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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Engineering Aspects of Cyclone Tracy Darwin, Australia, 1974

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Engineering Aspects of Cyclone Tracy Darwin, Australia, 1974

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Issued June 1976

Library of Congress Cataloging in Publication Data

Marshall, Richard D.

Engineering aspects of Cyclone Tracy, Darwin, Australia, 1974.

(NBS building science series; 86)

Supt. of Docs. no.: C13.29/2:86

1. Wind-pressure. 2. Darwin, Australia--Storm, 1974. I. Title. II. Series: United States. National Bureau of Standards. Building science series; 86.

TA435.U58 no. 86 [TA654.5] 624'.176 76-19011

National Bureau of Standards Building Science Series 86

Nat. Bur. Stand. (U.S.), Bldg. Sci. Ser. 86, 39 pages (June 1976)

CODEN: BSSNBV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1976

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.29/2:86). Price $1.05 (Add 25 percent additional for other than U.S. mailing).

ABSTRACT

During the early morning hours of December 25, 1974, the city of Darwin was devastated by the most damaging cyclone ever to strike the Australian Continent. Winds of up to 75 m/s caused extensive damage to housing in particular, requiring the evacuation of approximately half of the 45,000 residents to other major cities in Australia. This report is a result of the author spending several days on temporary assignment with the Department of Housing and Construction-Australian Government to inspect the damage, and to participate in discussions regarding the establishment of new design criteria and construction practices for cyclone areas. The fact that most of the damage was caused by wind forces rather than a combination of wind and storm surge greatly simplified the assessment of damage and structural performance. The experience at Darwin points out the danger in depending too heavily upon past experience and intuition in the design of housing. It also makes clear the need for additional research into the behavior of certain building materials under repeated loads and missile impact, and the racking strength of walls subjected to uplift loads.

Key words: Buildings; cyclones; disasters; structural engineering; tides; wind.

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1.0 INTRODUCTION

Cyclone Tracy, which struck Darwin, N.T. in the early morning of December 25, 1974, was the most damaging cyclone ever to strike the Australian Continent. In the four to five hours required for the storm to pass over Darwin, approximately 50 lives were lost and damage in excess of $300,000,000 (US) was done to buildings and other structures. This report is an attempt to describe the more common types of buildings in Darwin and their performance under extreme wind conditions. Some residential areas suffered almost complete destruction while other areas of the city experienced only moderate damage. The wide variety of construction and the fact that most damage was due entirely to wind effects rather than a combination of wind and storm surge make possible some important and meaningful deductions and point up several areas that should be given closer attention in designing structures for wind-prone areas.

2.0 STORM SUMMARY

2.1 DEVELOPMENT AND LANDFALL

Cyclone Tracy originated as a tropical depression in the Arafura Sea near 8S-134E early on December 20, 1974. The storm system moved off in a southwesterly direction and was classified as a tropical cyclone during the evening hours of the 21st. On the morning of the 22nd, Tracy was located at 9S-131E, or approximately 200 km north of Darwin. It continued to move toward the southwest for the next two days, entering the Timor Sea and passing some 50 km west of Bathurst Island on the morning of December 24. Shortly thereafter Tracy made an abrupt change in direction and headed southeast, directly toward Darwin. At midnight Tracy was located just off Point Charles or 30 km WNW of Darwin, moving to the ESE at approximately 8 km/hr (see Fig. 1). Landfall (passage of the leading eye wall) is believed to have occurred somewhere between East Point and Nightcliff shortly after 0300 hours on the 25th, the eye passing directly over the Royal Australian Air Force (RAAF) Base and Darwin International Airport (see Fig. 2). Extreme winds persisted over the greater Darwin area until approximately 0600 hours. Tracy continued on a southeasterly course, dissipating over Arnhem Land during the remainder of the 25th.

2.2 WIND SPEEDS

The only detailed wind speed record obtained during the passage of Tracy was that of the Bureau of Meteorology at the airport. The Dines anemometer was mounted on a 10-meter mast and the recorded gusts correspond to an averaging period of from 2 to 3 seconds. Gusts of 12 m/s were recorded over the period 1300 to 1930 hours on the 24th with a steady increase up to 24 m/s at midnight. Gusts of 40 m/s were being recorded at 0200 hours on the 25th and the peak recorded gust of approximately 57 m/s occurred just after 0300 hours. At this point, the anemometer was struck by flying debris and no further wind speed measurements were obtained.

Estimates of maximum wind speeds (3-second gust at 10 meters) in Cyclone Tracy range from 60 to 75 m/s. Based upon peak departures from the mean just prior to failure of the airport anemometer and the observed passage of the eye wall shortly thereafter, a maximum speed of 70 m/s seems reasonable. Several observers are of the opinion that wind speeds on the rear edge of the eye exceeded those on the leading edge. There is no way to confirm this, but many structures apparently suffered the heaviest damage just after passage of the eye. The average speed of passage is believed to have been 6 to 8 km/hr. Winds in excess of 50 m/s extended outward 10 to 12 km from the center.

2.3 BAROMETRIC PRESSURE

The barograph record obtained by the Bureau of Meteorology dropped below 990 mb at 0030 hours, reached a minimum of 940-950 mb at 0400 hours and recrossed 990 mb at approximately 0730 hours. This record was obtained at the city office which is located just to the south of the estimated eye path. The diameter of the eye is believed to have been about 10 km, based on radar pictures obtained at 0400 hours while Tracy was passing over Darwin. The diameter of the calm area would have been slightly less than this since the radar image represents the location of the rain bands.

2.4 STORM SURGE

The maximum surge level (departure from predicted tide) recorded at Darwin Harbor was 1.6 meters at 0215 hours on December 25 [1][1]. The maximum predicted tide of 5.3 meters occurred at 0116 hours [2]. Since the astronomical tidal range at Darwin is approximately 8 meters, the storm surge caused very little structural damage. The eye of Cyclone Tracy passed to the north of Darwin Harbor, thus creating higher surge levels at the northern beaches due to the clockwise circulation. It is estimated that a maximum water level of 9 meters (8 meters above town datum) occurred at Casuarina Beach [1]. This level includes wave effects and is approximately 4 meters above predicted high tide. Had Cyclone Tracy coincided with the highest astronomical tide, some of the lower sections of Darwin would have been flooded to a depth of approximately 3 meters.

2.5 COMPARISON WITH OTHER INTENSE TROPICAL STORMS

Whatever the maximum wind speeds, Cyclone Tracy must be ranked as an extremely intense tropical storm and compares with two notable U.S. hurricanes; Hurricane Camille which struck the Mississippi Gulf Coast in 1969 and Hurricane Celia which caused heavy damage to Corpus Christi, Texas in 1970 [3, 4, 5]. Significant characteristics of these storms are listed below:

	Tracy	Camille (1969)	Celia (1970)
Central pressure (mb)	940-950	905-915	940-950
Maximum wind speed (m/s)	60-75	75-85	70-75
Diameter of eye (km)	8-10	8-10	20-30
Radius of winds > 50 m/s (km)	10-12	30-50	25-30
Forward speed (km/hr)	6-8	20-25	20-25
Maximum storm surge (meters)	1.6	7.4*	2.8*

(*) Includes astronomical tide.

Other notable cyclones affecting Darwin occurred on January 7, 1897 and on March 10, 1937 [6]. The 1897 event is believed to have been the most intense cyclone to strike Darwin prior to Tracy with extensive damage to the city and trees either flattened or stripped of branches. Twenty-eight deaths were recorded and a minimum barometric pressure of 950 mb was observed at Point Charles Lighthouse. As with Tracy, the direction of travel was SE. The 1937 cyclone approached from the NW and caused very rough seas with waves breaking over the cliffs at Fannie Bay and Emery Point. Wind

[1] Figures in brackets indicate literature references on page 15.

gusts of 44 m/s and a minimum pressure of 975 mb were recorded. Most trees were stripped of branches.

3.0 TYPES OF BUILDINGS AND DISTRIBUTION OF DAMAGE

3.1 GENERAL

All areas of Greater Darwin suffered substantial wind damage, the severity depending upon the type of construction and degree of wind exposure. The purpose of this section is not to describe the damage in detail, which will be covered in subsequent sections, but rather to describe the predominant types of buildings by subdivision and the general distribution of damage.

3.2 TYPES OF BUILDINGS BY SUBDIVISION

The following tabulations are necessarily subjective and are intended to convey a general description of types of buildings located in the various subdivisions of Darwin. See Figure 2 for subdivision locations.

Darwin City: Commercial buildings up to three stories, government administration buildings, city office buildings and several historic buildings constructed prior to 1900. Three recently constructed reinforced concrete buildings of 10 and 11 stories, one 8-story load-bearing brick masonry building, several apartment buildings of two and three stories. Some industrial buildings and petroleum storage tanks in the railway area along Francis Bay. Several transit sheds and a power plant next to Darwin Harbor. Very few single-family dwellings.

Larrakeyah: Military area on Emery and Elliot Points, Darwin Hospital, one-and two-story commercial buildings, apartment buildings and single-family dwellings.

Stuart Park: Railway workshops, some light industrial buildings, several apartment buildings and single-family dwellings.

Fannie Bay and Parap: Single-story commercial buildings, primarily single-family dwellings and some apartment buildings of two and three stories along Fannie Bay. Darwin High School.

Winnellie: Large steel-framed warehouses and multiple-bay industrial buildings.

Narrows: Single-family dwellings and apartment buildings.

Ludmilla: Single-story commercial buildings and single-family dwellings.

Coconut Grove and Nightcliff: Single-family dwellings, apartment buildings up to 4 stories and some single-story commercial buildings.

Northern Suburbs: Includes all subdivisions north of airport and east of Nightcliff. Primarily single-family dwellings, schools, shopping centers and a few apartment buildings.

Darwin International Airport: Terminal building, aircraft hangars, RAAF operations buildings and military housing adjacent to Narrows and Ludmilla subdivisions.

3.3 DISTRIBUTION OF DAMAGES

Shortly after the passage of Cyclone Tracy, a survey of damage to houses in Darwin was carried out by the Northern Territory Housing Commission [7]. Approximately 85 percent of the houses in Darwin (estimated at 8,000 units) were surveyed, the subdivisions of Tiwi and Anula (see Figure 2) being excluded because many of these houses were still under construction and the destruction in these subdivisions was very close to 100 percent. RAAF housing was also excluded from this survey. The results are as follows:

Subdivision	Destroyed (Percent of houses in each subdivision)	Intact
Darwin City	38	9
Larrakeyah	29	4
Stuart Park	24	10
Fannie Bay and Parap	33	11
Narrows	5	29
Ludmilla	32	6
Nightcliff	54	4
Millner	33	3
Rapid Creek	37	6
Jingili	51	7
Moil	75	2
Alawa	57	3
Wagaman	72	2
Nakara	97	0
Wanguri	86	0

It is fairly obvious from the above tabulation that the major damage occurred in the northern suburbs and that Narrows and, to some extent, Stuart Park suffered less damage to housing than did most other areas of Darwin. The Narrows area runs along the upper reaches of Ludmilla Creek and is at a lower elevation than adjacent subdivisions. Stuart Park is located on fairly irregular terrain and while many buildings were directly exposed to the wind, several sections were protected by hills and ridges. The northern suburbs, on the other hand, had very little protection, particularly after the surrounding trees had been stripped of their branches. The entire area rises gently from Casuarina Beach north of Nightcliff and thus experienced scant reduction in wind speeds due to terrain roughness. It is quite likely that Winnellie, Stuart Park, Larrakeyah and Darwin City did benefit from terrain effects, particularly in the early stages of the storm passage.

Because of the different styles of construction and changes in design criteria and construction materials that accompanied the growth of Darwin, it is not possible to deduce local maximum wind speeds on the basis of housing damage alone. A comprehensive study of simple structures such as road signs and flag-poles which showed no evidence of missile impact provided valuable information on extreme speeds and wind direction [8]. Based on this study the following description of wind conditions during the passage of Tracy was deduced:.

Location	Maximum Speeds	Range of Direction
Darwin City & Larrakeyah	50-60	NE to SSE
Fannie Bay & Parap	55-65	NE to S
Winnellie & Narrows	55-65	NE to SSW
Airport	60-70	NE to SW
Nightcliff	60-70	NNW to SW
Northern Suburbs	65-75	NW to WSW

4.0 PERFORMANCE OF BUILDINGS

4.1 HOUSES

4.1.1 Background

The vast majority of houses in Darwin were constructed for the Department of Housing and Construction or for the Northern Territory Housing Commission. There are some privately constructed houses and several prefabricated housing systems which were introduced within the past two or three years. The design of housing was largely based upon intuition and experience with very little attention given to the rational estimation of wind loads and load capacity. An exception to this was the newer prefabricated housing systems whose designs were subjected to a careful review prior to acceptance by local authorities. Design wind speeds for Darwin varied somewhat through the years and included adjustments for type of exposure, expected life of structure and height above ground. Design speeds of 45 to 50 m/s were used from 1951 to 1972 at which time the new code provisions for wind loads (AS CA34.2) were adopted [9]. This code, subsequently re-issued as AS 1170 Part 2-1973 specifies a basic design speed of 56.4 m/s for Darwin and allows reductions for terrain roughness. Following the adoption of AS CA34.2, a category 3 (mean velocity profile described by a power law with an exponent of approximately 0.25) terrain was assumed with a corresponding basic design speed of 39.4 m/s. Hindsight suggests that category 2 terrain (exponent of 0.15) or a design speed of 56.4 m/s would have been more appropriate.

Of approximately 7,000 houses surveyed, more than 50 percent were damaged beyond repair and only some 400 units could be considered to be intact with minor damage to roofing, wall cladding and windows. Of those considered to be repairable, the vast majority suffered substantial damage to roofing. The following sections describe some of the more common housing systems and their performance during Cyclone Tracy.

4.1.2 High-Set Houses

By far the most popular style of house in Darwin is the so-called "high-set" house constructed for the Department of Housing and Construction. Although there are several variations the basic unit consists of an elevated platform and light timber frame with a gable roof (see Figure 3). The plan dimensions are approximately 7 x 16 meters with the platform some 2.5 meters above ground. Prior to 1968 galvanized steel pipe columns with cross-bracing were used to support the platforms (see Figure 4). These were superceded by concrete columns on simple spread footings and the cross-bracing was replaced by concrete block shear walls installed between 4 adjacent columns, the resulting enclosure serving as a laundry room or storage space.

The frames of the older high-set houses were constructed of 2 x 4 in. (nominal) wood studs with let-in diagonal bracing and the 6 mm (1/4-inch) asbestos cement wall cladding was not counted on to provide principal resistance to racking. In more recent construction the let-in bracing was eliminated, the stud sizes were reduced to 2 x 3-in. (nominal) and both the corrugated galvanized iron (CGI) roof cladding and asbestos cement wall cladding were assumed to provide sufficient resistance to racking in the roof and wall planes. Following Cyclone Althea which struck Townsville in 1971, certain changes were introduced to improve the wind resistance of new housing in tropical areas. These changes included the addition of steel rods or "cyclone bolts" extending from the roof trusses down through the walls to the underside of the floor joists. Nails were replaced by self-drilling wood screws with neoprene washers for the attachment of CGI cladding and reinforced concrete bond beams were added to the concrete block shear walls. Another important feature of the high-set houses, and most other houses in Darwin for that matter, is the widespread use of prefabricated wall panels containing jalousie windows and ventilation louvers. The frames and mullions in these units are extruded aluminum sections.

The high-set houses performed reasonably well in the older subdivisions such as Fannie Bay and Larrakeyah where there was some protection provided by other buildings and trees and where the wood frames contained diagonal bracing. Many of these older houses were roofed with corrugated asbestos cement sheets. In the northern suburbs, however, the new high-set houses suffered extensive damage. The failure of upwind buildings created a source of missiles which undoubtedly played a major role in the widespread damage observed in the northern suburbs. This tended to be a self-sustaining effect as other structures failed downwind. The sequence of failure is believed to have been loss of roof cladding and purlins, followed by collapse of roof trusses and large unsupported walls, particularly in the living rooms. The racking strength of the walls was reduced by missiles fracturing the asbestos cement cladding and these sheets completely failed once racking deformations occurred. In many cases the entire wood frame was removed from the elevated platform (see Figure 5). The piers and platforms generally remained intact, but there were cases where the entire structure collapsed or where the piers were racked following failure of the concrete masonry shear walls due to overturning (see Figure 6). No failures of the older steel pipe columns were observed (see Figure 4). A typical connection between the concrete pier and floor beam is shown in Figure 7. Note that the floor joists are toenailed to the nailing strips which are attached to the steel beams by "Ramset" studs. Some high-set houses used metal cladding on the endwalls as seen in Figure 6 and this generally performed very well, being much more resistant to missile impact than the asbestos cement cladding. The cyclone bolts which were installed in all houses built after mid-1972 (see Figure 8) do not appear to have made any significant difference in performance since the main problem was a lack of racking strength once the asbestos cement cladding had failed. Many instances of endwall failure were observed (see Figure 9), suggesting inadequate corner connections and roof-wall connections at the gable ends. The performance of roof cladding is dealt with in a separate section of this report.

4.1.3 Conventional Single-Story Houses

Houses constructed for the Northern Territory Housing Commission were, for the most part, single-story slab-on-grade structures. There were several variations of this system but the cavity wall with bond beams was by far the most common. A typical cavity wall is shown in Figure 10. In several cases bond beams were provided only along the sidewalls and were inadequately tied through the walls to the footings (see Figure 11). This system generally performed very poorly with many cases observed in which the entire roof structure was removed intact and the ties between inner and outer leafs or wythes (each continuous vertical section of wall one masonry unit in thickness) of the cavity walls appeared to be inadequate. Both brick and concrete block were used for the exterior wythe. A few of the newer houses were of timber frame construction with brick veneer on the endwalls. Overall performance of this type of construction was generally poor. Some units in Wanguri and Anula, under construction at the time of Cyclone Tracy, utilized precast-tiltup concrete panels and performed exceptionally well.

4.1.4 Prefabricated Houses

Of the several prefabricated housing systems used in Darwin, only two were investigated in some detail and are described herein. The first is a high-set house with the same general floor plan and overall dimensions as the timber high-sets constructed for the Department of Housing and Construction (see Figure 12). All components are of precast concrete with welded and grouted beam-column connections. Columns are 200 x 200 mm in cross-section and the beams are 300 mm deep and 75 mm wide. The floor and roof panels are approximately 50 mm thick except for the edges which are 100 mm thick. A screed course is placed over the floor panels and the roof panels are bolted into sockets provided in the top edge of the beams. Wall panels lock into slots provided in the beams and columns. Conventional aluminum window frames, jalousie windows and metal louvers are also used in these houses. A conventional truss-purlin-CGI roof is placed over the ceiling panels, the timber plate being bolted down with the precast ceiling panels. This system would have performed very well had it not been for the fact that anchor bolts were installed only along the perimeter of the roof, even though the interior ceiling beams contained bolt sockets (see Figure 13). The result was that many of the panels were lifted from the interior beams, causing the perimeter anchors to fail.

Some of the ceiling panels shifted enough to drop off of their supporting beams, causing damage to wall and floor panels. In some cases the ceiling panels were flipped over and fractured adjacent panels (see Figure 14). This occurred after loss of the CGI roof cladding and roof trusses. One house had obviously received a heavy missile impact, causing failure of a second story corner column. The beam-column connection detail revealed by this failure is shown in Figure 15.

The second prefabricated system inspected is a single-story dwelling with a gable roof as shown in Figure 16. The walls are sandwich panels of 6 mm asbestos cement with a polyurethane core. The panels are framed with steel "H" sections (two channels back to back) and the roof system consists of welded, light-gage steel members. Roofing varied from structure to structure, the type shown here being "Decramastic," a steel sheeting stamped into the shape of tiles and coated with an asphaltic compound. Sandwich panels are also used for the ceiling, the channel framing also serving as the bottom chords of the trusses. This detail allowed the ceiling to act very effectively as a diaphragm. Although there were some window failures and substantial loss of roofing, this system performed exceptionally well. The walls and roof trusses exhibited no permanent deformations and the resistance of the sandwich panels to missiles was far superior to the ordinary asbestos cement cladding used on the high-set houses.

4.1.5 Privately Constructed Houses

Several privately constructed houses performed well with damage being limited to loss of CGI roof cladding or tiles and some broken windows. The house shown in Figure 17 is located in Nakara and has a welded steel frame with brick veneer. Note that the roof tiles have been replaced since the storm. Commercially produced timber connectors were used in many of these houses to attach purlins and trusses.

4.2 SCHOOL BUILDINGS

4.2.1 General

Several school buildings were constructed in Darwin over the past two years, particularly primary schools in the northern suburbs. Time did not permit a detailed study of all school buildings, but it is generally agreed that most of these buildings performed very well. Darwin High School served as the main center for recovery operations and provided temporary shelter for victims of Tracy while evacuation plans were being formulated. Design wind speeds for the newer schools in Darwin are not known to the author, but were probably between 50 and 55 m/s. It is important to note that most of these structures would have served well as community shelters during the passage of Tracy. The buildings described in this section were quite closely inspected and are believed to be representative of recent school construction in Darwin.

4.2.2 Millner Primary School

This complex consists of an auditorium and two-story classroom buildings connected by covered walkways. Construction is steel frame with concrete and brick masonry walls and roofing is steel pan-type sheet with hidden locking clips. The entire auditorium roof and most of the cladding over the covered walkways failed as did some portions of the roofing on the classroom buildings (see Figure 18). It is believed that the loss of roofing followed the failure of window panels on the windward side of the buildings. Two large infill masonry walls were blown in, falling onto the stairway leading to second-floor classrooms.

Of particular interest at this school were the temporary classrooms shown in Figure 19. Construction is cold-formed steel frame and steel cladding. They suffered a number of missile impacts and some loss of windows, but remained intact. The anchorage system depended solely on the dead weight of the concrete piers and footings and performed very well. One case of partial anchorage failure due to overturning of the piers was observed. Again, these units would have provided adequate refuge.

4.2.3 Darwin Community College

Darwin Community College is located just west of Nakara and was one of the more interesting complexes inspected because of some rather unusual structural failures. The main classroom building is a two-story reinforced concrete structure with masonry spandrel walls. The roof system consists of pan-type steel sheet carried by bar joists which are bolted to the column tops. A view of one-half of the north or windward wall is shown in Figure 20 and it is obvious that cracking has occurred in all of the columns just above the level of the second floor. The other half of the windward face of the building is shown in Figure 21. The roof structure has been folded over the exposed interior wall, and the second-story spandrel wall and several columns have failed. It was originally believed that the column failures were due to a poor splice detail, i.e., insufficient bar lap and column ties. However, a closer inspection revealed a quite different mode of failure. Following loss of the windows and/or spandrel walls the bottom chords of the bar joists failed in compression due to the high uplift pressures on the roof cladding and absence of any lateral bracing of the bottom chords. This, in turn, displaced the column tops and caused them to fail in combined bending and tension. This sequence of events was quite clear, both in the failed section and in the portion which was still standing.

A number of failures of masonry walls were observed in the buildings housing the metal and woodworking shops of Darwin Community College. These buildings have structural steel frames and concrete block walls as seen in Figure 22. The walls were unreinforced and are believed to have failed by direct wind loading since there was no source of debris upwind of these structures. There was no apparent damage to the steel frames.

Damage to student housing, located downwind of the main classroom building, is covered in a subsequent section.

4.3 APARTMENT BUILDINGS

No damage statistics on apartment buildings were available at the time the author visited Darwin. However, it was quite obvious that apartment buildings performed considerably better than did houses. It was observed that a substantial number of the people remaining in Darwin after Tracy were being lodged in apartments and that the highest density of apartments is in the subdivisions of Stuart Park, Larrakeyah and Darwin City. These subdivisions are believed to have had slightly lower wind speeds than did other parts of the city, but the relatively good performance of this class of structure can be largely attributed to better structural detailing. These buildings are typically two or three stories with reinforced concrete floor slabs and loadbearing walls of brick or concrete masonry. Roof decks are either steel purlins and CGI cladding or reinforced concrete. Figure 23 shows typical units in Darwin City.

Structural failures generally involved loss of roof decks and, in a few cases, collapse of masonry walls on the top floors following loss or buckling of purlins. Most roof failures are believed to have been initiated by breakage of windows or failure of doors on windward faces. No cases of primary structural damage were observed in apartment buildings with reinforced concrete roof decks. The building shown in Figure 24 is located in Millner, very close to the center of estimated storm track. Damage was limited to some broken windows, loss of an infill wall in the stairwell and partial failure of an equipment enclosure on the roof.

4.4 PUBLIC BUILDINGS

4.4.1 Government Office Blocks

These buildings are concentrated in the SE portion of Darwin City and are typically two and three story structures with steel or reinforced concrete frames. Design wind speeds are believed to have been in the range 49 to 58 m/s and maximum speeds in this area during the passage of Tracy are estimated at 50 to 60 m/s. Damage was generally limited to broken windows and partial loss of roofing. The amount of debris available for missile damage was markedly less than in other parts of Darwin. A very interesting observation was the effectiveness of sunscreens in protecting windows from missiles. Note the impact points in Figure 25. It is also possible that the sunscreens served to reduce the wind loading on cladding panels and windows.

4.4.2 Darwin Hospital

Darwin Hospital is located in Larrakeyah adjacent to the military area on Emery Point and was designed for a wind speed of 58 m/s. It is a 3-story reinforced concrete structure with sunscreens (see Figure 26) and has a relatively clear wind exposure. This building performed very well and continued to function during the storm, switching over to emergency power when the main distribution system failed. Maximum wind speeds in this area were probably in the range 55-60 m/s. As with the city area, relatively small amounts of debris were available to cause missile damage.

4.4.3 Historic Buildings

Several buildings constructed prior to 1900 have been preserved as historic buildings and are of interest because of their previous exposure to intense cyclones. These buildings are all quite similar in physical size and type of construction, having timber roof trusses and load-bearing walls of native stone approximately 400 mm thick. Most of these buildings suffered extensive damage in the cyclones of 1897 and 1937. Typical damage is shown in Figure 27.

4.5 TALL BUILDINGS

Several new hotels and office buildings have been constructed in Darwin since 1970. These include the 10-story MLC Building and the 11-story Travelodge (Figures 28 & 29) in the Darwin City area. Both are of reinforced concrete flat plate construction with concrete shear walls. Most wind damage was superficial, being limited mainly to loss of pan-type roof cladding and broken windows. There proved to be no substance to the rumor that a large missile caused the partial failure of the brick and concrete block endwalls of the Travelodge (see Figure 29). An identical failure occurred at the same level on the opposite end, undoubtedly due to extremely low surface pressures downstream of the separation points. The change in wind direction in this area would have been sufficient to create identical pressure distributions at each end of the building. The design speeds are not known, but inspection teams reported no evidence of cracking or plastic action in either structural system. Occupants did report noticeable oscillations during the storm passage. Water damage was extensive in these and other tall buildings following loss of roof cladding and glass breakage.

4.6 INDUSTRIAL BUILDINGS

Most of the industrial buildings are located in Winnellie and Stuart Park. Maximum speeds in Winnellie are believed to have been 55-60 m/s and slightly lower in Stuart Park. Structural details and materials used in most of these buildings are very similar to U.S. practice; i.e., cold-formed rafter sections, purlins and girts with 26 ga. CGI cladding. Wind bracing was usually limited to diagonal rods in one or two wall panels, the cladding being counted on for most of the in-plane stiffness. Most builidngs had a concrete masonry infill wall and small office area at one end, the other end consisting of girts and CGI wall cladding. In many cases the purlins were tied directly into the concrete masonry wall, the end rafter being eliminated.

The overall performance of industrial buildings was good, but damage to these light-frame structures in some areas of Winnellie was heavy. It was quite apparent that these buildings had little variation in ultimate load capacity; if one building of a particular type failed, most others of that same type also failed. It is quite likely that failure of rollup doors, windows, and flashing led to gross cladding failure because of sudden increases in internal pressure. Many cases of purlins being buckled upward were observed and this often led to failure of the masonry endwalls to which they were anchored. In other cases the roof cladding was removed by direct pullout of the fasteners, but was more often due to fatigue failure in the material adjacent to the fasteners. This often resulted in total collapse, particularly where the cladding provided the only source of racking strength in the roof planes. A typical failure is shown in Figure 30. Several buildings suffered complete loss of roof and wall cladding without the frame collapsing. In these cases, however, a conventional system of diagonal bracing had been installed in the roof and wall planes.

The buildings shown in Figure 31 are located in Stuart Park and, excepting some loss of wall cladding, they performed very well. These buildings have 22 ga. CGI cladding with 16 mm washers under the fastener heads. This detail, in conjunction with the ridge ventilators undoubtedly had much to do with the overall good performance. Ridge ventilators effectively lower the internal pressure and reduce the uplift load on the roof. This observation has been made in previous surveys of wind damage.

5.0 PERFORMANCE OF MATERIALS AND STRUCTURAL SYSTEMS

5.1 GENERAL

The behavior of certain materials and subsystems under repeated loading and attack by windborne debris was an important factor in the overall performance of buildings in Darwin and deserves special attention in this report. It raises serious questions as to the validity and application of design criteria based solely upon static load tests of builidng elements and structural subsystems. Although many of the failures observed can be explained by extreme loading, poor workmanship or poor design, there was overwhelming evidence of consistently poor performance of certain materials and structural subsystems during the passage of Cyclone Tracy. These are discussed in the following sections.

5.2 CORRUGATED GALVANIZED IRON CLADDING (CGI)

As with other tropical regions of Australia and, in fact, throughout the world, CGI cladding is widely used in Darwin. There are many variations in the sheet profiles and types of fasteners, by far the most common being a sinusoidal cross section with self-drilling, self-tapping fasteners equipped with a neoprene sealing washer. Immediately following Cyclone Tracy, laboratory tests and field inspections of single-family dwellings and industrial buildings were carried out by the Housing Research Branch, Department of Housing and Construction to establish the reasons for the widespread failure of CGI in Darwin [10]. These investigations are continuing, but preliminary findings indicate that low-cycle fatigue was the predominant failure mode. Repeated load tests carried out at approximately 30 percent of the ultimate static load capacity produced failures after 2000 to 3000 cycles. A typical failure is shown in Figure 32. Data obtained in recent full-scale investigations of wind loading [11] suggest that this combination of load and number of cycles would have been exceeded in slightly less than one hour for the wind speeds occurring in the northern suburbs. This suggests that the fastening system in current use (typically 15 mm diameter screw heads with screws installed at every second or third crest) will have to be radically altered. Possible improvements include:

a) Installation of fasteners in valleys rather than on ridges
b) Larger washer or screwhead diameter
c) Battens placed over the CGI and bolted into the purlins

5.3 ASBESTOS CEMENT CLADDING

The asbestos cement cladding used on most of the high-set houses and some of the single-story dwellings proved to be very susceptible to missile impact. This was a major factor in the poor performance of those structures which depended entirely on cladding for racking strength. Static load tests did not reveal this deficiency and it is likely that performance would have been substantially better had a tougher material such as plywood been used. It is interesting to note the drastic improvement in impact resistance where the same material is used in sandwich panel construction (see Figure 33). Conventional nailing of asbestos cement sheets subjected to repeated racking loads deserves additional study.

5.4 MASONRY CAVITY WALLS

Many failures of masonry cavity walls were observed. Lack of bond beams and lateral loading due to purlin buckling were often the cause of these failures. However, a number of cases were observed where the crossties were either inadequate or improperly installed and the inner and outer wythes did not act together in resisting lateral loading. Since Australian practice with respect to masonry cavity wall construction is quite similar to that here in the U.S., this high incidence of failure is cause for concern. Most load tests on masonry walls have been carried out with vertical compression loads applied to simulate deadload. This load condition overestimates resistance to racking and lateral loads when uplift forces are sufficient to offset the deadload. In many cases observed in Darwin, it is likely that the uplift forces transmitted through the purlins were sufficiently high to place the entire wall in tension.

6.0 UTILITIES

6.1 POWER GENERATION AND DISTRIBUTION

6.1.1 Stokes Hill Power Station

The Stokes Hill Power Station supplies the entire greater Darwin area with electrical power and is located at the extreme southern tip of the city. It does not function as part of a grid system and was thus essential to recovery operations. Damage was primarily due to water entering switch gear following loss of roof cladding. A trawler was washed ashore directly over the cooling water outlet structure, but this did not require any immediate repair work. The one reinforced concrete and three steel stacks at the station suffered no apparent damage and the station was placed in partial operation within two days after the storm.

6.1.2 Electrical Distribution

With the exception of the main transmission line running across Darwin to the northeast (conventional steel space-truss towers), most distribution lines were heavily damaged and required complete replacement. Most power poles were either steel lattice structures or prestressed concrete and failures were generally due to accumulation of CGI cladding on the conductors and poles. Many lamp standards also failed due to debris loading (see Figure 34). Primary distribution lines were put back in service within one to two weeks after the storm.

6.2 COMMUNICATIONS

Darwin is connected through a microwave link to the national communications network and most lines in the city are buried. The microwave tower and related equipment in Darwin City experienced only light damage and telephone communications were thus partially restored within hours after the passage of Tracy.

6.3 WATER AND SEWERAGE SYSTEMS

Damage to water and sewerage systems was minimal, primarily due to the fact that there was very little erosion due to storm surge and wave action. Most of the disruption was caused by lack of electrical power at pumping stations. Of the half-dozen or so large elevated water tanks in Darwin, none suffered any noticeable structural damage. The extremely heavy damage in the northern suburbs required that most of the water mains in that area be shut down until individual service taps could be closed.

7.0 CONCLUSIONS

Cyclone Tracy was an extremely intense storm which passed directly over the city of Darwin. The unusually slow forward speed (6-8 km/hr) and long duration of extreme winds is believed to have been a key factor in the extensive damage to buildings, housing in particular, and revealed weaknesses in structural systems that would quite likely have resisted an equally intense storm of shorter duration. While certain construction practices and building materials used in Darwin are not commonly found in the U.S., much of what happened should be given proper attention in future revisions of wind load design criteria and indicates a need for additional research in the following areas:

a) Behavior of CGI cladding and fastening systems under repeated loads
b) Resistance of brittle materials such as asbestos cement and fiber board to missile impact
c) Racking strength of wall panels subjected to uplift loads
d) Behavior of housing systems subjected to unusually high internal pressures resulting from failure of doors and windows
e) Performance of brick and concrete masonry cavity walls for various conditions of edge support and load combinations, including uplift.

8.0 ACKNOWLEDGEMENTS

The author wishes to express his special thanks to Dr. George R. Walker, Senior Lecturer, Department of Engineering, James Cook University of North Queensland, for making most of the technical data contained in this report available and for providing invaluable assistance and guidance during the brief period available for the inspection of damage. This report is the result of the author spending several days on temporary assignment with the Department of Housing and Construction, and the assistance of members of the engineering staff, both in Darwin and Melbourne, is gratefully acknowledged.

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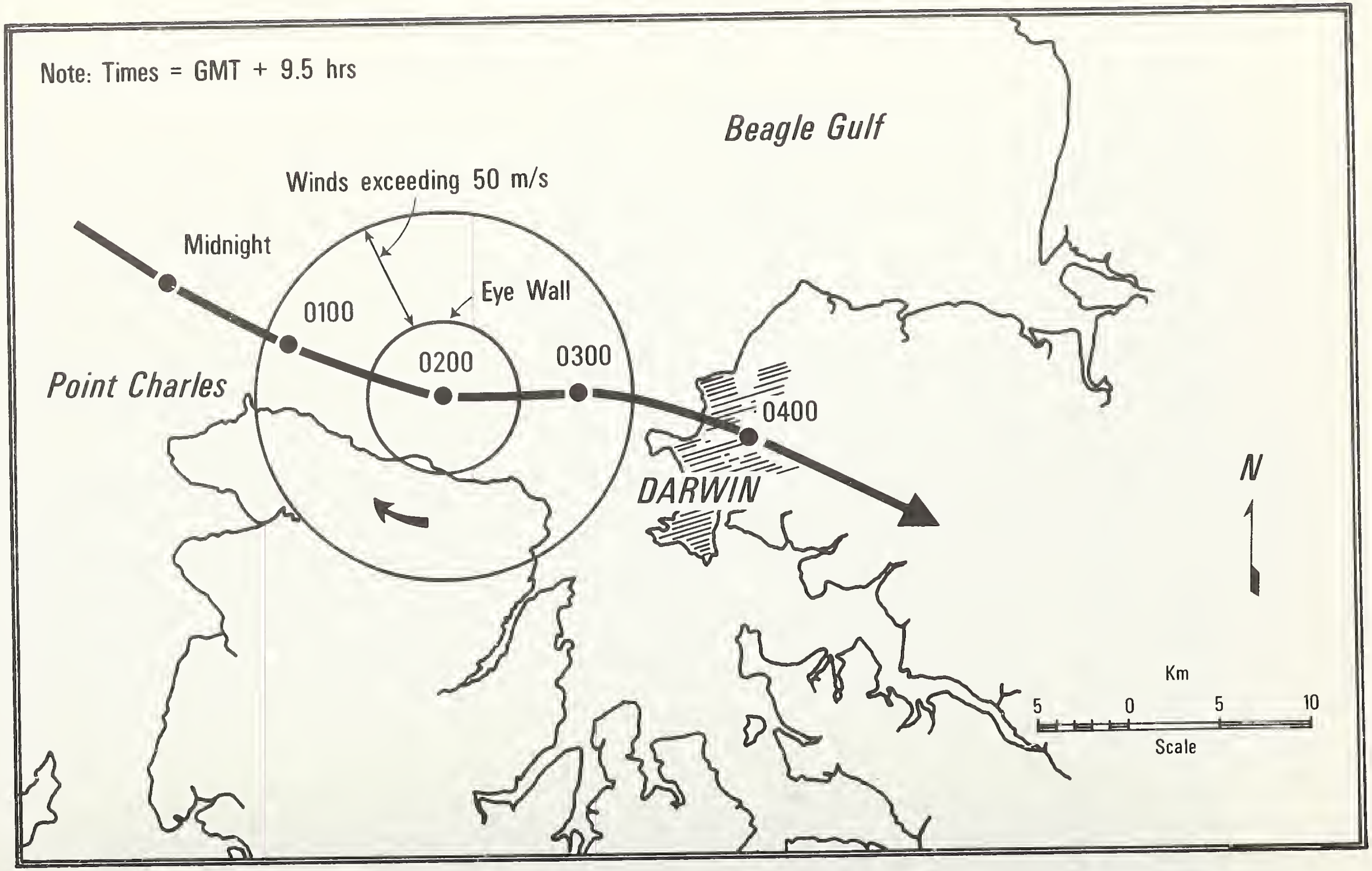

Fig. 1. Approximate track and position of Cyclone Tracy at 0200 hrs., December 25

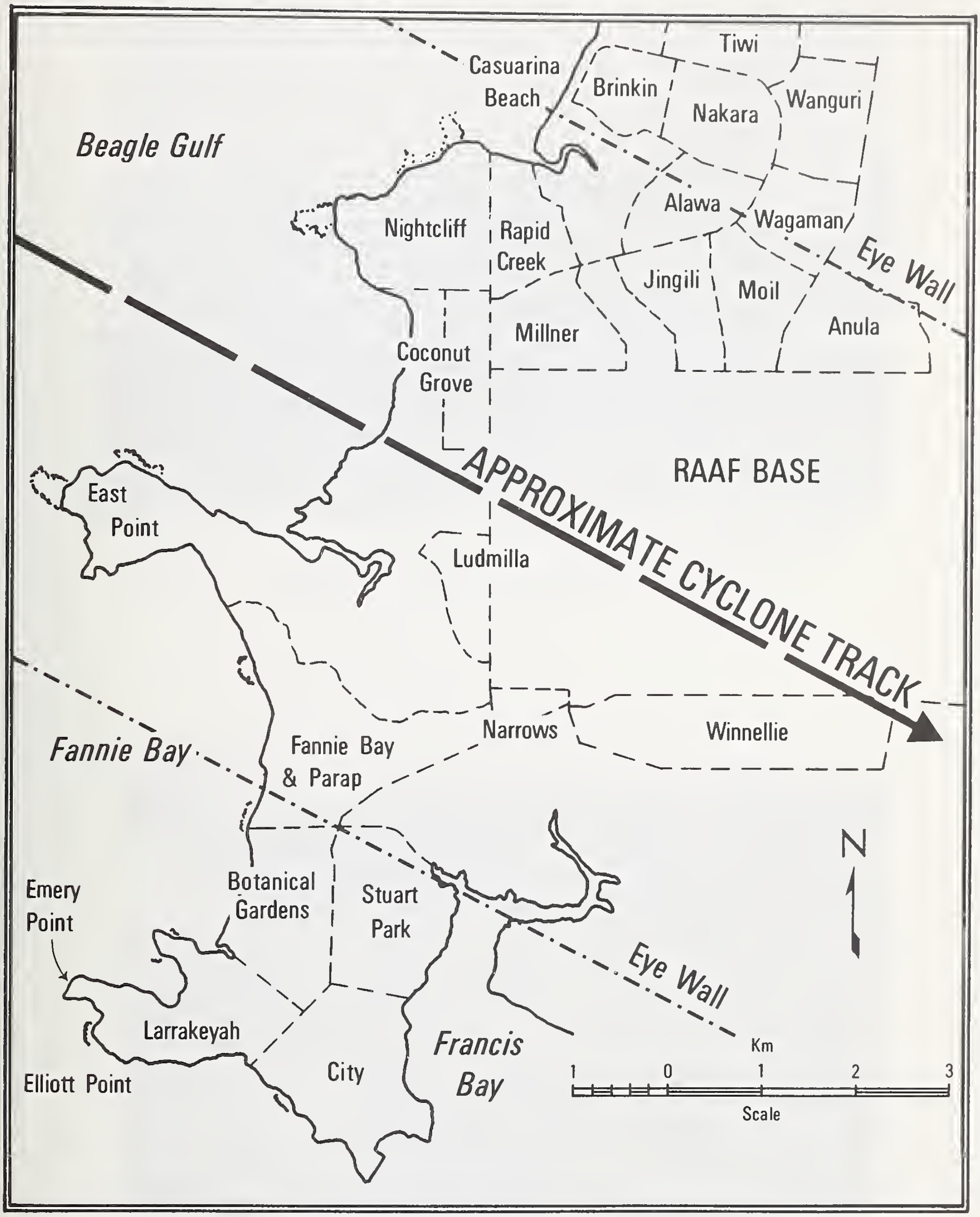

Fig. 2. Approximate cyclone track across Darwin

Fig. 3. Typical high-set house

Fig. 4. Pipe columns used in older construction

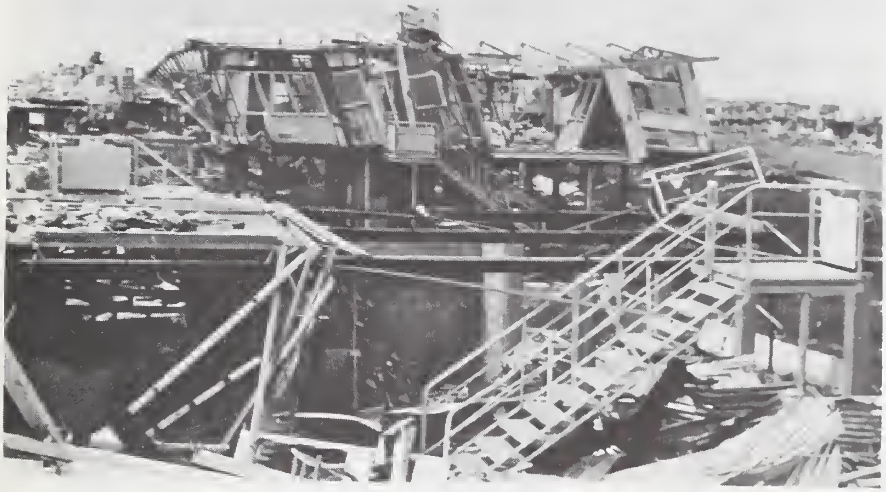

Fig. 5. Severe racking and loss of timber deck

Fig. 6. Failure of concrete block shear walls and racking of concrete piers

Fig. 7. Typical floor systems and pier anchorage

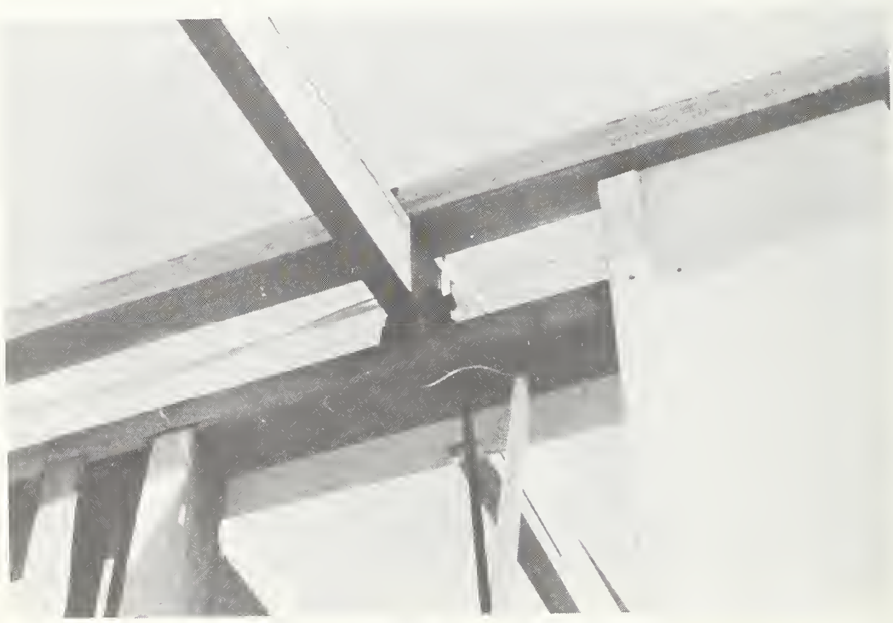

Fig. 8. Cyclone bolt and rafter connection

Fig. 9. Failure of endwall

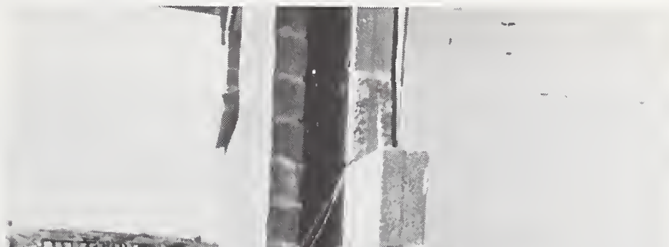

Fig. 10. Failure of brick and concrete block cavity wall

Fig. 11. Concrete bond beam and timber plate (single-story construction)

Fig. 12. High-set house with precast concrete frame and interlocking precast concrete panels.

Fig. 13. Ceiling panel anchorage - bolt and adjacent panel missing

Fig. 14. Overturned ceiling panels - CGI cladding and roof framing completely removed.

Fig. 15. Beam to column connection - precast concrete high-set

Fig. 16. Prefabricated house with asbestos cement-polyurethane sandwich panels and steel wall and roof frames

Fig. 17. Privately constructed residence with welded steel frame and brick veneer

Fig. 18. Auditroium - Millner Primary School

Fig. 19. Temporary classrooms - Millner Primary School

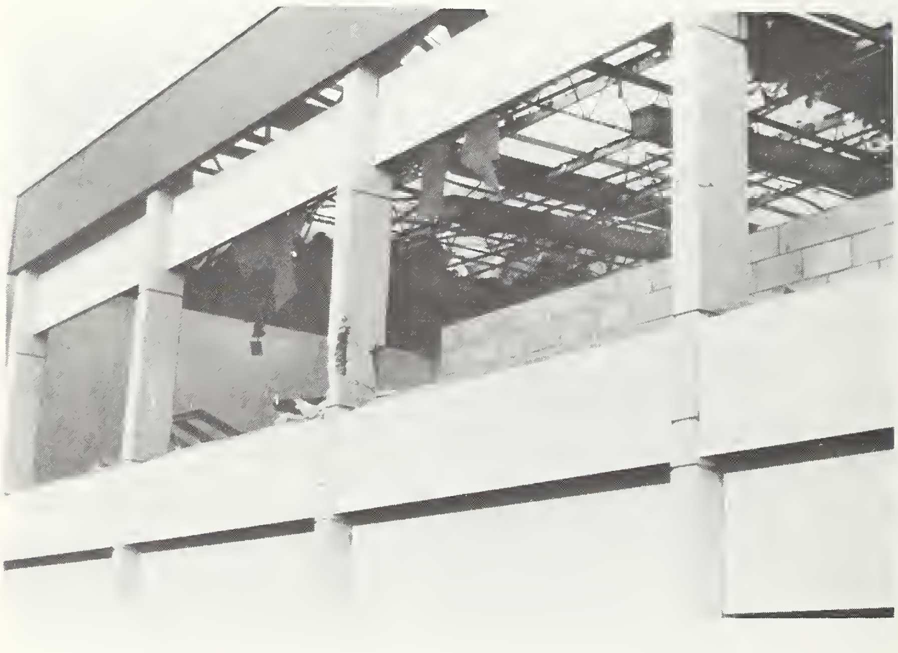

Fig. 20. Academic Block - Darwin Community College

Fig. 21. Failure of second story (view immediately to right of Fig. 20)

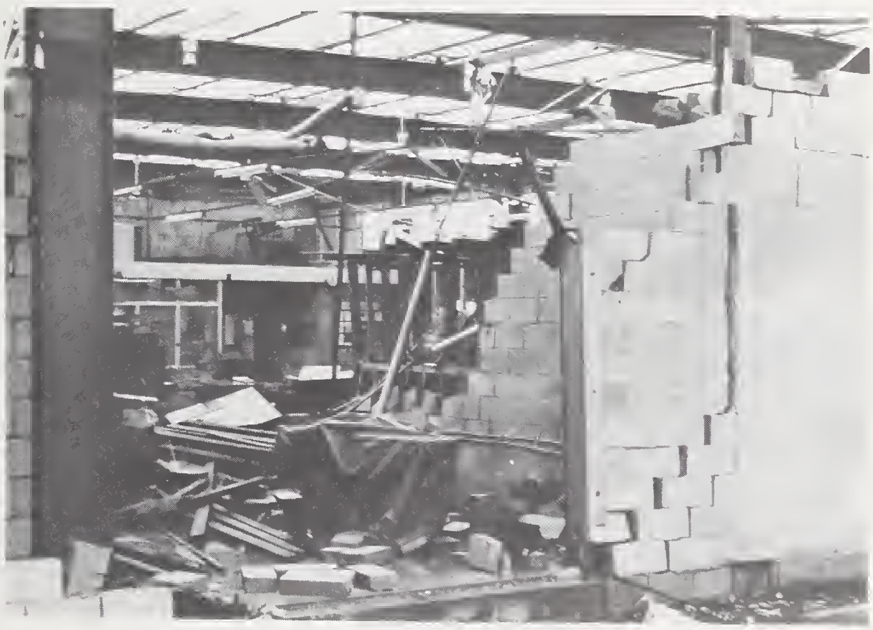

Fig. 22. Woodworking shop - Darwin Community College

Fig. 23. Apartment buildings in city area

Fig. 24. Apartment building in Millner

Fig. 25. Sunscreen showing points of missle impact

Fig. 26. Darwin Hospital - Larrakeyah

Fig. 27. Historic building in Darwin City - hip roof completely removed

Fig. 28. MLC Building - Darwin City

Fig. 29. Travelodge - Darwin City (similar damage at opposite end)

Fig. 30. Industrial building - Winnellie

Fig. 31. Railway shops - Stuart Park

Fig. 32. Typical fatigue failure of CGI cladding

Fig. 33. Missle damage to asbestos cement-polyurethane sandwich panel

Fig. 34. Failure of lamp standard due to debris loading

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U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS BSS-86	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE Engineering Aspects of Cyclone Tracy Darwin, Australia, 1974			5. Publication Date June 1976 6. Performing Organization Code
7. AUTHOR(S) Richard D. Marshall			8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 4615132 11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)* National Bureau of Standards Department of Commerce Washington, D. C. 20234			13. Type of Report & Period Covered Final 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 76-19011

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

During the early morning hours of December 25, 1974, the city of Darwin was devastated by the most damaging cyclone ever to strike the Australian Continent. Winds of up to 75 m/s caused extensive damage to housing in particular, requiring the evacuation of approximately half of the 45,000 residents to other major cities in Australia. This report is a result of the author spending several days on temporary assignment with the Department of Housing and Construction-Australian Government to inspect the damage, and to participate in discussions regarding the establishment of new design criteria and construction practices for cyclone areas. The fact that most of the damage was caused by wind forces rather than a combination of wind and storm surge greatly simplified the assessment of damage and structural performance. The experience at Darwin points out the danger in depending too heavily upon past experience and intuition in the design of housing. It also makes clear the need for additional research into the behavior of certain building materials under repeated loads and missile impact, and the racking strength of walls subjected to uplift loads.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Buildings; cyclones; disasters; structural engineering; tides; wind.

18. AVAILABILITY	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
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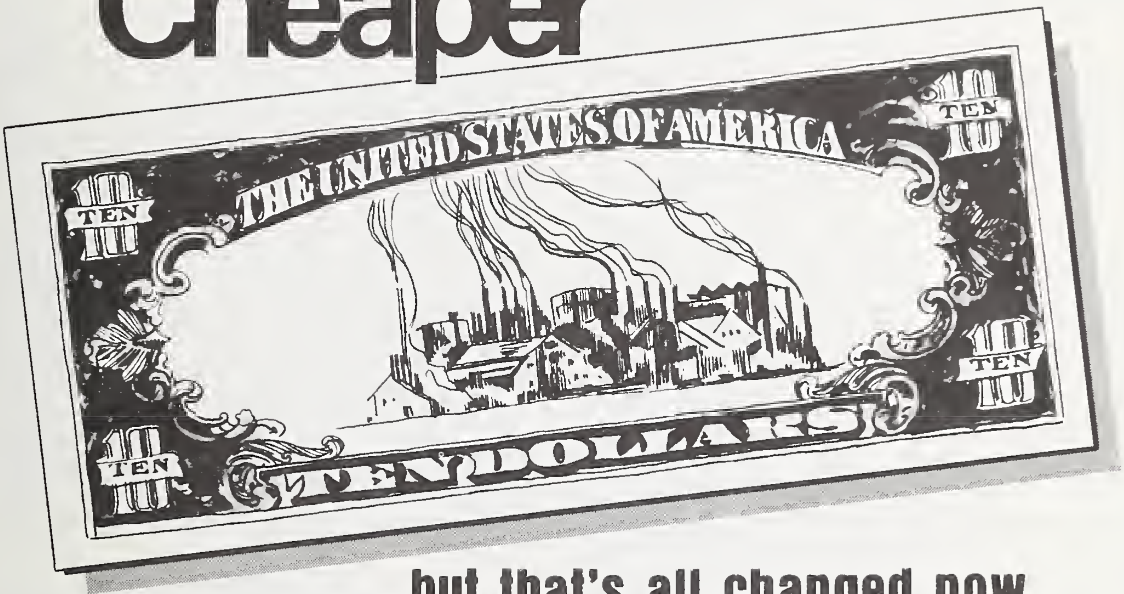

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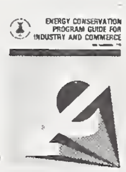

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