JAMES COOK CYCLONE STRUCTURAL TESTING STATION

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INVESTIGATION of DAMAGE to STRUCTURES FOLLOWING CYCLONE CONNIE

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PREFACE

Publication of this Technical Report marks the commencement of co-operative research between the Cyclone Testing Station and Curtin University of Technology. The author, Mr Boughton, is senior lecturer at the School of Civil Engineering of that university. Formerly he was Mount Isa Mines Research Fellow at the Cyclone Testing Station.

Logistically it was far more efficient for Mr Boughton to travel from Perth to investigate the effects of Connie than for somebody to travel from Townsville. The Cyclone Testing Station is most grateful to him for making his report available for publication and also to the Head of the School of Civil Engineering for his co-operation.

INVESTIGATION OF DAMAGE TO STRUCTURES FOLLOWING CYCLONE CONNIE

G.N. BOUGHTON, SENIOR LECTURER, SCHOOL OF CIVIL ENGINEERING

SYNOPSIS

Cyclone 'Connie' crossed the Western Australian coast near Port Hedland on 19th January, 1987. The cyclone was a moderate tropical cyclone (Intensity 2 on the Saffir-Simpson scale of five) and had an estimated maximum speed of approximately $45ms^{-1}$ at Port Hedland.

The winds would have applied only 50% of design load to most structures. The performance of many structures in greater Port Hedland showed little or no damage, commensurate with the low loads applied. However, a number of buildings suffered structural damage that indicated systematic deficiencies in those buildings.

Some of the damage was confined to details conventionally regarded as peripheral to the main structural system. Nevertheless, the damage had structural implications, in that internal pressures were substantially altered by the damage, and in some cases, adjacent structural elements were overloaded by partially detached components.

Other damage was observed in buildings that had successfully withstood previous larger cyclonic events. This damage was a consequence of hidden damage from the previous events and/or deterioration of components due to corrosion.

INVESTIGATION OF DAMAGE TO STRUCTURES FOLLOWING CYCLONE CONNIE

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1.0 INTRODUCTION

Cyclone Connie crossed the Western Australian coast, approximately 20km east of Port Hedland at 7 pm. on 19 January 1987. Strong winds were observed at Port Hedland for five hours prior to the crossing and for two hours after the crossing.

Some damage to buildings was caused by the winds, but the press reports stressed the adequate performance of structures as most damage observed was superficial. Indeed, the most conspicuous damage was to vegetation. However, in the light of the relationship of the recorded wind speed to the design wind speed for Port Hedland, the fact that any damage to buildings occurred at all indicated that some systematic weakness may have been exposed. A tour of inspection of damaged buildings in Port Hedland was arranged to examine those weaknesses.

The observations and recommendations of that tour are reported in this work. It does not claim to be an exhaustive account of the damage wrought by tropical cyclone Connie as a number of damaged buildings in the Wedgefield light industrial area were not inspected, neither were some at the nearby town of Whim Creek. However, over 30 damaged buildings were inspected, and consistencies in the damage patterns could be observed. The emphasis of the report is on the general lessons to be learned from the damage, although particular failures are used to illustrate the broader issues.

1.1 Port Hedland

Greater Port Hedland is a town of approximately 13000 people (Australian Bureau of Statistics, 1987) on the Western Australian coastline at approximately 20° Latitude. The 1981 census figures show that the town has approximately 3400 dwellings of which only 2% are privately owned, and 20% owned by government housing authorities. Port Hedland supports the port activities of two large mining companies and a salt extraction company. It also operates as a regional centre for the North Pilbara.

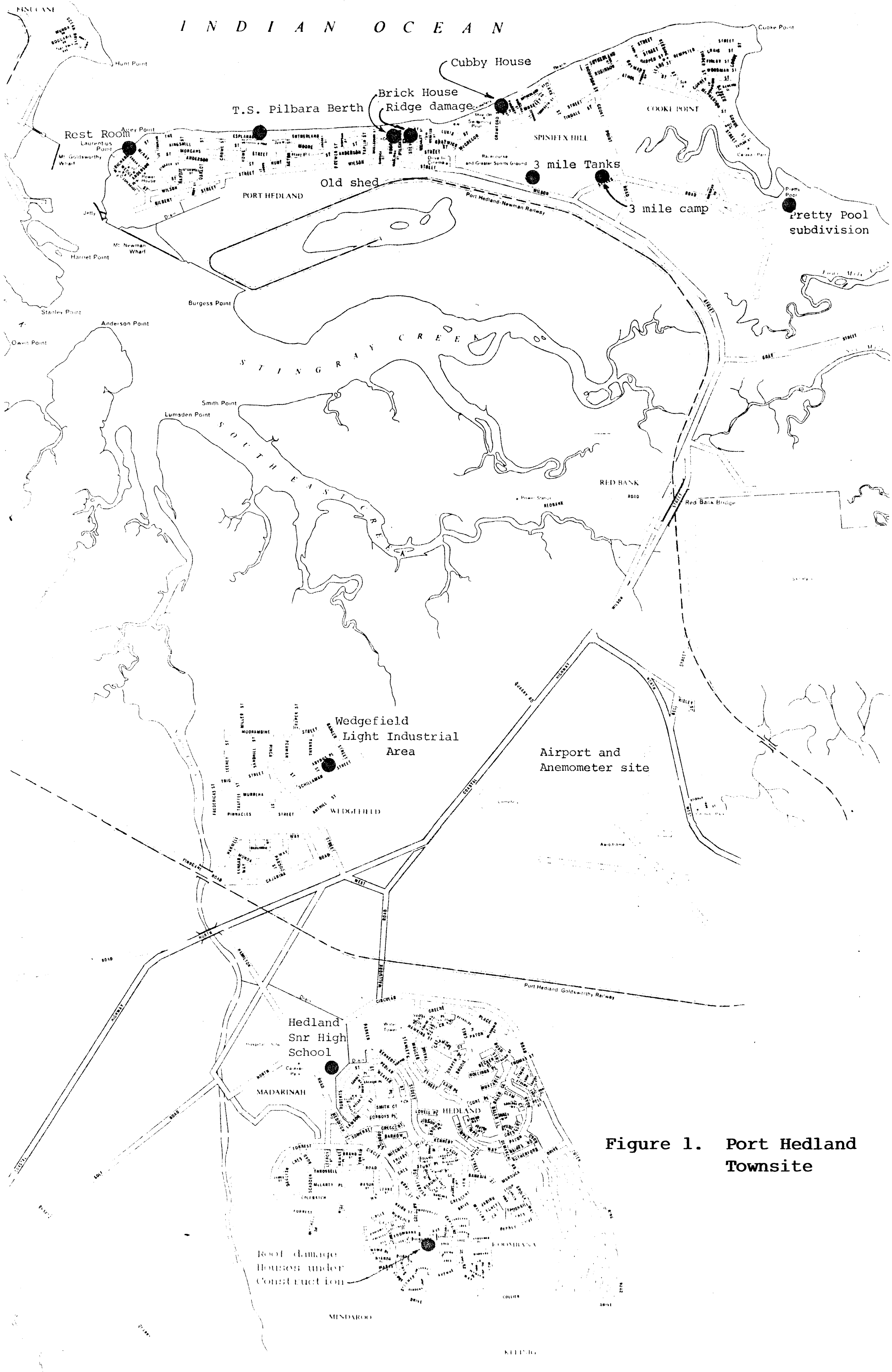

Figure 1. Port Hedland Townsite

The low number of privately owned dwellings is characteristic of the towns in the Pilbara, with a large proportion of citizens employed by large mining companies, banks and other infrastructure support industries or government agencies and authorities. The 1981 census figures (Australian Bureau of Statistics, 1987) showed that in Port Hedland approximately 20% of the workforce was employed by government, 73% by private companies and 7% was self employed.

Figure 1 shows a map of greater Port Hedland. The historical town centre is adjacent to the port in the northern portion of the town. This area also houses the ore handling operations for the Mt. Newman Mining Company. In the late nineteen sixties a new town centre was planned in South Hedland, and much of the recent housing and commercial development has taken place in that area. The government offices, senior high school and many of the larger shops are located in South Hedland. The airport land (on which is situated the Bureau of Meteorology Office and a Dines anemometer) is east of South Hedland. The light industrial activity that has developed in Hedland since the growth of the mining industries in the early nineteen sixties has been concentrated in the Wedgefield light industrial area.

1.2 Building Construction in Port Hedland

This subsection contains some observations of the author, which do not necessarily represent the opinion of the shire council or other building regulatory bodies. The houses constructed for the government agencies and large companies in the town have a higher level of supervision than many houses constructed elsewhere in Australia. The majority of houses in both the old Port Hedland area and the newer South Hedland area have therefore been well scrutinized at the construction stage. Programmed maintenance activities are organised by the large companies as well as by government housing agencies.

By contrast, the Wedgefield Light Industrial area appears to have had a much lower level of building supervision than the buildings in the other parts of the town. Many sheds appear to have been erected with little regard for the frequent occurrence of tropical cyclones historically associated with the region. Some buildings have been relocated to their present sites and show signs of deterioration due to rust in steel members or white ant activity in timber members.

Many of the houses in the older port area are of timber frame construction with fibre cement external cladding. Many of these have been constructed on piles with timber floors 600mm to 1000mm off the ground. Roofing material on these houses is predominantly a corrugated profile steel sheeting fixed variously with lead headed nails or screws. Some houses have had roofs replaced a number of times due to damage caused by past cyclones. Most of the older houses were fitted with overbattens which consisted of a steel angle section mounted above the roof sheeting immediately over the external walls of the house. This overbatten was secured to the underside of the floor by long bolts passing through the frame members. Those that had not been fitted with overbattens at the time of construction were modified to include the overbattens after damage caused by cyclone 'Joan' in 1975. Most of these houses have removable storm shutters made from either plywood or an expanded metal mesh to protect windows.

The more recently constructed housing in the Port area and in South Hedland is of slab on grade construction with a light gauge steel frame supporting a timber truss roof. The external cladding is mainly brickwork with plasterboard used for internal linings. 'Trimdek' profile roof in colourbond is almost universally used as the roofing material on the more recent housing, and is screwed into timber battens at every crest. Some modern houses also incorporate overbattens, but most do not.

1.3 Cyclone Awareness of the Community

The State Emergency Service and the Bureau of Meteorology are active in providing publicity to house holders on procedures to be followed during the cyclone season in Port Hedland. The leaflets distributed give emphasis to clean up operations, safe storage of belongings, the significance of the various alerts and warnings that are issued, and recommended practices for sheltering during the passage of cyclones. Port Hedland has had a large number of tropical cyclones pass very close to it, and as a result the State Emergency Service operations are quite conspicuous. Most of the population are aware of the damaging nature of tropical cyclones and adhere strictly to the recommended procedures and practices.

However, familiarity also can breed contempt, and the West Australian press carried reports of individuals who flaunted the warnings during cyclone Connie. The itinerent nature of a large proportion of Port Hedland's population means that education programmes must continue to ensure that all residents have due awareness of the potential of tropical cyclones to cause disruption to the community.

2.0 METEOROLOGICAL INFORMATION

Tropical cyclone Connie was a cyclone corresponding to a SS2 on the Saffir-Simpson scale of 5. By comparison, records available (Major, 1978) show that Port Hedland has experienced wind speed equivalent to no very severe cyclones,three severe cyclones and eleven moderate cyclones since 1950. However, the wind speeds recorded at the Port Hedland airport during cyclone Connie were the highest for approximately seven years.

2.1 Recent History of Tropical Cyclones in the Port Hedland Area

Many of the buildings whose structural performance is discussed in Section 3 of this report date back to the late 1960's or early 1970's. During their lifetime they have been subject to high winds generated by a number of tropical cyclones. Pertinent details for the cyclones that produced the higher wind speeds are summarized in Table 1. Their tracks are shown in Figure 2.

Table 1 shows that there have been three cyclones with stronger peak gusts and four with higher average wind speeds in the past twenty years. Of these cyclones, Joan, Leo and Lena gave a very similar range of wind directions to that observed in cyclone Connie.

2.2 Preliminary Information on Tropical Cyclone Connie

This subsection contains preliminary information passed on by officers of the Bureau of Meteorology, the results of conversations with townspeople and examination of simple structures.

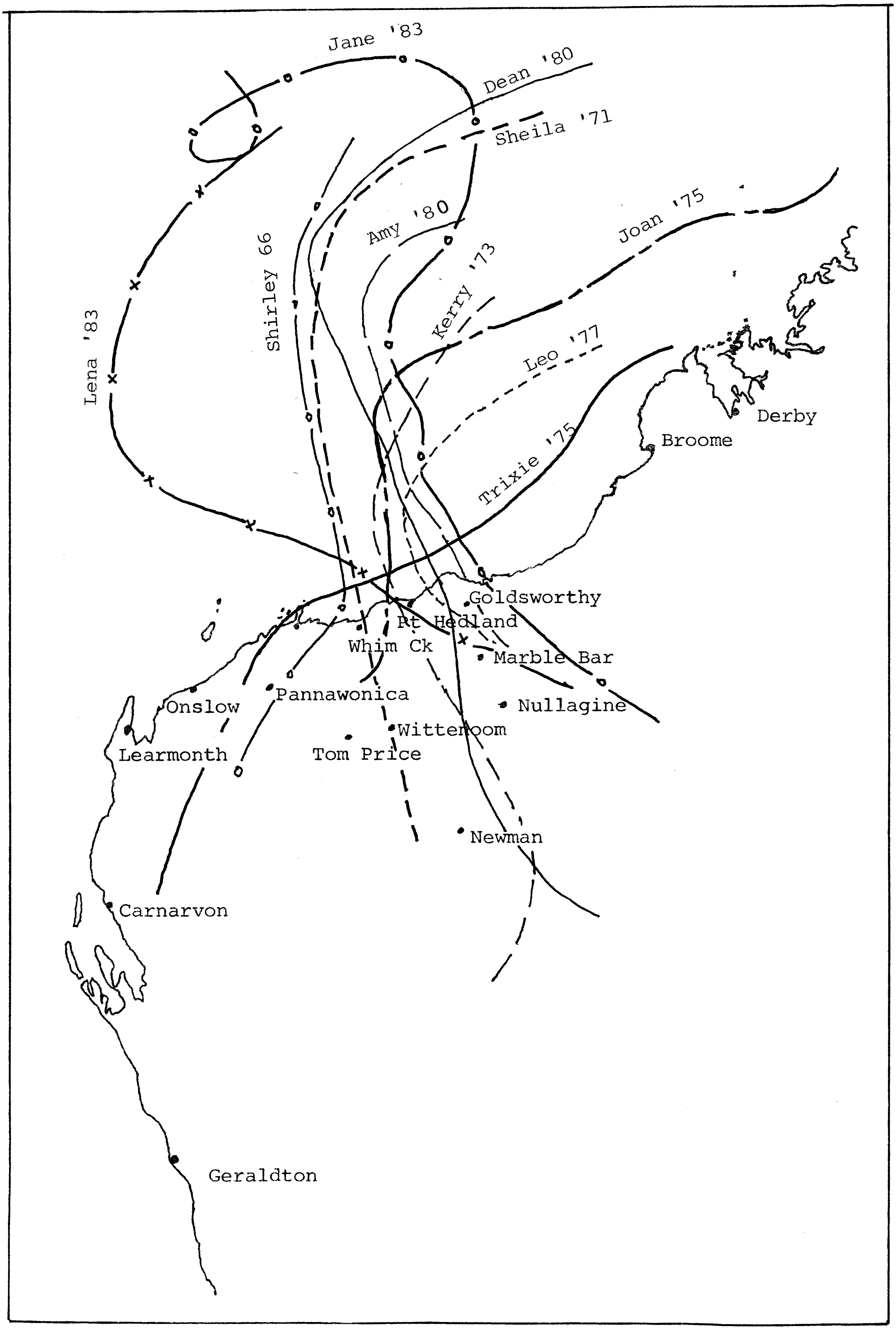

Figure 2. Tracks of recent significant cyclones to affect Port Hedland

TABLE 1

DATA ON RECENT TROPICAL CYCLONES TO AFFECT PORT HEDLAND

Date	Name	Wind Speed(ms^{-1}) average	max	Damage
2 Apr 66	Shirley	30	38	
3 Feb 71	Sheila	26	35	
22 Jan 73	Kerry	24	36	**
18 Feb 75	Trixie	23	35	*
8 Dec 75	Joan	39	58	**
27 Mar 77	Leo	33	56	
10 Jan 80	Amy		36	
1 Feb 80	Dean	36	54	*
1 Feb 82	Graham	23	33	
9 Jan 83	Jane		33	
8 Apr 83	Lena	28	43	*
19 Jan 87	Connie	(27)	(45)	*

Notes:

1. Figures in brackets for Connie are preliminary.
2. Wind speed figures are taken at Port Hedland airport.
3. Central pressures represent the estimate of the central pressure of the eye at the time the cyclone made landfall.
4. Damage indicators are based on

no indicator	-	minor damage
*	-	moderate damage
**	-	significant damage
***	-	severe damage

2.2.1 Information from Bureau of Meteorology Reports

Cyclone Connie developed from monsoonal activity off the North Kimberley coast. It was first declared a tropical cyclone at 1 pm on 17th January 1987. The path of the cyclone is plotted in Figure 3 and shows that its progress was characterized by a generally south westerly movement at approximately 10-15 kph.

The eye of the cyclone crossed the coast an estimated 20 km west of Port Hedland with a central pressure of approximately 955 hPa. The eye did not extend to Port Hedland, but pressure measurements by ships at sea and property owners tended to confirm the pressures estimated by the Dvorak satellite imagery analysis.

After landfall, the cyclone continued on a southward track, passing to the east of Whim Creek and Wittenoom and to the west of Newman. The distribution of rainfall records show that centres to the west of the cyclone's path registered higher falls than those to the east of the path. The weather radar patterns also confirmed the rainfall distribution.

High wind speeds were experienced at Port Hedland between 2pm on 19th January, 1987 and 8pm on 19th January, 1987. However, winds with an average speed of more than $15ms^{-1}$ were experienced for a 24 hour period as shown in the portion of the anemometer trace from the Port Hedland airport shown in Figure 4. The anemometer trace also shows that the predominant wind direction prior to landfall between 6pm and 7pm was easterly. After landfall the wind direction shifted through the north-east and north to the north-west. The peak gust of $45ms^{-1}$ was recorded when the wind was from the eastern quarter.

The barometric trace (not included in this report) showed a dip to 960 hPa between 6pm and 7pm on 19th January. The shape of the trace indicated that the recording station was not far from the eye of the cyclone.

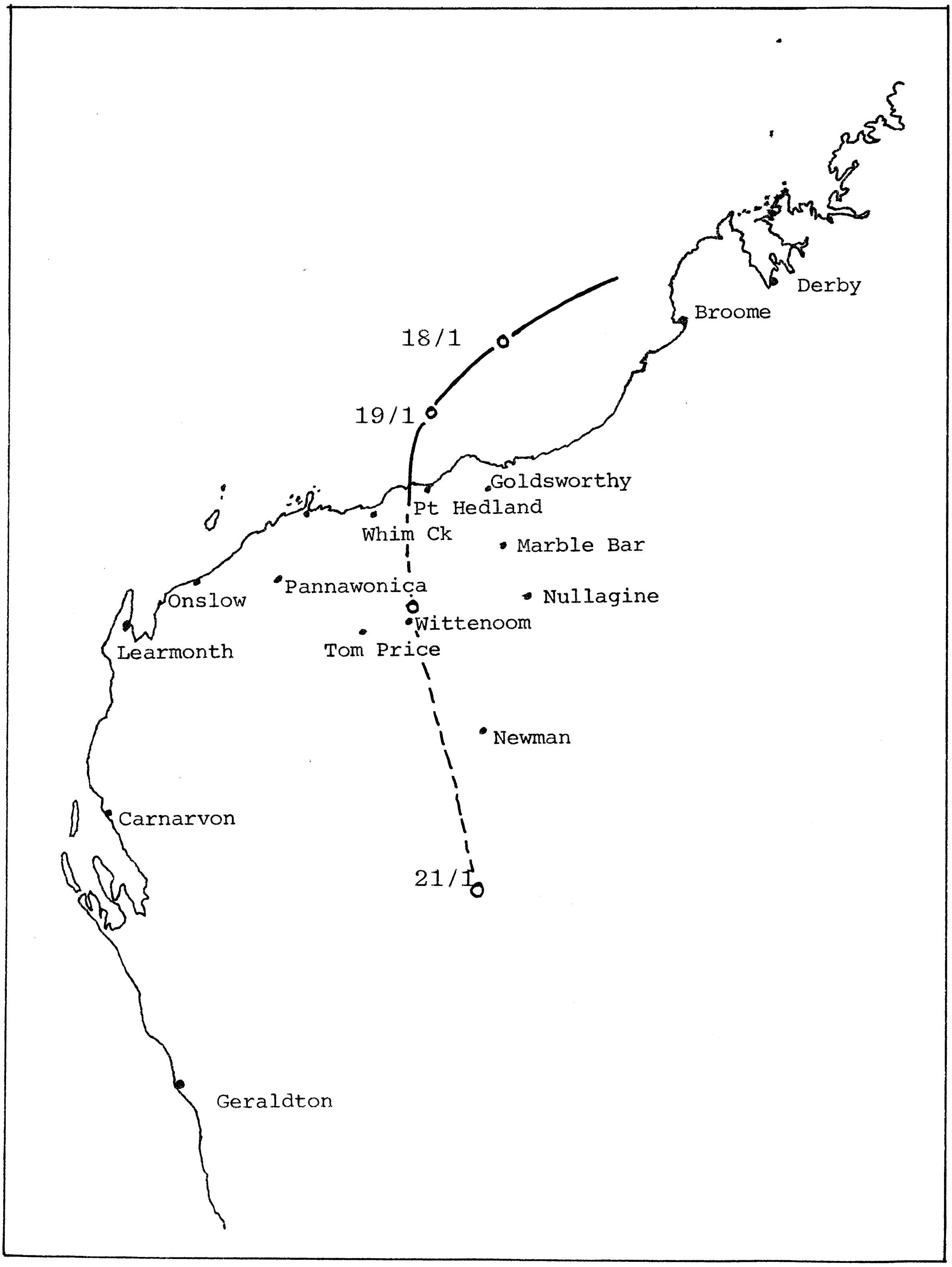

Figure 3. Preliminary estimate of cyclone 'Connie' track

2.2.2 Information From Discussions With Townspeople

The wind for most of the daylight hours of the 19th January was from the east. Between 6.45pm and 7pm, there was a slight reduction of wind speed noticed by approximately half of the townspeople interviewed. The anemometer trace showed a reduction in speeds of similar characteristic to that mentioned.

At about the time of the slight reduction, the wind direction changed through north and continued to the north-west where it remained until daylight.

These observations are quite consistent with the anemometer trace, and came from individuals in the port area, South Hedland and Finucane Island. They confirm that the eye of the cyclone passed to the west of Finucane Island, and are not inconsistent with estimates (made from weather radar images) that it passed 20 km west of the town.

2.2.3 Wind Speed Estimates From Examination Of Simple Structures

Examination of tree damage in the exposed part of the town facing the ocean indicated that average wind speeds at that location may have been as high as $40ms^{-1}$. (Amadore, L.A., Bucey, J.F., Talib, B.D. and Yanga, S.O., 1985). Corrected to the equivalent wind speed at a 10 metre height in terrain Category 2 instead of terrain Category 1 gave an average wind speed of 35ms, marginally higher than that derived from the anemometer trace at the Port Hedland airport.

Tree damage in South Hedland, some 7kms inland was commensurate with an average wind speed of $30ms^{-1}$, marginally less than that estimated for the Port. However, the assessment was not sufficiently sensitive to be able to attach any significance to the difference in wind speeds estimated for the Port and South Hedland.

Some road signs were blown over, but an examination of the signs showed that the footings had rotated in the soil. There was no evidence of yielding in the legs of any of the signs. This enabled the calculation of upper bounds to the wind speed at a number of locations:

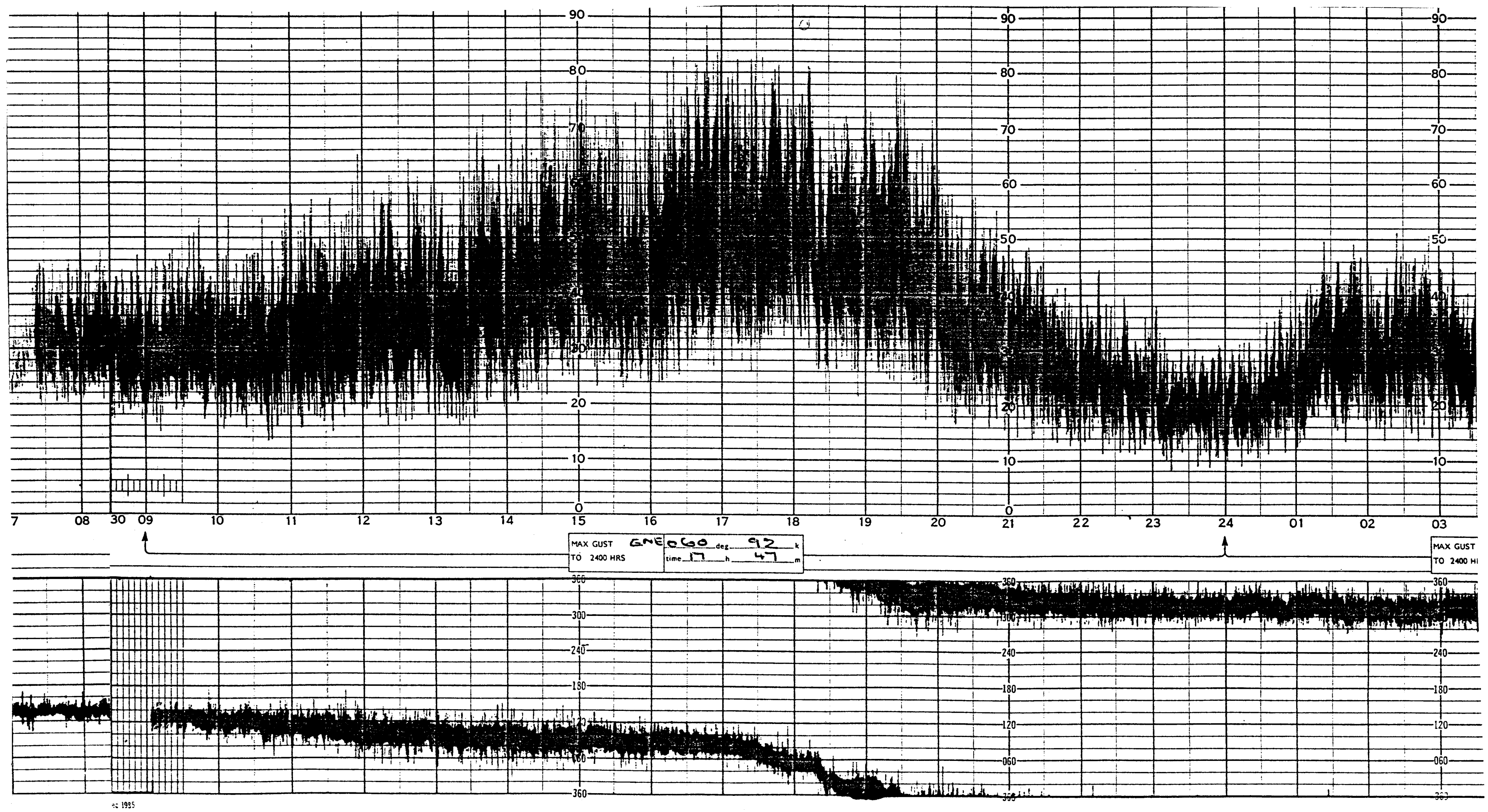

Figure 4. Port Hedland Dines Anemometer Trace

(i) One sign with a terrain category 1 approach to the north in the Port area showed that the maximum wind speed under those conditions was less than $57ms^{-1}$.

(ii) Another with terrain category 2 approach to the east in a similar location indicated an upper bound to the maximum wind speed of $52ms^{-1}$ at the height of the sign.

The equivalent wind speed in terrain category 2 at 10m had an upper bound of $58ms^{-1}$ from the east and $57ms^{-1}$ from the north.

In order to calculate a lower bound for the maximum wind speed in the Port area, caravans were examined. All vans in the park had been tied down, many over the top of the complete van. Chafing on the paintwork showed that some load had been moved by the wind. By assuming that the vans would have overturned if unrestrained, it was possible to calculate a lower bound on the maximum wind speed of $46ms^{-1}$.

The upper and lower bounds established for the maximum wind speed are not inconsistent with the $45ms^{-1}$ recorded at the Port Hedland airport. The study could not show a significant difference in effective wind speed at 10m height in terrain category 2 between the two population centres.

2.2.4 Comparison with Saffir-Simpson Scale

The international Saffir-Simpson Scale, reproduced as Table 2, has five classification points. With respect to wind velocity, cyclone Connie's effect on Port Hedland was classified as an intensity 2 event. With respect to central pressure it was classified as an intensity 3 event, and as the Port Authority facilities were unmanned, no record of tidal fluctuations was available at the time of publication. Its intensity with respect to storm surge is as yet unknown.

Records show that an event such as tropical cyclone Connie has a return period in the Port Hedland area of between 5 to 8 years.

TABLE 2

INTENSITY SCALE OF TROPICAL CYCLONES

Magnitude	Saffir Simpson Scale	Central Pressure (mb)	Maximum Wind Gust (knots)	m/s	Maximum Storm Surge (m)
Mild	1	>990	40-60	20-30	0-1
Moderate	2	970-985	70-90	35-45	1.5-2.5
Severe	3	950-965	100-120	50-60	3-4
Very Severe	4	930-945	130-150	65-75	4.5-5.5
Catastrophic	5	<925	160-180	80-90	6-7

3.0 EFFECT OF CYCLONE CONNIE ON BUILDINGS

The damage to buildings caused by cyclone Connie was not severe. However, the peak gust wind speed recorded at Port Hedland Airport of $45ms^{-1}$ would indicate that the maximum loads applied to structures at that location were approximately 50% of the current design wind load. The maximum wind speed estimated by ground truthing in the Port Hedland town centre indicated that the applied load may have been as high as 60% of the current design load at that location.

The reported damage, even though light, was in excess of the levels commensurate with an applied load of 50 to 60% of the current design wind load. The performance of some of the thirty two buildings that were inspected will be outlined in the remainder of this section.

3.1 Buildings at Hedland Senior High School

Conspicuous flashing damage to the main classroom block in this complex and loss of some louvres in the gymnasium/hall building meant that this group of buildings was included high in the media lists of damage. However, some other buildings on the site were studied in which no damage was observed in spite of dubious structural provisions to resist wind loads at the time. Figure 5 shows a site plan of the buildings in the Hedland Senior High School.

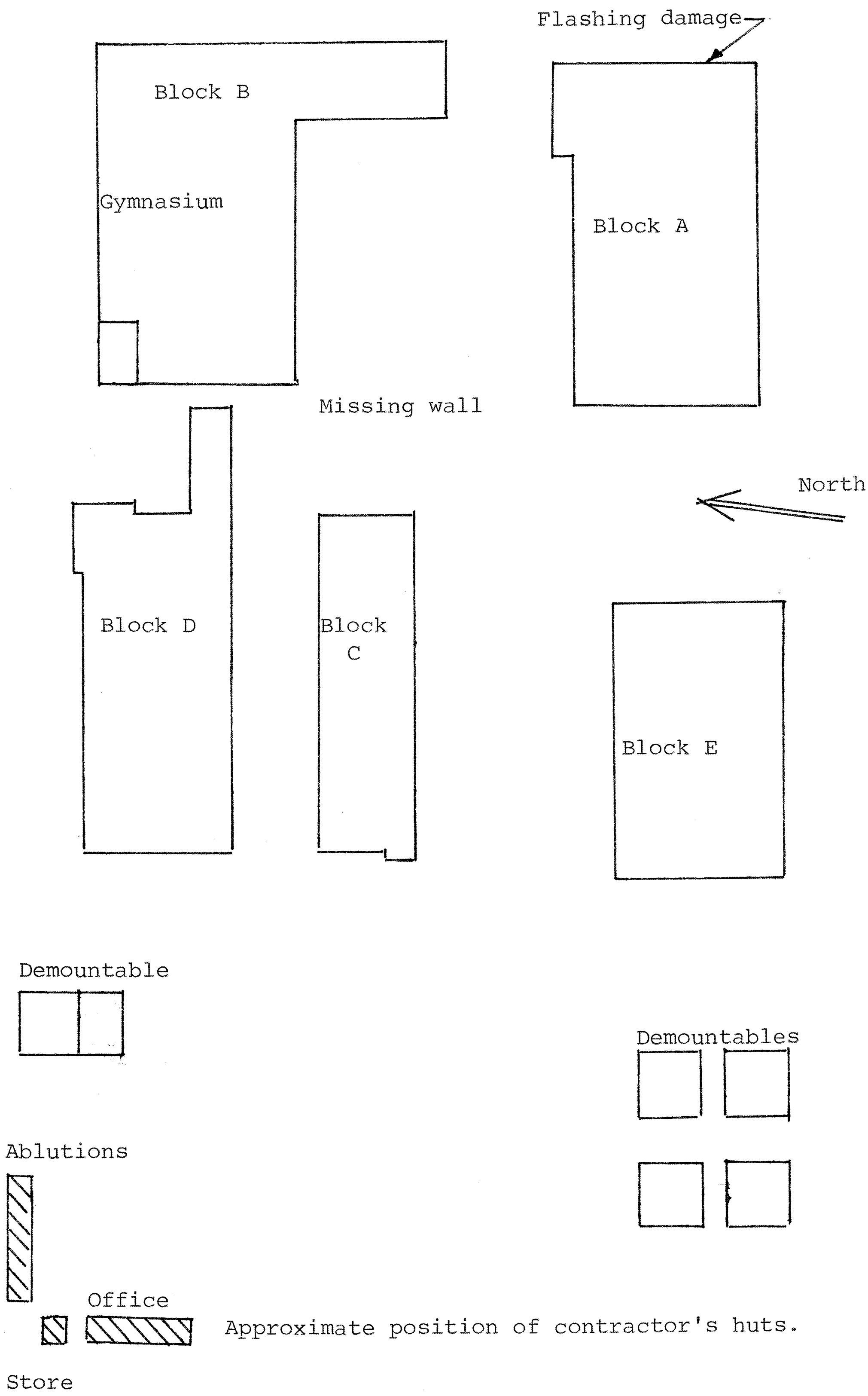

Figure 5. Hedland Senior High School - Site Plan

The school is located in South Hedland and wind speeds at that location were probably similar to those recorded at the nearby airport.

Examination of records of cyclone damage caused by past cyclones in the Port Hedland area (Bureau of Meteorology, 1987) has shown that roofing damage was caused to the Hedland Senior High School during cyclone Kerry in 1973 (with a maximum wind speed recorded at the airport of $36ms^{-1}$), cyclone Trixie in 1975 ($35ms^{-1}$) and cyclone Joan in 1975 ($58ms^{-1}$). Specific details of the nature or the location of the damage were not available, but some repair work to damaged roofing over the manual arts wing was noted in an inspection of the roof.

3.1.1 Flashing Damage to Main Classroom Block

The roof flashing on the eastern side of this block had been removed for a distance of approximately 12 metres. A portion of the damaged flashing is shown in the photograph in Figure 6.

Figure 6. Photograph of Flashing Damage Hedland Senior High School

The flashing at that location was a two part aluminium sheet fixture secured by self tapping screws into timber products under the sheeting as shown in Figure 7. The lower piece was fixed over the top of the fascia panel and served as cladding for the eaves overhang. A second piece of aluminium flashing was screwed to the lower piece, passed over the roof sheeting and was fastened to it along the two ribs closest to the edge of the aluminium roofing as shown in Figure 7.

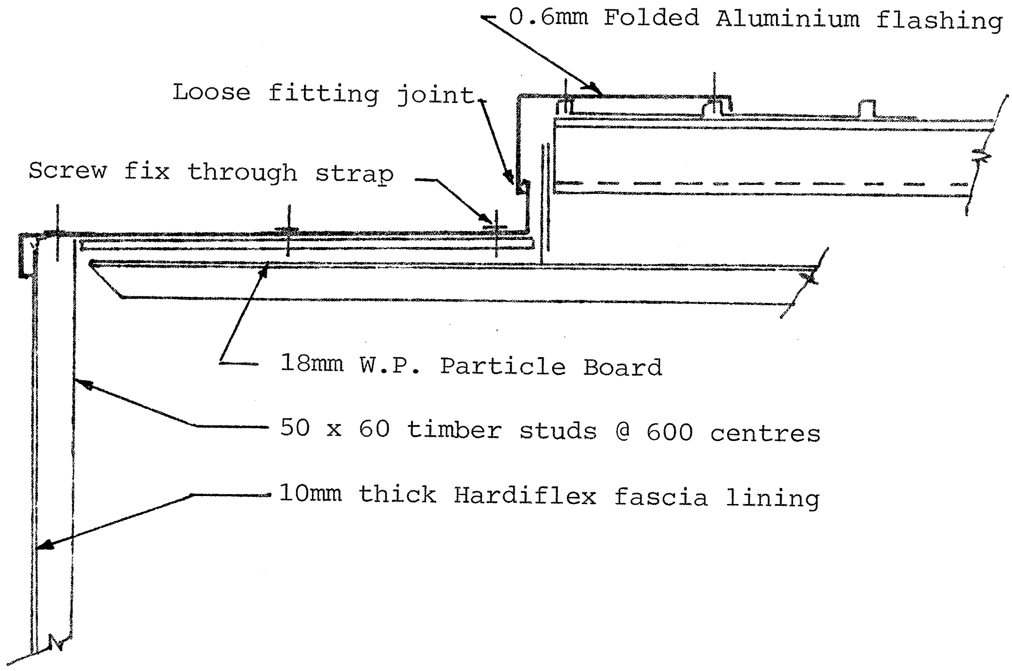

Figure 7. Detail of the flashing and attachment as designed

The detail shown in Figure 7 was taken from the design drawings, but a few minor differences between the detail as installed and that shown on the drawings may have contributed to the failure of the flashing.

(i) The connection to the fascia stud as shown in the drawings, passed into the end grain of the stud. On the installed flashing the fastener into the fascia stud was placed through the edge of the flashing, between the fascia adjacent panels and into the side of the stud.

(ii) Three fasteners were used on the top of the lower part of the flashing, but the one closest to the edge of the roof had been displaced inwards so that all of the screws were anchored in the particle board.

(iii) A screw between the top portion of flashing, and the lower portion at the overlap, ensured that the two parts were effectively joined.

A sketch showing the 'as constructed' flashing is shown in Figure 8.

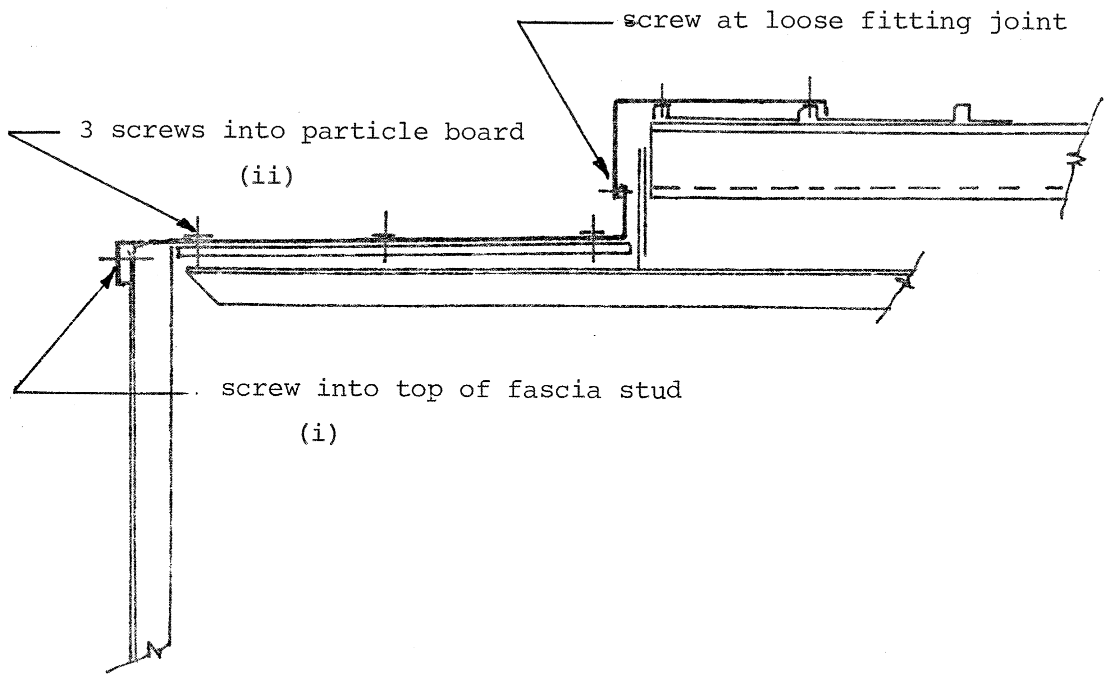

Figure 8 Sketch of flashing and attachment as constructed

The postulated failure mechanism for the flashing was as follows:

The screws at the eastern edge of the flashing (shown as (i) in Figure 8) in some instances had split the timber in the fascia stud as they

were installed within 25mm of the top of the stud. These screws had pulled out of the stud without tearing the aluminium of the flashing. Some of the screws may have been worked out in previous cyclones, as there were other places where the screws were missing although the flashing had remained in place in spite of their loss.
Calculation of the wind load applied to each fastener by the peak gust recorded in cyclone Connie, shows that approximately 50 N had to be resisted in shear. AS1720 (1975) indicated that fixed with appropriate end distances, the screws should have had a permissible working load of nearly twenty times that load. Clearly, the deterioration in the timber associated with the splitting due to low end distances has resulted in a very significant reduction in the strength of the connection.

Once the wind had lifted the front of the flashing, the screws pulled out of the particle board (shown as (ii) in Figure 8). The particle board had deteriorated due to water damage in the past, and in many places had disintegrated leaving holes as shown in the photograph in Figure 9.

Having lifted the entire lower portion of the flashing, the large loose flapping piece of flashing caused rapid failure of the top flashing. The screws on the joint between the two pieces ensured that the freed lower portion of flashing remained attached to the upper portion, and could assist in its removal.

At the corner of the roof, the flashing had remained attached to the aluminium roof sheeting and had caused it to lift, breaking a number of secret fixings. The lifting of the roof sheeting may have also been assisted by positive pressure on the underside of the roofing. The internal pressure was due to the opening created by the removal of the flashing.

Had the wind speed been significantly greater, the damage to the roof itself would probably have spread from one corner to a significant proportion of the roof. Under those circumstances the cause of the failure may not have been attributed to the flashing loss, and more particularly to the withdrawal of the screws in the edge of the flashing into the fascia studs.

Figure 9. Deterioration of Particle board under the Flashing

The damage indicated above, occurred during the early part of the passage of the cyclone when the wind was blowing mainly from the east. An 8 metre section of similar flashing on a different roof was removed during the second portion of the cyclone when the wind was blowing from the north-west. For this flashing the failure mechanism was similar, but the flashing was screwed to plywood rather than to particle board. The screws had also withdrawn from the plywood.

The following recommendations were made that in replacing the damaged flashings:

(i) Waterproof plywood be used under the flashing in lieu of the particle board, and

(ii) a longer lip over the fascia be used to enable the fixing screw to have a larger end distance. (At least 100mm is required by AS1720-1975).

The sketch in Figure 10 illustrates the recommendations.

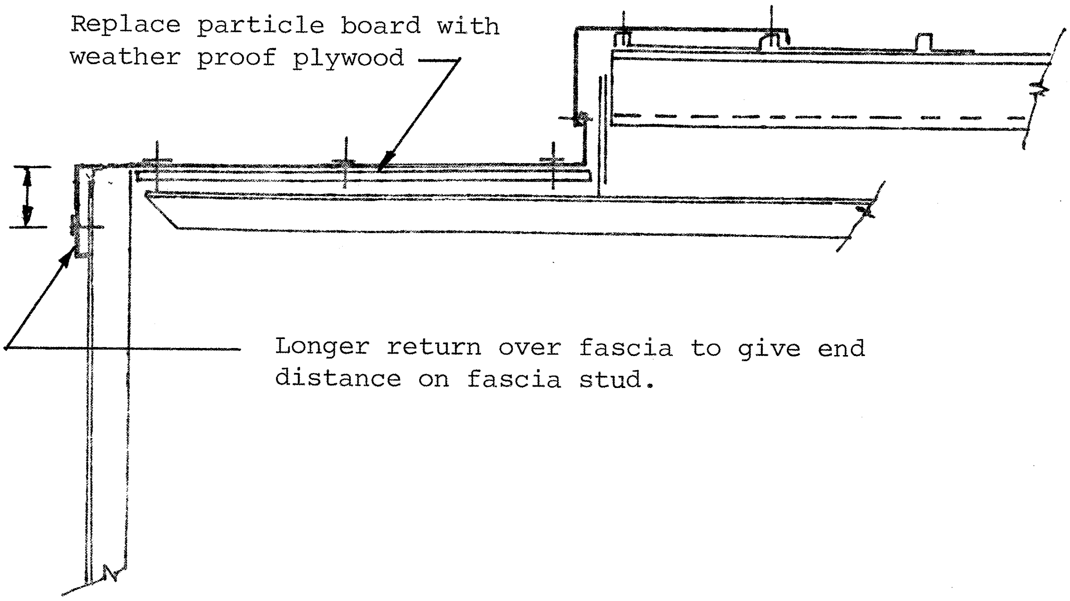

Figure 10. Recommended Reconstruction Of Flashing

3.1.2 Louvre Damage to Gymnasium

Prior to the occurrence of tropical cyclone Connie, redevelopment work on the gymnasium had been commenced. Part of this redevelopment including the replacement of all high level louvres in the gymnasium with fixed glass windows and the installation of an airconditioning system. As a result of the impending removal of the louvres, cracked louvres had not been replaced.

The number of broken louvres was less than the number of louvres that remained. It was postulated that the cracked louvres broke other blades in the same panel after failure.

The calculated maximum pressure that the louvres in the gymnasium would have sustained was 0.65kPa. This was based on an assumed internal pressure coefficient of -0.4 and an external pressure coefficient of

0.8. The assumption of an internal pressure coefficient of -0.4 was conservative and based on the large number of 'leaky' louvres on the leeward wall. Undamaged louvres should have been capable of carrying pressures well in excess of that value. However the failure of cracked louvres was quite consistent with such a load.

3.1.3 Stability of Roof on a Room with One Wall Removed

During the course of the alterations currently in progress on the school, a complete westward facing wall was removed from a room adjoining the north-western quarter. This room would have been subjected to full internal pressure.

The roof of the room was inspected and found to be free of any damage. Under the loadings experienced in cyclone Connie, the combination of full internal pressure and uplift on the exterior surface was similar to the effect of uplift on the exterior surface alone, under design wind loadings.

In an adjoining change room, a roof light had been removed by the wind. The roof light was one of five identical ones in the complex, and the others remained quite intact. The room under the roof light was separated from the room with the missing wall by a brick wall and a closed door. It is postulated that sufficient leakage around the door was possible to increase the internal pressure in the change room as well. Under the combined action of internal pressure and external suction, the roof light was broken and subsequently carried away by the wind.

The position of the roof light debris was consistent with the postulation that its failure occurred when the wind was blowing predominantly from the north or north-west.

3.1.4 Stability of Temporary Builders Huts

Associated with the alterations to a number of buildings in the Hedland Senior High School Complex, some temporary builders' huts had been erected to the west of the main school buildings as shown in Figure 5.

These temporary buildings, shown in Figure 11, consisted of an office and amenities wing, (shown to the left of the picture) a small storage shed, (with door open in the centre of the picture,) and an ablution wing (to the right of the picture). The easterly winds during the early part of the cyclone would have blown normal to the office wing and small tool store, but protection may have been afforded by the permanent school buildings. During the later part of the cyclone, the wind was normal to the ablution wing and passed over essentially open playing areas immediately up-wind of the building.

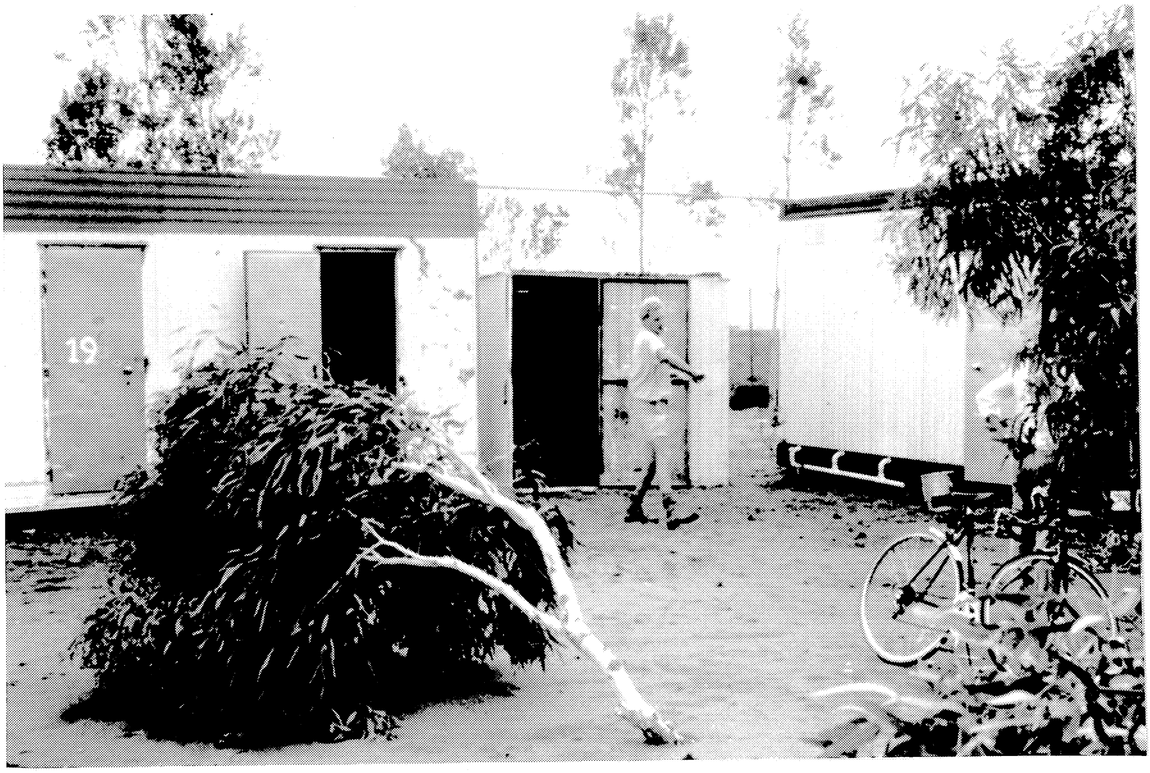

Figure 11. Temporary Builder's Huts - Hedland Senior High School

Under the conditions estimated to be prevailing during the maximum recorded gust, the ablution wing experienced an overturning moment of approximately 100 kNm using the coefficients presented in AS1170-II (1983). This overturning moment could have been resisted by weight forces alone if the total mass of the ablution block was in excess of 7.2 tonnes. Estimates of the mass of the block returned values marginally less than that. The theoretical calculations showed that overturning of the building should have been initiated.

No sign of damage to pipes leading into the ground behind the block was observed, so it is unlikely that any rotation of the building occurred. A number of reasons for the discrepancy between the calculated and the observed effects have been postulated.

(i) The estimate of the weight of the structure was in error.

(ii) The pressure coefficients given in AS1170-II(1983) over-estimate global loads on the structure.

(iii) Plumbing provided a connection to the ground which was strong enough in this instance to resist the balance of the overturning moment.

(iv) The peak gust experienced at the site was less than that recorded at the anemometer site.

Any of the above reasons or any combination of them make a plausible explanation of the behaviour of the ablution block. However, it is most unlikely that in a design event, the block would have escaped damage. The provision of tiedown to prevent overturning is recommended for caravans elsewhere within the town and should also have been employed on temporary sheds erected near permanent structures in the 'cyclone season'.

3.2 Ground Level Water Tanks at the Three Mile

The Water Authority of Western Australia has constructed three two million gallon ground level water tanks at the location called 'the Three Mile'. Roof damage was sustained by two of these tanks. The two damaged tanks were constructed six years apart, but used essentially similar designs. They were sited in an environment that had terrain category 2 approach terrain to the east and to the north-west. A site plan is shown in Figure 12.

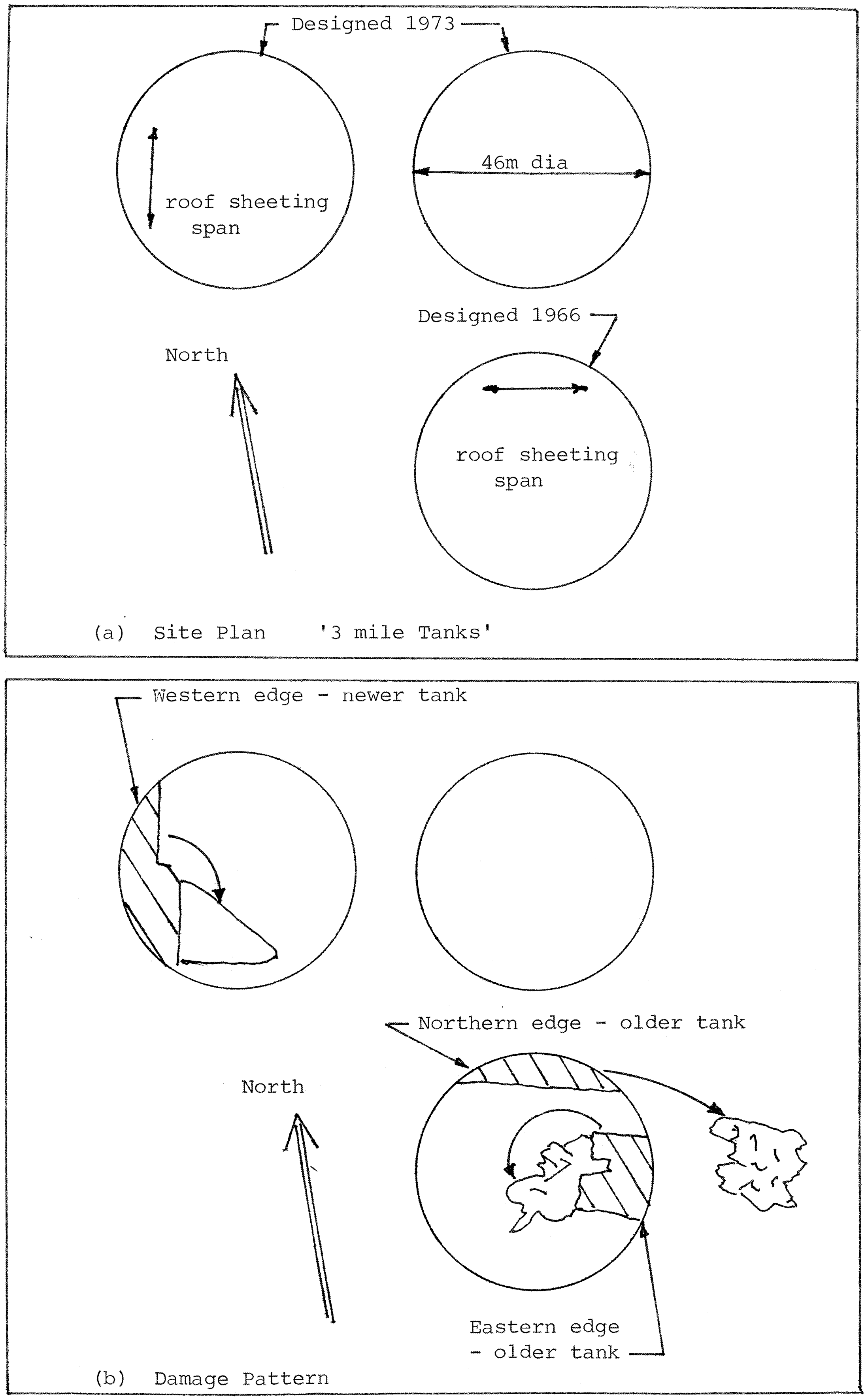

Figure 12. Site Plan and Damage Location
3 Mile water tanks.

3.2.1 Roof Fixing System

The roof sheeting was a steel profile that was normally secretly fixed using pan fixing slips and side fixing clips, but screws with large diamond shaped washers had also been utilised at every pan to fasten the sheeting to every batten.

The design drawings for the tanks called for all fixing clips and screws to be fastened to 100mm x 75mm jarrah nailing pieces. These timber nailing pieces, spaced at approximately 3.5m centres were bolted along the top of galvanised rolled steel joists (RSJ) as shown in the portion of the design drawing reproduced as Figure 13.

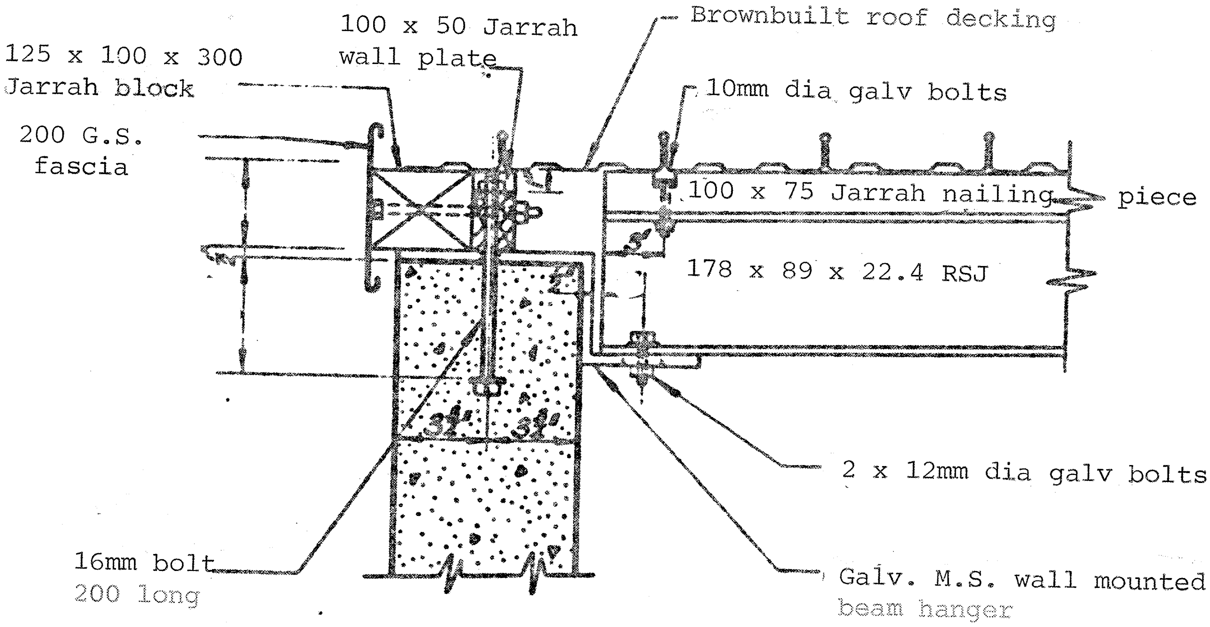

Figure 13. Detail of Roof Fixing - Tanks

Figure 13 shows that the bolts that fastened the timber batten along the top of the RSJ were recessed at the top to allow for flush fitting of the roof sheeting. Also the bolts were specified as galvanised.

The photograph in Figure 14 shows the roof sheeting, fixing clips, nailing piece and RSJ. No washers were observed under the head of the bolts in the timber.

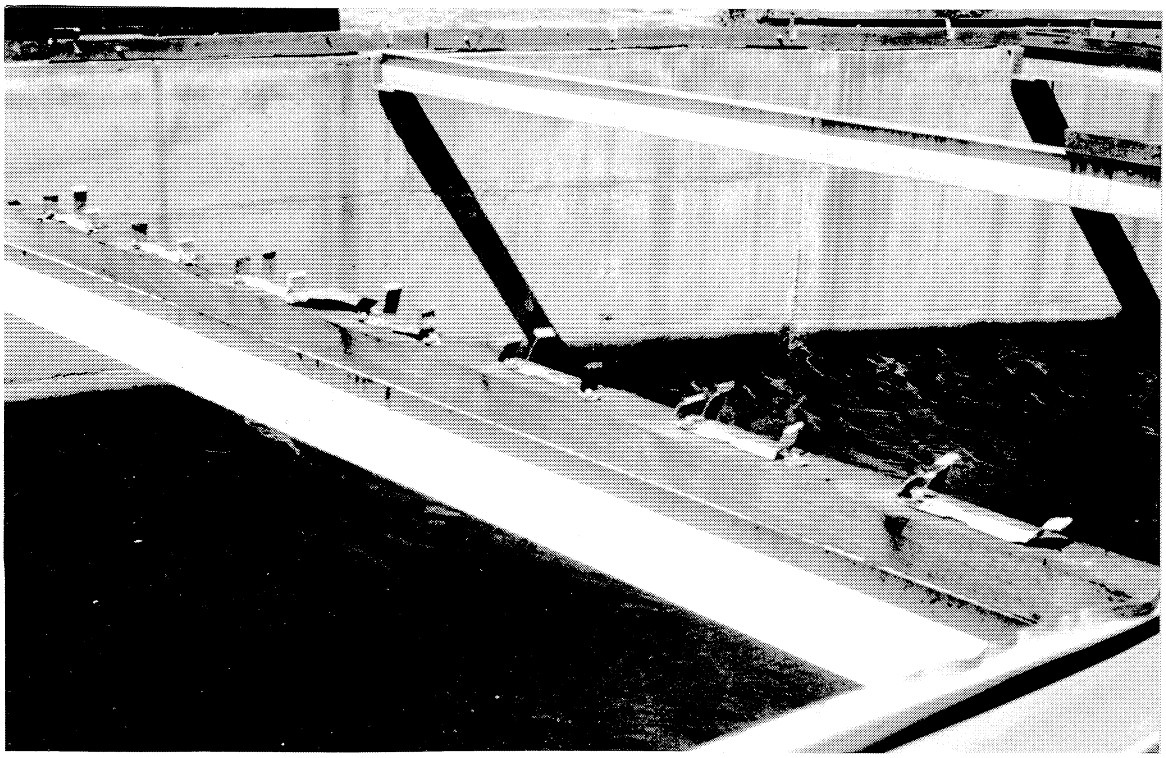

Figure 14. Photograph of Roof Fixing System - Tanks

The connection between the RSJ purlins and the concrete tank wall was accomplished differently on the two tanks. The newer tank showed no sign of distress at the connection, but on the older tank, failures of 3 such connections were observed.

On the older tank, a Z shaped steel bracket was bolted to the underside of the purlin and rested on top of the concrete wall as shown in Figure 13. A bolt cast into the concrete wall secured both the wall plate and the Z shaped bracket.

3.2.2 Damage to Roofing - Older Tank

Figure 12 includes a sketch showing the extent of the roof subjected to damage. The distribution of the debris from the two damaged areas indicated that the damage on the eastern edge of the tank was caused by winds primarily from the east, and that on the northern edge was caused by winds from the north-west.

Figure 15 shows the roofing from the eastern edge of the tank folded back onto the roof by easterly winds and subsequently pushed into an untidy heap by the later north-westerly winds.

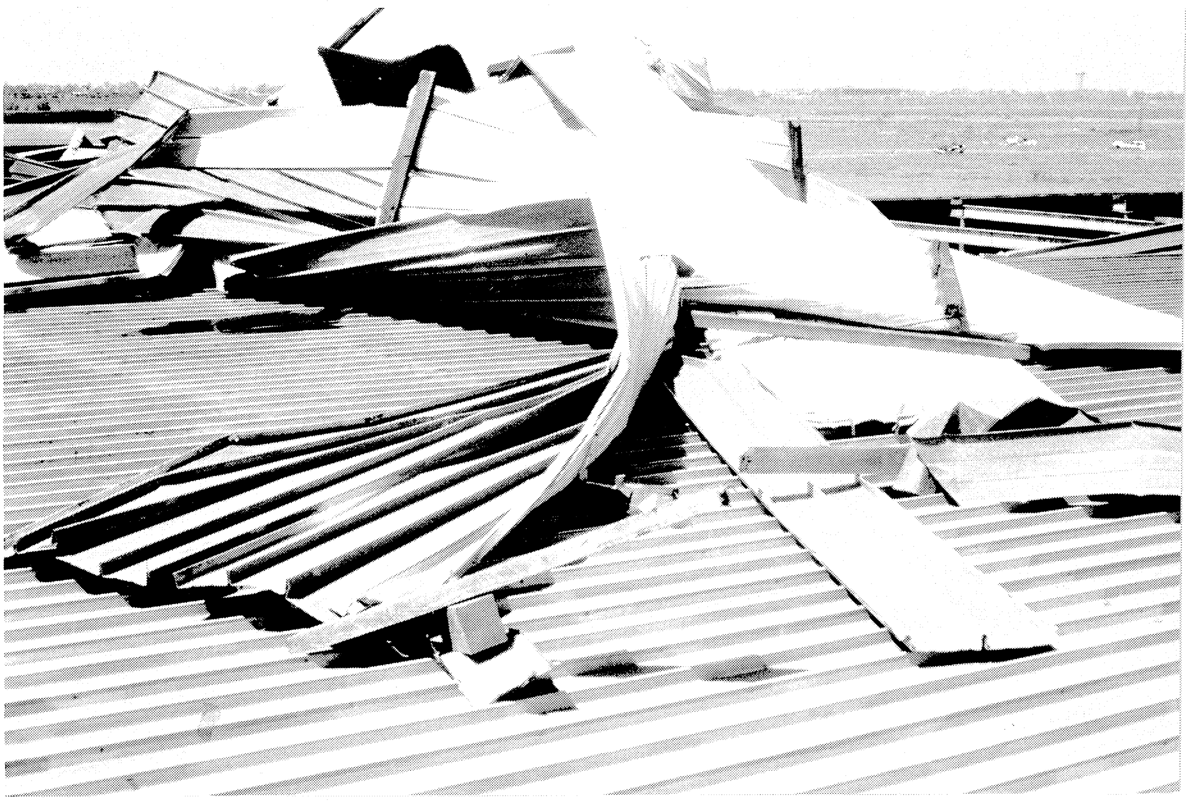

Figure 15. Roof Sheeting from eastern edge of older tank

It is postulated that the damage to the older tank was caused by two factors, the effects of which were impossible to separate.

(i) A nut on one bolt that secured the purlin Z shaped bracket to the top of the concrete wall may have been missing. The thread on the bolt was examined, and no sign of fresh damage due to the forced removal of the nut could be seen.

(ii) Many of the bolts securing the timber nailing piece to the RSJ purlin had corroded so that the metal area remaining was in many instances considerably less than half of the original area. As these bolts were the only ones in the roof structure showing signs of such severe corrosion, there is doubt as to whether the original fasteners were galvanised. The top of the galvanised purlin, which was also in intimate contact with the timber, was showing no signs of damage.

An examination of the loads on the nailing piece during the passage of cyclone Connie, showed that the bolts should have had sufficient strength to carry the load at only one eighth of the nominal shank area. It is possible that reductions in shank area to that value had, by corrosion, occurred in a few isolated cases and initiated the failure. Alternatively the combination of a reduction in shank area to 50% of nominal area on the edge nailing piece and the missing purlin connection nut would also have caused failure at the applied load.

Figure 16 shows the northern edge of the older tank. One bolt that had secured the timber nailing piece can be seen remaining in the closest steel purlin. In some cases where the bolts had sufficient strength, the nailing piece was dragged over the bolt head, leaving a hexagonal shaped hole in the timber. The use of a washer under the bolt head would have prevented such a failure. Two purlins were missing from this part of the tank (locations arrowed). The third purlin from the camera was removed by withdrawal of the holding down bolt from the concrete, and the fourth by fracturing the metal of the Z shaped bracket.

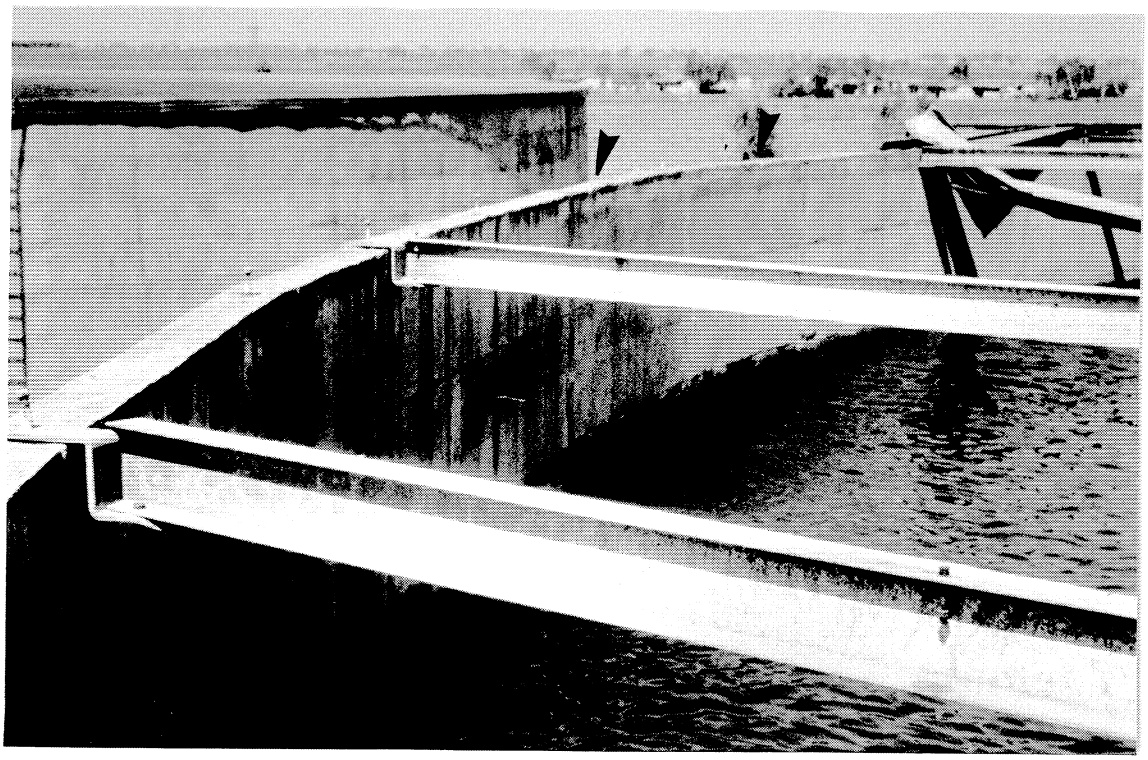

**Figure 16. Missing Sheeting and Purlins
– Northern Edge older tank**

For this portion of the roof, it is highly likely that both the withdrawal of the bolt from the concrete and the failure of the Z bracket were initiated in previous cyclone events.

Of the Z bracket failure surface, less than 10% showed fresh metal, with the remainder corroded. Such a failure surface could have been caused by fatigue due to load cycling some time in the past during the passage of a cyclone.

Likewise, the spalled concrete in the vicinity of the withdrawn bolt showed staining commensurate with damage caused five or more years previously. Water Authority records showed that damage to the roof sheeting and clips had occurred to this tank in previous cyclones. This may have released load from the damaged purlins prior to their complete failure in those events. However the direct fasteners in every pan, installed after cyclone Joan may have allowed sufficient load to be carried by the sheeting to cause failure of the purlin end connections in the next structural level of the tank.

Once the failure sequence had begun, tensile failures in the nailing piece bolts allowed the separation of the nailing pieces from the purlins with the resulting loss of a significant portion of roofing.

3.2.3 Damage to Roofing - Newer Tank

The failure of this 13 year old roof was initiated at the edges. The roofing over the edge nailing piece was observed to be very severely corroded. Figure 17 shows the advanced state of corrosion at the edge of this tank. This allowed the separation of the roof sheeting from the fixings at the edge. The extra load attracted by the next purlin following the release of the edge of the roof caused failure of the nailing piece bolts over the purlins. The bolts on this tank were observed to be corroded to a similar extent as those on the older tank.

Figure 17. Corrosion of Sheeting - Newer Tank

3.2.4 Comments on Failures

The three parts of roofing damage noted on these tanks all had corrosion as a major contributing factor. The corrosion of the nailing piece fasteners may have been due to the use of non-galvanised bolts and was certainly accelerated by the damp corrosive environment in the tank air space.

Bearing in mind the exceptionally corrosive atmosphere in the tank roof structure, the use of a bolting system that cannot be readily inspected for deterioration is not a good design detail.

Some failures may have been caused by damage to connections by previous cyclones. These fasteners were completely hidden by the roof sheeting and related timber work, and could not be readily inspected for deterioration.

The large purlin spacing employed in these tank roofs meant that upon failure of one or two structural connections, the surrounding ones were overloaded. This caused precipitation of large scale damage which will prove costly to repair.

There was no opportunity to inspect the same structural connections on the tank that remained intact due to their inaccessibility as mentioned above. No comments can be offered with respect to its good performance in the light of the poor performance of the others.

3.3 Houses Under Construction

The observed damage to housing was mainly confined to houses that had been under construction at the time of passage of the cyclone. The damage to three such houses will be discussed in this subsection.

3.3.1 Roof Damage

A house in South Hedland had the roof sheeting partially fixed prior to the high winds and it therefore sustained damage to a portion of the roof sheeting. Figure 18 shows the house after the damaged sheeting had been bent back and screwed into place as a temporary measure to keep rain water out of the ceiling space. The damaged roofing was in the centre and on the right hand side of the picture.

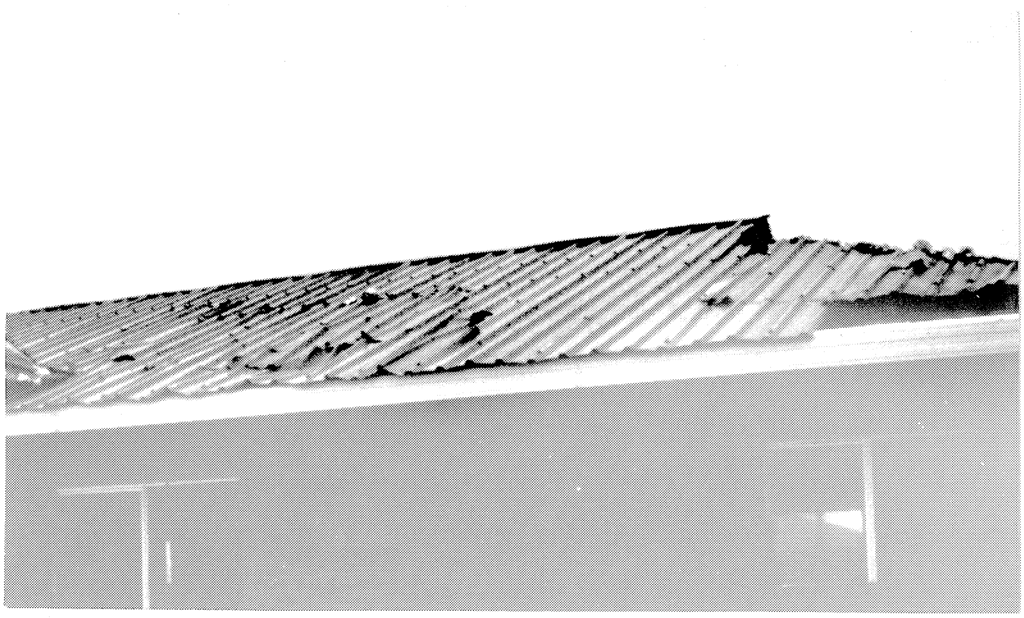

Figure 18. Damaged Roofing On A House Under Construction

The damaged part of the house had a terrain category 2 exposure to the easterly winds. The recommended fastening method for terrain category 2 is one fastener at every Trimdek crest with batten spacing at a maximum of 970 mm (Lysaght, 1986). The battens had been installed in accordance with those recommendations, but all the screws had not been installed. There was a large area on the eastern slope of the roof that appeared to have been fastened by one fastener every fourth crest.

Where the roofing had been secured in accordance with Lysaght's recommendations, near the ridge line, the damage that had occurred elsewhere in the roof had been arrested. This damage had significance in that it indicates an upper bound to the safety factor inherent in the Trimdek recommendations for tropical cyclone areas.

With the applied loads to the roof of 50% of design load and one quarter of the recommended fasteners installed in the roof, the unit load per fastener was twice that recommended at design load. As failure of the sheeting/fastener system had occurred, the upper bound on the factor of safety of the system was 2.0. Currently utilised test procedures for building products to be installed in tropical cyclone-prone areas of Australia allow nominal factors of safety as low as 1.6 for mutiple sample tests. (Experimental Building Station, 1978). The calculated upper bound for the factor of safety was not at odds with that implied in satisfying the test requirements.

3.3.2 Ridge Capping Damage

Ridge capping damage was observed on three houses that were under construction. In each case insufficient fasteners had been installed. Figure 19 shows typical damage of this type, where the roof sheeting had been installed in accordance with the manufacturer's recommendations but the ridge capping had been fastened with only six fasteners per length. The good performance of some of the ridge capping fixed in this very nominal fashion was surprising.

Figure 19. Ridge Capping Damage

3.3.3 Brickwork Damage

A double leaf brickwork house under construction in a terrain Category 1 environment suffered damage to brick walls in the north eastern corner of the house. The bricks were unsupported at the top of the wall and failed in bending at foundation level. The damage was caused by winds from the north, blowing directly off the ocean.

A large amount of reinforcement had been provided in the cavity, presumably to secure the roof to the remainder of the house. However, as it was not bonded to the masonry, it could not assist the brickwork to resist the wind loads by cantilever action. After the installation of the roof structure, the wall would have been supported at top and bottom and the maximum bending moment in the brickwork would have been reduced by a factor of four. An upper bound on the factor of safety of the completed wall, supported at the top, and allowing for internal suction in the house, was calculated as being 1.2.

This low factor of safety would indicate that additional structural provisions to carry loads away from the large window in that wall were warranted. Figure 20 shows the base of the damaged brick wall.

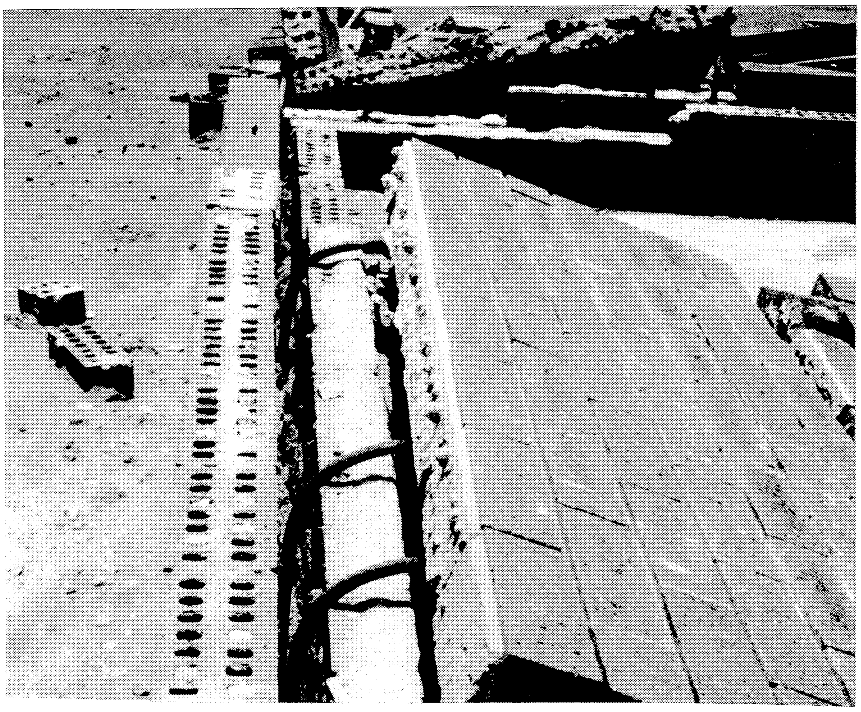

Figure 20. Damaged Brickwork On A House Under Construction

3.4 Aboriginal Housing At The 'Three Mile Camp'

The 'Three Mile Camp' was located within 1km of the tanks detailed in Section 3.2 and consists of a number of houses constructed with metal frames and light guage steel cladding. An example of the housing is illustrated in Figure 21.

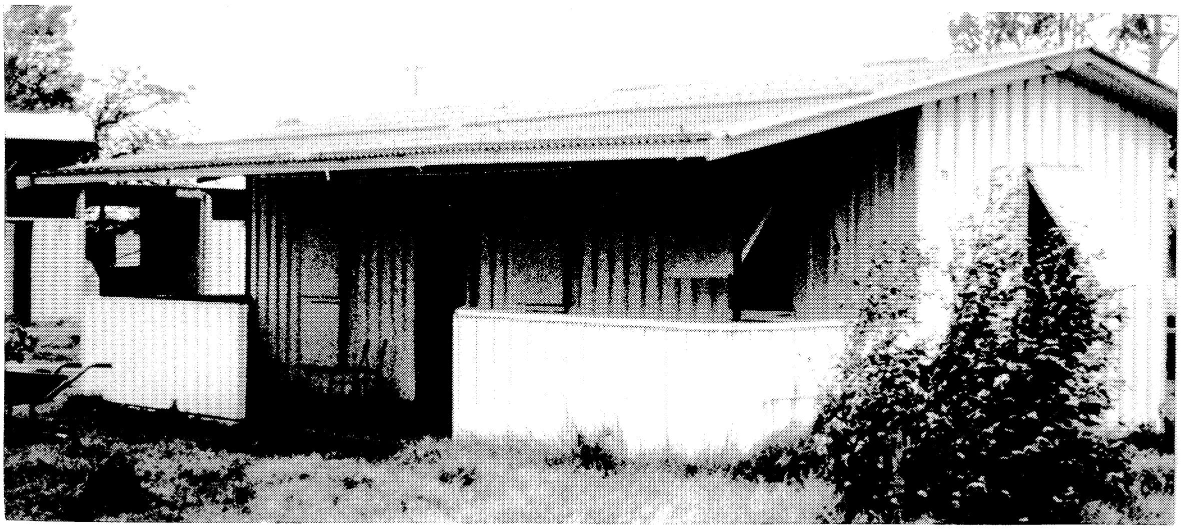

Figure 21. Housing At The 'Three Mile Camp'

The housing provides rudimentary shelter with minimal lining. The windows are fitted with storm shutters, two of which are shown open in Figure 21. The roof sheeting was fixed in accordance with current recommendations for cyclone areas and remained undamaged. An open verandah was provided on the north side of every house. The northern row of houses would have had terrain category 2 exposure to the open verandahs, and there was no sign of any damage to the cladding or structure.

The adequate structural performance of the houses under loads equivalent to approximately 50% of design wind loading contrast with the poor performance of steel framed Aboriginal housing at Borroloola (Boughton and Reardon, 1984) subjected to 10% greater load. In that case the verandah was cantilevered from the roof and many of the openings were not fitted with shutters.

However, while the structural performance of the Port Hedland housing was adequate under the loads applied during cyclone Connie, the storm shutters and doors admitted water which inundated belongings and bedding inside.

3.4.1 Occupant Constructed Additions

Two of the 'Three Mile Camp' houses incorporated occupant constructed additions which sustained damage during cyclone Connie.

In both cases the additions were built using re-cycled building materials and cladding was fastened at larger spacings than recommended for cyclone-prone areas.

3.5 Some Buildings In The Wedgefield Light Industrial Area

A number of industrial buildings in this location were inspected. However, two have been selected for special comment. The ones not detailed in this report were damaged principally because the construction of the building had not followed recommended practice for cyclone areas. In all cases except one, roofing was damaged, with the exception being the loss of some wall cladding on the leeward side of the building, due to inadequate fastening.

3.5.1. Wall Damage To A Toilet/Shower Block

This building, pictured in Figure 22, lost the privacy screen at the entrance to the door in the right-hand side of the building (arrowed). The position of the damaged screen, lying in front of the building, indicated that the damage occurred when the wind was blowing from the north-east. This quarter corresponded to the highest velocity winds recorded during the cyclone.

Figure 22. Toilet/Shower Block in Wedgefield Industrial Area

The cladding of the structure had demonstrated that it was capable of withstanding the maximum wind, and there was no sign of racking failure of the screen. However, examination of the timber frame of the building showed that there had been deterioration due to insect or termite attack. This had resulted in loss of strength of the timber frame. Tensile failure of the weakened wood had caused overturning of the privacy screen. Figure 23 shows a detail of the timber in the vicinity of the primary failure (arrowed).

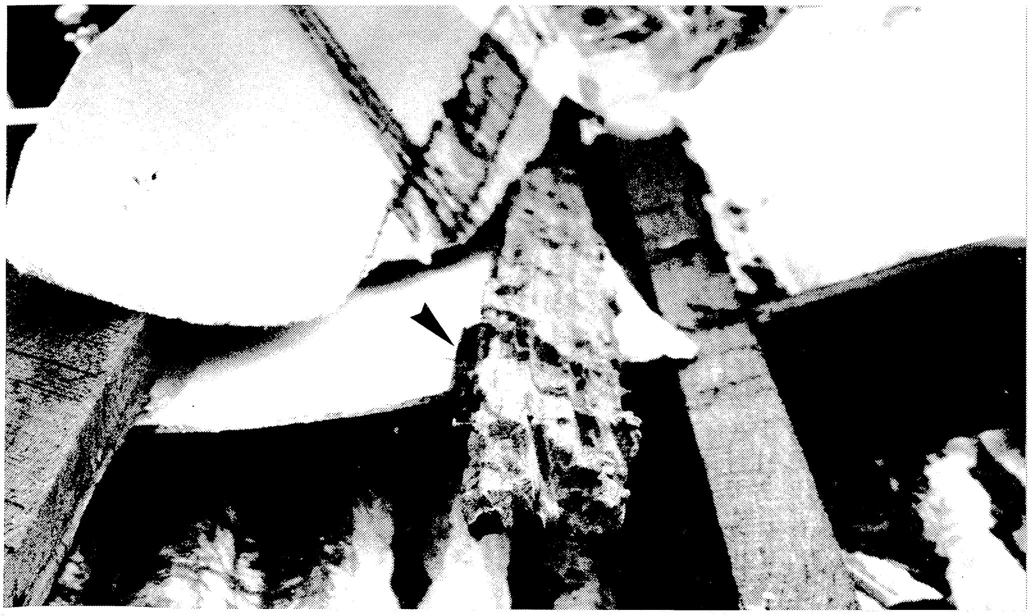

Figure 23. Termite Attack in Frame Timber

Other timber in the building also showed signs of deterioration, but the timber in the screen carried more than twice as much tension as any other frame member.

The tensile stress in the timber at failure was calculated to be 1.5 MPa, certainly much less than the expected failure stress in sound hardwood. The deterioration in timber quality had resulted in a drop in strength to less than one thirtieth of its expected value.

3.5.2 Damage To A Shed And Lean-To Structure

This structure, which prior to the passage of the cyclone had consisted of a small closed shed with an attached carport, was totally demolished and dismembered by the combination of debris attack and high winds.

It appears that the collapse of the shed occurred while the winds were predominantly from the east, and then northerly winds moved part of the roof structure some 40 metres from the rest of the shed. The roofing was a steel profiled deck fastened at every crest to timber battens. These had then been bolted to a steel frame in the carport and were nailed to other timber components of the shed frame. The walls of the shed were clad with fibre cement sheeting and incorporated timber braces on two of the four frames.

Figure 24 shows the remains of the shed lying on its side. The panel facing the camera was an unbraced wall which had been damaged by the Trimdek lying in the foreground. These unused sheets had been stacked nearby prior to the passage of the cyclone but had become airborne debris during the strong northerly winds. The loss of racking strength of that wall caused a lateral failure of the shed by combined racking and twisting, once the wind had started to shift from the east to the north. This had caused lateral bending of the unbraced carport legs.

Figure 24. Damaged Shed

The metal framed carport roof was subsequently detached from the rest of the shed which had remained fixed to its footings, and moved to its resting place against a transportable building, Figure 25. It had damaged a parked car en route.

While it is impossible to state with certainty that the shed and carport would have remained unscathed had the debris not perforated the cladding, certainly the airborne debris was instrumental in the damage to the shed, and by implication, may have contributed to the damage of the parked car and a transportable building.

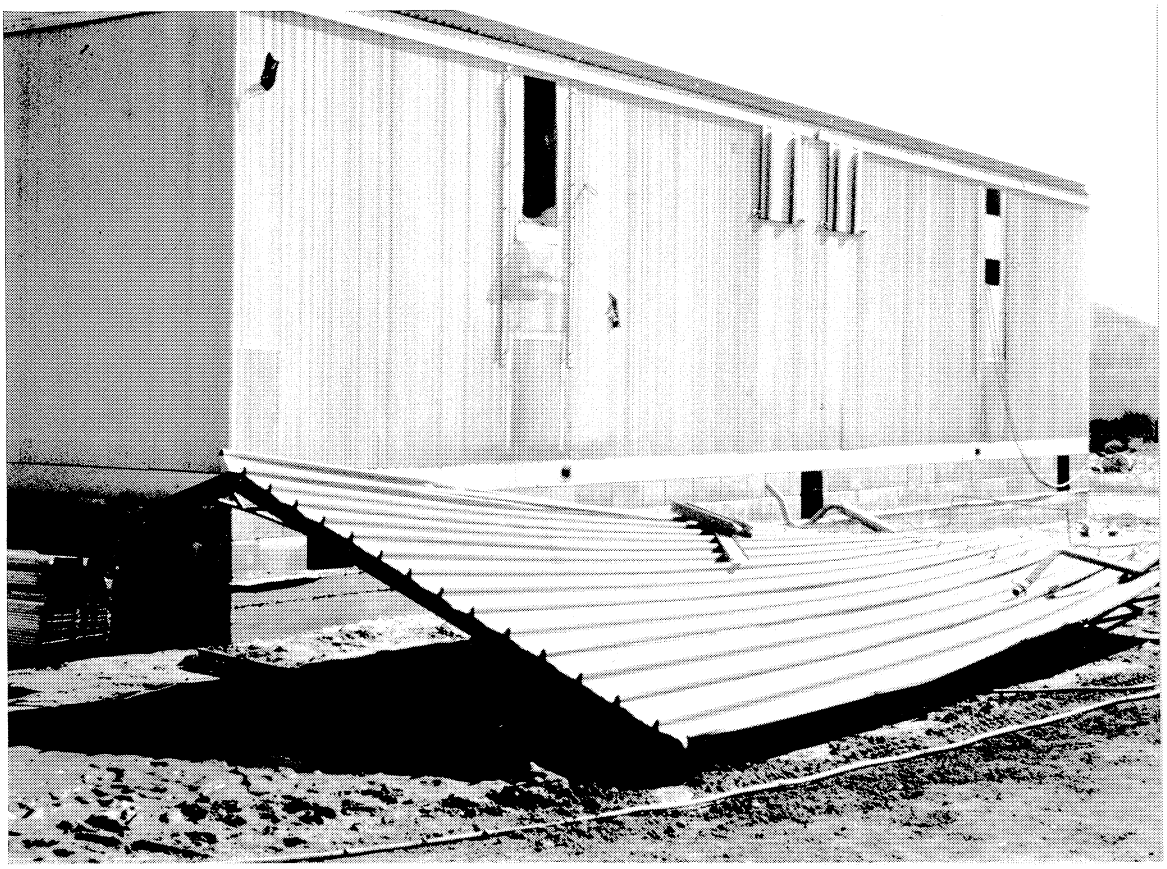

Figure 25. Detached Carport Roof

The damage incurred underlines the importance of ensuring that all materials that have potential to become airborne debris are stored in a manner that prevents them from damaging other structures.

3.6 Some Other Buildings In Port Hedland

This section contains description of the performance of three buildings within the town of Port Hedland that could not be included in the previous classifications.

3.6.1 Rest Room Block Near Port

This building was constructed with hollow concrete block walls and a flat secretly fixed roof. The building was unlined and had metal louvre windows protected by mesh shutters. The principal damage to the building was the removal of the roof sheeting as shown in Figure 26.

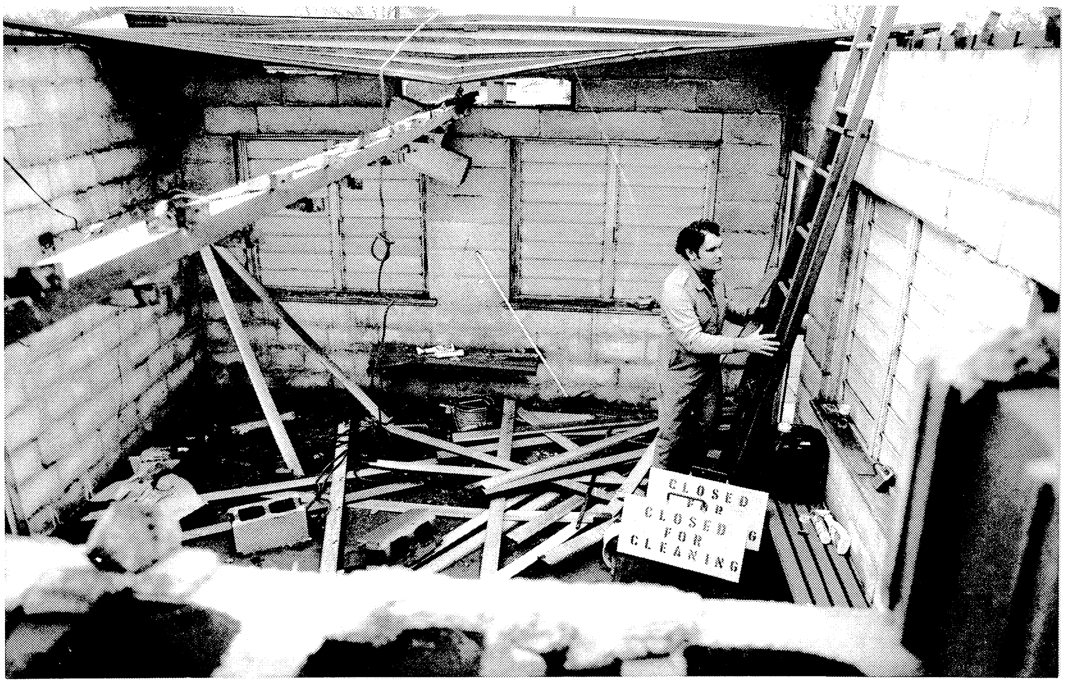

Figure 26. Damage To Roof Of Rest Room

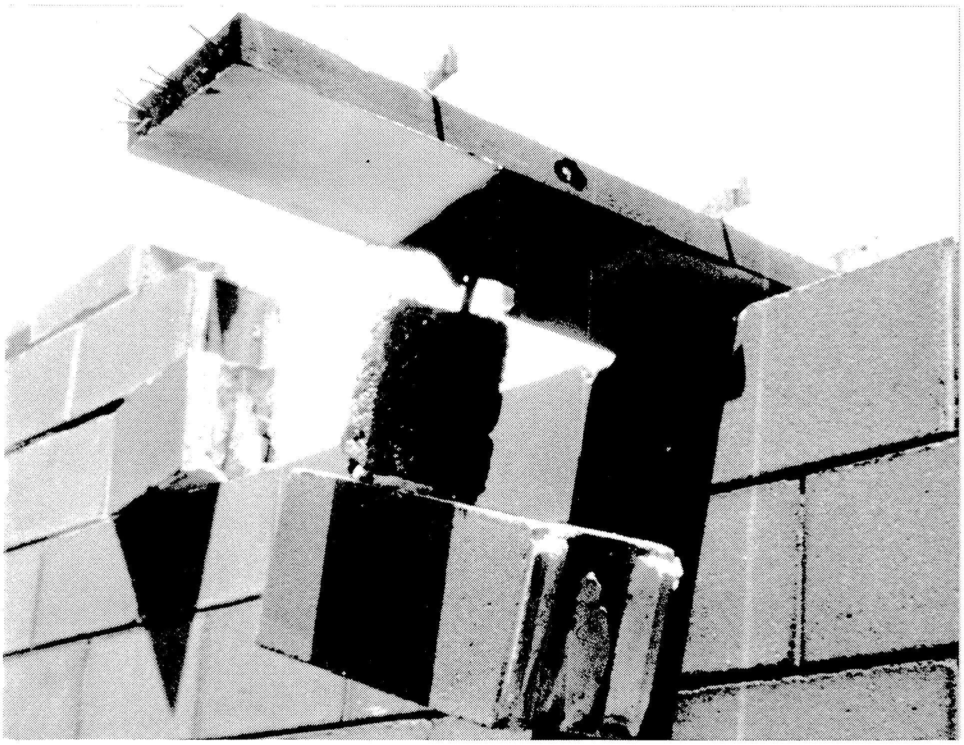

Figure 27. Inadequate Purlin Anchorage

A single purlin that had spanned the length of the building had also been detached from the wall. Figure 27 shows that the purlins had been connected to only two hollow blocks. No bond beam or evidence of reinforcement in the masonry walls could be seen. The two top rows of blocks had been removed from parts of the building during the course of the roof loss. Cracking was extensive at the corners of the building and above the windows.

The construction of the building, and in particular the restraint of the purlins, did not conform with recommendations in the Masonry Code of Practice (1984). At higher wind speeds the damage to the walls could have been much more substantial than that observed.

3.6.2 Roof Damage To An Old Store Building

A very old building, currently used as a storage area for the Boab Community Centre, lost a portion of its roof structure. The corrugated steel roof had been nailed securely to the purlins and appeared to have survived previous tropical cyclones with minimal damage. Two sheets of roofing may have been fitted within the last fifteen years, but most appeared to be more than twenty years old. However, some of the battens had separated from the remainder of the roof structure. Figure 28 shows the damaged building.

Calculations on the battens show that they had sufficient strength in themselves to carry design wind loads, and so should certainly have survived the winds in cyclone Connie. However, the bolts securing the battens to the end trusses did not have sufficient end distance. The end distance used for the 10mm bolts was approximately 20mm. On that basis, it is surprising that the loss of the roof had not occurred eleven years earlier in cyclone Joan. Examination of the battens showed that the timber in the vicinity of the end had deteriorated. This may explain why the building was able to withstand the higher loads of cyclone Joan but not those in cyclone Connie.

Alternatively, the wind load associated with previous cyclones may have caused damage to the timber which accumulated over the years and led to failure under the generally lower loads in cyclone Connie.

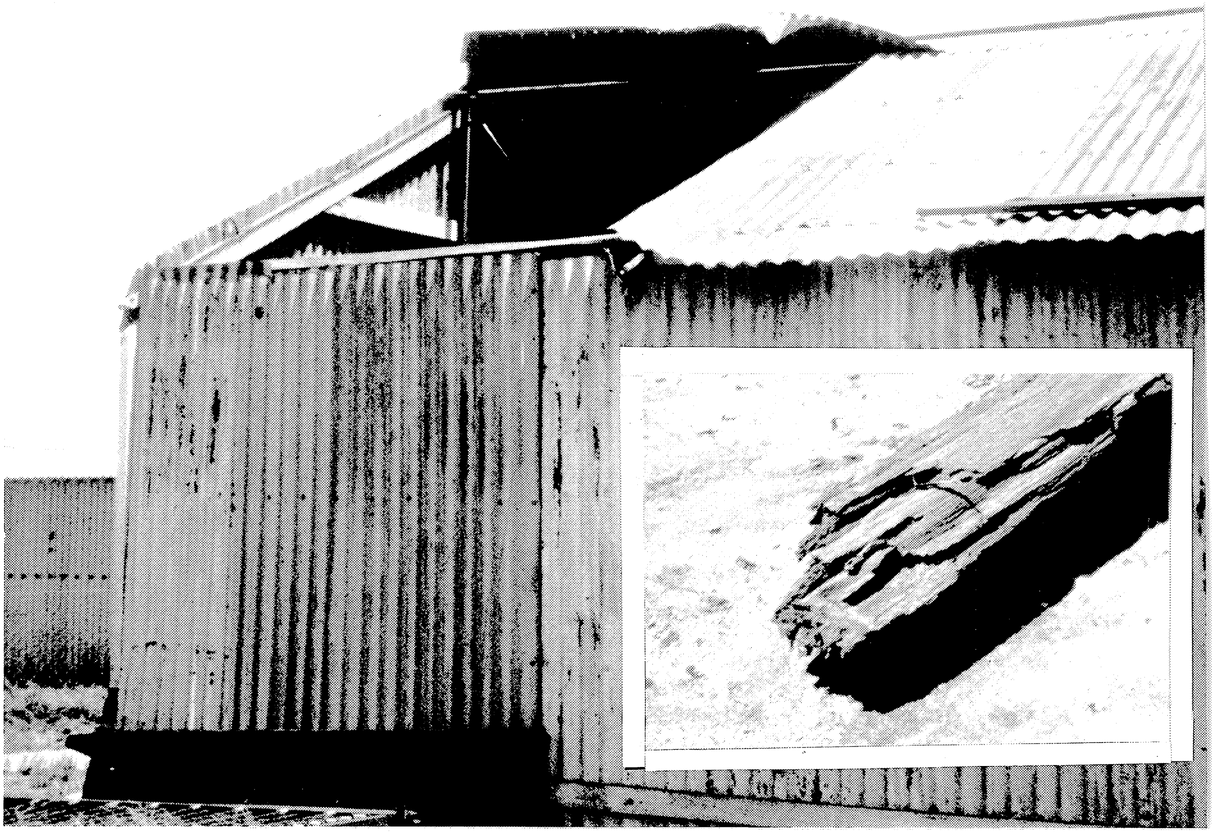

Figure 28. Roof Damage To An Old Timber Framed Shed
(Inset purlin deterioration at end)

3.6.3 A Child's Cubby House

This structure, made of a light gauge angle steel frame with pine packing case roof and walls, had a terrain category 1 exposure to winds from the north and north-west. It had been tied down by a loose 3mm galvanised wire over the top of the roof into a star picket on either side. It is illustrated in Figure 29, and apart from a slight racking deformation, is still quite serviceable!

The good structural performance no doubt reflected the very effective venting of the internal air space, but still offers much food for thought!

3.7 'Superficial' Damage

Much of the damage to buildings caused by cyclone Connie was classified as superficial, as the main structure was left intact. However, much of the superficial damage observed had some structural significance.

Figure 29. Child's Cubby House

3.7.1 Soffit Damage

Soffit damage was observed to the Community Services Hostel - "Moorganya" which faced the ocean. Soffit damage was also observed in a house under construction in South Hedland. In another house with a terrain category 1 exposure in the Pretty Pool subdivision, an eaves vent was blown in. In all of these cases, the damage would have allowed pressurisation of the roof space. They demonstrated the possibility that external suction on roof surfaces could be combined with internal pressure even in locations not usually regarded as being at risk of debris attack. All of the buildings mentioned had storm shutters fitted.

None of the roof structures showed signs of damage at the low loads applied. However, it was demonstrated that internal pressurisation of roof spaces was not necessarily linked to debris attack on walls and windows.

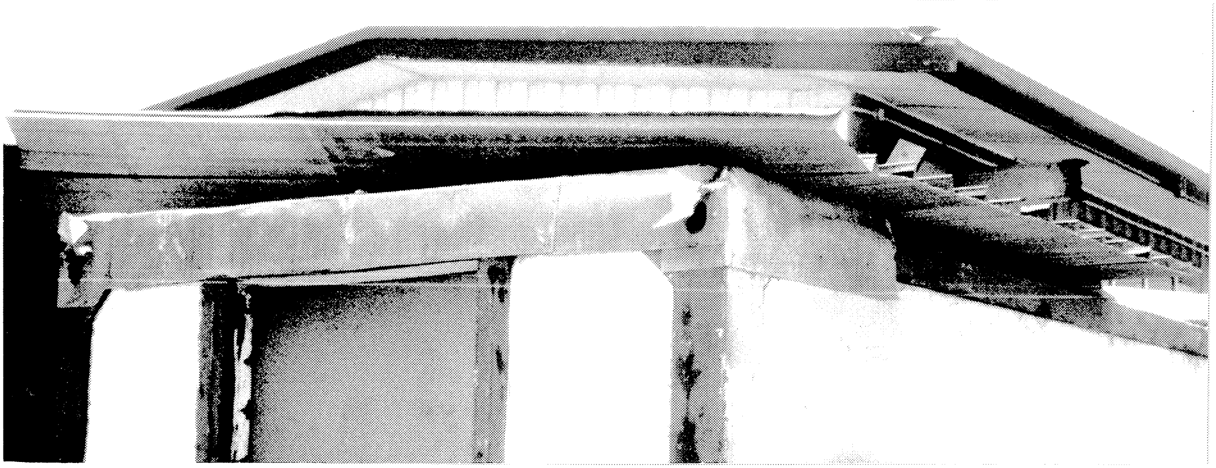

Figure 30. Small Temporary Building With Damaged Roof.

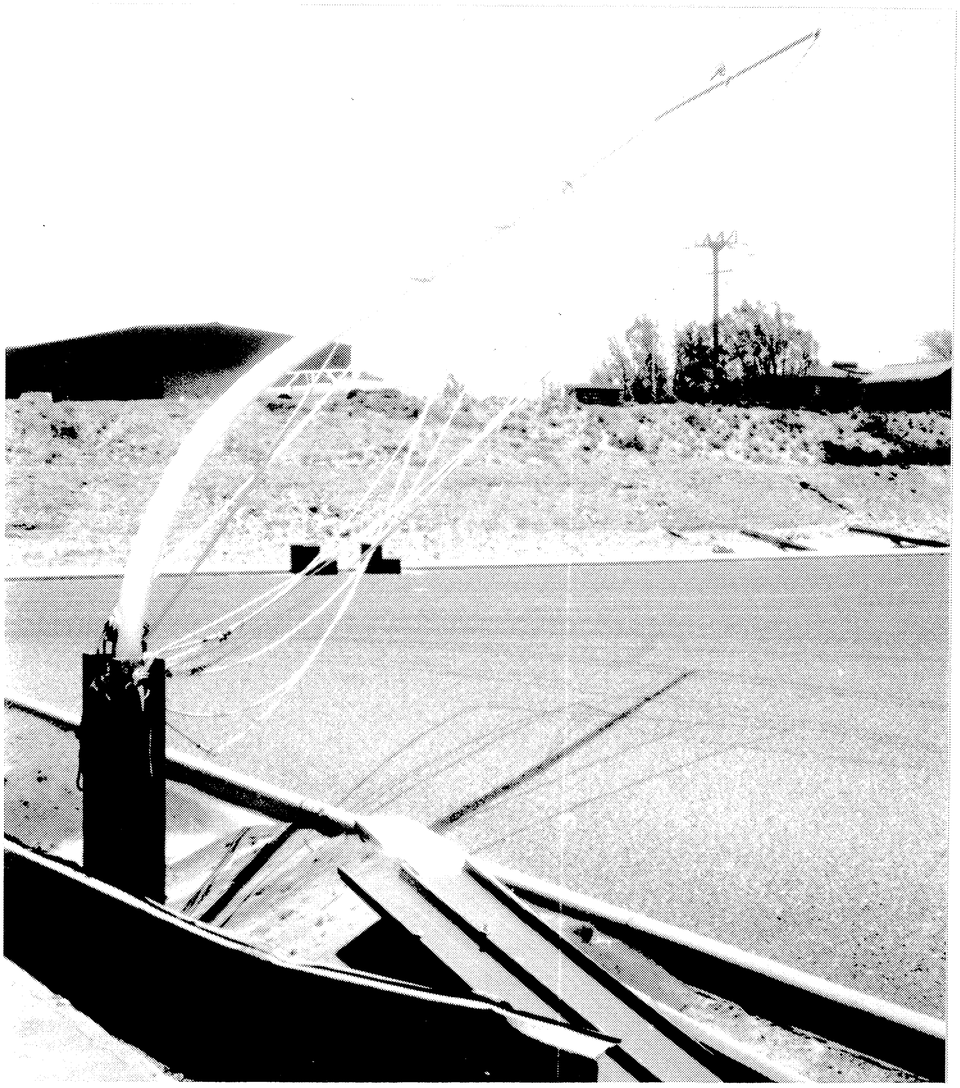

Figure 31. Damage To Permanent Mast By Dislodged Sheeting

3.7.2 Damage To A 'Temporary Structure'

A small transportable building with a second roof, no doubt provided to keep the building cooler, suffered some damage to its second roof. The building was located on the waterfront at the T.S. Pilbara berth, and had terrain category 1 exposure to the north and north-westerly winds. The damage to the building itself, pictured in Figure 30, was not significant and the building remained serviceable.

Some of the roof sheeting removed from the building was caught by a permanent mast nearby and caused some damage to the mast as illustrated in Figure 31. While the value of the mast was not very significant, the incident emphasises the point made in Section 3.1.4, that inadequate temporary structures can place nearby permanent structures at risk due to debris attack.

3.7.3 Damage to Shade Cloth

Reardon, Walker and Jancauskas (1986) discussed the performance of shade cloth structures and the generally high levels of damage they sustained in tropical cyclone 'Winifred' in north Queensland. Shades at the Pt Cooke Sporting Club were damaged by cyclone Connie as shown in Figure 32. Adjacent shades that were nominally identical sustained no damage which may indicate a sensitivity to age of material or tension of the fastening.

Figure 32. Damage to Shade Cloth

3.7.4 Environmental Damage

The most conspicuous damage in Port Hedland was that to trees. Some of the trees such as the one shown in Figure 33 had signs of timber rot, but others had fallen over due to root failure. Many of these trees that had fallen were irrigated by trickle systems even though they had achieved a reasonable size. It was postulated that in those circumstances the root system was poorly developed due to the provision of regular surface water. As such it did not have the structural strength to hold the tree upright in cyclonic conditions.

Such trees pose a particular threat where they are close to buildings.

Figure 33. Damage To Ageing Tree With Well Developed Rot

Damage to cars and buildings alike was also caused by sandblasting. This effect was most noticeable in areas with terrain category 1 exposure such as the Pretty Pool subdivision and the foreshore.

4.0 Implications Of The Performance Of Buildings

The wind loads applied to structures during the passage of cyclone Connie were approximately 50% of those for which modern buildings should be designed. Buildings should therefore have sustained no damage. As current design practice used working stress methods, expected failure loads should have been at least three times the loads applied to buildings by cyclone Connie.

4.1. Deterioration Of Components

Many of the failures observed in Port Hedland could be attributed directly to a reduction of strength by corrosion of metal, or deterioration of timber due to splitting, rot or insect attack. The implication is that maintenance of structural connections and details in buildings should be pursued with a similar thoroughness to that of the installation of those details.

In some cases, the damage observed may have been initiated in previous cyclones. Provided there is sufficient strength in structural elements to keep all parts within their safe working range, damage should not commence even in a design wind event. The provision of access to check critical structural details would enable preventative maintenance to be performed following the passage of severe tropical cyclones in which damage has been initiated.

4.2 Redundancy In Roof Structure

Nearly all of the damage observed to completed buildings was damage associated with structural elements in roofs. Generally, recommendations for the design of building components for tropical cyclones that have been implemented since 1975, have lowered stress levels in structural elements within roofs. However, the failures observed after cyclone Connie indicated that the roof system of many structures does not incorporate significant redundancy. Failure of one or two elements can precipitate failure of a large number of other elements by overloading. The performance of the roof on ground level tanks illustrated this point well. The flashing damage at the High School also led to commencement of failure of a larger portion of roof. For buildings in which it is desirable that progressive failure of the roof structure be halted in spite of the loss of some structural elements, it may be necessary to reduce stress levels further. This would allow the increase of loads due to the failure of adjacent elements to be accommodated without allowing the propagation of damage. This practice may be considered appropriate on buildings with a designated post-disaster function.

4.3 Roof Space Internal Pressure

The adequate performance of cyclone debris screens commonly used on windows in Port Hedland prevented significant glass damage during cyclone Connie However, the soffit and flashing damage that was observed on a number of buildings had allowed pressurisation of the roof space independently of window damage. The implication is that roof space positive internal pressure can be caused by failure of other elements which generally are not considered in the structural design of the building. Unless all claddings and fittings have been structurally designed to resist cyclonic winds, it may prove necessary to assume full internal pressurisation of the roof space in the design of the roofing irrespective of the presence of cyclone screens.

5.0 CONCLUSIONS

1. While the most obvious damage to buildings was superficial, some valuable information on the structural performance of buildings could be ascertained. Many of the failures described in this publication would have led to more significant damage at higher wind speeds which may have precluded the identification of the first element to have failed.

2. The estimated maximum wind speed of 45 ms-1 at 10m height in terrain category 2 subjected buildings to approximately 50% of the current design loads. These loads were less than those experienced in three other tropical cyclones in Port Hedland in the past twelve years.

3. Some failures observed were directly attributed to deterioration due to corrosion of metal fasteners. In particularly corrosive atmospheres, metal fasteners should be designed to facilitate regular inspection and if necessary replacement with minimal interference to the function of the structure. Alternatively oversized fasteners could be installed in inaccessible locations to allow for material loss due to corrosion.

4. Deterioration in concrete and timber was also observed. Some of this may have been due to accumulated damage from previous cyclonic events. The accumulative effects of cyclic loading on structural fasteners should be further investigated.

5. Deterioration of particle board used in a roof structure has highlighted problems in the use of structural elements of materials whose strength can be affected by humidity or moisture ingress in tropical cyclones. Further research on the effect of moisture on the structural properties of commonly used building material is justified.

6. Damage to roof systems highlighted the lack of redundancy within the roof structure. In essential buildings, redundancy may have to be incorporated by deliberately lowering allowable stress levels in all fasteners.

7. Positive internal pressures should be assumed for roof spaces unless all cladding elements are specifically designed to resist debris and wind loads.

8. Temporary structures which are expected to remain in place during the cyclone season should be adequately restrained if their demise may present a risk to nearby permanent structures.

9. The effectiveness of clean-up activities in the light industrial area was noticeably less than in other areas. This led to proportionately more airborne debris in that area and a higher level of superficial and structural damage. The higher incidence of makeshift and temporary structures in the industrial areas also contributed to the higher level of damage.

10. Tree damage to buildings could be reduced by ensuring that irrigiation water is only provided during the first one or two seasons after planting. This will allow the development of deeper penetrating root systems. Well developed root systems reduce the probability of trees breaking below ground level.

6.0 ACKNOWLEDGEMENTS

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