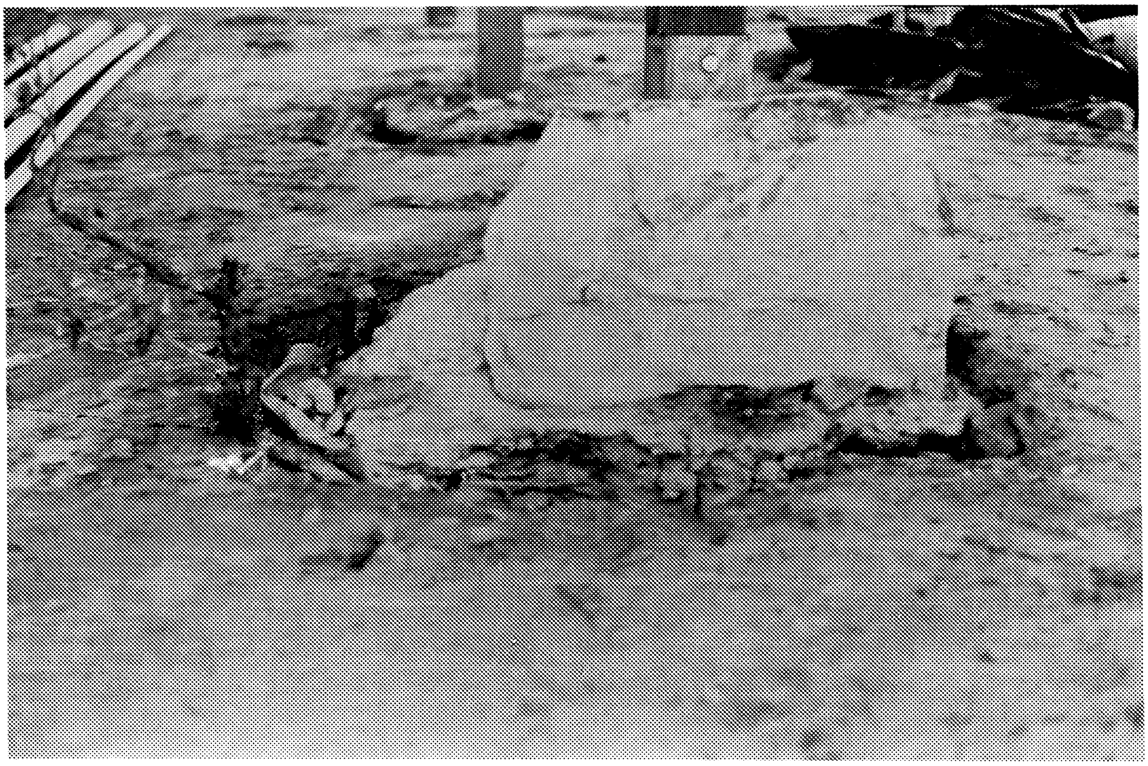

Figure 27 The same house showing uplift of footings

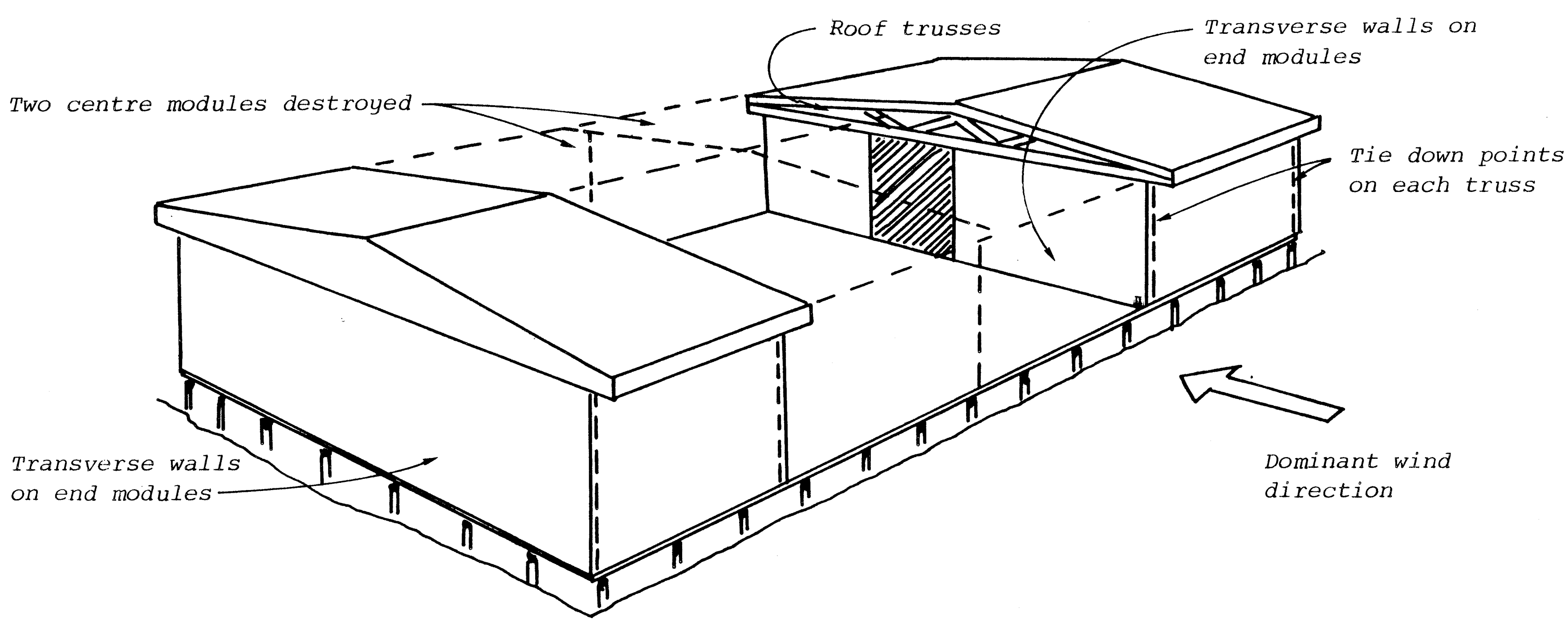

Figure 28 Sketch of Kindergarten Building

the floor with a rod at each end. The ceiling was fixed to the bottom of the purlins, and the whole roof structure was tied to the walls in each module. Each end module had side walls and internal walls which made them rigid box type structures, however the centre two modules effectively consisted of only the roof, external wall at each end of the truss and the floor. With little intermodule connection there was no restraint to racking of the centre modules other than that lent by bracing action of the roof sheeting.

The lateral loads on the windward wall had pushed the two centre modules in leaving the roof on the floor, but the end modules were still quite sound as shown in Figure 29. The roof sheeting had carried a large amount of the lateral load from the centre modules to the end modules, and tearing of the sheeting at the lap joints as shown in Figure 30, indicated that some movement had occurred within the roof diaphragm prior to failure. This failure could have been prevented by tying the roof trusses together effectively at each joint between modules.

(iv) A High Set Light Gauge Steel Framed house - The Welfare House: This house was supported on steel columns with very solid welded steel bracing and a blocked in laundry underneath. The floor deck was quite intact and the sub-floor bracing showed no signs of distress. However the house above floor level had sustained considerable damage as shown in Figure 31. The most obvious damage was the failure of the roof over the front half of the house. The basic construction of the house was a series of light gauge steel framed panels forming the walls with Z section steel purlins bolted to the tops of each wall mullion. The direction of the strongest winds was nearly normal to the front wall, and in this part of the building the large rooms gave a total of only four purlin tie down points over the entire width of the house. The high uplift forces on the top of the roof near the windward edge, coupled with significant uplift under the wide eaves caused high loads to be transmitted to the bolts tying the purlins to the wall mullions. These bolts tore slots in the mullions and hence the purlins lifted away from the top of the wall. The loss of the roof over the windward wall meant that it was no longer available to support the top of the wall and as a result the windward wall has been pushed inwards along much of the front of the house. The loss of this wall undoubtedly

Figure 29 Kindergarten Building showing end modules intact.

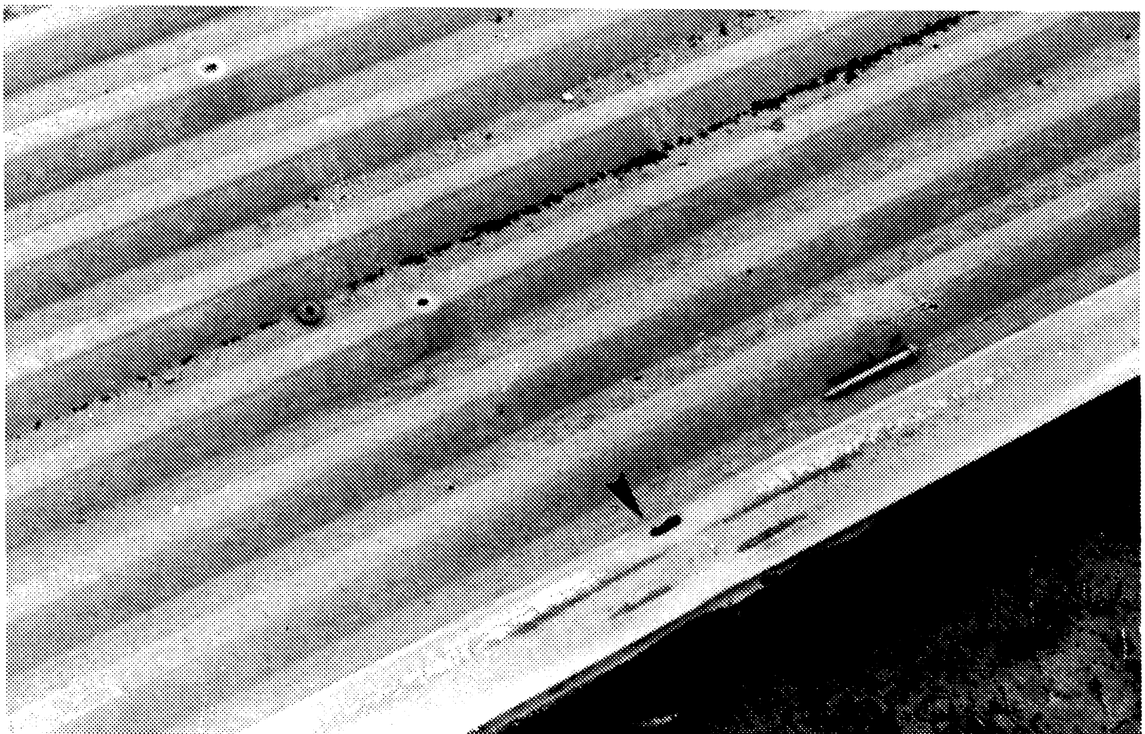

Figure 30 Detail of roofing from kindergarten. Note slotted holes at lap.

Figure 31 'Welfare House' - severe damage.

Figure 32 'Welfare House' from end showing roofing folded back along centre line.

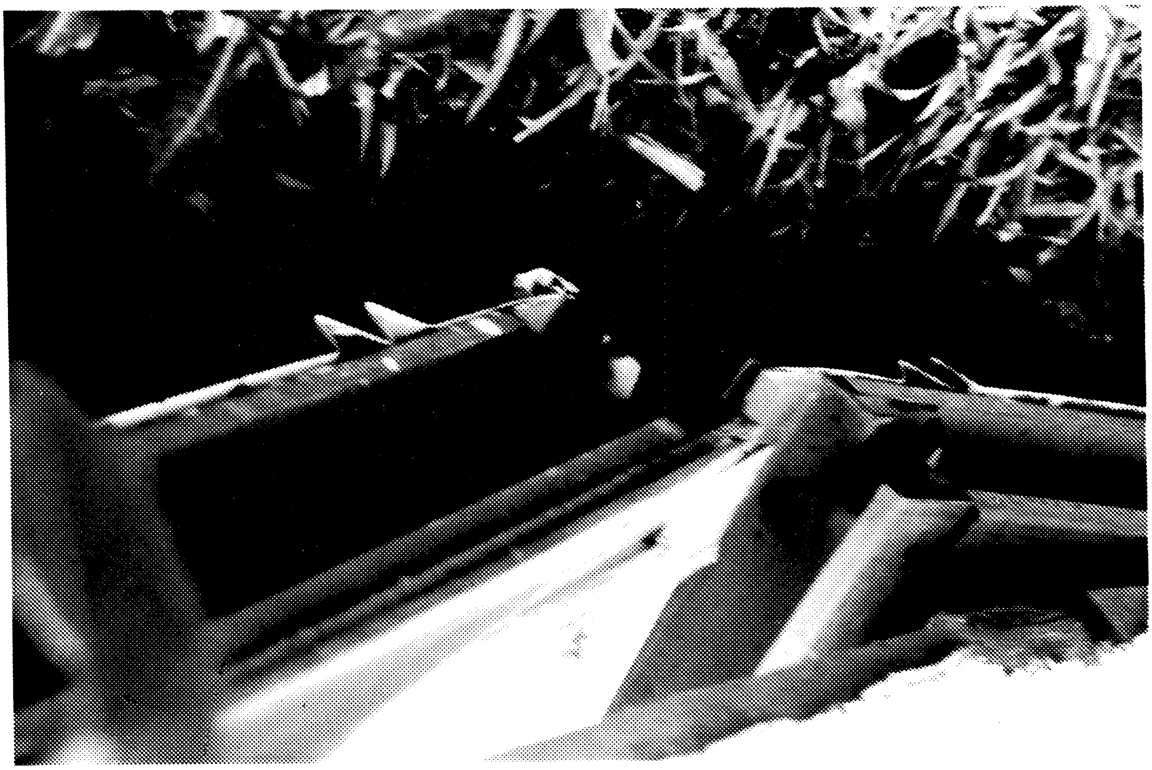

Figure 33 Detail of failure between top of walls and purlins. Note holes in top of mullions are torn.

would have caused an increase in internal pressure which would have assisted in the removal of more of the roof sheeting. However the purlins on the back half of the roof were tied down at more than 6 locations due to smaller room sizes being utilized at the back of the house. This factor, together with the generally lower external uplift pressures on the back half of the roof contributed to the purlins in the back half of the house remaining fastened to the walls and the roof in place. The roof sheeting had been bent in two along a line that roughly followed the centre of the roof, with the roof sheeting from the front half lying on top of the roof sheeting on the back half as shown in Figure 32. Many of the purlins were still attached to the sheeting, but just removed from the walls over the front part of the house. This house again illustrated the important function performed by the roofing as a bracing element in that once it had been lost, the whole structural integrity of the house was jeopardised. This type of failure has been demonstrated on a house tested in the Cyclone Testing Station's full scale house testing project (Boughton & Reardon 1984a). The failure of the top of the light gauge steel wall mullions in tearing, shown in Figure 33, could well have been assisted by fatigue in the steel due to the repetetive nature of the uplift forces and if so bears similarity to failures in light gauge steel sections experienced in controlled cyclic loading tests as part of the Station's work.

5. IMPLICATIONS OF THE PERFORMANCE OF BUILDINGS

The estimates of the peak gust wind speed at the town of approximately 50 ms^{-1} are marginally less than those experienced in Townsville during the passage of cyclone Althea in December 1971, and significantly less than current design wind speeds for cyclone areas.

The estimated wind speed would have placed loads on buildings that for the peak gust would have been more than 53% of design load but less than 68% of design load based on the current Australian Standard - AS 1170 part 2 - 1983. At these loads the probability of major structural failure should be very low indeed, as the ultimate strength should be considerably greater than the design load, but as can be seen from Section 4, there was significant damage to many buildings in the town. The cause of the damage for some buildings was a complete lack of design for high winds, and this seemed more prevalent in the temporary buildings. Other buildings had provision for securing the major structural elements, but insufficient attention had been paid to securing the cladding.

5.1 Control over Building Standards

In the past there appears to have been little control over building standards in the town. Many of the buildings owned and maintained by government authorities did have building supervision during construction, and the most recent of these performed well. This is a direct benefit from the expereience of cyclone 'Tracy' and the tightening of building regulations as a result of intensive research in the years since 1975. The police station complex held the most recent government buildings and had sustained no structural damage. This was consistent with the applied wind loads being very much less than the design load. Few other buildings would have been designed to the Northern Territory Cyclonic Areas Deemed to Comply Standards, but at least one and possibly two high set houses in the town were built to comply with Queensland building regulations. In both of these, poor attention to detail with site works caused some damage - the loss of a carport for one and lifting of roof sheeting at the corners on the other.

Some of the older government buildings such as the Pre-school Building and the 'Welfare House' which probably predated the Deemed to Comply Standards sustained major structural damage due to underdesigned connection details, in spite of the supervision of their construction. The importance of adequately designed connections in structures cannot be over emphasised.

In many of the privately owned buildings in the town a sincere effort had been made to build in such a way as to minimize damage in high winds, but others had been built with no attention to high wind resistant construction. The damage to these buildings could invariably be traced to skimping on connections holding down either the roof or the whole structure. Certainly competent building supervision could have eliminated much of the damage to those structures. This in turn would have drastically reduced the amount of windborne debris.

Supervision of all building construction within the town could have substantially reduced the amount of damage by ensuring that due attention was paid to connection provisions for high winds.

5.2 Effect of Internal Pressures

The damage pattern seemed to indicate that internal pressures played a large role determining the overall building performance. A general lack of window damage was commensurate with the wind speeds estimated for the cyclone at Borroloola, with most glass failures attributed to debris damage. Many buildings therefore had a net internal suction which would have assisted the restraining action of the roof sheeting fasteners. However, the buildings in the Aboriginal camp showed that the orientation of those buildings which had dominant openings in one wall, determined the fate of the roof. With net internal suction, the roof fasteners were capable of resisting the net uplift, but with a positive internal pressure the fastening system did not have sufficient reserves of strength and most of the roof failed during the passage of the cyclone.

These observations were supported by the light steel buildings with large openings in all walls that allowed a net internal suction. This was highly instrumental in preserving the roofs in spite of the very light fasteners securing the purlins to the walls. The internal suction on these buildings would have increased as the external uplift on the roof increased thus stabilizing the roof against failure at even higher wind speeds, but it seems a shaky premise to use for design purposes. With large amounts of air moving through the house, objects such as mats or sheets of cardboard may have blown over windows and louvres on leeward walls, and net internal pressures may then become positive. In Darwin the louvres of leeward walls were often observed to blow shut and hence give rise to positive internal pressure.

The role internal pressure plays in high winds is very important and the most responsible design approach is to assume the highest possible internal pressure. This assumes damage to windward windows but not to leeward windows. Under these conditions, which certainly prevailed in some Borroloola buildings the maximum uplift forces are placed on the roof sheeting and structure.

5.3 Bracing Strength of Claddings and Linings

Many buildings relied solely on the cladding and lining to provide resistance to lateral forces. At the loads applied in cyclone 'Kathy' these mechanisms for force transfer performed well, and the only racking failures observed were in buildings that were either under construction at the time or had suffered roof loss. The damage pattern was similar to that seen after the passage of cyclone 'Althea' in Townsville where lateral loads were not high enough to cause widespread racking failures.

5.4 Tying Down of Light Buildings, Boats and Caravans

Because of the significant amount of warning given prior to cyclone 'Kathy' together with the experience gained in preparation for cyclone 'Jim' some effort was made to clean up the town and secure potential debris. However the winds were sufficiently strong to overturn caravans and light sheds that had not been secured. Boats suffered a similar fate, and aside from the fact that each of these items represented a reasonable monetary investment in themselves, they became potentially dangerous items of airborne debris. No doubt the people of Borroloola have learnt that these light objects must be adequately tied down. The importance of having solid tie down facilities where caravans and boats are usually stored, should be given good publicity throughout the cyclone zone in October or November each year to alert all owners.

5.5 Aboriginal Housing

This is an area that has had much discussion from sociologists and architects, but also needs to have input from engineers. The large number of Aboriginal communities around the tropical coast line places their housing in a location that is at risk from tropical cyclones. As such it must not only be suitable to their way of life and social environment, but must also be structurally capable of providing continued shelter during and after the high winds associated with cyclones.

The Aboriginal population of Borroloola was more than four times the European population and most of the Aborigines lived in camp style settlements in or near the town. These camps suffered severe damage during the cyclone, and had it not been for the evacuation procedures undertaken, injury and possibly loss of life would have taken place in the camps during the high winds. The extensive damage of these areas left less than 25% of the houses as being appropriate for shelter after the event. As a group, the camp accommodation failed due to poor connection details and hence could not fulfil its role as a safe cyclone shelter or as effective post cyclone accommodation. Engineering input to Aboriginal housing is just as important as it is to European housing and will help minimise the impact of cyclones on these communities.

6. CONCLUSIONS

1. Cyclone 'Kathy' as it struck the coast appeared to have much the same wind speed as cyclone 'Tracy'. However at Borroloola the wind speed had reduced considerably, and maximum gust speed was estimated at between 46 and 52 ms^{-1} (165 to 190 kph).

2. The structural damage to buildings in the town reflected shortcomings in their design and/or construction.

3. All of the buildings constructed to current building regulations for cyclone prone areas had damage to trim only, or to on-site additions.

4. Many roof sheeting failures had originated near edges or corners where no attention had been given to the high localised uplift pressures in those areas. The provision of extra fasteners at those points could have prevented any major damage to the buildings.

5. Internal pressures appeared to have played an important role in determining roof performance. Some houses with strong internal suctions performed well while identical houses with internal pressures lost large portions of their roof.

6. The bracing capacity of claddings and linings was well demonstrated on houses that relied on stressed skin to resist racking forces. Other houses that lost their roof structure showed that the walls deformed without the stiffening effect of the roof cladding.

7. Some failures previously observed in full scale house tests and laboratory tests at the James Cook Cyclone Structural Testing Station were observed on houses at Borroloola. There were:

   (i) failure of inadequately nailed batten straps,
   (ii) slotting of roof sheeting subject to high shear loads,
   (iii) tearing failure of light gauge steel at overstressed purlin tie down points,
   (iv) failure of walls in bending after removal of the roof structure,
   (v) failure of inadequately fastened steel roof sheeting by fatigue initiated tearing at the fasteners,
   (vi) lifting of foundation blocks out of the ground on light weight structures.

   These observations will provide a useful link between research activities and practical structural problems.

8. Adequate building supervision of all new structures in communities within cyclone areas can dramatically reduce the wind damage after events such as cyclone 'Kathy'.

9. Efficient tie-down of caravans, boats and light sheds can minimize the damage to these expensive items of household and recreational equipment. It will also reduce hazards of large mobile airborne debris.

10. The study has isolated the following areas as requiring further research activity.

(i) The securing of existing houses to meet current building standards, and the structural upgrading of houses transported from outside cyclone-prone areas into cyclone-prone regions.

(ii) The structural aspects of suitable Aboriginal housing.

(iii) The interaction between wall structural systems and roof systems within houses.

(iv) The role of internal pressures in failure mechanics of buildings.

(v) Implementation of building inspections for remote areas.

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