JAMES COOK CYCLONE STRUCTURAL TESTING STATION

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REPORT ON DAMAGE CAUSED BY CYCLONE ISAAC IN TONGA

TECHNICAL REPORT NO. 13

November 1982

DEPARTMENT OF CIVIL & SYSTEMS ENGINEERING
POST OFFICE JAMES COOK UNIVERSITY
TOWNSVILLE 4811

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ISBN 0 86443 086 8
ISSN 0158-8338

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CYCLONE ISAAC IN TONGA

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SUMMARY

Tropical cyclone Isaac developed off Samoa and travelled through the island Kingdom of Tonga passing directly over some islands in the group. The highest wind gust recorded was 170 km/hr and the lowest pressure was 976.4 mb, but they were measured away from the eye of the cyclone. A storm surge of about 1.7 metres occurred.

The island of Tongatapu, where most Tongans live, had severe damage caused to villages on its north western peninsula. Approximately fifty percent of houses in these villages sustained damage to roof and wall structure. Damage at the capital, Nuku'alofa was considerably less, but some islands reported damage to more than 90% of houses. Investigations of some of the damaged buildings revealed that few cyclone precautions were included in the construction of houses. Generally concrete block houses performed better than timber framed houses. School buildings survived the winds better than halls of similar construction. Recommendations have been made for rebuilding to resist future cyclones. Apart from building, food crops were decimated, some water supplies polluted and fishing boats wrecked.

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1. INTRODUCTION

The Kingdom of Tonga is comprised of about 169 islands varying in size from more than 300 square kilometres to less than one square kilometre. The Kingdom has a total area of about 363 000 square kilometres of which only 668 square kilometres is land. Tonga is located in the South Pacific between 15°S and 23.5°S, 173°W and 177°W and consists of three groups of islands. Tongatapu in the south, Ha'apai in the centre and Vava'u to the north. The population of Tonga is about 96 500 of which some 65 000 live on the island of Tangatapu.

Each island group has its main island and capital city. Nuku'alofa is the capital of Tangatapu, the largest island comprising about half the total land area of the Kingdom. The Royal Palace is located at Nuku'alofa. In the Ha'apai group the main island is Lifuka whose capital is Pangai. It is located some 175 km from Tongatapu. About 340 km north of Tongatapu is Neiafu, capital city of Vava'u island.

Tropical cyclone Isaac hit the Tongan islands on March 2nd and 3rd, 1982. It destroyed buildings, ruined crops, caused innundation by sea water and disrupted services. Initial estimates of the damage were in excess of T$20 million.

The authors arrived at Tongatapu on March 8th and stayed for ten days. For most of that time travel between islands was very difficult as there were no commercial flights or boats. Australian and New Zealand planes and helicopters were used to transport relief goods and medical supplies to the islands but had no room for passengers, especially academics. However the authors were very fortunate to be offered passage on an inter-island ferry, hired by the Red Cross to distribute tents, food, water and other needed goods. They spent three days on the ship visiting seven islands in the Ha'apai group. This gave them a much broader view of the extent of damage caused by the cyclone as they can report on not only the most populated island, Tongatapu, but also the worst affected area, the Ha'apai group. Most of this report relates to Tongatapu, but reference is often made to the other islands.

Tropical cyclones are not a new experience in Tonga. In another publication (Oliver and Reardon, 1982), the authors list 108 tropical cyclones affecting Tonga in the last 158 years. Whilst there may well be some inaccuracies in this list it does reflect the overall risk to Tonga from tropical cyclones.

2. METEOROLOGICAL DATA

2.1 Development and Track

Isaac originated as a small depression within a broad low latitude convergence zone at 13°S, 171°W some 450 km north west of Apia (Samoa) on 27th February 1982. An accurate reconstruction of the track is not easy. As there was no radar coverage, satellite cloud imagery was the main source of data but this often does not allow a cyclone to be located exactly. Also, this part of the Pacific ocean is on the edge of the field of view of both the Japanese and U.S. satellites. However, despite those constraints an estimate of the track was made by the Meteorological Officer at Nuku'alofa, and shown in Figure 1. Because Isaac made no major departures from its anticipated track, this reconstruction appears acceptable.

The storm was confirmed a tropical cyclone by 1900 on March 1st and by 2400 had sustained winds close to the centre estimated to be 65 km/hr. A large well defined eye was apparent on satellite cloud pictures by 1000 on March 2nd when its estimated speed of movement was 9-18km/hr. At 0100 on March 3rd Isaac was 56 km east of Vava'u with estimates of 148 km/hr sustained speed and gusting to 222 km/hr.

Tropical cyclone Isaac was a relatively small system compared with other cyclones. No estimate has been made of the eye diameter as it cannot be reliably determined from the satellite pictures, nor from the estimated period of the lull at those islands over which the eye passed.

The Fiji Meteorological Service report states that Isaac passed over the Ha'apai group at 0700 on March 3rd having maximum sustained winds of 148 km/hr. The authors subsequently visited the islands of Ha'afeva and

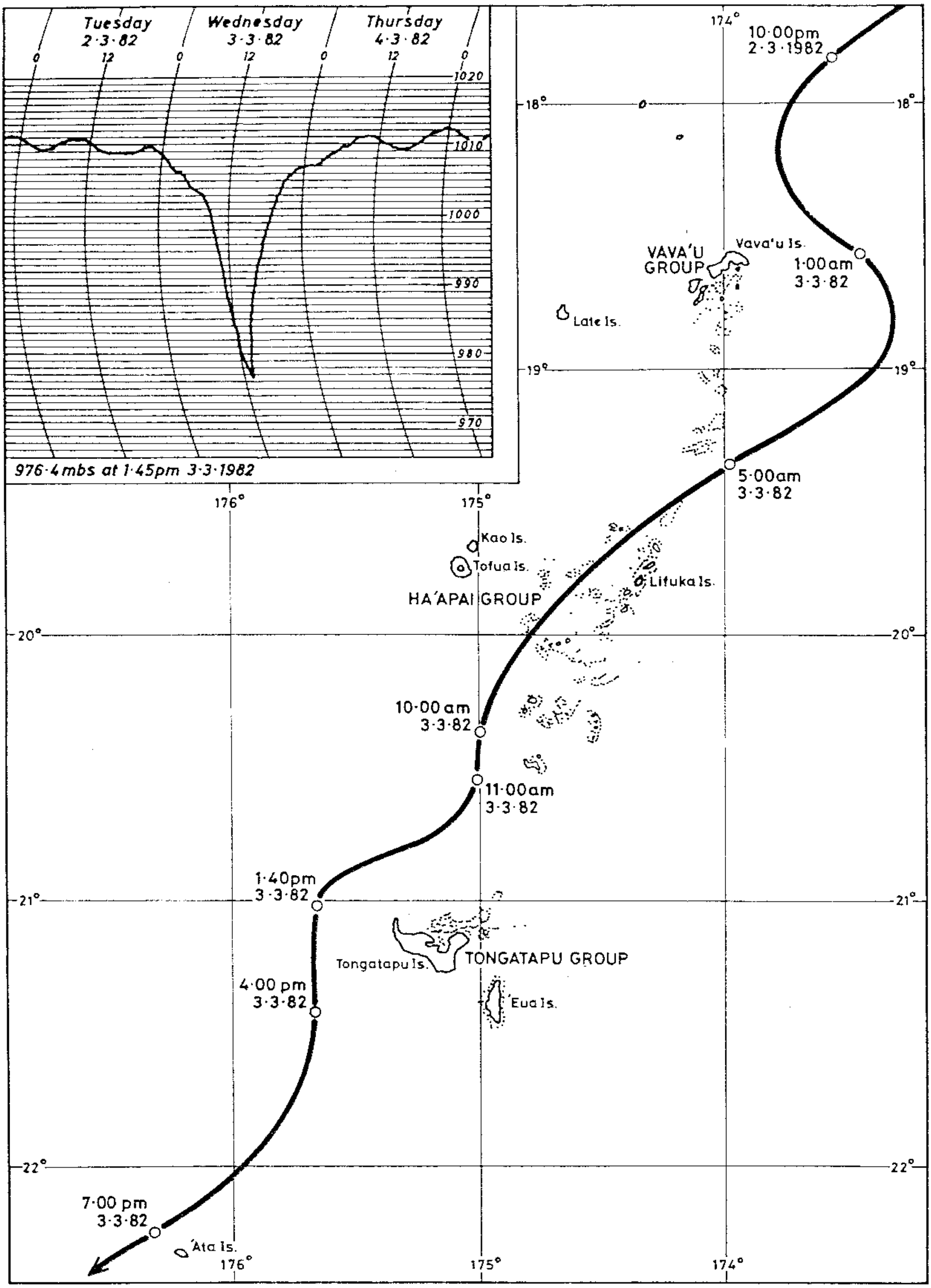


Figure 1. Reconstructed track of tropical cyclone Isaac. Insert shows section of barograph chart at Nuku'alofa.

Matuku, each of which experienced a lull varying from ten to twenty minutes' duration. This evidence, together with the damage pattern, confirmed the report that the eye passed directly over the Ha'apai group. Figure 2 shows the butts of two large trees on Ha'afeva, felled in opposite directions by the wind, indicating that there was a complete reversal of wind direction and that the intensity from each direction was severe.

Cyclone Isaac continued on its south-westerly track and was placed 24 km to the north-west of Nuku'alofa (Fiji Meteorological Service Tropical Cyclone Isaac Report) at 1300 on March 3rd. Weather records showed that at 1345 on March 3rd Nuku'alofa recorded its highest wind gust at 170 km/hr and lowest pressure of 976.4 mb. The strongest sustained winds in Tongatapu were estimated at 130 km/hr. The estimated maximum gust at Fua'amotu Airport, some 15 km south east of Nuku'alofa, was 152 km/hr and the barometric pressure was measured at 988 mb. The cyclone centre was some 25-30 km west of Nuku'alofa at 1500 hours.

Conditions at Nuku'alofa were severe for about four hours, from 1100 to 1500 hours, with most of the damage being caused during the period 1330 to 1500 hours. The wind declined quite rapidly after 1500 hours as the cyclone moved past the Tongatapu group of islands. At 1900 Isaac was 128 km south-west of Nuku'alofa.

No measured minimum central pressure within the eye is available. The nearest barometer was at Nuku'alofa where a minimum reading of 976.4 mb was recorded. Allowing for the cyclone to be about 25-30 km from Nuku'alofa at that time, a reasonable estimate of central pressure would be 950-960 mb.

There was not a lot of rainfall associated with the cyclone. A total of about 150 mm fell on March 2, 3 and 4th, most of which fell between 1000 hours on March 3rd and 1000 hours on March 4th.

2.2 Storm Surge

When a developed tropical cyclone moves across the sea, the associated low pressure within the eye causes the sea to rise relative to its level outside the eye. This phenomenon is known as storm surge. When the cyclone makes landfall the increased sea level may cause inundation of the surrounding area. The magnitude of the inundation is dependent upon a number of factors, including the central pressure within the cyclone's eye, the shape of the sea bed, the local shape of the coast line, the height of the tide and the tidal range.

Cyclone Isaac passed by Tongatapu at near to high tide and caused the sea water to cross the beach front road at a number of positions along the northern coast line. Some low lying areas were inundated for distances up to one kilometre inland. From debris entangled in fences, it is estimated that the surge crossed the road at a height of about 0.6 metres. This would place the storm surge at about 1.7 metres above high tide, which is quite compatible with the estimate of central pressure. It is not possible to determine the effect of waves on the debris level, but the level did appear reasonably consistent over considerable distances.

3. BUILDING CONSTRUCTION

3.1 General

As previously mentioned, the island of Tongatapu represents about half the land area of Tonga and contains about two thirds of the Kingdom's population. The capital Nuku'alofa, contains a number of modern buildings including some three or four storey hotels which, together with the Royal Palace, would constitute Tonga's prestigious buildings. They were generally of concrete framed construction and were probably engineered to New Zealand building standards. Apart from these there would be few other engineered buildings in Tonga.

Smaller commercial buildings, shops, factories and the like at Nuku'alofa were possibly marginally engineered, that is the form of construction was well above that used for domestic buildings but may not have satisfied engineering analysis. It is probably that many commercial buildings in the villages on Tongatapu were in this marginally engineered classification. It is also probable that the further a building was located from Nuku'alofa or the regional capital Pangai or Neiafu the more marginal would be the engineering component.

Figure 2. Wind felled trees blown in opposite directions, Ha'afeva Island

Figure 3. Fale with modern wall construction

This situation of marginally engineered buildings is due to the lack of building regulations, which the Ministry of Works started to phase-in during 1981. Therefore very few buildings would have the advantage of being constructed to the new regulations.

Apart from commercial buildings the most common non-residential buildings were churches. Each village had at least one church, and some had as many as three. Some of these were obviously constructed by local labour, but others appeared to be of engineered construction. The type of construction probably reflected the overseas aid available to the church community.

There are few qualified builders in Tonga. Those that are qualified work on the construction of commercial buildings. Qualifications are usually gained in New Zealand or Australia, with the builder returning to Tonga to instruct others who are learning their skills on the job. This leads to a situation where the worker may attain a high degree of practical skill in bricklaying or carpentry, but lacks any knowledge of the theory as to why certain procedures are taken and the ramifications in changing them.

3.2 Housing

On Tongatapu most houses were of European style rather than the traditional fale of woven palm leaves. Approximately sixty percent had timber framing with the rest being divided equally between concrete block and fale. Nearly all of the European style houses had corrugated galvanized steel roofing, although occasionally the two styles were combined, Figure 3.

Houses are usually built by the owner and his relatives, possibly with the help of a supervisor. This has possibly resulted from the tradition of building woven palm fales, where the men of the family erect the wooden frame and lash the palm leaf roof in position while the women weave the palm fronds to form walls. There was no obvious effort to build the European style houses to resist wind uplift forces, despite Tonga's history of cyclone activity.

It was reported that an average house on Tongatapu would cost about T$8000, compared with a wage of about T$800 p.a. (It is believed that the wages vary considerably from this average figure!). The house would be about 7 x 4½ m timber framed construction, consisting mainly of living and bedroom areas. None of the basic building techniques used in Australia, Adams and Smith (1980), Reardon (1978), SAA (1977) or those recommended for other developing countries, Eaton (1980), were incorporated into house construction. Whilst the lack of electricity on building sites would have prevented the use of power driven tools, and may have made the use of bolts more difficult, it would not have affected the use of metal framing anchors, bent metal straps and the like. It was apparent that these devices for joining timber were either unavailable, too expensive or their value unappreciated.

The need for reinforcing concrete block houses was recognised, possibly because this type of construction was more like that used for commercial buildings. On Tongatapu 6 or 8 mm steel rods were used approximately every fifth core, which was then filled with concrete. This compares with the Australian practice of using 12 mm rods every sixth core. Bed joint reinforcing was even observed in a commercial building, Figure 4, at Pangai.

On the islands, where the cost of transporting blocks from Nuku'alofa was very high, reinforcing was often considered an unaffordable luxury. On one occasion the authors observed barbed wire used as a substitute for solid reinforcing. Of course the fact that it stretches considerably under load makes it useless as reinforcing.

Slab construction was interesting, Figure 5, insomuch as the actual slab was a very thin layer of concrete poured onto consolidated earth contained in a perimeter of two courses of blockwork. This was apparently satisfactory, as with roof truss construction the roofing loads are supported by the outside walls only which are directly over the blockwork. There are no internal load bearing walls, so the thin slab supports only the load from foot traffic of the occupants.

4. DISTRIBUTION OF DAMAGE

4.1 On Tongatapu

Of the three groups of Tongan islands, most damage occurred at Ha'apai, followed by Tongatapu and Vava'u. This was to be expected as the eye of cyclone Isaac passed directly over some islands in the Ha'apai group.

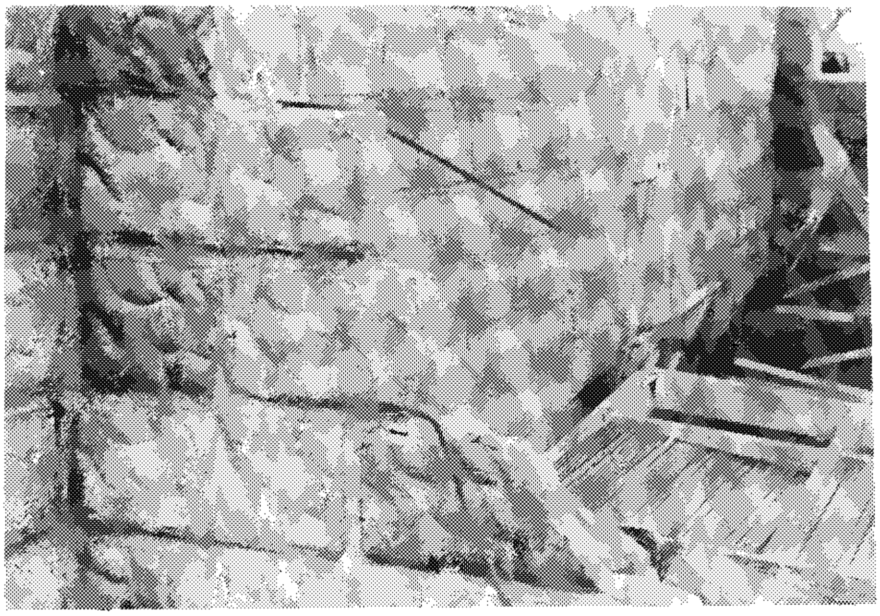


Figure 4. Bed joint reinforcing in blockwork construction

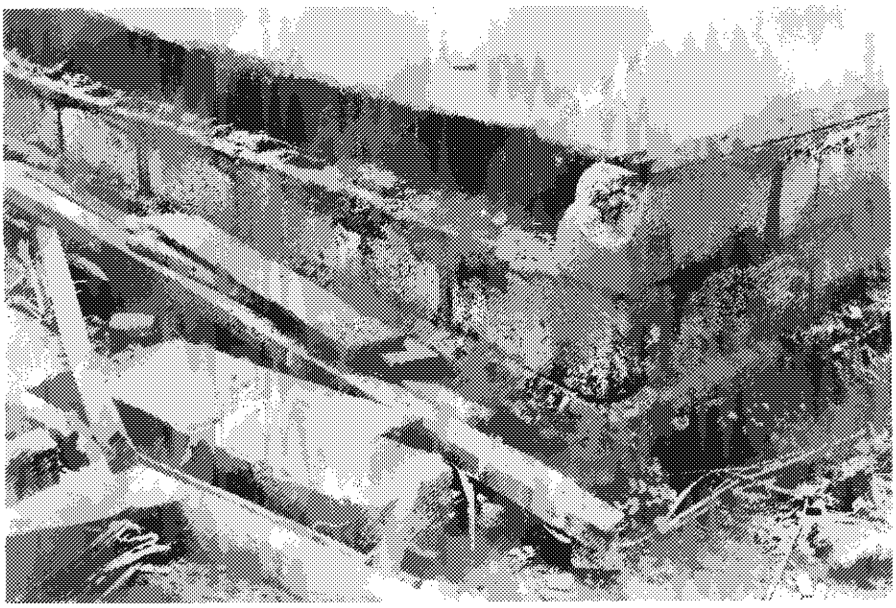


Figure 5. Typical floor slab for domestic construction. Note nominal thickness of concrete.

As Tongatapu is the centre of population and government, official damage investigations started there rather than at the islands of Ha'apai. However the relief work, which included the distribution of food, medical supplies and tents, was conducted wherever it was needed.

The Tongan Ministry of Works (1982) initiated a survey of the extent of damage on Tongatapu, soon after the event. They classified damage into the following five categories:

None

Slight: such minor items as lost gutters or flashing from roofs, one or two broken louvres, minor or incidental damage from flying debris, and the like.

Moderate: including loss of sections of roof sheeting and beginning of damage to roof timbers; windows and doors broken; bad damage from flying debris, and the like.

Severe: loss of complete roof, including most of the timbers, partial collapse of wall sections plus extensive internal partition damage and the like.

Total: damage so severe as to render re-building impossible.

The survey teams covered the entire island of Tongatapu, assessing all buildings, and produced some very useful statistics. They surveyed 10,065 buildings, including 8693 houses and estimated a total damage cost of T$4.5 million of which T$2.9 million was to housing.

Figure 6 shows a distribution of damage to dwellings based on the two highest categories, Severe and Total. As would be expected the villages on the north-west peninsula experienced the most damage, as they were only about 15 km from the eye. More than forty percent of houses were severely damaged or destroyed. This compares with less than five percent severely damaged or destroyed on the north-eastern area. The estimated cost of damage to buildings, mainly housing, in the north-western peninsula was in excess of T$1 million.

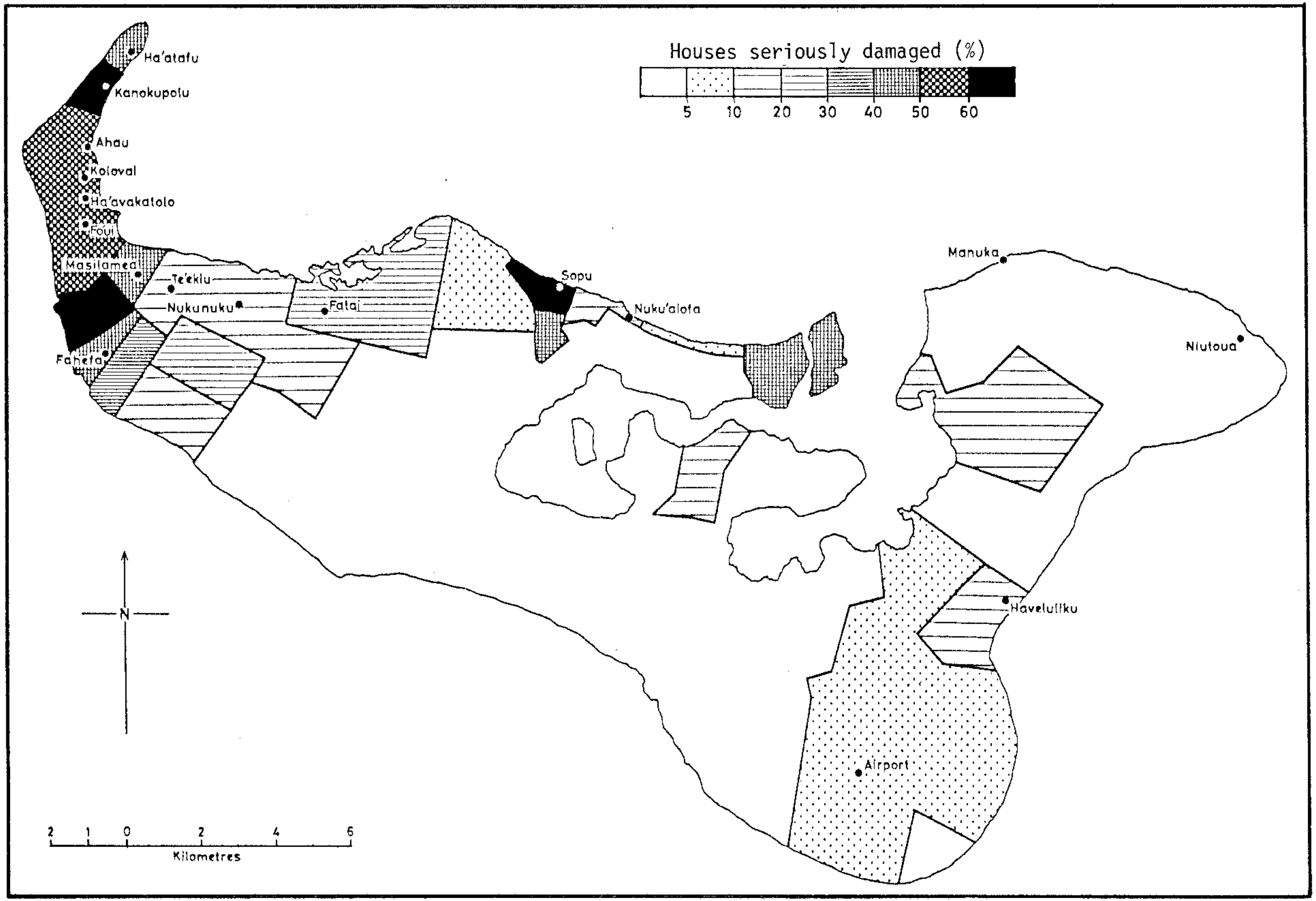


Figure 6. Distribution on Tongatapu of houses classified as having "severe" or "total" damage (Government Survey).

Unaware of the Ministry of Works survey, the authors conducted their own survey of the north western peninsula, using the categorization of damage outlined in Leicester and Reardon (1976). These seven categories are more definitive than those used by Works, for example "half roofing off" or "all walls down" are easily quantified.

At Kolovai the authors surveyed 267 buildings and found 43% to have negligible damage and 25% to have lost all walls. Structural damage to roofs or walls was noted on 109 occasions (41%). This percentage is somewhat less than the 50-60% recorded by the Works survey, but it does agree that severe damage in the north-west area was extensive.

4.2 On Other Islands

Neither party conducted a full survey of islands in the Ha'apai group or Vava'u group. The authors visited seven islands in the Ha'apai group, including Matuku and Ha'afeva over which the cyclone travelled. All of the small islands, with only one village on the island, reported severe damage to most buildings. The extent of damage was estimated by the authors to be of a similar order to that of the north-western peninsula of Tongatapu. Thus most of the damage was structural failure of buildings rather than loss of cladding.

Although the authors made a quick tour of each village they did not have sufficient time to conduct proper surveys. They made enquiries of the Town Officer on each island about the number of houses destroyed. The following information was supplied:

Nomuka	180 houses, 160 damaged
Mangau	16 houses, 13 damaged
Fonoi Fua	21 houses, 7 damaged
O'ua	50 houses, 48 damaged
Matuku	14 houses, 13 damaged
Ha'afeva	200 buildings, 190 damaged

As well as houses, a number of churches were observed to be damaged.

Whilst language difficulties may have caused the above figures to be inexact, they certainly reflect the overall scene of devastation on these islands.

Figure 7. Building damage at Pangai, Lifuka Island.

At Pangai, principal village on Lifuka, the main island in the Ha'apai group, the extent of devastation would be similar to that of north-western Tongatapu. That is, approximately fifty percent of the buildings would have severe or total damage, as defined in the Ministry of Works classification. As Pangai was a large village there were a number of commercial buildings, schools, halls and churches. Many of these were damaged to an extent similar to the houses. Figure 7 shows the extent of damage to houses and commercial buildings in part of Pangai. Once again there was insufficient time to conduct a proper survey to categorize the types of damage.

The authors were unable to obtain any statistics on the distribution of damage on the other small islands in the Ha'apai group, but estimate that it would have been of a similar intensity to that of the islands visited.

5. PERFORMANCE OF BUILDINGS

5.1 General

From the descriptions given in Sections 3 and 4 of this report one may anticipate that the overall performance of buildings was not satisfactory. This would be a sound conclusion, and examples of the inadequate performance together with probable reasons will be outlined in this Section. Most of the examples will relate to Tongatapu, but a few will be of damage on islands of Ha'apai group.

5.2 Housing

Damage to housing was typical of that reported from other wind storms (Leicester and Reardon, 1976a). The predominant form of damage was to the roof, being either loss of roofing or loss of part of roof structure. A typical example of that type of failure is shown in Figure 8, where the roof sheeting and roofing battens have been blown off. Figure 9 shows a more severe example where the entire roof structure was lifted intact from this house at Pangai. It is obvious therefore that there was insufficient hold-down securing the trusses to the wall framing.

The same type of damage occurred on the islands, Figure 10, where construction was often a mixture of traditional and European styles, galvanized iron roofing with woven palm walls.

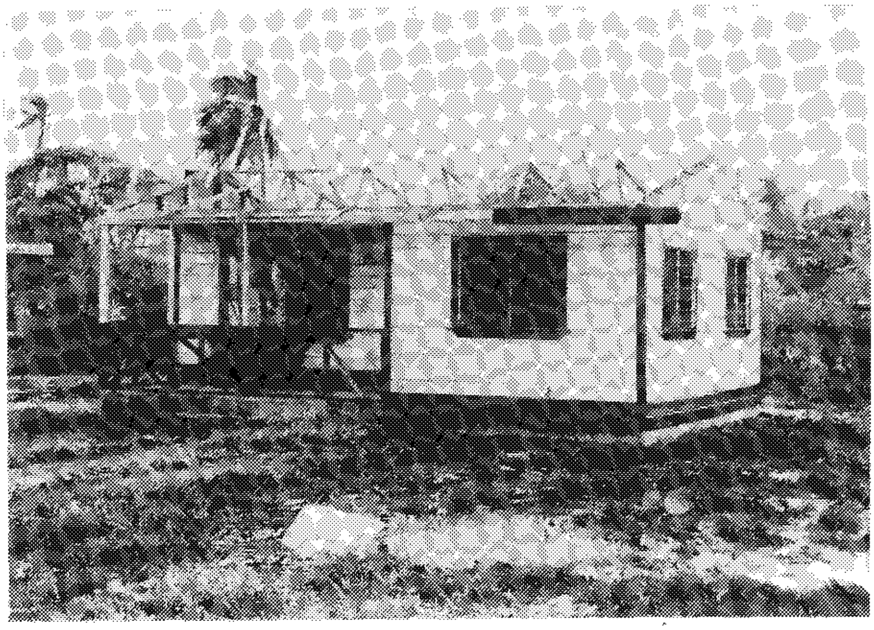


Figure 8. Roofing and some roof structure blown off.

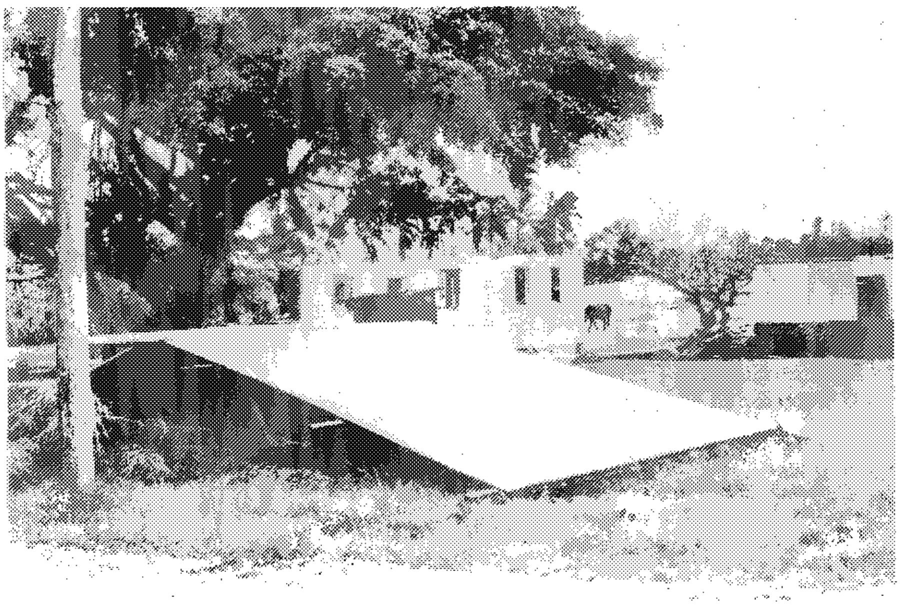


Figure 9. Entire roof structure blown off.

In the European style houses roof trusses not only supported the roofing, but helped to tie the outside walls together, as there were often few internal walls. Thus the loss of trusses made the walls vulnerable to lateral collapse. Figure 11 shows such a wall failure resulting from damage to roof structure.

Total wall failure occurred on a number of occasions, Figure 12. This house, at Sopu, lost its entire roof structure which landed some fifty metres away. This loss, together with the lack of wall bracing, resulted in the failure of all walls. An inspection showed that the bottom plates were securely attached to the slab, but there was only nominal attachment of studs to bottom plate.

There were many occasions where all walls failed and were blown clear of the floor area. This happened not only in the villages of the north-western peninsula, Figure 13, but also at Sopu near Nuku'alofa and on islands in the Ha'apai group. Figure 14 shows a remaining platform floor on the island of O'ua where forty-eight of the fifty houses were reported damaged. Of further interest was the fact that a group of three houses at Niutoua on the north eastern side of Tongatapu were totally destroyed. However the houses were on a ridge about 16 metres high and half a kilometre from the beach, with open ground in between. About twelve other houses in the same group had minor damage to roof and roofing.

The timber framed houses were usually built about three quarters of a metre above ground, on concrete or timber pole stumps. These stumps were not braced, and it is believed that they were embedded less than half a metre into the ground. There were only a few occasions on which lateral failure of the stumps was observed, such as shown in Figure 15, at Pangai. Actually the stump failure shown in that figure is typical of what would result from storm surge. However severe storm surge did not occur at Pangai, and further, the stumps are leaning towards the sea which is incompatible with storm surge.

So far the discussion of damage to houses relates to timber framed construction which would constitute about 60% of Tongan houses. Most of the remaining houses were of concrete block construction, and their observed performance was significantly better than that of timber framed construction. In their survey of nine north-western villages on Tongatapu, the authors

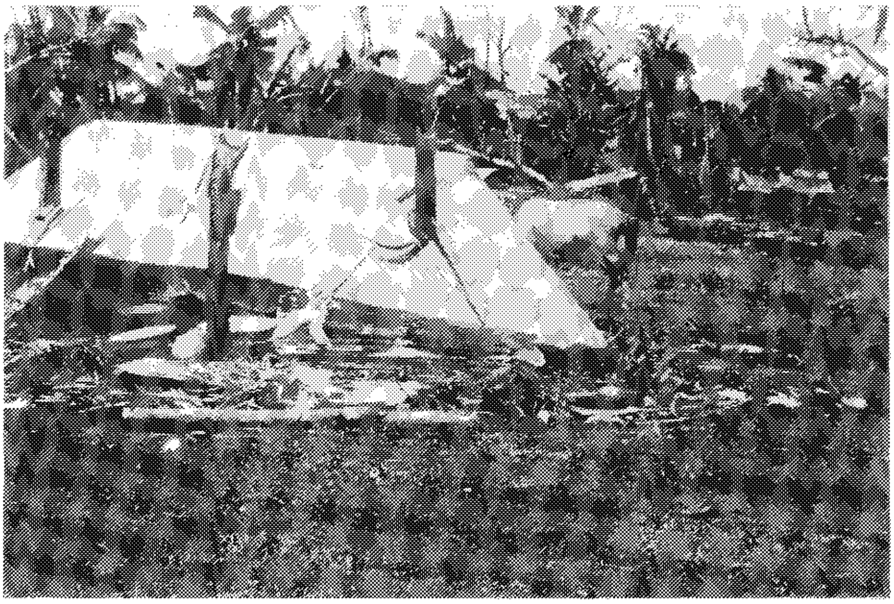


Figure 10.   Roof structure lifted off fale.

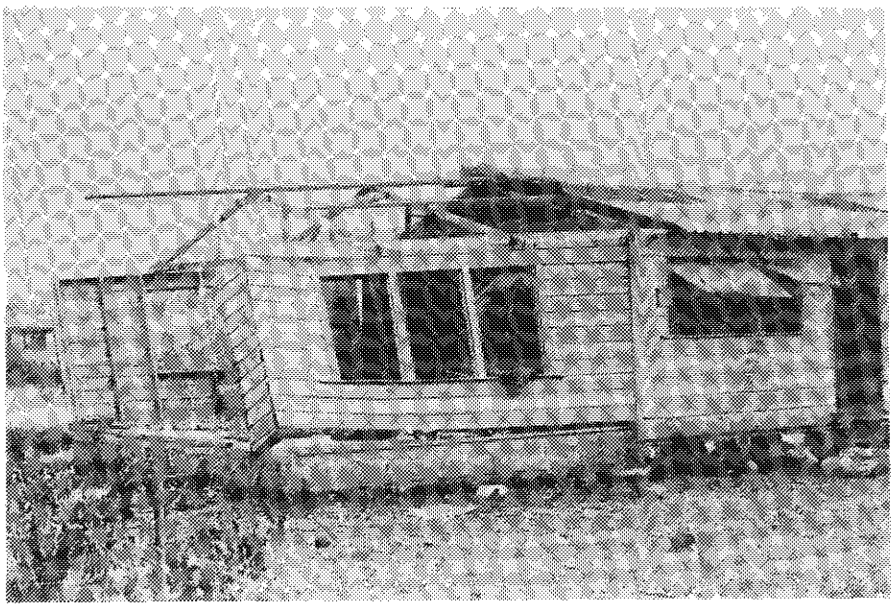


Figure 11.   Severe damage to walls.

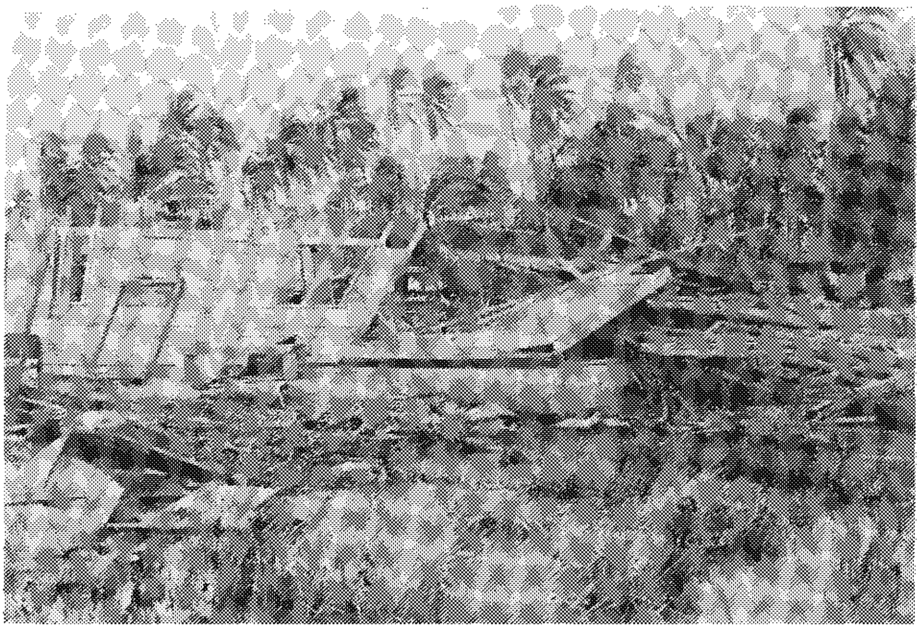


Figure 12. Total failure of house.

Figure 13. Walls blown clear of floor.

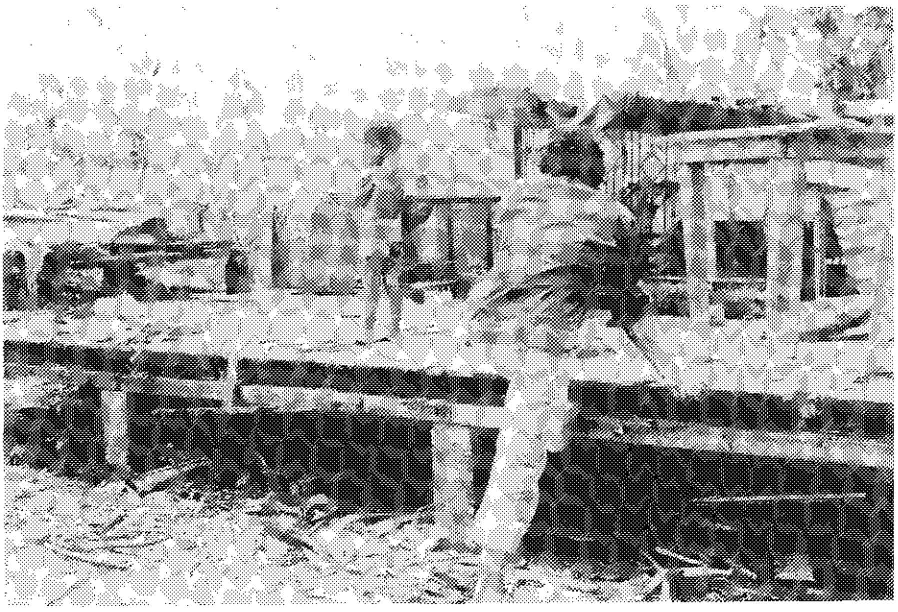


Figure 14. Only platform floor remaining, O'ua Island.

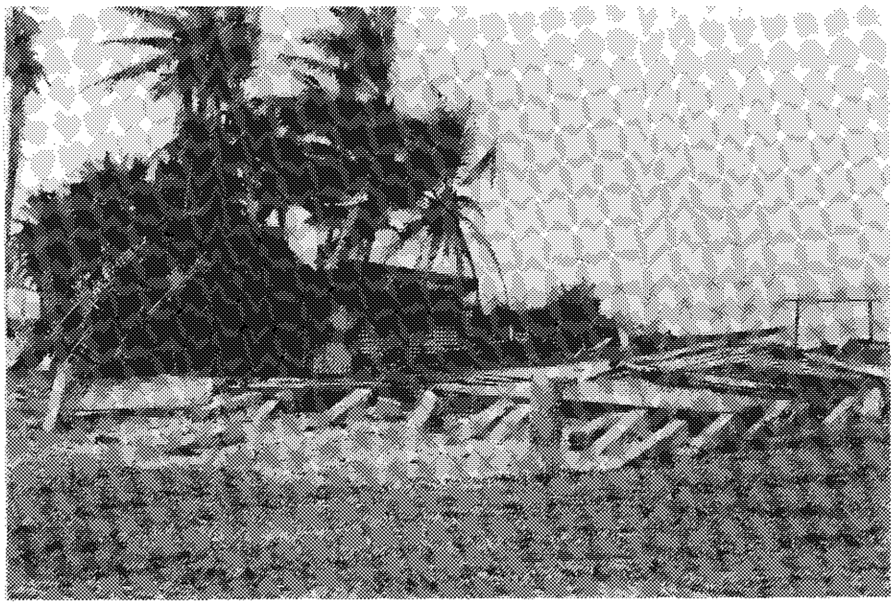


Figure 15. Stump failure, Pangai.

noted that only 45% of the 584 timber framed houses were virtually undamaged (classified as negligible) whereas 70% of the 114 concrete block houses were classified similarly. This difference is not easy to reconcile, as most minor damage occurs to the roof structure and roof sheeting which would be virtually the same in both cases. The most probable solution is that a person having sufficient skill as a block layer would know enough about building to ensure that the roof structure was securely anchored. This would not necessarily apply for timber framed construction which is easier for the "amateur" and for the extended family building team.

Despite its better performance in resisting the furies of cyclone Isaac, concrete block construction cannot be recommended as the preferable form of construction because the islands of Tonga are in an earthquake zone.

Although there was a considerable amount of building debris scattered about, there was little evidence of missile damage even to windows. However, many owners boarded up their windows during the cyclone warning period, Figure 16.

As would be expected, most fales had either minor damage or collapsed totally. Their structure does not allow for partial collapse. On a few occasions, bare fale frames were observed, but it was not clear whether these had been stripped of their walls and thatched roofing, or were in the process of being rebuilt.

5.3 Industrial and Commercial Buildings

Industrial and commercial buildings basically fall into two groups, those at Nuku'alofa and those in the villages. Buildings in the former group had a distinct advantage over the latter. They included the prestigious buildings of Tonga which would have been engineered to resist cyclone wind forces. Further Nuku'alofa did not experience the maximum winds from cyclone Isaac, therefore the buildings were not put to a severe test. The survey conducted by the Ministry of Works showed that about 85% of the 300 industrial and commercial buildings in the Nuku'alofa area had only slight or no damage.

There were only a few industrial and commercial buildings in the villages, but their performance was similar to that of the houses. About 50% of industrial and commercial buildings had significant damage, mainly loss of roof sheeting and damage to roof structure. There were some cases where walls were damaged also, due to the loss of lateral bracing provided by

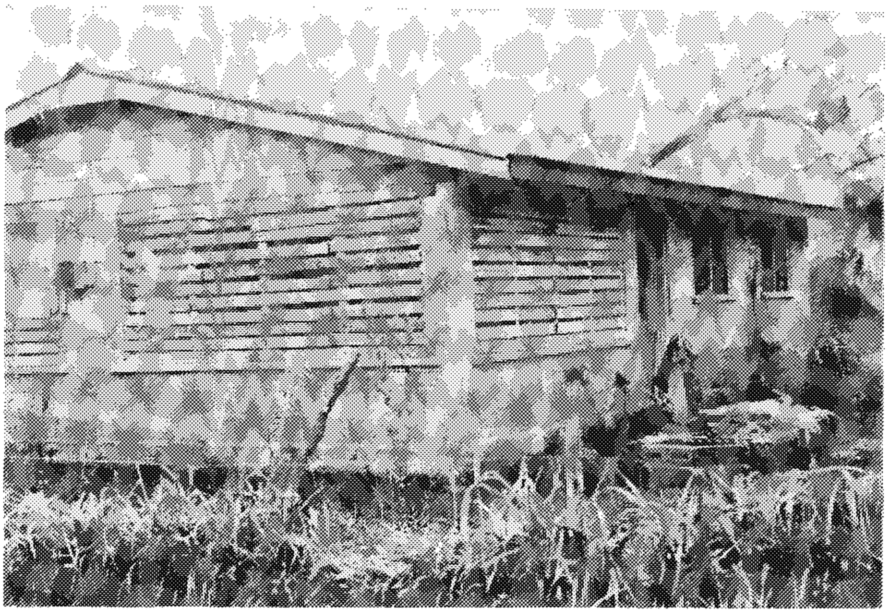


Figure 16. Windows boarded up prior to cyclone.

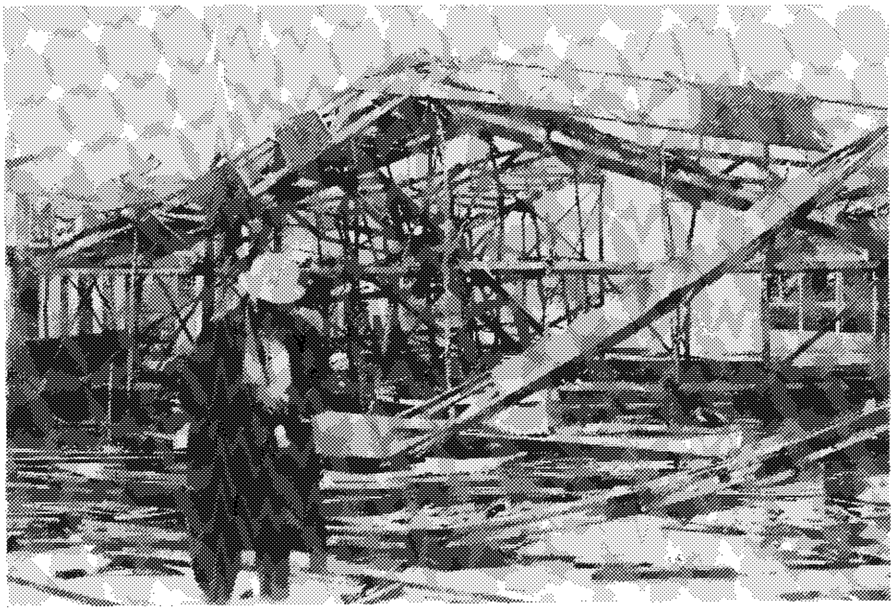


Figure 17. Damage to roof structure of hall.

the roof structure. Figures 17, 18 and 19 show three different aspects of failure of a large hall at Pangai. Figure 17 shows the roof sheeting and purlins having been blown off and some of the timber roof trusses collapsed sideways. Figure 18 illustrates the tie down mechanism used for the trusses. (The entire wall has blown over as a unit!). The reinforcing bar from the pillar was bent over the top chord to secure the truss. Having lost the lateral support provided by the trusses, the wall was unable to resist the horizontal wind forces, and failed as a cantilever. Figure 19 shows failure due to insufficient bond strength. It is suspected that the quality of concrete was not very high and that voids were frequent. Similar failures were observed for other buildings of concrete block construction.

5.4 Churches and Schools

The performance of church structures varied considerably. One church at Kolovai, in the north-west of Tongatapu appeared to be completely untouched by the cyclone as illustrated in Figure 20; yet the church was located in an area where houses were badly damaged. The performance of this church probably reflects the building standards affordable by a more affluent community. Other smaller simple wooden churches in the same area were badly damaged by the winds of cyclone Isaac.

On the islands the churches were usually built to standards similar to domestic buildings, and performed in a similar manner. However, on the larger islands some more substantial churches were built for their larger congregation. These usually performed better.

Figure 21 shows a badly damaged church at Pangai. The roof structure was blown off, one wall blown in and a row of massive concrete pillars inside the church was blown over. A close inspection of the pillars revealed that they were unreinforced. It is very difficult to estimate the age of the church, but it may well have been fifty years old, in which case unreinforced pillars could have been an accepted form of construction.

The overall performance of churches was similar to that of halls which are of basically the same construction. The loss of roof structure caused severe stress on the walls, which were usually unable to cope. This performance applied both to timber framed and blockwork construction.

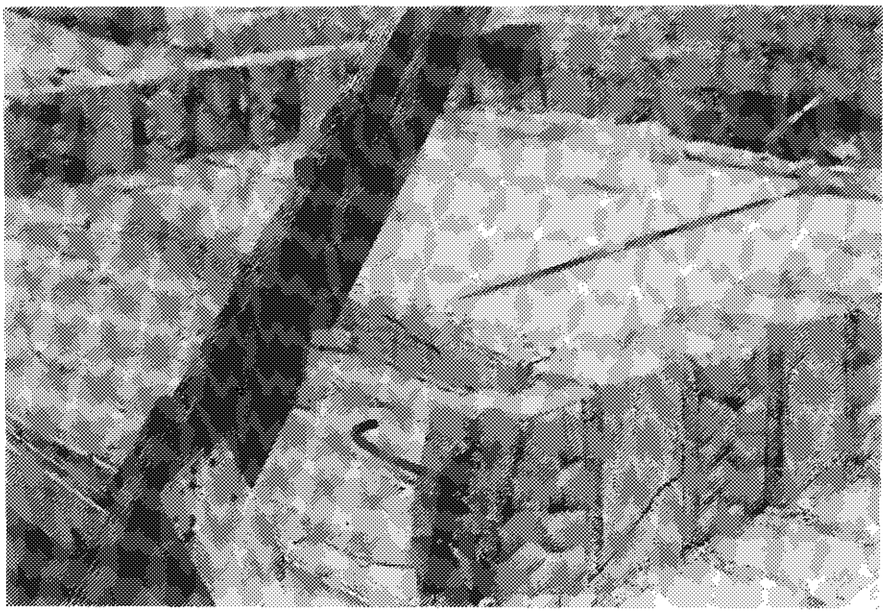


Figure 18. Tie down detail for trusses. (Note: wall has been blown over).

Figure 19. Wall failure due to insufficient bond strength.

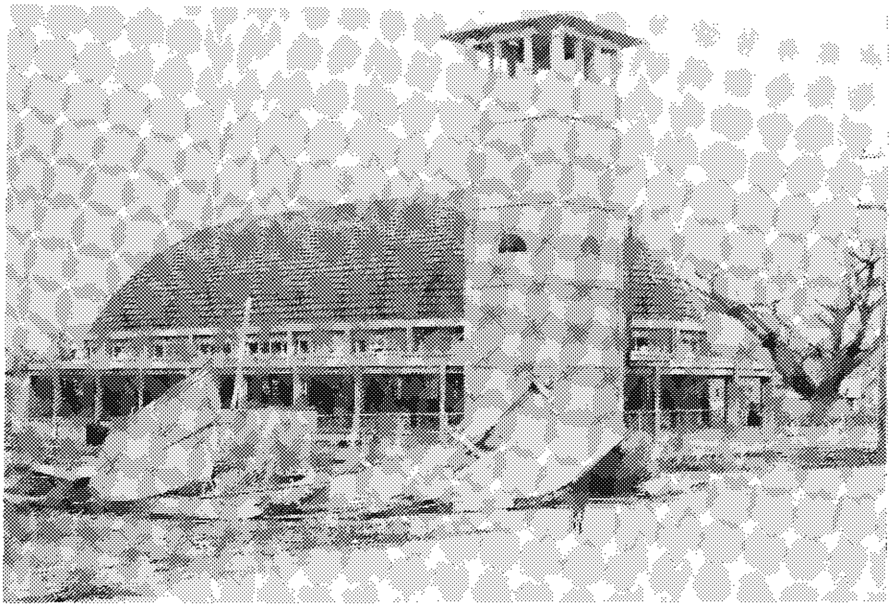


Figure 20. Undamaged church, north west Tongatapu.

Figure 21. Church at Pangai.

There were a number of secondary schools at the principal town of each of the three island groups. These buildings performed better than the similarly constructed churches and halls. On five separate occasions the authors observed roofing and roof battens blown off school buildings, but the trusses remained. Figure 22 shows this damage at Atenisi University (also surrounded by storm surge water) at Sopu, Tongatapu. Obviously the roof trusses were more securely fixed to the walls for school buildings than for some churches. Wall failure was not observed for school buildings. There would have been two factors contributing to this, the roof trusses tying the walls together and the internal classroom walls providing some bracing for the external walls.

6. EFFECTS OF STORM SURGE

As mentioned in Section 2, observations on Tongatapu by the authors have led to an estimation of storm surge height of about 1.7 metres above high tide. The surge crossed the road beside the beach at a height of about 0.6 metres.

The part most affected by storm surge was the village of Sopu, and surrounding areas, immediately to the north west of Nuku'alofa. This area had previously been swampland, but was settled in recent years by people migrating to the city from other islands. Its proximity to the city made it attractive.

The sea swept five houses from their stumps and carried them about ten or fifteen metres. Figure 23 shows one such house and the remaining stumps and steps. As is usual in a flood situation, the houses still appeared to be reasonably sound. They did not break up, although two had wall damage where they collided. All of these houses fronted the beach road. Apart from them, there appeared to be no other structural damage to houses from storm surge.

Some residents of Sopu reported the sea water rising rapidly in their houses, and reaching waist height in about fifteen minutes. The inundation reached approximately one kilometre inland in some places, although the average would have been considerably less, a few hundred metres. The sea water remained in some houses for up to three days, and even a week after the cyclone it still surrounded some houses built on very low lying areas, Figure 24. It was prevented from returning to the sea by a low mound running parallel to the road.

The surge would have occurred on low tide in the Ha'apai islands. This, together with the fact that small islands are less affected by surge, as

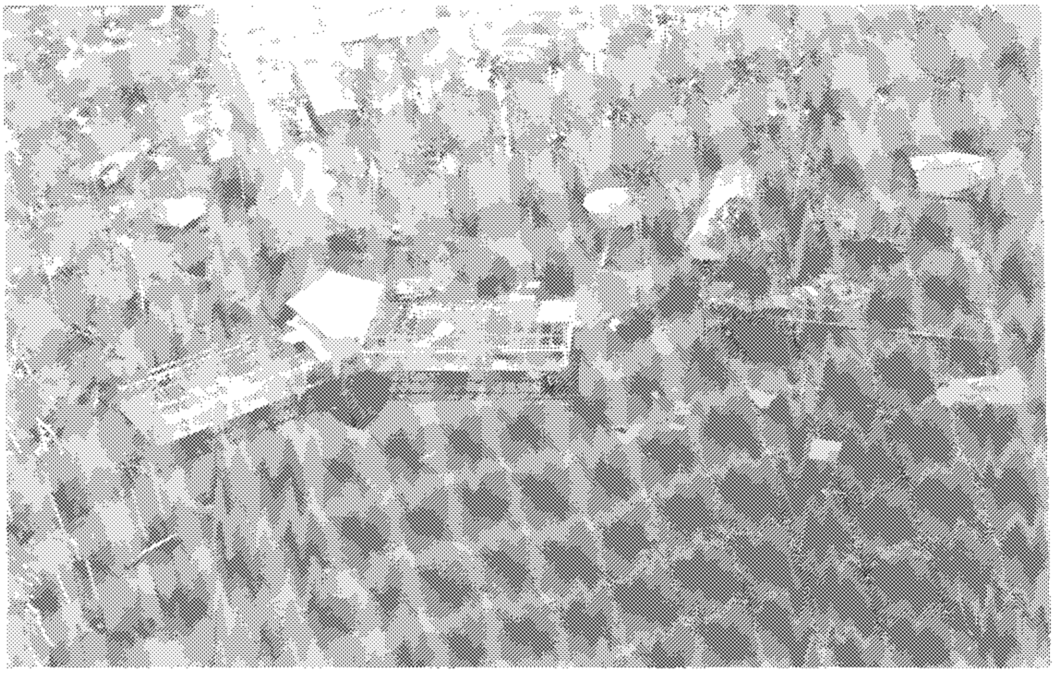


Figure 22. Loss of roof cladding, Atenisi University.
(By courtesy Tonga Chronicle)

Figure 23. House washed from stumps by storm surge.

the sea can circumvent the island, meant that surge was not a problem on the islands visited.

7. SOCIO-ECONOMIC EFFECTS

7.1 General

A comprehensive report on the effects of cyclone Isaac on the society and economy of Tonga has already been published by the authors (Oliver and Reardon, 1982) and therefore only a few brief statements will be made herein to complete the overall picture.

Remarkably, only six deaths and about 150 injuries were reported as directly contributable to cyclone Isaac. However, thousands were left homeless, food crops were destroyed and water polluted.

7.2 Shelter

Family ties are very strong in Tonga. Therefore many of those made homeless were welcomed into the homes of relatives who were not so seriously affected by the event. There were still many others who had to rely on international relief aid to provide tents as temporary accommodation. Tents are not a very satisfactory means of accommodation in a tropical environment, but they were the only means of providing shelter in a relatively short time. Of course there were some hassels as the tents sometimes arrived with an inadequate number of supporting poles or with the wrong types of supports, but these were only short term problems. On Tongatapu the tents were sometimes erected on the site of the damaged house, Figure 25, but preferably tent cities were established on well drained sandy areas. Two such camps were located at Sopu to house the victims of the storm surge. Electricity was supplied to these camp sites just two weeks after the event.

On some of the islands, relief shelter did not come quite so rapidly, although the Australian and New Zealand helicopter squads appeared to be doing a marvellous job supplying medical provisions, treating injuries and rectifying polluted water supplies. Possibly the bulkiness of tents slowed down their distribution. There were many cases of families in makeshift shelters assembled from building debris, or still managing in partly demolished buildings about two weeks after the event. There was no new building material available for repairs and so makeshift repairs were made using the

Figure 24. Surge waters still surround damaged house, one week after cyclone.

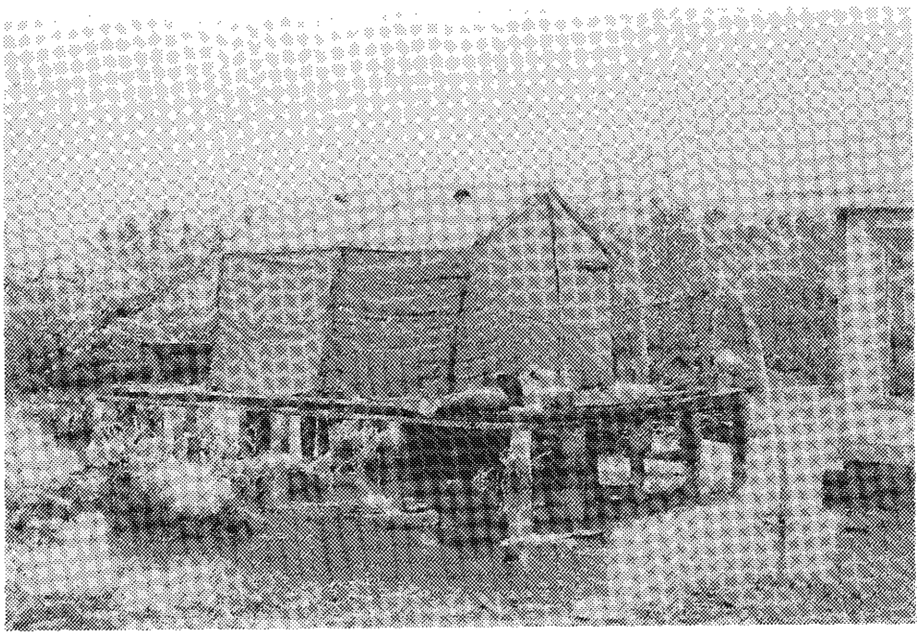


Figure 25. Emergency accommodation.

damaged material. There was also a serious shortage of nails and building tools.

Apart from shelter and building materials, other items needed were cooking utensils, blankets and kerosene for cooking and lighting. Most of these items were provided from international aid and the Red Cross.

7.3 Food

There was no shortage of food immediately after the event, in fact there was a surplus of windfall fruit, such as coconuts. However, the damage to fruit trees, coconut, breadfruit and banana, would seriously affect future crops. It was estimated that about one quarter of a million coconut palms were blown down, and the entire crop was wind damaged. Past experience has shown that full recovery from such an event may take from five to eight years. The damage to banana crops was quite high, with estimates of 90% blowdown in some areas. Replacement of this crop would take about nine months. Breadfruit trees were uprooted because of their shallow rooting system. About 60% of the crop was lost.

Pigs are the only livestock that play a significant part in Tongan farming, and there did not appear to be a significant loss of stock.

The Tongans gain protein from fish but the fishing industry was seriously affected by the cyclone. Not only were fish traps broken by the violent seas, but many boats were wrecked and outboard motors lost or damaged. Until other boats can be made or bought, and motors replaced, the Tongan diet may have to include even more carbohydrate. It is unlikely that sufficient fish could be caught from the shore to feed the villagers.

7.4 Water Supplies

In the areas where storm surge occurred wells were inundated, but the main water reticulation system on Tongatapu was not seriously affected by the cyclone.

On some islands there were serious problems and fresh water had to be transported in. Covers were blown off water tanks, allowing leaves and branches to be blown in or salt spray to pollute the supply. The problem was further compounded by tanks being blown off stands or by damage to gutters and piping feeding rainwater into the tanks. Thus even though it rained after the event the rainwater could not be efficiently collected to replenish supplies.

8. REBUILDING TO RESIST CYCLONE WINDS

8.1 Basic Concepts

8.1.1 General

The basic concepts of building to resist high winds, be they from cyclones, hurricanes, tornadoes or thunderstorms are the same throughout the world. The building must be constructed to resist uplift forces acting on the roof and lateral wind forces acting on the wall. The forces must be transferred from member to member and joint to joint until they reach the ground. If any member or joint does not have the capacity to resist the forces imposed on it, failure may occur. The consequences of this failure may be minimal or they may be catastrophic. It is the role of the person designing the building to ensure that for a given design wind speed, no failure occurs.

8.1.2 Hold down

The provision of a suitable hold down mechanism is an essential element in resisting wind uplift forces. In domestic construction the timber frame itself is usually sufficiently strong to be able to withstand the uplift forces, but problems occur with joints. A suitable chain of strength from roofing to foundations is illustrated in Figure 26 (Reardon and Aynsley, 1979). This is typical of that used for framed construction in the cyclone prone areas of Australia. Of course it demonstrates only one method of hold down, there are others that may be equally suitable. However the concept of securing one member to the other, or of capturing a number of members within the confines of one bolt is clearly shown.

In concrete masonry construction the blocks resist the gravity loads and the reinforcing is used to resist uplift forces. Full details of cyclone-resistant masonry construction have been published by Boughton and Reardon (1982). Figure 27, taken from that publication, gives details of a blockwork wall suitably reinforced to resist uplift forces.

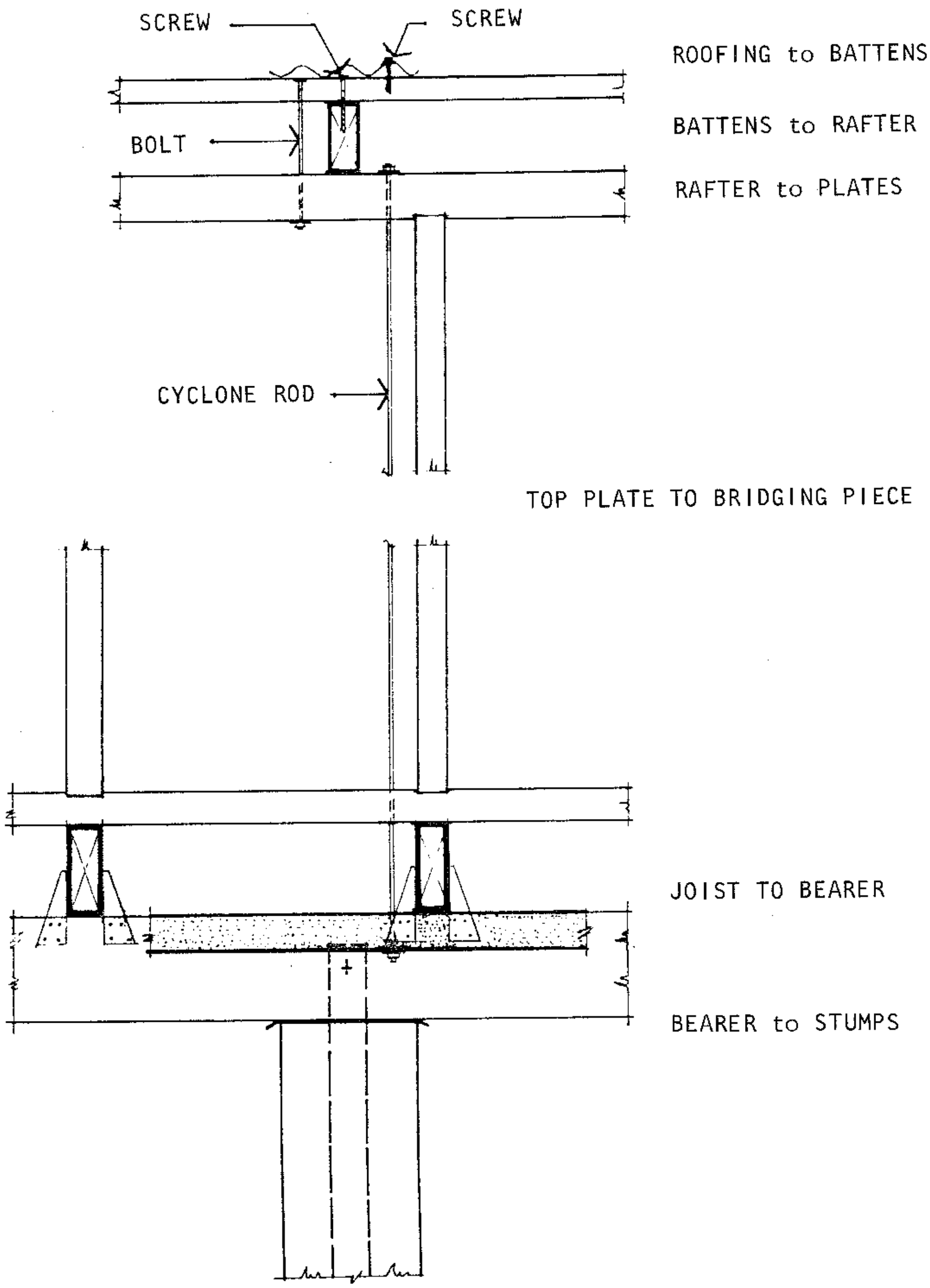
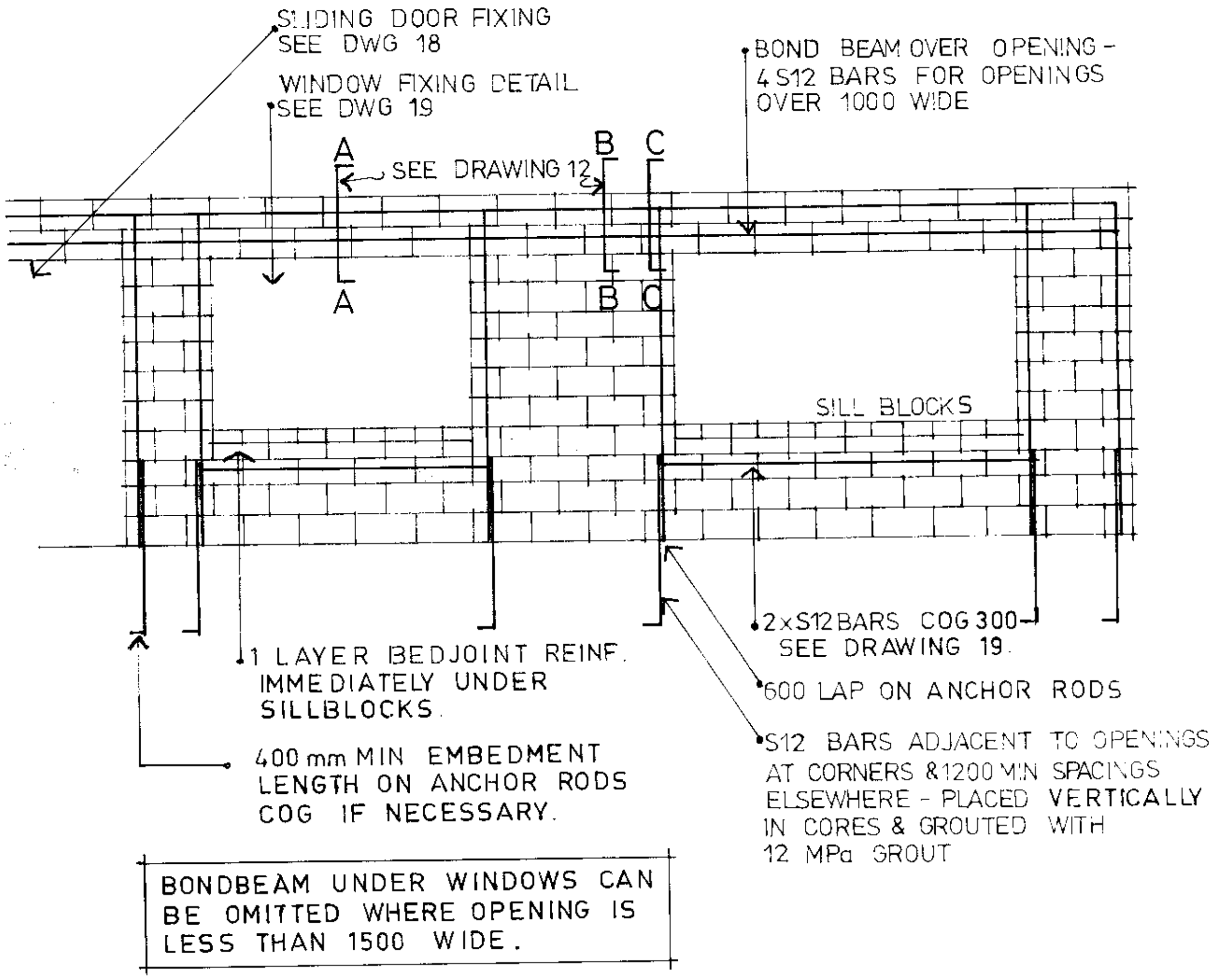


Figure 26. Typical hold down details.



DETAILS OF REINFORCEMENT IN OUTSIDE WALLS

scale 1:50

Figure 27. Cyclone resistant blockwork construction.

JAMES COOK CYCLONE STRUCTURAL TESTING STATION
CYCLONE TESTING STATION
Department of Civil and Systems Engineering, Post Office, James Cook University, Townsville, 4811. Telephones 814754, 814270

8.1.3 Bracing

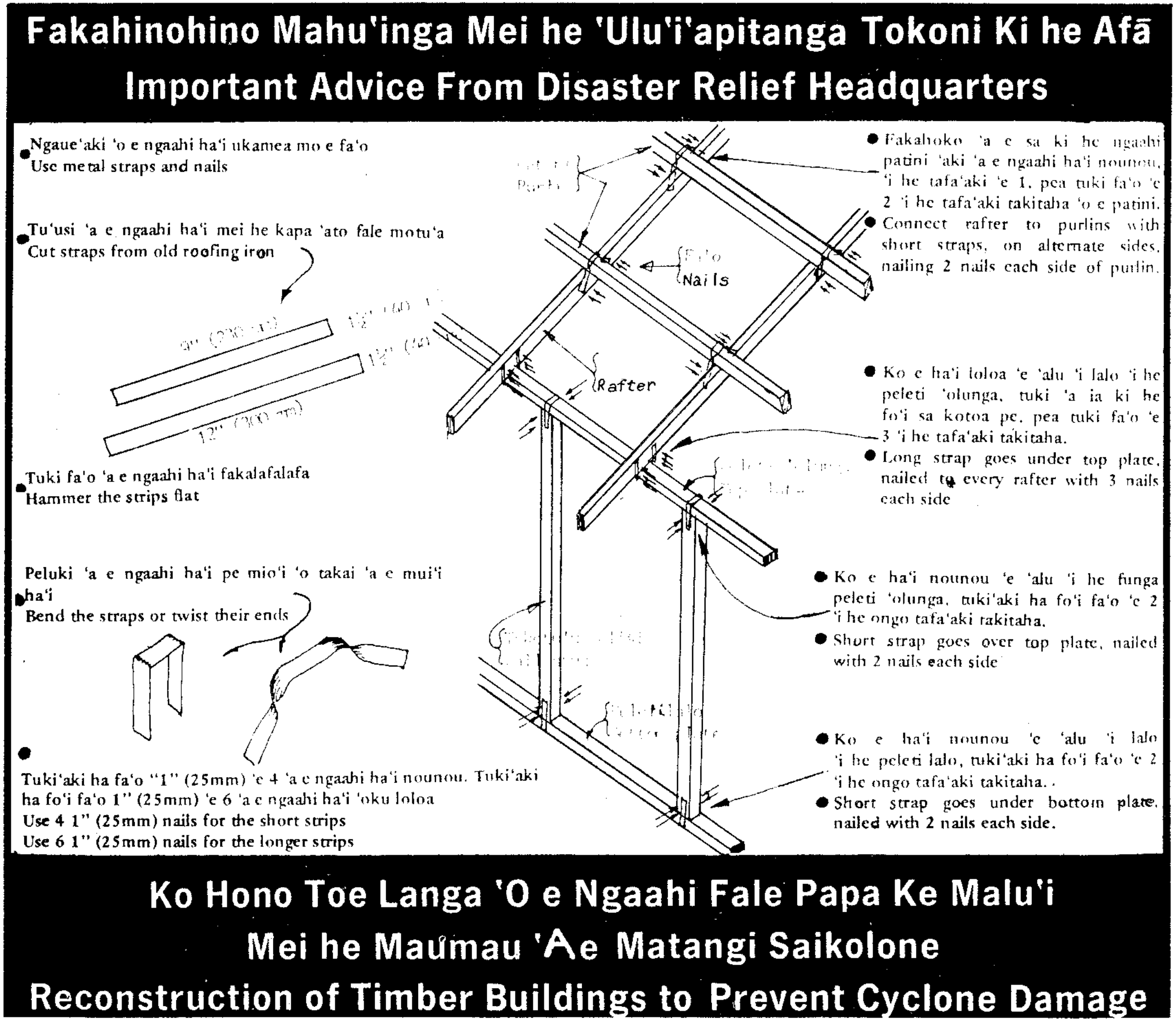
The horizontal forces caused by wind on a building must be transferred to ground by bracing members or bracing walls. An internal or end wall capable of bracing an external wall will prevent it from being blown inwards or sucked outwards. Bracing in the plane of the roofing or the ceiling is also quite important as this prevents external walls from bending between bracing walls.

The concept of bracing has always been part of building construction, but in recent years more emphasis has been placed on it, as examples of inadequate bracing have been observed in damage investigations, Walker 1975, Leicester and Reardon 1976. Generally the amount of bracing used by a builder to keep his frame square is insufficient to resist the horizontal forces generated by the design wind. There is a tendency in Australia towards the use of diaphragm bracing to resist wind frames, either by utilizing existing wall cladding or by introducing a diaphragm specifically to do the job. The diaphragm must be well fixed to the frame and special provisions made to resist overturning forces.

8.2 A System for Tonga

The authors were asked to produce some simple recommendations for use by the Tongans to reconstruct their damaged housing. They were published in the first edition of The Tonga Chronicle after the cyclone, Figure 28. The aim of the recommendations was to provide some relatively simple tie-down procedures which could be used as an interim measure until proper reconstruction could be implemented. With this in mind, the recommendation was made to cut the straps from old roofing iron which had blown off buildings but could not be re-used. It was estimated that the recommended strapping technique would be suitable for a house in a village when the wind speed measured by an airport anemometer would be gusting to about 180 km/hr, that is for a gust wind speed of the same order as that measured at Nuku'alofa during Cyclone Isaac.

It should be stressed that the above recommendations relate only to interim repairs. Whilst the concept is satisfactory for permanent repairs or new buildings, the use of straps cut from old steel roof sheeting is not recommended as a permanent measure.



Fakahinohino Mahu'inga Mei he 'Ulu'i'apitanga Tokoni Ki he Afā
Important Advice From Disaster Relief Headquarters

- Ngaue'aki 'o e ngaahi ha'i ukamea mo e fa'o
  Use metal straps and nails
- Tu'usi 'a e ngaahi ha'i mei he kapa 'ato fale motu'a
  Cut straps from old roofing iron
- Tuki fa'o 'a e ngaahi ha'i fakalafalafa
  Hammer the strips flat
- Peluki 'a e ngaahi ha'i pe mio'i 'o takai 'a e mui'i ha'i
  Bend the straps or twist their ends
- Tuki'aki ha fa'o "1" (25mm) 'e 4 'a e ngaahi ha'i nounou. Tuki'aki ha fo'i fa'o 1" (25mm) 'e 6 'a e ngaahi ha'i 'oku loloa
  Use 4 1" (25mm) nails for the short strips
  Use 6 1" (25mm) nails for the longer strips

- Fakahoko 'a e sa ki he ngaahi patini 'aki 'a e ngaahi ha'i nounou, 'i he tafa'aki 'e 1, pea tuki fa'o 'e 2 'i he tafa'aki takitaha 'o e patini.
- Connect rafter to purlins with short straps, on alternate sides, nailing 2 nails each side of purlin.
- Ko e ha'i loloa 'e 'alu 'i lalo 'i he peleti 'olunga, tuki 'a ia ki he fo'i sa kotoa pe, pea tuki fa'o 'e 3 'i he tafa'aki takitaha.
- Long strap goes under top plate, nailed to every rafter with 3 nails each side
- Ko e ha'i nounou 'e 'alu 'i he funga peleti 'olunga, tuki'aki ha fo'i fa'o 'e 2 'i he ongo tafa'aki takitaha.
- Short strap goes over top plate, nailed with 2 nails each side
- Ko e ha'i nounou 'e 'alu 'i lalo 'i he peleti lalo, tuki'aki ha fo'i fa'o 'e 2 'i he ongo tafa'aki takitaha.
- Short strap goes under bottom plate, nailed with 2 nails each side.

Ko Hono Toe Langa 'O e Ngaahi Fale Papa Ke Malu'i Mei he Maumau 'Ae Matangi Saikolone
Reconstruction of Timber Buildings to Prevent Cyclone Damage

Figure 28. Rebuilding advice given in the Tonga Chronicles 12-3-82.

During the damage investigation the authors noted a distinct lack of bolts in domestic construction. This could have been associated with the lack of electricity to building sites, and thus the need to use hand tools to drill holes. But as labour is far cheaper than materials on Tonga, it is more likely that the cost of bolts precludes their use. As they would have to be transported from some other country, the weight of bolts would make them far less competitive than light gauge steel straps and nails.

The following system is recommended as a guideline for future domestic construction. It is based on the same system as shown in Figure 28, the use of timber members and metal straps as joints. It does not mean to preclude any other form of construction of jointing medium. One of the basic assumptions is that the house will be in a village surrounded by other houses and trees, it will not be in an exposed position. The system assumes roof trusses 5 metre span and at 600 mm spacing, and timber wall studs at 450 mm spacing. The following points should be noted:

1. If the timber is a medium density hardwood, all members can be 100 x 38 mm. Battens may be 75 x 38 mm.

   Softwood timbers would need to be of larger cross section.

2. Metal straps may be used at all joints. The straps should be galvanized and be of 30 x 1 mm cross section (not old roofing iron).

   The nails should be 25 mm long and 2.8 mm diameter.

3. Fasten roof sheeting to purlins at every second corrugation.

4. Purlin/rafter joints are suitable with 2 nails at each end of the strap as shown in Figure 28.

5. Rafter/top plate joints are also suitable as shown, with 3 nails at each end of each strap.

   If the trusses are longer than 5 m span, or if they are spaced at 900 mm centres, two straps should be used at each end.

6. Top plate/stud joints may be made as shown, with two nails each end, provided that studs are spaced no wider than 450 mm and trusses are no further apart than 600 mm centres. Otherwise three nails per end may be needed.

7. Stud/bottom plate joints should be made the same as top plate/stud joints.

8. Bottom plates should be attached to the sub-floor structure adjacent to each stud, and in the same manner as the stud/bottom plate connection.

9. Bracing should be used frequently on all external walls and some internal walls.

It must be stressed that the points listed above are guidelines only. If implemented they will give a better cyclone resistance than was evident during cyclone Isaac. They must not be taken to represent "cyclone-proof" construction.

Some other recommendations for cyclone resistant construction (Reardon and Aynsley 1979, Eaton 1980, Boughton and Reardon 1982) have already been mentioned. A very comprehensive set of recommendations for Sri Lanka was produced by Wittenoom amd Macks (1979). Most of the details given in that publication would apply to the Tongan situation. Also the Fijian Public Works Department (1980) has produced a set of deemed-to-comply details which would be suitable for Tonga. Thus there are available a number of design recommendations and details that could be used as guidelines for the reconstruction programme in Tonga.

8.3 Upgrading Existing Structures

The authorities of Tonga, as with other governments of cyclone devastated cities, are now faced with the difficult task of having to assess the potential risk in future cyclones of buildings that were partly damaged by Isaac. This is not an easy task, but it certainly should be undertaken to prevent premature collapse of those buildings in future events, and the likelihood of flying debris.

After a cyclone there is always a rush to repair damage as quickly as possible. Sometimes interim measures are taken so that shelter can be obtained in a relatively short time. This is quite understandable, and recommended in the circumstances. However, interim measures are usually not to a standard required of cyclone resistant construction, and therefore need to be upgraded before the next cyclone season. The upgrading process is not easy, as it may require the temporary removal of roof sheeting to strengthen the roof structure. Similarly wall cladding may have to be removed to repair the wall structure.

Some buildings may be beyond repair. They should not be left derelict, but should be demolished to prevent them from disintegrating in future cyclones.

After an event such as cyclone Isaac, the provision of new building standards to which new buildings can be built is essential. But, of equal importance is the recognition of the hazard presented by partly damaged or scantily repaired buildings, and taking measures to reduce this risk.

9. CONCLUSIONS

Cyclone Isaac would not be considered a severe event by world standards. From the estimates of wind speed and central pressure it would probably be considered a moderate cyclone with a return period of about forty years.

As would be expected, engineered and marginally engineered buildings performed considerably better than domestic buildings, although most of the engineered buildings were at Nuku'alofa, away from the areas most severely affected by the storm.

The poor performance of domestic buildings reflects the need for suitable standards to which they should be built. There is no doubt that efforts were made to build sound housing but either a lack of knowledge or a lack of suitable building components, such as framing anchors, thwarted those efforts.

The Tongan government now has an opportunity to introduce building regulations, possibly in the form of deemed-to-comply details, so that new construction will be cyclone resistant. Examples of such details are readily available.

Due consideration should be given to restricting the rebuilding of houses in the surge zone, especially at the low lying Sopu area where the surge water stays trapped by the land formation.

10. REFERENCES

Boughton, G.N. and Reardon, G.F. (1982), "Blockwork House to Resist High Winds - Construction Details". Information Bulletin No. 3, James Cook Cyclone Structural Testing Station.

Eaton, K.J. (1980), "How to Make Your Building Withstand Strong Winds". BRE Seminar on Low-income Housing, St. Vincent. UK Building Research Establishment.

Leicester, R.H. and Reardon, G.F. (1976), "A Statistical Analysis of the Structural Damage by Cyclone Tracy". Civil Engineering Transactions, Institution of Engineers Australia, Vol. CE18, No. 2, pp. 50-54.

Leicester, R.H. and Reardon, G.F. (1976a), "Wind Damage in Australia - a pictorial review with particular reference to domestic and other low rise structures". CSIRO Division of Building Research.

Ministry of Works (1982), "Structural Damage Report Following Cyclone Isaac, Tongatapu Only", Tonga.

Oliver, J. and Reardon, G.F. (1982), "Tropical Cyclone Isaac: Cyclonic Impact in the Context of the Society and Economy of the Kingdom of Tonga". Centre for Disaster Studies, Disaster Investigation Report No. 5, James Cook University of North Queensland.

Public Works Department (1980), "Design Data for Light Timber Framed Construction", Suva, Fiji.

Reardon, G.F. and Aynsley, R.M. (1979), "Houses to Resist Cyclone Winds - Construction Details". Information Bulletin No. 1, James Cook Cyclone Structural Testing Station.

Smith, P.R. and Adams, R.H.T. (1980), "Domestic Construction Manual", Queensland Institute of Technology and Queensland Master Builders Association.

Standards Association of Australia (1979), "Draft Manual for Guidance on Construction of Houses in High Wind Areas", DR 77109.

Walker, G.R. (1975), "Report on Cyclone Tracy - Effect on Buildings", Vol. 1, Department of Housing and Construction.

Wittenoom, R.A. and Macks, K.J. (1979), "Design of Buildings for High Winds - Sri Lanka". Part 6 of Volume 3 of Technical Assistance to Sri Lanka on Cyclone Resistant Construction. Department of Housing and Construction.