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LOW-COST BUILDING MATERIALS AND CONSTRUCTION SYSTEMS

DP/RAS/82/012

Technical report: Seminar/Workshop on Typhoon-resistant Housing Designs and Construction Systems, Manila, Philippines, 10-16 December 1986*

Prepared for the Governments of the the Member States of the
Regional Network by the United Nations Industrial Development Organization,
acting as executing agency for the United Nations Development Programme

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SUMMARY

This seminar was highly successful in identifying common problems related to the design of housing in typhoon-prone areas within the network. It also provided instruction in ways to solve those problems and some limited practice in the implementation of the solutions. However, the application of solutions in each country can be facilitated by continued involvement of the regional network. The typhoon-resistant design housing for low-cost housing has the potential to save a large sum of money within the network in the long term, so it should therefore be pursued as actively as possible at present.

1.PURPOSE OF SEMINAR-WORKSHOP

The explicitly stated objectives of the seminar workshop were as follows:

- to provide a venue for participants from member countries to identify problems, issues and corresponding solutions related to typhoon-resistant housing design and construction systems.
- to familiarise the participants with the existing research development studies conducted by international organisations on typhoon-resistant housing designs and construction systems.
- to identify possible areas of training and research which can be undertaken to effect information exchange in technology transfer.

As the participants were drawn from member countries of the UNDP/UNIDO Regional Network in Asia for Low-Cost Building Materials, Technologies and Construction Systems, the purpose of the seminar was to meet these objectives as they applied to low-cost housing.

A further objective was stated in the opening session of the seminar/workshop and related to the form of output to be produced in the workshop sessions. It was highly desirable that the outputs be in a form that could be directly applied in each country either in continuing research and development or incorporated into future house designs.

As the seminar proceeded, it became obvious that the expectation of many participants and speakers was that this seminar workshop was to be the first step towards the establishment of appropriate methods of typhoon-resistant design and construction for housing and not necessarily an end in itself. This expectation seemed to be at odds with the objective alluded to in the previous paragraph. Never the less, the workshop sessions were structured to produce some typical structural details that could be incorporated into typhoon-resistant housing designs and would also establish a basis for continuing investigation.

In this way it became a possibility that both of the additional objectives mentioned above could be satisfied.

1.1 Structure of the Seminar-Workshop

The regional secretariat had programmed three full days of seminar activities, one day of site visits and two full days of workshop activities.

The seminar activities included the presentation of papers by each of the participants from the regional network to facilitate the identification of problems and issues related to typhoon-resistant housing, and the exchange of research findings within the network. A number of experts from the Philippines also presented the results of research activities within that country. Both the International Consultant and the National Consultant presented papers in the seminar session that led to the more practical aspects to be pursued in the workshop sessions.

Ample opportunity for questioning was incorporated in the seminar programme to allow free interchange of information between the participants.

The programming of the workshop sessions was left quite open to allow flexibility for the consultants in achieving the objectives indicated by the participants themselves in the opening session. The programming of the workshop sessions is presented in detail in Section 3.1.

1.2 Attendees at the Seminar/Workshop

Two participants from Touga
One participant from Fiji
Two participants from Sri Lanka
One participant from China
One participant from Bangladesh
One participant from Indonesia
Approximately 25 participants from the Philippines - these included research workers, designing architects and engineers and students of architecture.
Five invited experts from the Philippines
One National Consultant
One International Consultant
Four full-time supporting secretariat staff

2. INPUTS TO SEMINAR

As indicated in Section 1.1, the programmed input to the seminar consisted of papers from network representatives which largely presented the status-quo in participating countries; papers by experts from the Philippines which presented current and recent research activities; and papers by the consultants which provided technical information and background data for tyhoon-resistant design of housing.

2.1 Papers From Network Country Representatives

The papers presented by network country representatives all differed in style and format. In order to draw comparisons between the work presented by the representatives they have been interpreted below and treated under the following headings.

(a) scale of housing problem
(b) scale and type of damage by typhoons
(c) current plans for mitigation of damage to housing
(d) motivation to produce typhoon-resistant design
(e) building materials commonly available
(f) specific problems faced
(g) planned research activities

It is to be stressed that where these issues were not specifically addressed by the country representatives, the interpretation is that of the International Consultant.

2.1.1. Bangladesh

(a) Scale of Housing Problem

There is a very significant need for low-cost housing in this country. 80% of the population live below the poverty line and 65% below the extreme proverty line. Less than 4% of houses could be regarded as permanent structures, and there is a very significant shortage of skilled tradesmen and professionals to implement new housing schemes.

(b) Scale and Type of Damage by Typhoons

Bangladesh has experienced a large number of tropical cyclones, one of which has the dubious distinction of having caused the largest death toll of any tropical cyclone in recorded history. The reason for the large death tolls in this area is not the ferocity of the wind, but a combination of a large number of low-lying inhabited islands and significant storm surges causing inundation of land and houses. Most of the deaths have been by drowning. The problem is exacerbated by the fact that land is scarce, so newly risen islands are inhabited while still quite low. Also, people are reluctant to leave their belongings and property and seek refuge on higher ground.

(c) Current Plans for Mitigation of Damage To Housing

Currently government buildings are constructed in accordance with the East Bengal Building Code (1953). As a result, in most rural areas, schools can be regarded as permanent structures able to fulfil post-disaster functions. It is planned to embark on a 'nucleus house' construction programme, in which a typhoon resistant core is built for each family with floor level above twenty-three feet RL. This will be sufficient to provide basic shelter for family and belongings during the passage of a typhoon. Temporary structures can be added to the outside of the core to provide shelter for animals and additional rooms for accommodation.

(d) Motivation To Produce Typhoon-Resistant Design

The implementation of typhoon-resistant design seems to be a government initiative aimed at minimising the loss of life in typhoons. Most emphasis has been placed on ensuring that housing is located where storm surge damage can be minimised.

(e) Building Materials Commonly Available

The production of cement, lime, and bricks is energy intensive, so to minimise cost, the most common form of wall construction is mud brick for semipermanent housing and bamboo mats for temporary housing. Roofing is commonly thatch though corrugated steel sheets are being used on permanent and semipermanent buildings. Where possible, concrete walls and or roof are used for permanent buildings.

(f) Specific Problems Faced

The largest specific problem faced is the siting of houses to avoid storm surge, but maintain privacy and proximity to the agricultural land worked by the family.

With respect to design for wind, the materials available have some short comings. The mud used for walls deteriorates during the passage of typhoons and can crack when dry. Both of these effects cause loss of structural strength of the walls. Corrugated steel roofing is being used quite effectively but, training will be required to ensure that it is fastened in a manner that will prevent its loss in a severe typhoon.

(g) Planned Research Activities

Thin ferro-cement panels are being used to advantage in areas close the the major cities. At present transport of these panels to more remote settlements is a problem. Work will continue on the development of efficient building panels that can be produced under controlled factory conditions.

2.1.2. China

(a) Scale of Housing Problem

Housing in smaller settlements in the typhoon-prone areas seems to be at a high risk due to the lack of unified building standards, quality control and supervision in construction. As a result significant reconstruction must take place after the passage of some typhoons.

(b) Scale and Type of Damage By Typhoons

Significant damage to housing occurs during the passage of a strong typhoon with the pattern of damage being: damage to windows, then eaves and partial loss of roof. Some damage to walls may then occur followed in some cases by total collapse of the house.

(c) Current Plans for Mitigation of Damage To Housing

At present it does not seem possible to implement a nationwide code for typhoon-resistant housing due to the large variation in architectural and climatic requirements for housing from the north to the shouth of the typhoon affected area. As well, the nationwide variation in materials available for house construction means that implementation of a unified code will be difficult. However, a number of basic principles for construction have been identified which may lead to safer construction. These include limiting room and opening size to improve the integrity of walls, controlling the quality of masonry used, and incorporating ring beams tied to the foundations at each storey height.

(d) Motivation to Produce Typhoon-Resistant Design

At present inspections of damage following the passage of typhoons have indicated that general lack of structural integrity of houses has been a major contributing factor to the damage. The government has proposed the measures to reduce the level of damage in the future.

(e) Building Materials Commonly Available

These vary regionally, but frequently bricks or blocks are used to construct masonry walls. Some concrete walls are cast in-situ. Roofing materials show the greatest variation from flat concrete slabs (which generally perform well) to wooden roofs, bamboo, straw and tiled roofs.

(f) Specific Problems Faced

The main problem faced appears to be the implementation of some type of unified typhoon-resistant housing programme for the typhoon-prone coastline.

(g) Planned Research Activities

As much of the low-cost housing in China is multi-storey, considerable effort is being directed to solving wall stability problems. One possible solution is the use of pre-stressing to prevent crack formation in masonry. Continued research is being directed in this area.

2.1.3. Sri Lanka

(a) Scale of Housing Problem

The urban poor presents a very large problem for housing authorities in Sri Lanka. Provision of sanitation, safe water supplies as well as shelter are of paramount importance. Approximately half of the population in the urban areas lives in slum and squatter areas. In the five years (1977-1982) the government enabled the construction of 100,000 houses. Its current programme is for 1,000 000 houses.

(b) Scale and Type of Damage By Typhoons

Only three significant typhoons have made landfall in Sri Lanka this century, in 1907, 1964 and 1978. However, each of these caused significant damage to housing and other buildings on the east coast of the island.

(c) Current Plans for Mitigation of Damage To Housing

At present construction guides for typhoon resistant buildings are used only on government building, with private individuals or companies unwilling to spend extra money on the typhoon-resistant details necessary to comply with the manual.

(d) Motivation to Produce Typhoon-Resistant Design

The low frequency of occurrence of typhoons in Sri Lanka does not provide the public with an annual reminder of the need to incorporate structural details in housing as it does in other countries such as the Philippines, Fiji or Australia. As few home owners have insurance, it would require public recognition of the value of typhoon resistant design before it is incorporated in housing in a widespread manner.

(e) Building Materials Commonly Available

In the typhoon-affected areas the most common types of wall materials are wattle and daub, sun dried bricks and fired bricks although limited quantities of sand cement blocks are used. The most common roofing is cadjan (matted bamboo leaves) though tiles and to a lesser extent corrugated steel sheets are used. Timber usage is small due to the risk of termite and insect attack.

(f) Specific Problems Faced

The major problem appears to be the provision of housing for the urban poor. The government is assisting in the provision of land and loans to be repaid over 20 years for this programme. However, it seems unlikely that given the current economic constraints on owner-builders, they will voluntarily incorporate typhoon-resistant details in their houses.

(g) Planned Research Activities

The search for inexpensive building materials in continuing. Wattle and daub construction using jungle timbers has proved successful in the past and has demonstrated some resistance to the effect of typhoon winds. However, as jungle timber becomes scarce, the technique will become less common and unreinforced mud brick construction will become more popular. Ways must be found to make this type of construction typhoon-resistant.

2.1.4. Fiji

(a) Scale of Housing Problem

Unprecedented tropical cyclone activity in 1985 in Fiji has caused a rapid reappraisal of the structural safety of housing in Fiji.

(b) Scale And Type Of Damage By Typhoons

On average Fiji can expect 1.1 typhoons per year, however, recent years have shown many times that number. (There were five tropical cyclones in the Fiji group in 1985.) The recent cyclones have caused significant wind damage to western style housing and the traditional boorees alike.

(c) Current Plans For The Mitigation Of Damage To Housing

The Fiji Building Standards Committee has been formed to frame a national building code. This will provide design and construction information that will enable the use of local and imported materials in housing and other buildings in such a way that they can resist tropical cyclone winds with minimal damage. A publication - "Our War Against Cyclones" - has already been published and contains design criteria that will help to make houses cyclone resistant.

In order to ensure that the quality of workmanship is satisfactory, at present an engineer must provide a design certificate and a letter of completion for each house which indicates that it has been competently designed for appropriate winds and constructed in accordance with the design.

(d) Motivation To Produce Typhoon-Resistant Design

In Fiji the main motivation for the production of a national building code has come from the insurance industry. At present all houses for which a loan has been taken must be insured, and the insurance pay out in 1985 was substantial. Thus insurance companies have a vested interest in the improvement of the structural performance of housing in typhoon winds.

(e) Building Materials Commonly Available

Concrete blocks are currently manufactured in Fiji with the block manufacturers belonging to an association that ensures standards of quality are met. Also timber, both imported and locally available is used as wall framing with plywood cladding. Some thatch is still used as a wall cladding material. Roofing materials most commonly used include rolled galvanised steel sheeting (minimum thickness 0.42mm) and thatch.

(f) Specific Problems Faced

The development of an appropriate national building code is the most immediate problem at present. Development of engineering properties for locally available building materials will reduce the current dependence on imported building materials.

(g) Planned Research Activities

Although no building system research facilities currently exist in Fiji, it is planned to make use of Australian and New Zealand expertise to assist with the production of the building code.

2.1.5. Tonga

(a) Scale Of Housing Problem

Tonga has recently completed a large scale reconstruction programme following widespread damage to housing caused by tropical cyclone Isaac in 1982. The programme took two years to implement and has produced over 1200 replacement houses that have been designed and constructed to resist winds from tropical cyclones. Housing programmes are often hampered by a lack of capital and skilled labour. Generally, there is no shortage of unskilled labour.

(b) Scale And Type Of Damage By Typhoons

In the most recent tropical cyclone, both western and traditional (fale) types of housing were extensively damaged. Some storm surge damage occurred in low lying areas. As the kingdom of Tonga consists of a large number of small islands, many houses have very exposed conditions. In general, because of the coral origins of the islands there are few high locations and many houses are at risk from storm surge.

(c) Current Plans For Mitigation Of Damage To Housing

The current redevelopment programme has utilised a single engineered design of a two room, timber framed, plywood clad house which will provide basic shelter for a family in the event of another typhoon. The house can be used as the basis for an enlarged dwelling by extending it to include an enclosed kitchen or extra rooms. The standard house was tested using simulated tropical cyclone loadings at a full scale house testing facility located at Townsville, Australia. During the course of testing, one type of connection was found to be deficient. The house was subsequently modified, retested and found to be able to resist the design cyclone with minimal damage, which was mainly confined to the internal partition.

(d) Motivation To Produce Typhoon-Resistant Designs

The impetus for the current programme was provided by the large scale damage to buildings by tropical cyclone Isaac and the programme was enabled by contributions from a number of sources including the British Building Research Establishment, the New Zealand Government and the Australian Development and Assistance Bureau.

(e) Building Materials Commonly Available

The traditional fale construction utilized coconut palm leaves, local timbers and cane and bamboo. Western style buildings utilize almost exclusively imported building materials. Framing timber, plywood and fibre cement cladding, galvanised steel strap and roofing materials as well as nails and bolts must all be imported. Cement must also be imported.

Western styles of housing have been widely accepted due to the large number of Tongans that have migrated temporarily to Australia or New Zealand and returned. These people have become familiar with a Western lifestyle. Also, education using Western books and programmes has had sociological effects on professionals and the population in general which has led to the acceptance of Western housing.

(f) Specific Problems Faced

The high cost of imported building materials (currently 70% of the total house cost) could be reduced if suitable locally available alternatives could be found. Coconut timber is suitable if protected, but even so there can be problems with those parts buried in the ground or continually exposed to the elements.

There is a general problem with lack of experience and training in the use of imported materials.

(g) Planned Research Activities

Lack of research facilities in Tonga will hinder progress and more work needs to be performed on the determination of engineering properties of locally available products.

2.1.6. Indonesia

(a) Scale Of Housing Problem

Indonesia needs approximately 700,000 new houses each year to cope with its increasing population and to rehouse those currently in sub-standard accommodation. The wide variety in architecture throughout the nation introduces complexities to this task.

(b) Scale And Type Of Damage By Typhoons

Typhoons do not regularly occur in any part of Indonesia. Never the less wind squalls associated with thunderstorms have cuased damage to housing in the past.

(c) Current Plans For Mitigation Of Damage To Housing

Poor connection details have been identified in many of the houses recently damaged by wind. Also where no preservation is used on structural timbers, insect activity can lead to loss of material and hence strength. These problems must be addressed if wind damage to housing is to be lessened.

(d) Motivation To Produce Typhoon-Resistant Design

This item is not applicable to Indonesia.

(e) Building Materials Commonly Available

Extensive use is made of blocks in Indonesia. The constituents of the blocks varies throughout the nation, but lime, cement or pozzolana is used as a binder with sand or gravel as a filler. Frequently these blocks are much cheaper than clay bricks. Pulp cement board is also used as a wall material. Roofing is frequently made from ceramic tiles, cement tiles, corrugated asbestos cement sheeting or corrugated steel sheets.

(f) Specific Problems Faced

The main problem facing the development of housing systems in Indonesia is that of finding suitable low-cost building materials that are also durable.

(g) Planned Research Activities

The main research effort will be directed to finding low-cost durable building materials. This includes investigation into lightweight aggregates, pulp cement boards, design for earthquakes and investigation of soil-cement blocks.

2.2. Papers Presented By The Philippine Consultant And Other Experts from the Philippines.

As these papers are all available in published form, the comments in this subsection are by no means exhaustive but serve to put each paper into the general context of the seminar workshop. Some specific references drawn on by the international consultant during subsequent sessions are also highlighted.

2.2.1. Climatology

The fact that the Philippines is the most typhoon-prone nation in the world remains undisputed. Indeed, the Philippines seems a most appropriate location for a workshop such as this. Bawagan (1986) and R. Kintanar (1986) both referred to the annual frequency of typhoons in the Philippines meteorological region.

However, R. Kintanar made the point that typhoons in themselves are not disasters, rather it is the way our structures are damaged by them that makes a disaster out of a typhoon. Other problems can be caused by the immense volume of rain dumped by a typhoon, even though this rainfall is required by many areas to support agriculture.

Much climatalogical data is available in the Philippines, as it is for many other countries, however it is frequently not in a form that can be readily used by engineers and architects to formulate design guidelines for implementation by builders.

2.2.2 Housing In The Philippines

A number of speakers mentioned problems faced by housing authorities in the Philippines. These will be treated under the same headings used for the papers presented by network country representatives. The comments were drawn from the following papers: Bawagan (1986), Q Kintanar (1986), Tabujara (1986), Siopongco (1986).

(a) Scale Of Housing Problem

As of June 1984 the housing backlog in the Philippines was estimated at 1.2 million units. Projections over the next five years show that an additional 600,000 housing units will be required in urban areas and 1,200,00 will be required in rural areas. Also slum redevelopment programmes are in progess in the major cities.

(b) Scale And Type Of Damage By Typhoons

On average, 9 tropical cyclones per year cross the Philippines coastline of which 4 cause significant damage to housing and buildings. The accompanying rain from these events flooding of river basins can occur. The combined effects of flooding and structural damage cause hundreds of deaths each year and render thousands of people homeless.

(c) Current Plans For Mitigation Of Damage To Housing

Slum redevelopment programmes are aimed at replacing high risk shanty structures with low-risk housing complete with adequate sanitation and services. Also a self help book in Tagalog has been produced which shows construction details for small timber framed houses - "Sariling Sikap Sa Pagtatayo ng Bahay".

(d) Motivation To Produce Typhoon-Resistant Design

Various government agencies concerned with housing have, as part of their main objectives, the provision of safe low-cost housing for all income groups in the Philippines. It is sound economic management to ensure that government housing has minimal maintenance.

(e) Building Materials Commonly Available

The most common wall material used in government sponsored housing is hollow concrete blockwork with reinforcement and filled cores. For other housing, timber or bamboo framework provides a basis for plywood or bamboo matting cladding. Roofing in urban areas is almost universally corrugated galvanised steel sheeting. In rural areas nipa or cogun grass is the main type of roofing used.

(f) Specific Problems Faced

The provision of safe but low-cost housing for very low income earning families is the largest single problem faced by the nation. Education in the use of modern materials such as corrugated galvanised steel sheets is required. The evaluation of engineering properties of traditional materials such as bamboo, nipa and cogun is requred to develop recommendations for the use of these materials in typhoon-resistant housing.

(g) Planned Research Activities

Continuing research is planned into the use of alternative building materials, particularly those that utilize agricultural waste products or those such as coco wood that are currently available. Suitable low-cost housing for rural and urban areas needs to be developed using the structural properties of readily available local materials such as bamboo, nipa and cogun grass. Typhoon resistant trees are being sought to for use as reliable shelter around otherwise exposed houses.

2.2.3. Basic Principles of Wind Engineering

A number of speakers indicated the steps to be followed in the engineering design of any structure subjected to wind loads. The processes were outlined by Tabujara (1986) and R. Kintanar (1986) and quantified by Manahan (1986a, 1986b, 1986c).

The basic steps are as follows:

- Selection of design wind return period
- Selection of design wind speed
  (This is a function of climatological data, the height of the structure, the terrain in which the structure is located, and the topography in the vicinity of the structure).
- Conversion of design wind speed to pressure.
- Use of geometry of the structure to determine pressures on external and interal panels of the building.

Once these steps had been followed it was possible to undertake detailed structural analyses of housing to determine member and connection loads.

De Castro (1986) also outlined gust response factor methods and wind tunnel testing that could be used to determine wind loads on larger and more expensive structures.

2.2.4. Materials Used In The Building Industry In The Philippines

A wide variety of materials are used in domestic construction in the Philippines and many of these materials were outlined by the speakers.

Siopongco (1986a) gave a comprehensive coverage of the use of timber in housing. This included not only the use of timber structural members but also timber panelling, doors and floors. Some typical methods of providing connection between timber members were also illustrated. There are many species of timber native to the Philippines and engineering properties are not yet available for all of these.

Siopongco (1986b) reported on the state of the art with respect to bamboo construction. Engineering properties of bamboo are available for some of the more commonly used species. Connection details that have been traditionally used in bamboo construction need to be evaluated for strength to enable engineered designs of bamboo housing to be produced. Familiarity with bamboo construction techniques and the widespread occurrence and rapid growth of bamboo made its use for housing an attractive proposition if questions of strength and durability of the material can be resolved.

Lazaro (1986) discussed the use of masonry in housing. The most commonly used masonry construction method used in the Philippines is hollow concrete block construction. Lazaro's paper contained a number of sketches of details which showed effective methods of reinforcing masonry in such a way that it can resist typhoon and earthquake loadings.

2.3. Papers Presented By The International Consultant

Four written papers were prepared in advance of the seminar workshop without any knowledge of the other papers to be presented. The full text of these papers is included in Appendix A. Their titles are -

"Design Philosophies for Tropical Cyclones"
"Design Criteria for Tropical Cyclones"
"Structural Design of Housing for Tropical Cyclones"
"The Structural Response of a Tongan Hurricane House to Simulated Cyclone Loading"

2.3.1. Presentation Of The Papers

The presented papers differed from the written papers for two main reasons. A number of salient points presented in the papers were also covered by other speakers and the time available for the presentation did not permit a complete presentation of all the written material. Further, in order to comply with the availability of visual aids the presentation was divided into two parts, one relying on 35mm slides and the other on an overhead projector for visual effect.

(i) Slide Presentation

This made use of photographs of damaged houses, suitable cyclone-resistant connections and details, and highlighted line drawings to illustrate the result of the use of poor details, appropriate details to use to prevent damage and the importance of each and every structural element in housing.

The first slides introduced the phenomenon of tropical cyclones and the locations in Asia and the Pacific in which typhoons can form and cause problems. The meteorological properties of typhoons were contrasted with those of tornados. The large size and slow movement of a typhoon system means that buildings can be subjected to very strong winds for up to eight hours, during which time the wind may undergo significant changes in direction.

The concept of regional design speeds was introduced and related to the Saffir-Simpson Scale. In this way meteorologists could be asked to determine typhoon intensity for a given location and return period. The Saffir-Simpson scale could then be used to relate the central pressure to a design wind speed.

The effects of topography were demonstrated and the importance of designing a structure for a wind speed appropriate to its position in the topography was stressed. Likewise the protection offered by trees was called into question and the categories of exposure were illustrated with slides of damaged houses after the passage of a typhoon.

The wind speeds were related to load effects by further examination of damaged houses and illustrated on cardboard models of houses. Both the slides and the models were used to illustrate the high uplift on roofs near gable ends regardless of the roof slope. The aerodynamics of the whole house were then illustrated to explain the origin of all panel pressures on the external surface. Particular attention was paid to fluctuations in load on all suction surfaces.

The issue of debris in urban or semi-urban environments was then addressed. Only two design alternatives exist - the use of strong, tested storm shutters to protect openings; or the use of full internal pressure in the design of all elements in the house.

It was noted that once the loads had been determined on the whole building, the structural action of housing in transmitting these loads through structural elements within the building to groundis very complex. The structural integrity of a whole house is frequently only as good as that of its weakest element. Slides were then used to illustrate the effects of all elements in the house.

- Roofing fasteners are required to resist highly fluctuating uplift loads. Fatigue failures have been observed in roof sheeting at fasteners where an insufficient number of fasteners has been used.

- Batten fasteners must carry high uplift loads to the rafters. There is little point in securing the sheeting adequately to the battens if the battens themselves are not adequately tied down.

- Rafters or the roof structure must be adequately connected to the top of walls. The roof structure not only performs an important role in providing shelter, but is also required to provide stability to the top of walls. This dual role was illustrated using both slides and a cardboard model.

- The walls themselves must also be tied adequately to the foundations.

- Stability of the structure as a whole must be ensured by designing foundations with sufficient weight to resist the combined effects of uplift and overturning.

- The lateral load chain of strength was treated in a similar manner to the uplift load chain of strength. Strength of claddings and studs in bending needs to be considered. This is particularly true for glass panels in windows.

- The loads transferred by the studs to roof level must be carried by bracing in the plane of the roof. In many cases the roof sheeting itself can mobilise the bracing resistance but, in other cases either ceiling diaphragms or special bracing must be used to carry lateral loads to bracing walls.

- Bracing walls must be fastened to the roof structure with a stiff connection to effectively transmit loads from roof level back into the wall structure.

- Bracing walls must have sufficient strength to carry loads to ground without failure.

- Where elevated housing is employed, additional bracing between floor level and ground level must be incorporated in the structure.

(i) Presentation Using Overhead Projector Transparancies

Copies of the overhead transparancies used in the presentation are included in Appendix B.

This session presented a number of practical steps that must be implemented in the preparation of typhoon resistant design. The basic starting point is the determination of design criteria. In presenting their country papers many participants indicated that their design criteria had been borrowed from other countries, either the U.S., Australia, New Zealand or the U.K. This should be regarded as a temporary measure only as climatic conditions in the member countries in many cases differ quite markedly from those in the U.S., U.K., New Zealand or Australia.

In choosing an appropriate design return period, the statistical nature of typhoon occurrence must be recognised. By designing typoon-resistant housing, we are increasing the time interval between expected major repairs after the passage of typhoons. Unforseen circumstances, and the finite probability of the occurrence of a typhoon more intense than the design event, mean that it is possible that damage can still occur to a house that incorporates typhoon-resistant design. The level of damage that can be tolerated for the type of structure and location must be determined. This will be a function of community expectation, the type of structure, and the economy of the district. The frequency that this damage may be accepted must also be determined. For example if the structure incorporates a roofing material with an average life of ten years and the level of damage tolerated is slight damage to roofing only, then it seems unreasonable to design the building for a fifty year return period event. Possibly twenty years is more appropriate.

Until these decisions have been made, it is impossible to determine a design wind speed. Once the return period of the design typhoon has been determined, local meteorologists can estimate the intensity of the design typhoon. This will often be most easily presented as a central barometric pressure. The Saffir Simpson Scale can be used to determine an appropriate design wind velocity for the region.

This design wind velocity can then be used as a basis for the typhoon-resistant design of structures by conventional methods.

The importance of involving government, insurance industry personnel and community representatives in the making of design criteria decisions was stressed. Prior to investing valuable time in the design process, all interested parties must agree on the design criteria to be adopted.

The design process is one that can vary for different types of structures and three different approaches were briefly outlined.

(A) The first related to large engineered buildings in which the value of the building warrants a very detailed wind load study. An appropriate wind speed may be determined for each building based on the type and role of the building and on the results of mathematical models or wind tunnel tests on the topography in the vicinity of the building. The aerodynamics of the building may also be determined by wind tunnel tests. These tests can be used to determine wind loads on the structure, with detailed structural analysis being used to determine the loads on individual elements. The individual elements can then be designed for optimal performance at minimum cost. This type of process minimises material cost but at a significant investment of engineering effort. It is quite appropriate where material costs are high such as large commercial buildings, but quite inappropriate where material costs are low, such as houses.

(B) This method is most appropriate for small buildings which are to be mass produced. In this case a regional wind velocity would be used with wind code information to produce a wind speed at building height for an appropriate topographic description and exposure. The wind loads would be determined in accordance with a wind code and a crude analysis performed to determine the loads on elements, each one of which would be structurally designed.

This technique was used to design the Tongan hurricane house which was mass produced 1200 times. The technique calls for significantly less engineering input than that required by (A), however, it still enables material costs to be kept low without necessarily being optimal. It is quite compatible with the level of supervision expected on government housing sites.

(C) This method requires that all engineering input be directed in advance to the preparation of a manual which contains safe, tested design details for buildings of a stated size, in an appropriate category of exposure in a given region. The details would have been designed for the worst possible case within the scope of the manual. A prospective builder then decides which manual to use based on house size, exposure and region, then incorporates the structural details therein in the structure of the house. The application of the method to any one house requires no engineering input, but if corectly applied, the manual may produce some conservatism in the details which is quite compatible with low levels of supervision expected on many housing sites. This method is certainly the most flexible to apply, but it does require significant engineering and architectural input in the preparation of manuals.

The remainder of the session related to the practical implementation of typhoon-resistant housing designs. The steps for production of a typhoon-resistant design procedure included -

- choice of a design ultimate wind speed
- choice of a design process as indicated above
- * choice of appropriate details
- * testing of details
- * production of manuals
- training of supervisors

continuing evaluation of designs and design method

* indicates steps to be followed if design process (C) is chosen for the implementation of typhoon resistant design.

In the presentation, the importance of testing all of the details published in manuals was stressed. Also, considerable emphasis was placed on the continuing evaluation phase of the implementation. Further experience must be scientifically evaluated and lessons learned incorporated in the manuals or code.

Finally, in this presentation the cost of typhoon-resistant design was qualitatively examined. In Australia, the extra typhoon-resistant features add 5% to 10% to the cost of the building. In network member countries the cost may in some instances be higher due to the lower material and labour cost in the basic house and the higher cost of the generally imported, typhoon-resistant details. However, the point was made that typhoon-resistant construction represents an investment that should be offset against reconstruction costs following the passage of future typhoons.

3. INPUTS TO WORKSHOP

For the conduct of the workshop, the participants were divided into three groups. Each group contained participants from two overseas network countries, some delegates from the Philippines and some architecture students.

There were four programmed sessions which were programmed as indicated in Section 3.1.

3.1 Workshop Programme

Session 1.

8.30am - 9.00am	Briefing
9.00am - 9.15am	Address by International Consultant on design criteria.
9.15am - 10.15am	Group discussions on criteria to be used for - (i) large commercial/public buildings (ii) small shops/houses from modern materials (iii) small shops/houses from traditional materials.
10.15am - 10.30am	Address by International Consultant on implementation methods.
10.45am - 11.45am	Group discussion on implementation methods.
11.45am - 12.00noon	Report back, complete questionnaire for sessions 2 and 3.

Session 2.

1.30pm - 1.45pm	Address by International Consultant on typhoon-resistant details using modern materials.
1.45pm - 3.00pm	Preparation of details for timber construction.

3.00pm - 3.15pm	Break
3.15pm - 4.30pm	Preparation of details for masonry construction
4.30pm - 5.00pm	Report back on group progress

Session 3.

9.00am - 9.15am	Address by International Constultant on typhoon-resistant details using traditional materials.
9.15am - 10.30am	Preparation of details using coco wood, bamboo, cogun.
10.30am - 10.45am	Break
10.45am - 11.45am	Preparation of details using soil blocks etc.
11.45am - 12.00noon	Report back on group progress.

Session 4.

1.30pm - 1.45pm	Address by International Consultant on panel systems (requested by some delegates).
1.45pm - 2.15pm	Address by International Consultant on practical ways to implement typhoon-resistant design manuals.
2.15pm - 3.30pm	Group discussion on preparation of manuals
3.30pm - 3.45pm	Break
3.45pm - 4.00pm	Report back on group progress.
4.00pm - 4.30pm	Summaries by International Consultant and National Consultant.

Throughout the workshop discussion sessions, the National Consultant, Professor Geromino Manahan, the International Consultant, Mr Geoffrey Boughton and Dr Joachim Siopongco of Forest Research and Development Institute Products, were available as resource persons.

3.2. Session 1 - Design Critera and Implementation of Typhoon Resistant Design

The principle aim of this session was to assist delegates in understanding that typhoon-resistant design must be approached systematically, and was in fact, a decision making process. The technical decisions about detail geometry and materials that designers are used to making are the last decisions to be made.

Typhoon-resistant design is not an end in itself but, is one way of ensuring that money is effectively spent to improve the standard of living and accommodation for the populations of the countries represented. To illustrate this, a parallel was drawn between the decision processes involved in writing a cake recipe and the production of typhoon-resistant designs for housing.

The process of determination of design criteria was then addressed by each country representative. They had to decide on the -

- basic housing problem facing their country
- basic aim
- specific housing problems
- appropriate architecture
- level of damage tolerated
- frequency of damage deemed acceptable
- realistic cost of housing

For the second part of this workshop session, the aim was to concentrate on implementation of typhoon-resistant designs for different types of buildings. By including large commercial buildings as well as small houses, it was hoped that the design processes of each type of structure would be contrasted.

The main output from this session was a list of manuals needed for each country with some sort of assignment of priorities. Certainly the number one priority should have been highlighted.

At the conclusion of workshop Session 1, a questionnaire was distributed to all country representatives. This questionnaire drew on the activities of the first session and provided information that would enable subsequent design sessions to be directed at specific structures for each country.

In the questionnaire, each representative was asked to furnish the following information for a typical low-cost house of modern materials and one constructed from traditional materials:

- return period for design typhoon
- exposure condition most commonly encountered in typhoon-prone areas.
- basic geometry of the house which included floor height above the ground, height of walls, length of house and width of house.
- materials for walls
- materials for roof
- batten spacing
- rafter spacing

3.3. Session 2 - Typhoon-resistant Details Using Modern Materials

Prior to this session the results of the questionnaire were processed. The design typhoon return period was used to guess a design typhoon intensity and hence a wind speed. The Australian wind code AS 1170-II (1983) was then used to produce a structure height wind speed from the given exposure condition. This in turn was used to calculate loads on the panels of the house again using AS 1170-II (1983). A very rough structural analysis produced element loads which could then be used in the following session to choose appropriate details for each of the structural elements.

It is to be noted that this exercise was indicative only. Appropriate design criteria will have to be established by much more rigorous methods prior to the performance of actual designs. Also materials available for each country will have to be tested to determine strength of connections. Every effort was made to ensure that the loads were close to those likely to be encountered in each participant's country for this exercise, however it must be repeated once true design criteria are known.

The chains of strength for each house were detailed and for each connection in the chain, loads were matched against available strength in commonly used details. For timber, these connections included nails in direct withdrawal and nails loaded in single shear.

For masonry construction, no attempt was made to quantify the strength of walls due to the wide variation in mortar and block strengths used.

Rather emphasis was placed on the need to provide continuity of reinforcement to resist not only uplift but also latera loads.

3.4 Session 3 - Typhoon-Resistant Details Using Traditional Materials

No attempt was made to quantify the performance of these materials, but again attention was drawn to the need to provide a continuous chain of structural strength to carry both uplift and lateral loads from the extremities of the building to the ground.

The loads on the indivudual connections in these houses were calculated for each country and the following points made. Because of the lower life span of these structures, generally lower return periods were chosen for the design typhoon. This indicated that in any one typhoon event, more damage would be tolerated in buildings constructed of traditional materials than for those constructed of modern materials. Lower regional design wind speeds for houses built with traditional materials were produced than for buildings constructed from modern materials in the same area.

However, whereas houses constructed from modern materials are generally located in suburban or urban settings and hence can be considered as sheltered, houses that are constructed from traditional materials are frequently in rural settings and are often exposed on at least one face. The difference in exposure conditions in many cases meant that the actual structure height design wind speed was higher for the traditional housing than for that constructed from modern materials.

The smaller size of the houses constructd from traditional materials and closer member spacings meant that the element loads in these houses were frequently less than the equivalent element loads in houses constructed from modern materials.

There is a clear need for engineering data on the strength and stiffness of connections in traditional materials such as bamboo or bundled reeds to enable the process of design to continue to the selection of details.

The workshop session consisted of an exercise in sketching typical details that provide structural continuity within the house. It remained to test these details with materials appropriate for each country to determine their structural suitability.

Where details are found to be unsuitable it may be possible to improve their performance by using a more secure fastening or by reducing element loads by reducing spacing between similar structural elements.

Likewise, for detailing of walls from earth bricks, mud, wattle and daub, no attempt was made to provide quantitative designs due to the paucity of strength data on those materials. The workshop session was again qualitative, and produced sketches showing structural continuity between walls, between the walls and the roof structure.

3.5. Session 4 - Panel Systems and Manual Production

The address on panel construction systems made delegates aware of housing construction systems currently very popular in Japan and to a lesser extent Australia and the United States. Their main advantage is their speed of erection. Their structural strength is drawn from the fact that each panel is a structural element which can be securely fastened to all adjoining panels.

As light gauge steel is frequently used in framing elements for these systems, attention was drawn to the possibility of fatigue failures where stress concentrations occur near bottled connections. It is possible to design these panels and frames so that fatigue failures do not occur under cyclonic conditions. Also, as every panel forms part of the structural fabric of the house, if some are to be removed as part of architectural modifications later, the house must be checked to ensure that it still has structural integrity.

For the address on manual preparation, a number of suggestions were made. These were stressed as being guidance to make the manuals easier to use. Many of the suggestions related to the use of the manuals by illiterate or semiliterate people. They include the use of isometric sketches wherever possible rather than plans or elevations, minimal use of words, and inclusion of some form of easily identifiable object in each sketch to give scale.

However it was stressed that only tested details were to be included in any manual. Manuals produce standardisation, and standardisation of good details is to be sought after, but standardisation of inadequate details can lead to disasters of a huge scale.

Attention was also give to the requirements of checking the practicality of the manuals prior to publication and widespread distribution, by allowing a few builders access and asking for constructive comments. The need for public education and publicity was also stressed, to ensure that at the time the manuals were released the public understood that long-term savings could be made by using the manuals properly.

The group exercise for participants in this session was long range planning of manual preparation and timetabling of activities required, as well as drawing up rough guides for the table of contents for the manuals.

3.6. Outputs From The Workshop Sessions

All of the sketches produced in the workshop session were collected by the regional secretariat for subsequent publication. Representatives of network countries took home with them notes made by themselves that were relevent to their own country's problems and available materials.

More general outputs and observations of the International Consultant are included in Section 4.2.

4. EVALUATION OF THE SEMINAR-WORKSHOP

The inputs to the Seminar-Workshop from all participants showed that there is a great enthusiasm within the network to minimise the cost of typhoon damamge to housing. This enthusiasm meant that all of the expressly stated objectives could be met and the implied objectives could be satisfied at least in part.

4.1. Evaluation Of The Seminar Sessions

The country papers showed that the largest single housing problem facing all countries is the provision of sufficient safe, hygenic low-cost housing for low income earners. It appears to be houses occupied by those below the poverty line that are at greatest risk of damage by typhoons. Bangladesh has rather unique but very serious potential problems with regard to storm surge which dictates a particular structural form for safe housing in that country. Elsewhere the major problems caused by typhoons are the damamge to buildings.

It appears to date that most implementation of typhoon-resistant housing design has been confined to government buildings. In Fiji where insurance companies have played a prominent role in pushing for national house construction standards, more pressure has been exerted on the private sector. In Australia too, the insurance companies follow with keen interest, progress in research into the resistance of housing to tropical cyclones. The interest of the insurance companies indicates the sound economc sense of the use of typhoon-resistant design in the private sector..

If typhoon-resistant design of housing is to become widespread throughout the community, the public sector must be made aware of the economic gain to be achieved through its use. This can only be accomplished if publicity campaigns are mounted and builders and home owners alike are educated in the ways of good house design.

The country papers also indicated that there is a lack of understanding in the use of Western building materials which can lead to their use in an inappropriate manner and subsequent failure in typhoons. Again systematic education is the answer to this problem.

Problems with supply of building materials are not quite as easy to overcome. The large number of housing units required and the high cost of imported building materials means that low-cost locally available building materials must be used if existing shortfalls in housing are to be met. These materials are being sought using agricultural waste products such as bagasse, rice husks, coconut waste as well as locally available materials such as mud, bamboo, coco wood and nipa palm thatch. While the establishment of inexpensive manufacturing methods for these locally produced building materials represents a major step forward, the evaluation of resistance to decay, long-term reliability and engineering properties of not only the materials themselves but also the connections between those materials and other structural elements will take additional time. Many traditional materials currently used in house construction do not have well documented engineering properties for the materials or their connections. Nearly all countries in the network have planned further activity in this area, though few have facilities to perform the necessary testing.

The first stated objective, the identification of problems and issues, was met within the seminar sessions and this naturally led to the identification of areas in which further work was required. In this way, the third stated objective was also met.

The papers presented by both consultants and the other experts from the Philippines indicated that structural engineers can make a significant contribution to the design of housing that will continue to provide safe shelter during the passage of a typhoon. The basic principles of wind engineering as currently applied to engineered structures can be applied to low-cost housing, although there is often a tendency to use design criteria and structural safety factors that are appropriate to large commercial buildings, when designing housing that has a much lower expected life. As a result, the establishment of appropriate design criteria for housing is extremely important. These decsisions will require input from government officials, meterorolcgists, engineers, architects and financial planners.

Only once appropriate design criteria for each type of housing has been established can the work of the wind engineer be attempted.

4.2. Evaluation Of The Workshop Sessions

The workshop sessions were very enthusiastically attended and generally discussion continued past the programmed completion time. In most sessions the second part had to be curtailed because of time overruns on the first part. The sessions had been structured with the most important aspects covered in the first part and with reinforcement of basic principles covered in the second part, so that the effect of curtailment was not very significant.

The first workshop session on design criteria and implementation techniques generally forced participants to address new issues for their countries. It was recognised that this process in reality will take many months of work and correspondence in their own work environment, and that the workshop exercise was largely illustrative. However, the principle that return period for design events could be related to frequency of damage and the lifetime of building components was well understood. The different techniques for implementation of typhoon-resistant housing were also comprehended. Nearly all of the delegates favoured the production of manuals of typhoon-resistant features for small, low-cost housing. Most also identified the modern material small houses as having top priority followed by small houses constructed with traditional materials. This reflected the earlier comments with respect to general lack of understanding of modern materials.

Engineering properties for modern materials can be obtained from the manufacture or easily ascertained in laboratory tests to enable work to commence on preparation of manuals almost immediately. Much testing and material performance evaluation is required before manuals for traditional materials can be commenced, although it is hoped that the technology manuals initiated in previous network seminar workshops may provide a suitable starting point.

The second session, which covered design of typhoon-resistant details for modern materials introduced the participants to the process of matching applied loads determined from wind data to strengths of individual fasteners as determined by testing Among other points drawn out in this session were the following:

- where fasteners are used in parallel, the aggregate strength of the complete connection can be less than the sum of strengths of the individual fasteners. A derating factor of 0.9 was suggested.

- the importance of maintenance of structural connections was stressed. To that end all light gauge steel should be galvanised to prevent corrosion and resulting loss of strength.

- some problems were experienced in the following areas.

  Where many nails are used in a connection, care must be taken not to cause splitting of the timber.

  Where the roof structure was fastened to the top of masonry walls, there were problems with joing the two dissimilar materials in such a way as to give structural continuity without using costly details.

- the participants were urged to use ingenuity to overcome thse and other problems using materials and techniques commonly available in their own country, but to ensure that the details are appropriately tested.

The third session which centred on the production of design details that may be appropriate for resisting typhoon strength winds was also productive. Many of the issues raised here were similar to those raised in the previous session.

- particularly with reference to mud walls, maintenance is important. Cracks must be patched to ensure that walls behave as monolithic units.

- the connection between roof structure and mud, or mud brick walls proved difficult and engenuity was required to make use of available materials to provide continuity between the roof structure and walls.

- with bamboo construction, the position of nodes is extremely important. Cuts should be made close to nodes to prevent splitting of the culm.

- it is essential to use correctly treated traditional materials so that they have resistance to insect, fungus and rodent attack.

The final session saw the participants make a start on the layout and production of manuals and it was here that the largest variations in outputs were seen. Some outlined comic book style leaflets and others quite large, comprehensive manuals with index and cross referencing. Each may well be appropriate for particular countries. However, it should be borne in mind that the production cost of the manual may preclude the widespread distribution of large, expensive documents and hence lessen their effectiveness.

Simple manuals were seen as having wide appeal and providing the best possible vehicle for education of all sections of the community.

4.3. Overview Of The Seminar-Workshop

Aside from the formal seminar and workshop sessions there was other valuable interchange of information between the participants. The Philippine Consultant had available a number of resource materials and the International Consultant also took a number of publications to the seminar-workshop which were used as resource materials and made freely available to participants for their inspection. Quite a number of participants borrowed publications for one or two nights to study them in more detail. ist of resource materials taken to Manila by the International Consultant has been included on Appendix C.

The seminar-workshop addressed a very complex issue and the enthusiasm of the response from the participants was very impressive. As a result, the objectives of the seminar-workshop were effectively met.

The seminar achieved the objectives that related to identification of future research and training activities.

The workshop sessions provided some ideas that can be further developed by the participating countries to establish their own appropriate sets of typhoon-resistant design details for small housing. The workshop gave each participant first hand experience in different aspects of typhoon-resistant design. However, it must be stressed that many person-years of work will be required to bring workable designs to fruition on a scale that can provide solutions to each country's basic housing problems.

The workshop provided a pattern that must be applied by teams within each country and be accompanied by testing of locally available structural materials and details. To that end, the seminar-workshop was only the first step along the way providing typhoon-resistant design.

As a first step then, the seminar-workshop was very successful due to the combined effects of -

- enthusiasm among the participants
- efficiency of the organisation provided by the regional secretariat
- input from resource persons
- drafting support provided by the architects and architectural students present

5. RECOMMENDATIONS FOR FUTURE ACTIVITIES

Typhoons cause much damage to property in most of the participant's countries, and with existing housing backlogs existing in each country, they cannot afford to spend money on reconstruction following the passage of typhoons. Typhoon-resistant housing is not a luxury, it makes sound economic sense and must therefore be pursued. While the seminar-workshop was successful in addressing its objectives, follow up activities should be arranged to ensure that the principles learned and reinforced at this stage are successfully applied in each member country.

Some practical suggestions for follow up of the activities of the recently held seminar-workshop are given below.

5.1. Tasks For Member Countries

Each member country must determine design criteria for all parts of their country. Where the nation is large or widely spread there may be readily identifiable zones in which typhoons of different intensities can be expected.

Once the zones have been established then design criteria can be determined housing constructed from either modern or traditional materials in each zone. This will enable the task of typhoon resistant structural design to commence.

Concurrently, appropriate styles or each type of housing can be selected, and architectural drawings prepared of typical houses that will both appeal to the intended inhabitants and be within their price range. These drawings will be the basis of preparation of structural details.

Engineering properties of commonly used local building materials should also be sought. These should not only include the properties of the materials themselves but also the connections commonly used for these materials. The desired information should be in terms of failure loads. The lower five percentile failure load, is generally taken as the characteristic failure load and is an appropriate one to use for typhoon-resistanct design. A load factor or safety factor should be chosen by a structural engineer to relate to the level of damage that will be tolerated in the design typhoon.

This phase of the work will involve the performance of tests. Where fatigue may prove a problem tests involving repeated load/unload cycles must be applied in a manner similar to those experienced in typhoons. Where factilities do not exist for the performance advice can be sought from the following sources.

Professsor G. Manahan
Building Research Service
National Engineering Centre
University of the Philippines
NEC 102, Diliman
Quezon City.3004, Philippines.

Geoff Boughton
School of Civil Engineering
Curtin University of Technology
Kent Street
Bentley 6102
W.A., Australia.

Dr J Siopongco

Forest Products Research and
Development Institute
College, Laguna 3720
Philippines

Greg Reardon

Cyclone Testing Station
P.O. James Cook University
Qld 4811 Australia

All of the tasks indicated above provide essential groundwork for the preparations of manuals for typhoon-resistant housing design. The actual preparation of the manuals will draw on other skills outlined in this first seminar-workshop.

5.2. Follow Up Workshop

Because not all network member countries have appropriate testing facilities, there are going to be problems in determining the engineering properties of their building materials. Other problems will almost certainly be encountered when drawing up manuals. To solve these problems and to enable a further interchange of ideas and technology once more of the essential background work has been completed, it is suggested that a second workshop be held in approximately twelve months time. Such a workshop would provide valuable impetus to the determination of design criteria, architectural requirements of low-cost housing and engineering properties of materials.

The principal objective of this workshop would be the preparation of a first draft design and construction manual for low-cost, typhoon-resistant housing appropriate to each member country.

Secondary objectives would be the pooling of engineering information relating to the performance of building materials commonly used in typhoon-resistant design of housing and the establishment of uniform design methods for structural components of housing within the network.

Prior to attending such a workshop it would be expected that each country would have prepared appropriate design criteria for each type of housing in all its typhoon-prone zones, and architectural drawings showing typical acceptable and affordable low-cost housing using each of modern materials and traditional materials. It would also be expected that as much information as possible on the engineering properties of their building materials would be sent in advance of the workshop.

Prior to the workshop, the consultants would have collated and checked the engineering data returned so that it could be used by all participants in the course of the workshop. A guidebook to the writing of manuals on typhoon-resistant design of housing would also have been prepared in advance.

This workshop would provide an excellent opportunity for member countries to make rapid progress towards the implementation of low-cost, typhoon-resistant housing, and may significantly reduce the work loads of individuals charged with their preparation in the member countries.

The workshop will involve structural engineering calculations so that at least one representative from each country should be a structural engineer. As considerable emphasis will be placed on the production of a pictorial manual, architects or architectural students who will assist with the manual preparation should be grouped with representatives from the member countries.

If deemed necessary, a brief symposium could be held at the conclusion of the workshop to present the results of the workshop to a wider audience for their information and comment.

5.3. Related Network Activities

One outcome of the recently completed seminar-workshop was the need to continually evaluate the performance of building systems by maintaining dialogue with builders and by assessing building performance following the passage of typhoons.

A number of countries indicated that assessment of buildings was performed following damage from severe typhoons, but there seems little basis for comparison of the results of these surveys. The passage of a typhoon offers a unique opportunity for structural engineers to assess both those systems that appear to work and those that appear not to work. However, even though there is the potential to learn much about the performance of building systems, the extraction of the information from a tangled mess of houses, trees and possessions is a very specialised activity. Where it has been performed properly and adequately documented, people from many different nations can benefit from the experience and prevent similar disasters from happening in the future.

The network presents a good opportunity for nations in this region to exchange such information and also provides a good opportunity to develop a training programme. As the network also incorporates nations where earthquakes cause damage to building systems there is a good reason to include assessment of earthquake damage in the same training activity.

The implementation of damage assessment should be accomplished in two stages.

(i) A compendium of damage assessment experts should be made. Upon occurrence of a natural disaster that causes damage to buildings, experts from other countries could work alongside local engineers and produce composite reports. This would serve as on-the-spot training and would also assist in the production of uniform damage assessment reports that could be used by all regional network members.

This activity could be very quickly implemented and used during the next typhoon season if nececessary.

(ii) A formal training session could be introduced whereby representatives from each country are trained in the complex task of determining actual wind speeds from damage patterns, evaluating damage to determine the order of structural failures, the reasons for the failures, and the loads at which they occurred. Other issues are also involved and these include evaluation of intact buildings and establishment of reasons for their survival, and the detailed analysis of structural action within whole houses and partially damaged houses.

These types of analysis require a good understanding of the structural action of houses subjected to typhoon winds. While at first sight this appears trivial, in actual fact the large number of structural elements within even simple houses can make their analysis more complex than that of a tall building.

This training session which could incorporate the action of houses under earthquake loads if required, could be held in Quezon Province or in the islands of Samar or Leyte during August or September, as the examination of some actual houses that have been damaged would greatly assist the value of the seminar.

(iii) Some form of risk assessment within the network should be performed. At present, there are only qualitative notions of the risk faced by individual countries. A quantitative assessment of the risk to housing posed by natural disasters will enable economic decisions by housing authorities and private organisations in each member country to be based on extra rationally determined data.

6. CONCLUSIONS

The Seminar-Workshop on typhoon-resistant housing designs and construction systems, Manila, December, 1986 was successful in that it satisfied all of its initial objectives.

It has provided sufficient information to member countries to initiate their own programmes to implement typhoon-resistant design, and has also allowed exchange of information relating to specific problems faced by each country.

In many countries massive housing programmes are required to accommodate particularly the urban poor populations. In order to make effective use of money spent on housing in typhoon-prone areas, some engineered typhoon-resistant features must be incorporated into newly constructed housing.

Appropriate typhoon-resistant structural details can be incorporated at reasonable cost and therefore provide safety to the large economic investment represented by housing.

Each participant has received instruction in the requirements of typhoon-resistant design and various methods of achieving those requirements. The workshop sessions have provided opportunity to practice the implementation of those methods.

Some follow up activities will provide an opportunity for speeding up the lengthy process of implementation of typhoon-resistant design details in housing.

These activities include:

(i) Publication of a guide book for the preparation of typhoon-resistant details for housing.

(ii) Organisation of a workshop in approximately twelve monthstime for the preparation of first drafts of appropriate typhoon-resistant details for housing.

Other activities for the regional network have been suggested as a result of needs made obvious at the seminar-workshop.

These activities include:

(i) Formation of teams for rapid assessment of damage to housing after the occurrence of a natural disaster

(ii) Organisation of a training seminar to improve skills in assessment of damage to housing

(iii) Implementation of a housing risk assessment programme.

7. ACKNOWLEDGEMENTS

The author is very grateful to the staff of the regional secretariat for their assistance during the conduct of the Seminar-Workshop, which included such diverse tasks as purchasing sundry building materials for demonstration purposes and provision of transport to a number of different housing estates. He is also indebted to the services of Jacquie Kelly who diligently typed this report immediately following a well earned festive season.

8. REFERENCES

AUSTRALIAN STANDARDS (1983) AS1170-Part 2 "SAA Loading Code - Part 2. Wind Forces", Standards Association of Australia, Sydney.

All of these papers were presented at the Seminar-Workshop on typhoon-resistant housing designs and construction systems, Manila.

BAWAGAN, P.V. (1986)	Welcome Address
BOUGHTON, G.N. (1986a)	Design Philosophies for Tropical Cyclones (Copy attached in Appendix A)
BOUGHTON, G.N. (1986b)	Design Criteria for Tropical Cyclones (Copy attached in Appendix A)
BOUGHTON, G.N. (1986c)	Structural Design of Housing for Tropical Cyclones (Copy attached in Appendix A)
DE CASTRO, E.S. (1986)	High and Low Rise Building Systems in Steel Construction Designed to Resist Extreme Wind Speeds
KINTANAR, Q. (1986)	Keynote Address
KINTANAR, R. (1986)	Typhoon and Wind-Related Problems in the Philippines.
LAZARO, A.L. (1986)	Wind Resistant Reinforced Concrete and Masonry Structures.
MANAHAN, G. (1986a)	Wind Force and Pressure Modelling
MANAHAN, G. (1986b)	Basic Concepts: Designing for Typhoon-Resistant Building in the Philippines.
MANAHAN, G. (1986c)	Envionmental Considerations of Typhoon-Resistant Design for Buildings.
REARDON, G.F. and BOUGHTON, G.N. (1986)	The Structural Response of a Tongan Hurricane House to Simulated Cyclone Loading (Copy attached in Appendix A)
SIOPONGCO, J. (1986a)	Design and Construction Systems of Typhoon-Resistant Timber-Frame Housing
SIOPONGCO, J. (1986b)	Typhoon-Resistant Bamboo House Construction Systems.

APPENDIX A

Papers presented by International Consultant to Seminar-Workshop on Typhoon-Resistant Housing Designs and Construction Systems, Manila, 10-16 December, 1986.

Contains:

Design Philosophies for Tropical Cyclones, G.N. Boughton.

Design Criteria for Tropical Cyclones, G.N. Boughton.

Structural Design of Housing for Tropical Cyclones, G.N. Boughton.

The Structural Response of a Tongan Hurricane house to Simulated Cyclone Loading, G.F. Reardon and G.N. Boughton.

STRUCTURAL DESIGN OF HOUSING FOR TROPICAL CYCLONES

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ABSTRACT

The complex nature of the structural action of housing, together with the variation in housing types, building materials and construction technology available means that the structural design of houses to resist tropical cyclones must vary from place to place. This paper indicates the basic processes to be undertaken in performing the structural design of housing using either timber or masonry wall materials and a timber framed roof.

1. INTRODUCTION

Once design loads for a house in a specific location have been determined, it remains to create a structural fabric that will resist those loads. This is the process of design. While materials, style of construction, workmanship, and construction methods will vary from place to place, the basic principles of cyclone resistant design remain the same.

The terminology for timber framing adopted within this paper is as shown in figure 1.

2. STRUCTURAL ACTION OF HOUSING

Having indicated that structural engineers can make a contribution to the design of housing to resist tropical cyclones, it must be made clear at the outset that the structural action of housing is quite different from that of buildings with which structural engineers are traditionally associated. Larger engineered buildings have a structural framework through which all wind loads are directed to ground. These frames may incorporate beams, columns, moment connections and structural bracing systems. Cladding in such structures attracts wind load but sheds it immediately to the structural frame for dispersion to the ground. By contrast, housing also incorporates a frame, often referred to as a light frame. It serves as a solid base to which the cladding is fastened, but in many cases, the cladding can carry higher in-plane loads than the frame. House frames are thought of as beam elements but rarely as column elements and connections are never regarded as moment carrying. Wind loads are transferred throughout the fabric of houses via the fasteners and connections passing between the light frame and the cladding a number of times before reaching the ground. This makes a rigorous analysis of even a two room house subjected to wind loads more complex than the analysis of a five storey office block. A finite element analysis of a house would require anistotropic plate/membrane elements for the roof and wall cladding, small bending elements for the fasteners, larger bending elements for the frame, and truss elements that can carry only tension for the many straps and rods included in the structure of housing in cyclone-prone areas.

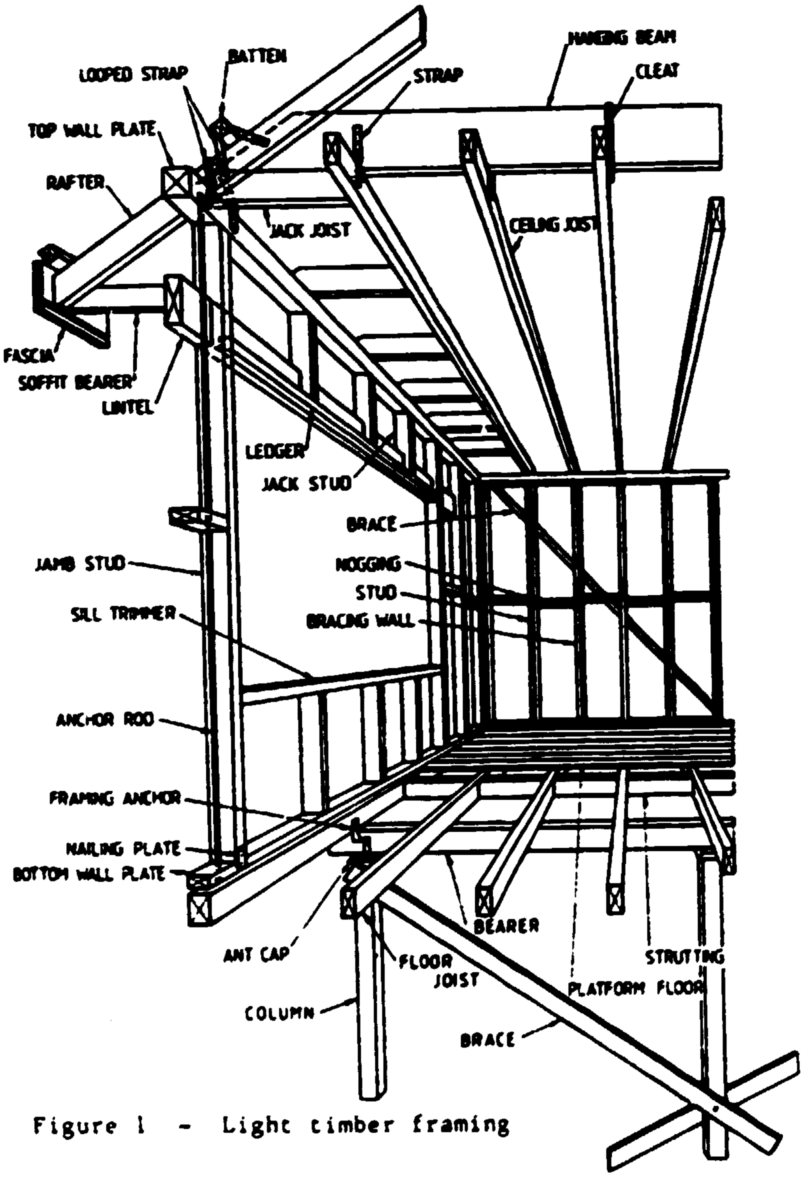


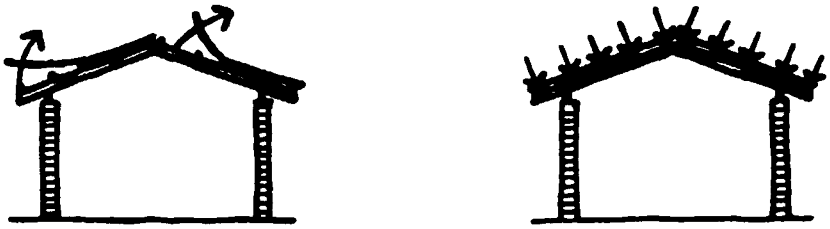
Figure 1 - Light timber framing

Fortunately enough information on the structural action of housing is available to enable good estimates of the loads carried by various elements to be found without the use of computer analysis programs. The structural action of a house can be thought of as a number of load paths carrying horizontal and vertical loads to the ground. Each of these load paths contains many elements, - connections, cladding, frame members, fasteners,- and each must remain intact for the load path to remain effective.

2.1 Load path for Uplift Loads

(i) The action of wind on a house produces a net uplift on the roof sheeting comprising an external suction, and an internal pressure on the underside of the sheeting. This load is carried by bending of the ribs in the sheeting to the lines of fasteners that run along the battens.

(ii) The fasteners, acting in tension, transfer the uplift forces from the roof sheeting to the battens. In the event of the sheeting/fastener system being unable to carry the required loads, the roof sheeting lifts off the battens as shown in figure 2. The load redistributions in the roof sheeting following such a failure generally cause overloading of adjacent fasteners and hence loss of sheeting over a significant porportion of the roof. Figure 2 shows the lifting of the roof sheeting from the battens close to the leading edge of the roof. Highest uplift is experienced in this region, and as a result, the failure modes depicted in figure 2 are the most common.



Fix sheeting properly to purlins.

Figure 2 - Roof sheeting disengagement due to failure of the sheeting/fastener system

(iii) The battens act in bending to carry loads from the sheeting fasteners to the rafters. Complications occur where battens are to be joined. Some practical joint details will be given in section 3.2.

(iv) Batten fasteners, again acting in tension, transfer the uplift forces from the battens to the rafters. In the event of a batten fastener being unable to carry required load, the battens would lift off the rafters as shown in figure 3. Again load redistributions following such a failure often cause over-loading of adjacent fasteners, and hence loss of battens with sheeting still attached over most of the roof.

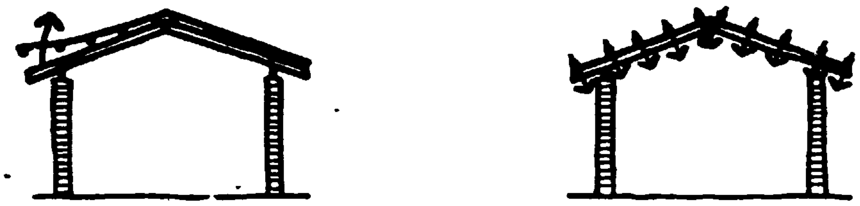


Figure 3 - Battens lifting from rafters due to the failure of batten fasteners

(v) The roof structural system must be capable of spanning between the tie down points. In general these are at the external walls. Where the rafters are not tied together at the ridge with sufficient strength, there is a possibility of large scale roof structure failure as shown in figure 4(a). Where trussed roof systems are not used with gable ended roofs either the ridge must be tied down or a lateral restraint provided at the top of the walls to prevent combined roof and wall failure as shown in figure 4(b).

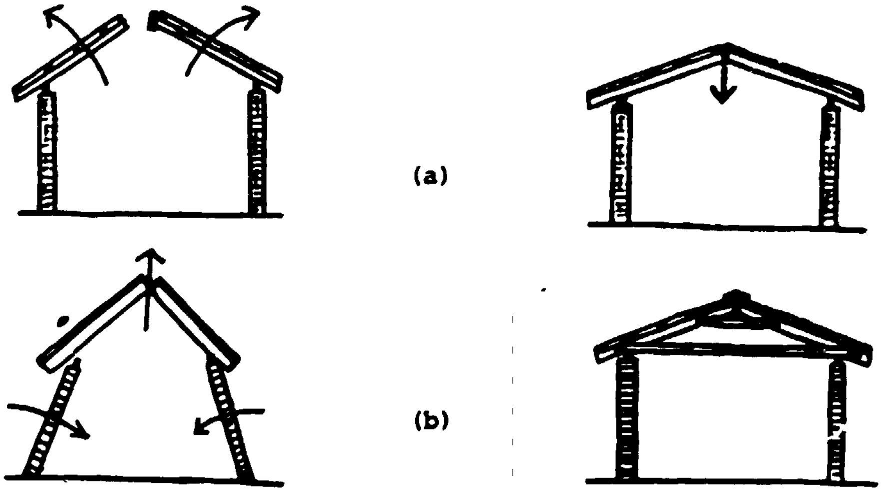


Figure 4 - Roof structure failures

(vi) The roof structure must be adequately tied to the tops of the external walls. This transfers load from the roof trusses or rafters into the wall systems of the house. Where the rafters are not tied correctly to the walls, the complete roof structure may separate from the top of the walls as shown in figure 5(a) and 5(b). This is a very serious failure, as the top of the wall relies on bracing in the plane of the roof to lend it lateral support. After loss of the roof, failure of the walls frequently follows as shown in figure 10.

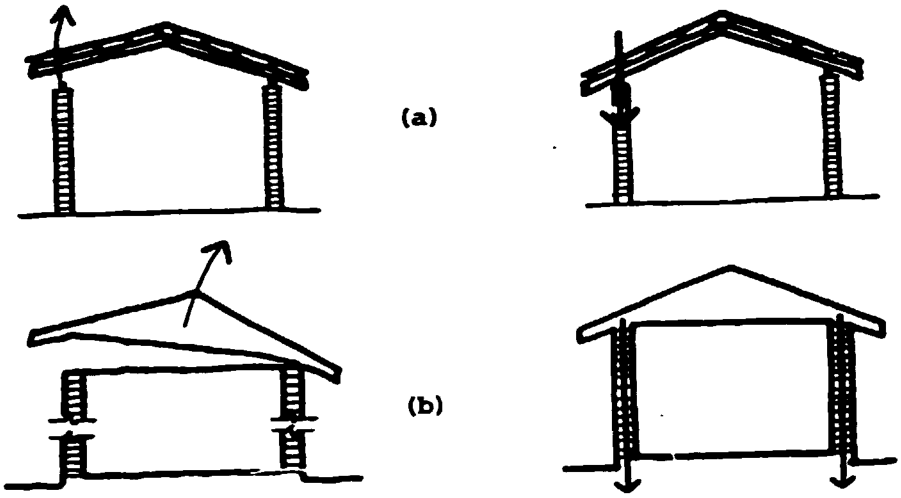


Figure 5 - Tie down of roof system to walls

(vii) The uplift load, now transferred to the top of the external wall, must be carried to the base of the wall. For timber framed walls, this is generally accomplished by tension members built into the wall structure. In masonry construction, tie rods are generally installed well into the wall. If the depth at which these rods are fixed is inadequate separation of the wall can result as shown in figure 6.

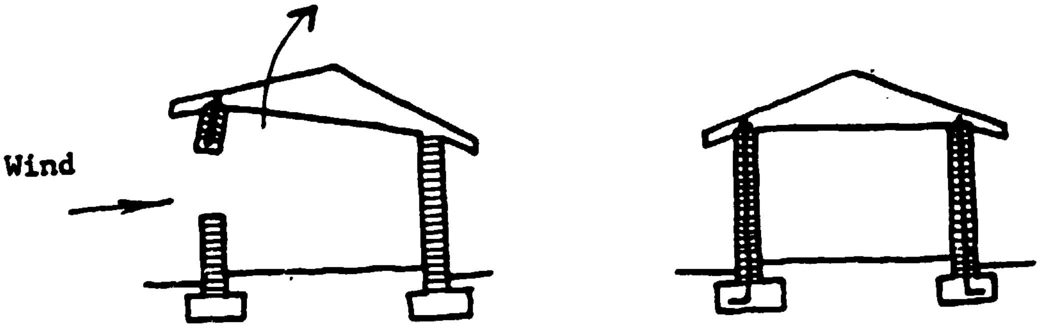
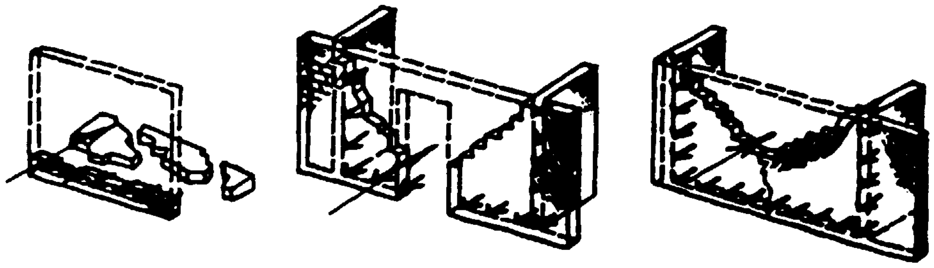


Figure 6 - Uplift forces must be carried from the top to the base of the walls

(viii) Masonry houses built on concrete floors provide opportunity to carry the roof tie down through to the foundations, thereby resisting the uplift forces with the combined weight of concrete footings, masonry walls and a concrete floor. However, houses with timber floors must incorporate a method of carrying the uplift loads to the floor support piles and thence to footings of sufficient weight to resist the uplift forces.

2.2 Load path for lateral loads

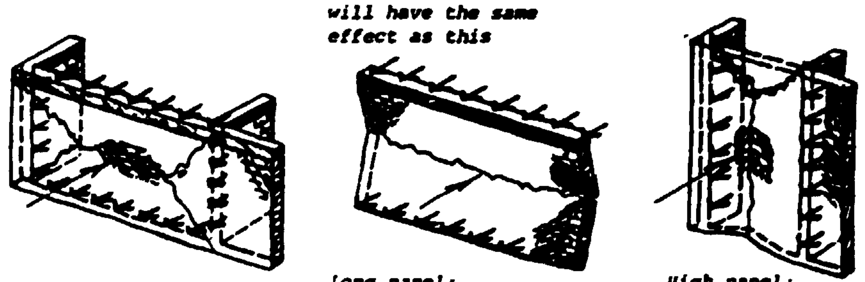
(i) Lateral loads are applied by wind pressure to the windward and leeward walls. Those walls must be able to carry the lateral loads by bending to other elements in the house. Timber framed walls have well defined structural action in which the sheeting generally spans horizontally between vertical studs. The studs carry loads to the floor and roof levels by bending. Masonry walls carry out of plane loads by bending in a manner not dissimilar to concrete floor slabs. Their behaviour is very significantly influenced by the edge conditions as shown in figure 7.



Supported 1 side only

Supported 2 sides
Note: A door or high opening in a panel supported on 3 sides will have the same effect as this

Supported 3 sides



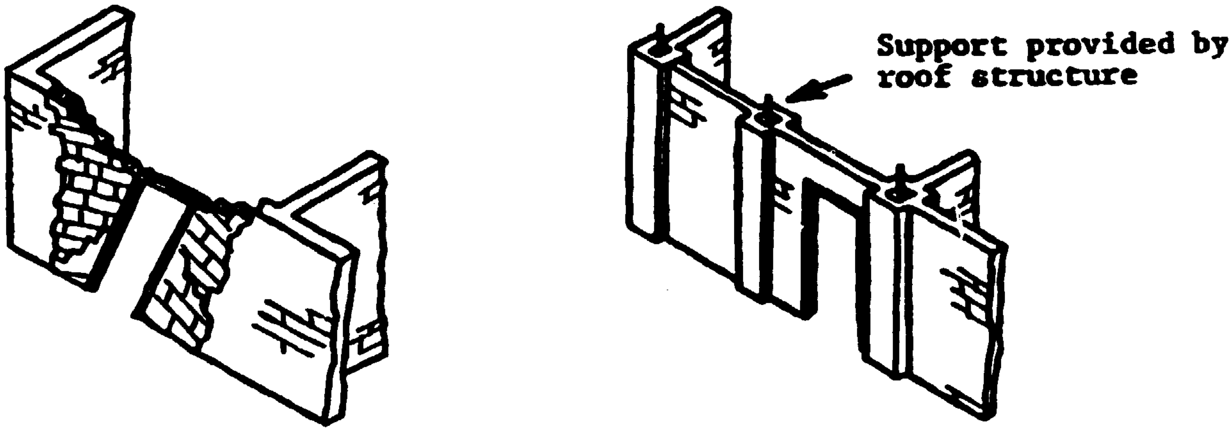
Supported 4 sides
(strongest)

Long panel:
Derives its strength from bending between the top plate and the floor.

High panel:
Derives its strength from bending between the two vertical supports

Figure 7 - The action of masonry walls under lateral wind loads

As the strongest configuration for masonry walls carrying lateral load is with lateral support around four edges, every effort must be made to ensure that the constructed configuration of the wall has beams around each side. Openings can significantly weaken masonry walls under lateral load and should be surrounded by bond beams as shown in figure 8.



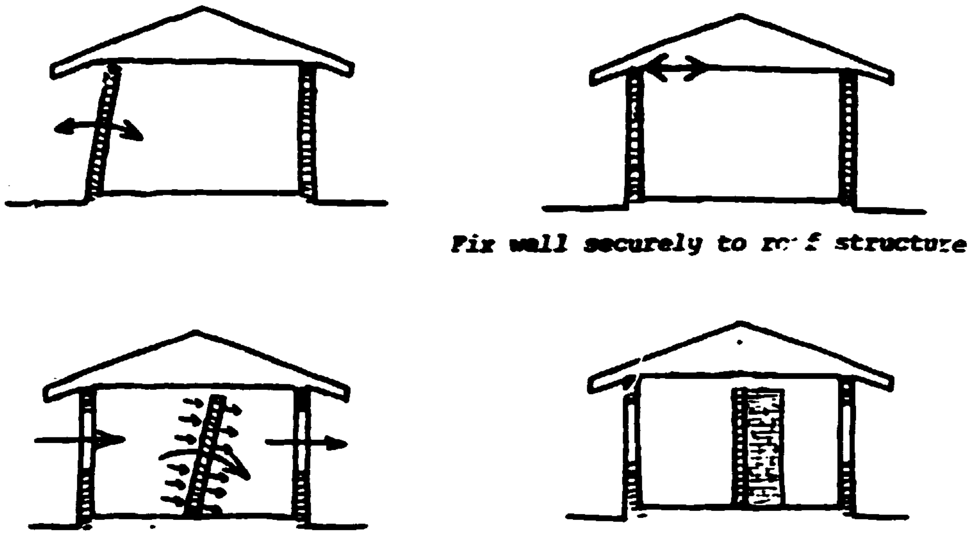
PANEL WEAKENED BY OPENING

provide an extra pier or filled core

Figure 8 - Openings in masonry walls

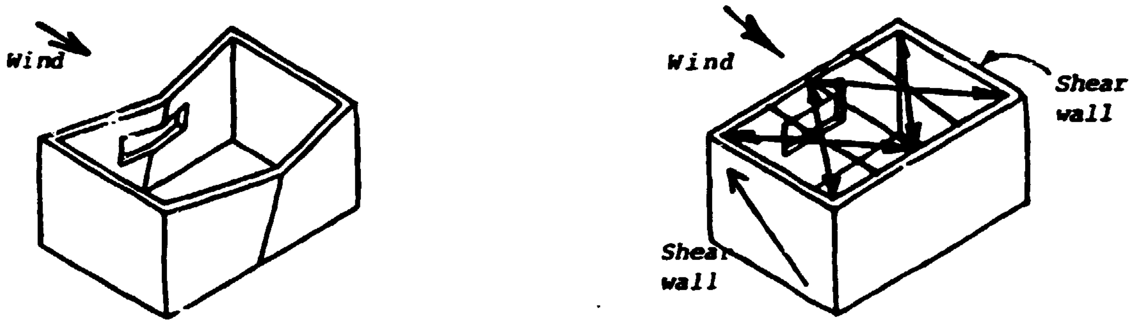
(ii) The walls must be adequately supported. In the case of external walls, this implies support at roof level, and in the case of internal walls, by piers or return walls. Where external walls are not tied properly at the top, they can fall inwards under the action of external pressure as shown in figure 9(a). Internal walls may also be subjected to considerable load where the combination of openings allows it. They should be designed to resist those loads by provision of supporting piers or return walls as shown in figure 9(b) to prevent toppling failure.

(iii) The loads at top of wall level are generally transferred to the roof structure which can span between the end walls of the house as a large horizontal truss if it is properly braced. In some cases, the roof sheeting itself may have sufficient in-plane strength to be able to act as a diaphragm. Figure 10 shows the failure mode of the house where insufficient bracing in the plane of the roof has been provided. Where sufficient roof bracing is installed the stiff end walls carry the load downwards to the ground by shear wall action, and the roof structure carries the lateral loads at top of wall level to them.



Fix wall securely to roof structure

Figure 9 - Lateral support for walls



Provide bracing at roof level to transfer horizontal forces to shear walls.

Figure 10 - Bracing in the plane of the roof spanning between shear walls.

(iv) The shear walls in the house must have sufficient strength to carry the lateral loads from the roof level to the floor. Where inadequate strength is available, racking failures can occur as shown in figure

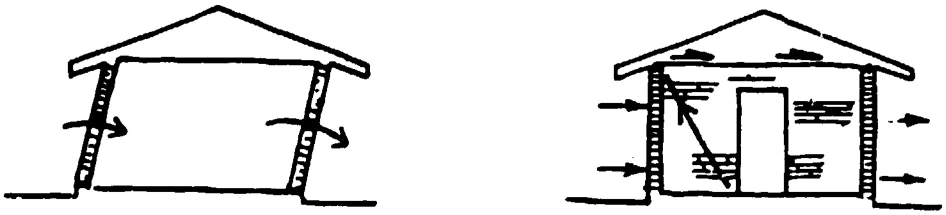


Figure 11 - Provision of bracing walls to prevent racking failure

(v) The shear walls and bracing walls thus provided must be adequately fixed to the roof structure to effect the lateral force transfer indicated above. The detail of the connection can be quite complicated and is discussed in section 4. Where this detail is inadequate, racking failures of the structure may still occur in spite of the presence of adequate bracing walls as shown in figure 12.

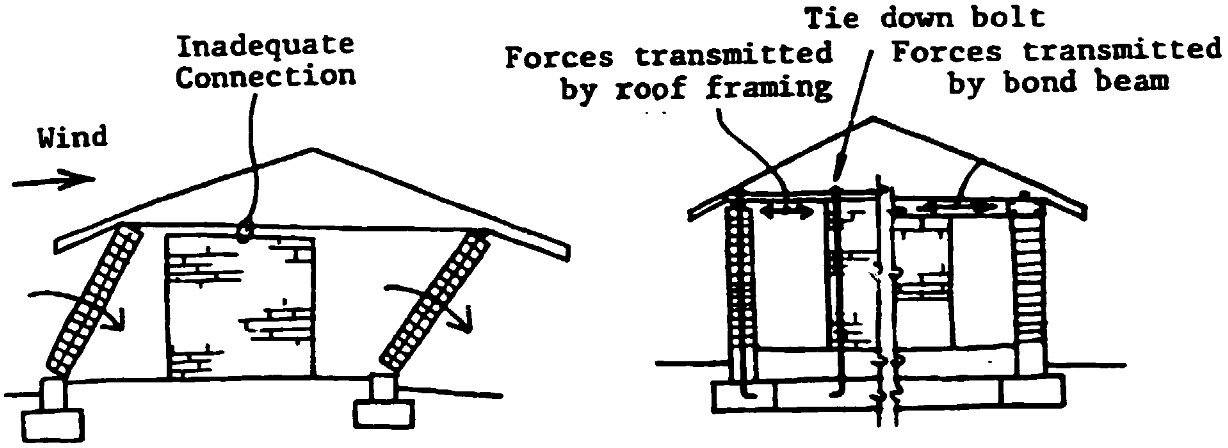
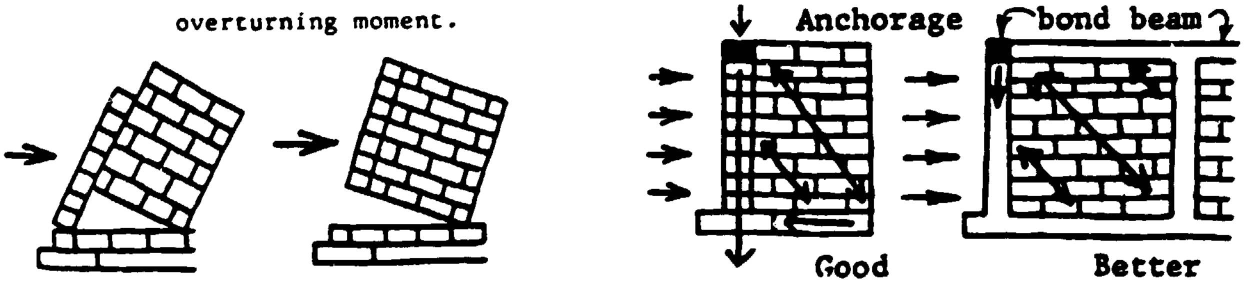


Figure 12 - Adequate connection of shear walls to the roof structure

(vi) The shear walls must be adequately tied down. Under the action of lateral load applied at the top of the wall, an overturning moment is established. This must be counteracted by tie down at each end of the wall as shown in figure 13. Tie down of shear walls is especially important in timber framed walls as their weight is not sufficient to generate resisting moments to counteract the overturning moment.



Provide anchorage to shear wall panels as shown above.

Figure 13 - Anchorage of shear walls to prevent overturning

(vii) Where houses have elevated timber floors, it is possible for the house to be rigidly braced above floor level but suffer racking failures below floor level as shown in figure 14. Bracing must be provided to prevent racking failure below floor level. Likewise, sufficient weight must be provided in the footings to prevent overturning of the complete structure.

Figure 14 - Bracing of the sub-floor support system

3. DESIGN OF HOUSES FOR UPLIFT

Each of the elements mentioned in the load path from the roof sheeting to the ground must be designed for uplift forces. The most appropriate system to be implemented in any given location is dependent on the materials readily available, and the skills established by the builder

3.1 Roof Cladding

Many different cladding systems are available ranging from tile systems that have large dead weight to very lightweight aluminium sheeting systems. Obviously the net uplift experienced by the tiles under the action of cyclonic loads will be lower than that on metal deck roofs because of the larger downward gravity forces experienced by the heavier ties. However, in all cyclones of intensity SS3 and greater, uplift forces on roofing are sufficient to exceed the weight force of both clay and concrete tiles.

ALL ROOFING MATERIALS MUST BE ADEQUATELY TIED DOWN.

The safe uplift load of each roofing and fastening system to be used in cyclone areas should be evaluated by testing, preferably using a test method that takes into account the repeated nature of wind loadings. In Australia most roofing system manufacturers have performed these tests and make the results freely available in their technical literature.

The technical literature should also specify recommended fastening systems, as the performance of the roofing/fastener is a function of fastener shank diameter, head diameter and washer material and size, as well as the roof sheeting properties.

3.2 **Batten Systems**

Timber battens generally must be jointed to provide sufficient length for use in housing. As the battens act in bending, the only feasible place to effect the join is over a truss or rafter. This may be performed in two ways.

(i) Side lapping is very effective, but leads to uneven lines of sheeting fasteners. This may be regarded by some people as unaesthetic and also creates difficulties in installing roofing fasteners so that they penetrate the battens.

(ii) Butting battens over rafters can cause problems with end distances for the fasteners. It is recommended that the battens be joined with an oblique cut as shown in figure 15. This allows maximum end distances to fasteners while still allowing the batten to be joined over the top of a rafter.

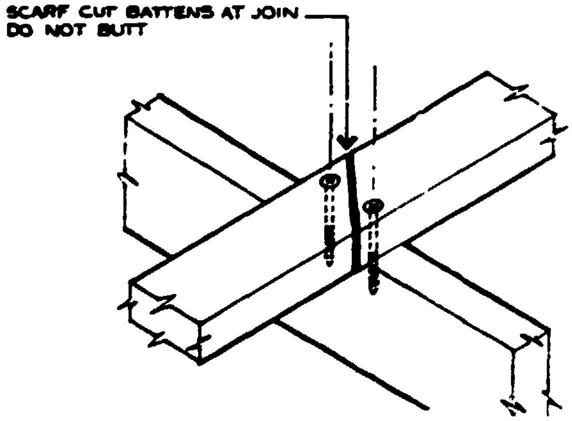


Figure 15 - Joining of battens with an oblique cut

Battens can be held down using many proprietry and generally available fasteners. The most commonly used in Australia include power driven screws, straight and twisted shank nails, straps nailed in shear, and proprietry plates. The screw connection is shown in figure 15, and provides a positive joint but requires power to drill and install. Nails can be used instead of screws in a similar configuration, but as the connection is in direct tension, withdrawal of the nails is commonplace, particularly if plain bullet head nails are used. Twisted shank nails have better holding power, but are harder than plain shank nails to install and are therefore not favoured by builders.

Nailing plates, framing anchors and twisted straps all provide resistance to uplift by placing nails in shear, and are therefore much less prone to nail withdrawl under load, when compared with nails acting in direct tension. However, each of these fastening systems utilize light gauge steel elements and should therefore be tested for fatigue resistance prior to specification for cyclone resistant construction. They are shown in a slightly different context in figure 16.

3.3 Roof Structure

The advent of nailing plates has made engineered roof trusses an economical proposition for houses in Australia. Whether trusses are manufactured in a factory or on-site, their analysis is reasonably simple, so adequate timber sizes and connections can be designed without great difficulty.

3.4 Roof Structure tie down

Again, this often is a problem of joining two pieces of mutually perpendicular timber. Similar fasteners to those used for batten fasteners can be used for this detail. The higher loads carried by these joints, and the use of larger member sizes preclude the use of nails and screws carrying load in direct tension. Figure 16 shows a number of alternative fasteners which include various combinations of framing anchors and looped straps. Also included is an overbatten method which uses bolts. The three different methods presented in that figure relate to three different load ranges. Method 1 has the lowest capacity and method 3, the highest.

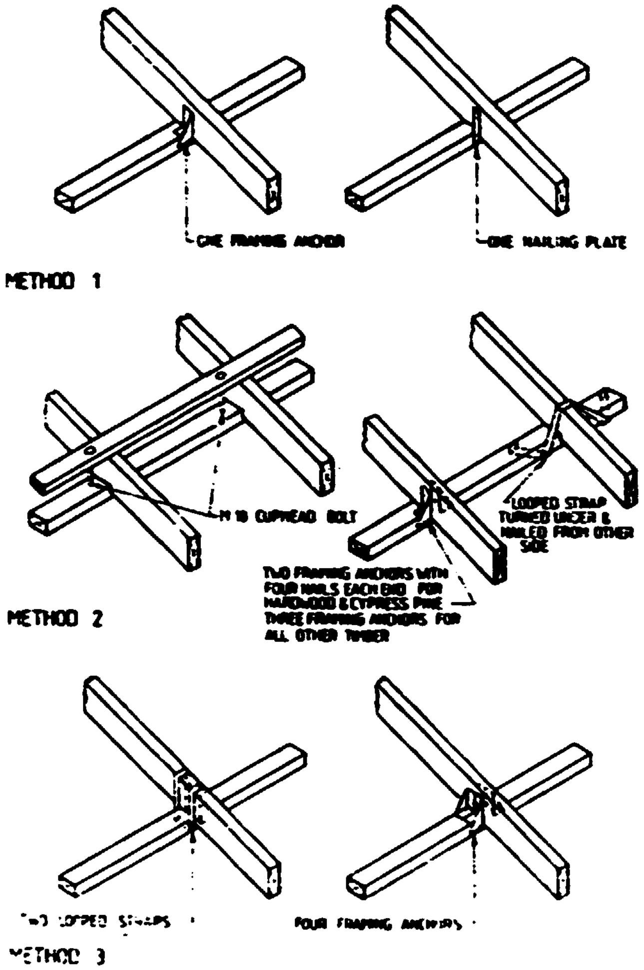


Figure 16 - Fasteners for fixing rafters and trusses to top plates

3.4 Wall tie down

Elements must be incorporated into wall structures that can carry tension from the top of the wall to the bottom. For masonry walls these elements are most commonly a number of steel rods that are cast into hollows in the wall, and embeded in concrete to provide protection from corrosion. Timber framed walls may on occasions incorporate plywood cladding which can be used to carry the uplift forces through the full height of the wall. Sufficient fasteners must be provided at top plate and bottom plate level to transfer the load into and out of the plywood panels. Steel rods can be placed adjacent to studs and tie the top and bottom plates together as shown in figure 17.

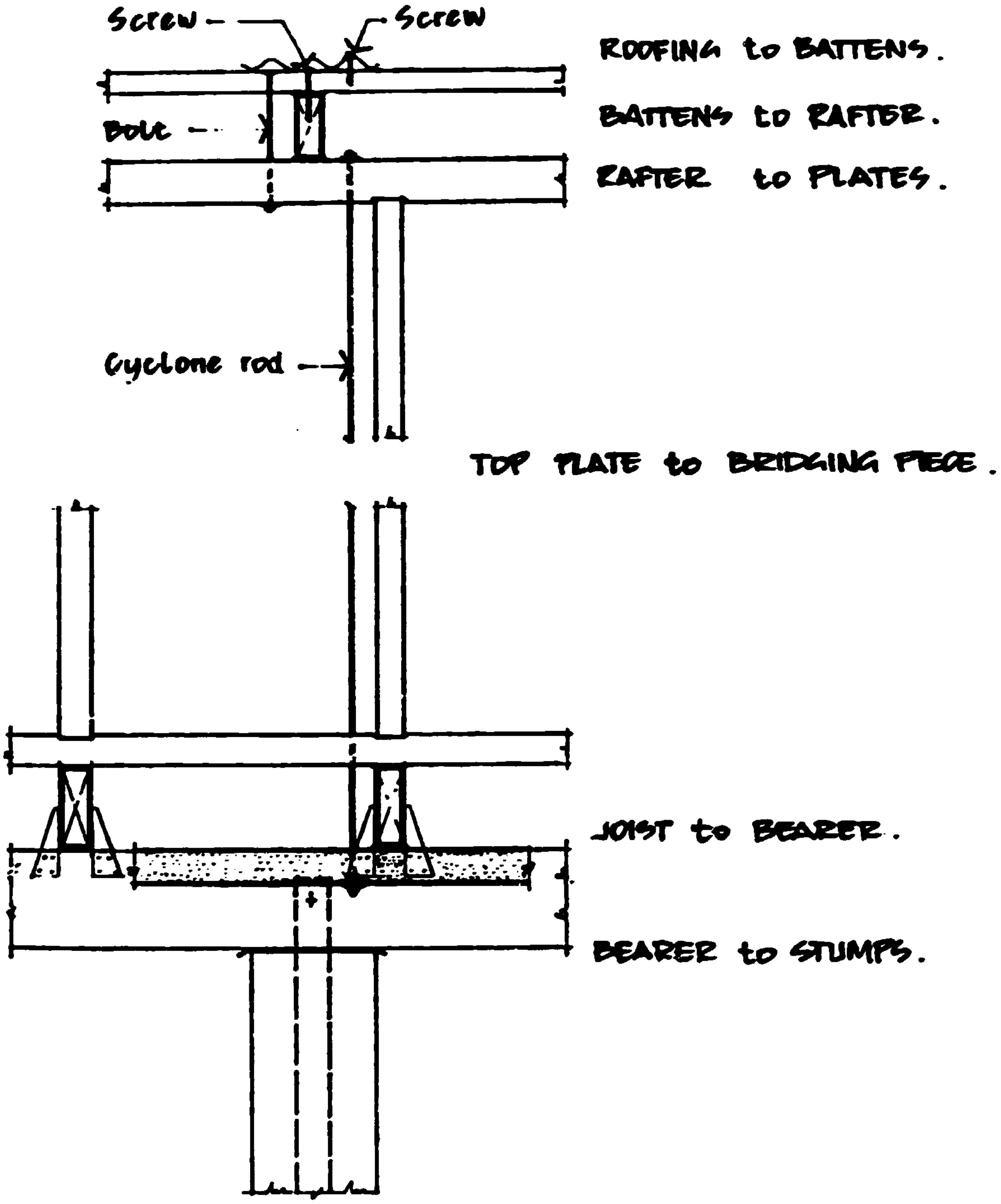


Figure 17 - Tie down rods in timber framed walls

3.5 Tie down of floor substructure

Where the timber floor of a house is supported some distance above the ground, the uplift forces must be carried from the floor joists to the stumps. This frequently calls for a positive connection between joists and bearers and then between bearers and stumps as shown in figure 17.

4. DESIGN OF HOUSES FOR LATERAL LOADS

Again, each of the elements mentioned in the lateral load path from the walls to the ground must be designed for lateral wind forces. In general these forces can be obtained by summing windward wall pressures and leeward wall suctions.

4.1 External wall systems

The design of timber framed walls for out-of plane forces can be accomplished using conventional engineering mechanics. The cladding material spans horizontally between the studs and the studs span vertically between top and bottom plates. The effects of noggings can be ignored.

However masonry walls present more problems. Because of the poor tensile properties of masonry, steel reinforcement is incorporated into the structure as shown in figure 18. Much of the reinforcement shown serves two functions

The vertical rods can be used to tie the roof structure to the foundations, and create strong bands in the wall that can carry significantly higher moments than the unreinforced masonry. They therefore reduce the horizontal span of unreinforced portions of the masonry walls. The vertical bars are also palced alongside all openings and again provide strong bands adjacent to a potential weakness in the wall.

The horizontal rods around the top of the wall allow the connection of the roof structure to a stiff bond beam capable of spanning between the vertical tie down rods in transmision of uplift loads from the roof to the floor. They can also span over openings such as doors or windows. The horizontal bond beam around the top of the wall stiffens to the top of the wall and prevents many of the failure modes shown in figure 7.

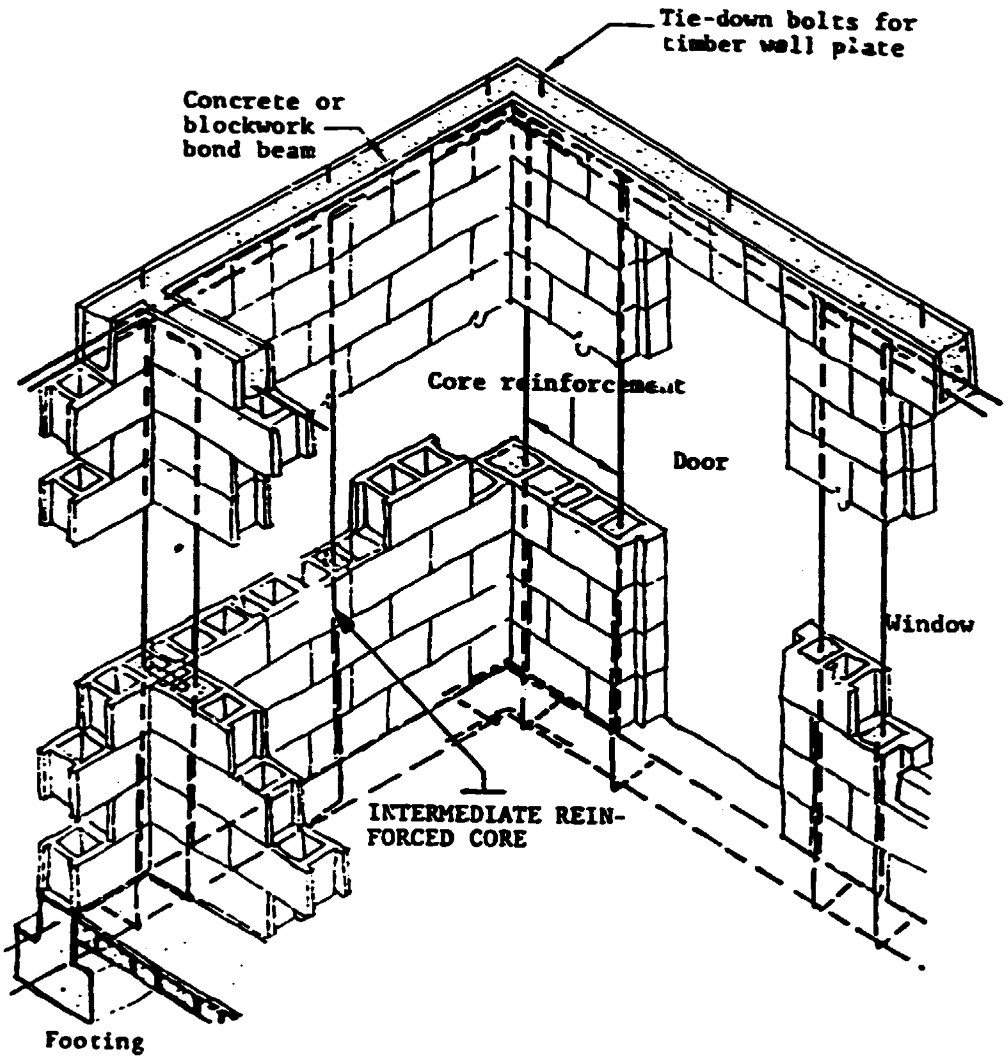


Figure 18 - Reinforcement of blockwork

4.2 Roof Bracing

Bracing in the plane of the roof can be designed by taking the uniformly distributed load at top of wall level and carrying it to designated shear walls utilizing the bracing as the web members of a large horizontal truss. Evidence in recent research work (Boughton, 1984) suggests that the roof sheeting itself is capable of carrying all of the required loads without support from bracing. However, if the roof sheeting is relied on for stability, then it must be very securely fastened, as its loss would mean loss of the entire building.

4.3 Connection between the roof structure and shear walls

The importance of providing a good lateral load transfer mechanism between shear walls and the roof structure has already been mentioned, however, where the roof structure is based on a truss system, it is important that no vertical load be transferred at internal walls. Where transfer points occur at mid chord in the truss, vertical loads could induce bending stresses in the lower chord of the truss. In some instances, these have caused flexural failure of the lower chord with resulting serious damage to the house.

The Queensland Home Building Code requires that all timber roof trusses have a 20mm gap between the underside of the bottom chord of the truss and the top of internal wall top plates to prevent undesirable flexure of the bottom chord.

Complex lateral transfer details have been devised that enable lateral loads to pass between roof structure and bracing wall while offering minimal transfer of vertical loads.

4.4 Bracing Walls

Masonry walls effectively tied down at each end function as bracing walls. However, timber framed walls require extra strengthening to function as shear walls. The extra strength can either be supplied by the wall cladding or by specially constructed timber braces. Many types of cladding including plywood and fibre cement sheeting have been tested as bracing panels. Figure 19 shows a typical detail of a bracing wall which utilises the shear rigidity and strength of its cladding to carry lateral in-plane loads. Note that tie rods are provided at each end to prevent overturning of the wall.

Either timber bracing or steel strap cross bracing can also be used to provide strength as shown in figure 20. Again the bracing panel has tie down bolts at each end to prevent overturning of the wall. The stiffener of this type of wall is generally less than that of the walls similar to that shown in figure 19. The strengths of all wall bracing systems are determined by testing.

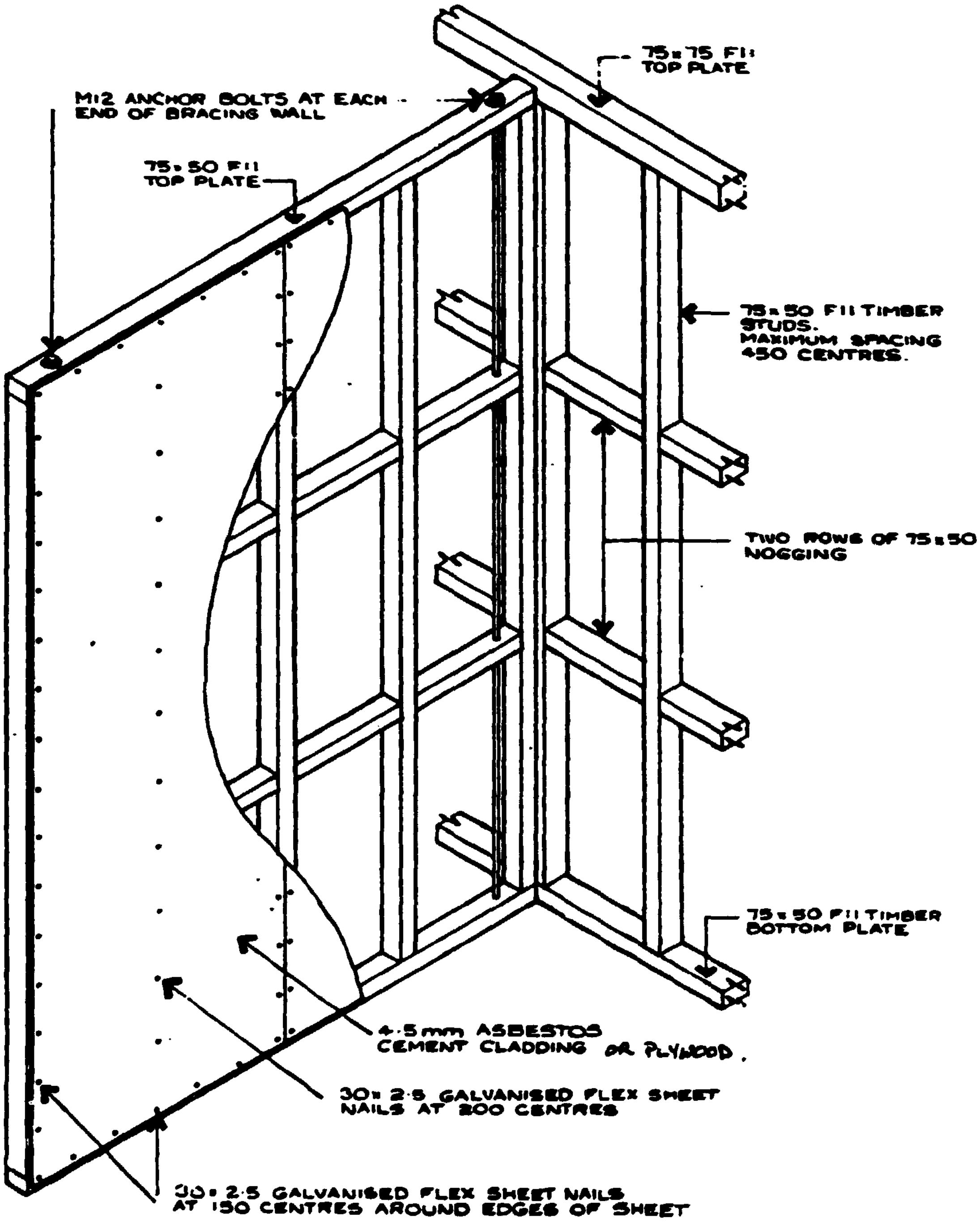


Figure 19 - Bracing wall utilising cladding for strength

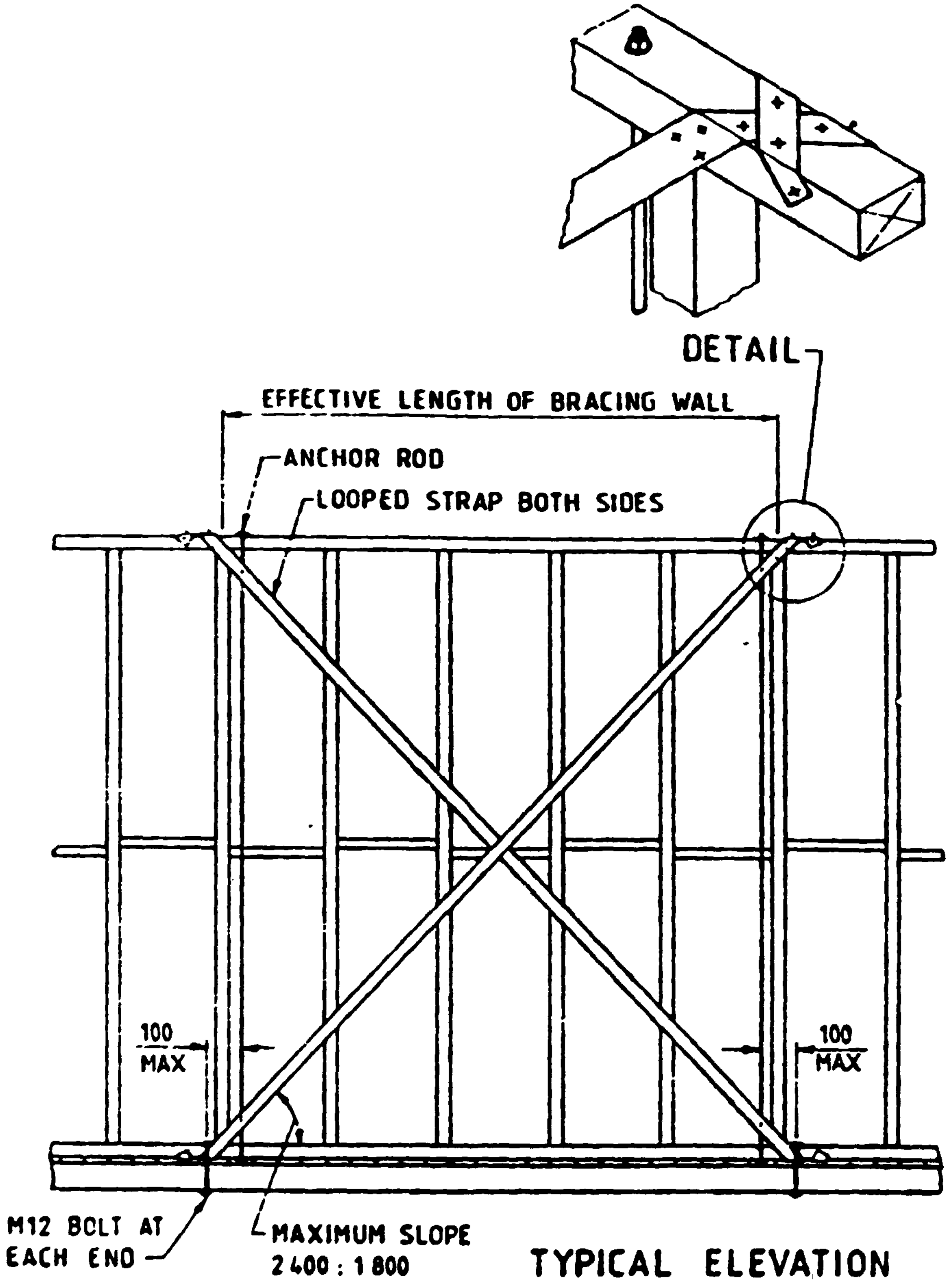


Figure 20 - Bracing walls utilising metal straps for shear strength

5. ROLE OF TESTING

The observation of damage caused by tropical cyclones has shown that failures often originate at connections. Great care must be taken in the design, fabrication and assembly of connection details to ensure that they will work as intended. Many of them have proved very difficult to examine theoretically, and their strength and stiffness properties are best determined by testing. With timber framed buildings, the strength of connectors can vary significantly with the species of timber used in the joint. This gives testing an even more important role.

The process of design involves matching available strengths with the loads that are necessary to resist the wind effects. Before design can be attempted, testing of components, elements and fastening systems must be performed to give the necessary design data.

5.1 Special considerations for Timber and Timber fasteners

Timber is a term that embraces many different species. It also has orthotropic characteristics. Thus when performing or evaluating tests on either timber, or fasteners in timber, it is necessary to take particular notice of the orientation of grain with respect to applied load, and the edge and end distances. Because each of these properties can influence the outcome of a test, it is important that they all are modelled in a manner that duplicates actual practice on location.

Timber is also characterised by defects. The presence of knots, twisted or crooked grain, small checks, and splits, and sapwood, or heartwood can all influence the strength of a timber connection or specimen. As a result, a large number of samples must be tested to obtain representative strength characteristics. In obtaining specimens for testing, every endeavour must be made to ensure that the timber comes from a number of different trees and if possible, from different areats.

The allowable stresses in timber are factored from characteristic stresses. A large number of samples must be tested to enable determination of the 5% confidence limit of strength.

Durability of timber is also an issue, in that many tropical cyclone-prone areas have high ambient humidities that can cause rotting of the timber and favour fungus growths which can also reduce the strength of timber. Where posible, fungus and rot-resistant species should be used, or alternatively, timbers that would otherwise be susceptible can be impregnated with preservatives.

In some areas too, borers and ant infestations may be a problem. The physical damage that these insects can cause may prevent the timber from carrying any load at all. Again some insect-resistant species of timber exist, and others can be impregnated with chemicals to render them resistant to attack.

5.2 Special considerations for steel

Many fasteners commonly used in the building industry are fabricated from various grades of steel. Steel in cyclone-prone areas suffers from two distinct problems.

The fasteners made from light gauge steel may be subjected to deterioration due to fatigue. This is particularly the case if they incorporate punched holes or other locations of stress concentration. The action of fatigue may mean that lower ultimate loads than those predicted by static tests, may be experienced during the repeated loadings characteristic of tropical cyclones. Testing of such fasteners, particularly where they are to be used in roof structures should be performed using a test sequence such as that indicated in the EBS (1977) publication, Technical Record 440, in which a large number of load cycles are specified. This type of test indicates the susceptibility of the detail to fatigue under repeated loading and will give appropriate ultimate loads for cyclonic conditions.

Steel fasteners used in tropical cyclone-prone areas may also be highly susceptible to corrosion damage. The environment in many cyclone-prone regions is hot, humid, and if in close proximity to the sea, salty. Many fasteners used in the construction of houses are in quite inaccessible positions for the performance of either maintenance or inspection work. It is highly recommended that all steel fasteners to be used in houses for cyclone-prone areas, including nails, be galvanised to ensure that their continued structural performance can be relied upon many years after installation.

5.3 Special Considerations for Masonry

Masonry products are generally highly variable to the large range of local materials used in their manufacture. Bricks and blocks vary with the constituents, and mortar strengths are a function of not only the grading of the sand, the sand/cement ratio and water/cement ratio, but also the temperature and humidity on the day on which it was used.

The use of masonry construction in cyclone prone areas must be undertaken by competent tradespersons and under guidance from a specification written particularly for local conditions and local materials generally encountered.

Reinforcing bars used in masonry construction are often not galvanised, however, where either the mixing water or the aggregates used are saline, only galvanised reinforcement should be used.

6. INCORPORATION OF CYCLONE RESISTANT DESIGN IN PRACTICE

The design of each and every house by a structural engineer from first principles would be a task of both daunting magnitude and high cost. Walker and Eaton (1985) recommend the use of standardisation to spread the design costs over a large number of houses. The standardisation may be on a number of levels. Three will be outlined here.

(1) **Standardisation of details based on load carrying capacity**

This system is used by both the Darwin Reconstruction Manual and the Sri Lanka Building Regulations (Sri Lanka Govt (1981)). It provides for a very high degree of user flexibility, but must be used by a person who is proficient in the basic principles of structural engineering.

The philosophy adopted by this type of standardisation is that the designer must calculate the loads on all panels in the house and use those loads to determine the maximum forces carried by each connection and element of the house. Test data is presented in the document in such a manner that it is easy for a designer to match maximum loads with details capable of safely carrying those loads. The selected details can then be incorporated in the structural fabric of any house in almost any location provided the load carrying capacity of each detail is larger than the load applied to it in an extreme event.

Standardisation in this manner has a very high user flexibility, and can be easily implemented by making an ordered collection of available and vetted test data. However, the fact that such a system can only be used by a qualified person increses the cost of its use. This cost increase may in some cases be slightly offset by the fact that as details are chosen purely on the basis of adequate strength, there may be little conservatism incorporated in designs produced.

(ii) **Standardisation of details based on location and terrain.**
This is the system adopted within the Queensland Home Building Code. It is restricted in its use to conventional detached single dwellings in sheltered locations. The details are therefore only applicable to buildings in flat sheltered terrain within one cyclone intensity zone. As such, the wind loads on all panels do not have to be calculated. There are some restrictions on the geometry of the building, but there is also limited flexibility in the placement of internal walls, size of rooms and the house, and materials to be used in construction.

The details included in the document, if applied with good workmanship would ensure that the constructed house would have adequate strength to resist cyclonic winds but at a structural cost marginally above that of conventionally designed houses. For most details, a small amount of conservation has been incorporated in the design to allow the geometry of the house to be flexible. Rather than specifying the performance of each detail in terms of the load it could sustain, the number of details or length of wall in a given sized house was specified.

The application of such a code could be implemented by regional inspectors without formal engineering training. After some years of use in Queensland, the code has received wide acceptance from builders, as it enables the rapid design of structural provisions for housing by inclusion of reference to the full document in any house specification. Both the builder and the supervisor are then bound to comply with the provisions of the code which minimises disputes over the structural integrity of housing.

The experience of a recent tropical cyclone in the north of

Queensland (Walker, Reardon and Jancauskas, 1986) and the results of full scale tests on a house constructed in accordance with the provisions of the Queensland Home building code (Boughton and Reardon, 1983) have both shown that the structural performance of the code is satisfactory.

A large amount of research and testing is required before such a code can be published, but the implementation of the code by the majority of people in the housing construction industry can be easily facilitated. The cost of implementation of the code is small. Structural engineers do not have to be employed in the design of conventional houses, but small extra costs may be incurred in the purchase of the building materials due to the conservatism in the code that is necessary to allow flexibility in the architecture of the houses.

(iii) Standardisation of complete houses

Following extensive damage to housing in Tonga in 1982 by cyclone 'Isaac' the Tongan Ministry of Works instituted a reconstruction program which utilised standard houses prefabricated in Tongatapu from a mixture of imported and local materials. The reconstruction houses could be entirely erected by unskilled labour using only hand tools in under a week. Because many identical houses were produced, it was possible to invest much structural engineering input in the design and testing of the house. In fact a complete house was tested for structural performance under simulated cyclonic conditions (Reardon and Boughton 1986).

The cost of implementing this high degree of standardisation was also small. Little skilled labour was required to erect the houses, and the high investment of structural engineering skill in the early stages of the programme ensured that optimal use was obtained from all of the structural details in the house. There was no expenditure on conservatism, the structural and functional provisions of the house had been reduced to the minimum required to perform adequately.

The construction programme involved a high degree of participation from local experts and tradespersons and could be very quickly implemented.

7. SUMMARY OF THE DESIGN PROCESS

Regardless of the type of standardisation chosen to practically implement rational design of house structures to resist tropical cyclones, the following steps must be included in the design process either implicitly or explicitly.

(i) examination of the proposed site to determine the susceptibility of the site to damage from storm surge. The house floor level should be well above the highest expected storm surge level taken at high tide.

(ii) selection of a regional basic ultimate wind velocity

(iii) modification of the regional basic wind velocity to give a site specific basic ultimate wind speed. This takes into account local topographic effects and shielding by adjacent structures.

(iv) use of pressure coefficients appropriate for the geometry of the house to derive external pressures and hence loads on all external surfaces.

(v) use of assumed dominant openings to calculate internal pressures and hence loads on all internal surfaces.

(vi) the summary of all external and internal surface loads to produce net structure loads.

(vii) selection of details to resist the net structure loads. These include

roof cladding	resisting uplift, spanning between battens
roof fasteners	resisting uplift, fixing cladding to battens
battens	resisting uplift, spanning between rafters
batten fasteners	resisting uplift, fixing battens to rafters
roof structure	resisting uplift, spanning between walls
rafter fasteners	resisting uplift, fixing rafters to walls carrying lateral loads, from top plates to roof structure.

wall top plates/ bond beams	resisting uplift, spanning between tie down points. carrying lateral loads, from walls to roof
tie down points	resisting uplift, securing top of wall to floor carrying lateral loads by preventing overturning
footings	resisting uplift, securing the floor to the ground
walls	carrying lateral load by out-of-plane bending carrying lateral load by in-plane shear
roof bracing	carrying lateral load to internal bracing walls
bracing wall connectors	carrying lateral load only to internal bracing walls from the roof
sub-floor bracing	carrying lateral load from floor level to ground level

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DESIGN CRITERIA FOR TROPICAL CYCLONES

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ABSTRACT

The design of buildings for tropical cyclones requires that a decision making process be undertaken in order that appropriate loads be determined. These decisions establish the design criteria and rely on meteorological information, terrain classification, aerodynamic principles and the end use of the structure.

This paper examines the establishment of appropriate design criteria to enable the structural design process to begin.

1. INTRODUCTION

In establishing a design philosophy for buildings in tropical cyclone-prone areas, it was found that the application of structural engineering principles could reduce the potential for community disruption and hardship due to wind damage from tropical cyclones.

In some countries, clearly laid out design criteria exist in loading codes, material use codes and test procedure manuals. In other countries these criteria have not been established and those in use in neighbouring areas may be quite inappropriate for social, economical or physical reasons. In these cases design criteria must be established from first principles to enable the structural design of buildings for tropical cyclones to have a rational basis.

2. DESIGN WIND SPEEDS

Design wind speeds in non-tropical cyclone prone areas are generally based on estimates of the 50 year return period wind speed. However, even in locations where relatively long duration records are available problems exist with the interpretation of recorded data to produce 50 year return period wind speeds. Terrain conditions in the vicinity of the measurement point may change over time, causing doubts to be cast on the validity of the record. Also periods of missing data can cause problems with the estimation of the statistical significance of the data, and comparison of records from nearby measurement points can produce conflicting information.

Traditionally the accepted process for non-cyclone-prone areas has included a Gumbel analysis of annual maximum wind speeds to produce an estimate of the 50 year return period wind speed. Safety factors have then been used to give an ultimate or extreme event wind speed.

However, this approach is not appropriate for the design of buildings in tropical cyclone-prone areas. The statistical description of tropical cyclone extreme winds is very different from that for temperate zone extreme winds. In temperate zones winter gales occur every year, although the speed of the maximum wind may vary from year to year. In cyclone-prone areas, a number of years may pass in which particular recording stations are not influenced by a tropical cyclone at all. The distribution of maximum annual wind speeds is therefore a combination of events associated with tropical cyclones, and much smaller events such as winds associated with thunderstorms. This has the effect of reducing the estimate of the 50 year return period wind speed thereby making it unconservative.

There is also evidence to suggest that the ratio of the probable extreme wind speed to the 50 year return period wind speed in tropical cyclone-prone areas is generally much higher than in non-cyclone-prone areas. A number of methods have been proposed for estimating extreme wind speeds in tropical cyclone affected locations but the limited length of record, heavy reliance on poorly defined data, and the common use of the Gumbel distribution to describe variability make most of them inappropriate as estimators of extreme wind speeds. Good records of extreme wind speeds in tropical cyclones are very rare, as the high winds that frequently cause much damage to buildings can also cause significant damage to anemometers.

Walker (1985) suggested the use of the Saffir-Simpson intensity scale to define wind speeds. This scale, reproduced in the paper 'Design Philosophies for Tropical Cyclones' relates expected wind speed and central pressure to a Saffir Simpson intensity number. Often records of central pressure are mor reliable than those of wind during the passage of tropical cyclones and the Saffir-Simpson scale allows rough correlation of wind speed with central pressure. In order to define a design wind speed for a given location, it is first necessary to determine an appropriate design cyclone intensity. This decision must be made with meteorological advice. In general, areas that have low frequencies of occurrence of cyclones will be subjected to severe cyclones (SS3), with basic ultimate wind speeds of 60 m/s. Localities that have historically been subjected to more tropical cyclones may have a higher probability of very severe tropical cyclones (SS4) and require basic ultimate wind speeds of 75 m/s. In localities that have a history of many tropical cyclones, then the basic ultimate wind speed appropriate to catastrophic tropical cyclones (SS5) may be chosen. This may be as high as 90 m/s.

The extreme wind speeds generated by other meteorological phenomena are likely to be of the same order as those generated by an SS3 tropical cyclone, so it is suggested that if an area is at any risk from tropical cyclones, it must be zoned for at least an SS3 event.

It is to be noted that these speeds refer to basic ultimate wind speeds. This term must be defined carefully as many current codes use similar terms to describe quite different phenomena. The basic ultimate wind speed corresponds to the highest probable gust speed in an event of that magnitude. In terms of building response, it could be reasonably expected that damage to the building would start to occur at about this speed. this speed is NOT the basic design velocity as currently defined in the Australian, New Zealand and other wind codes, which give wind speeds for working stress design conditions. Both the basic ultimate wind speed and the basic design velocity are defined as the speed at a height of 10 m above flat open terrain, typical of a large grassed field.

The wind speed thus obtained is a property of a region and may pertain to many towns, communities and buildings. In order to find an appropriate design wind speed for a particular building, due account must be taken of its setting.

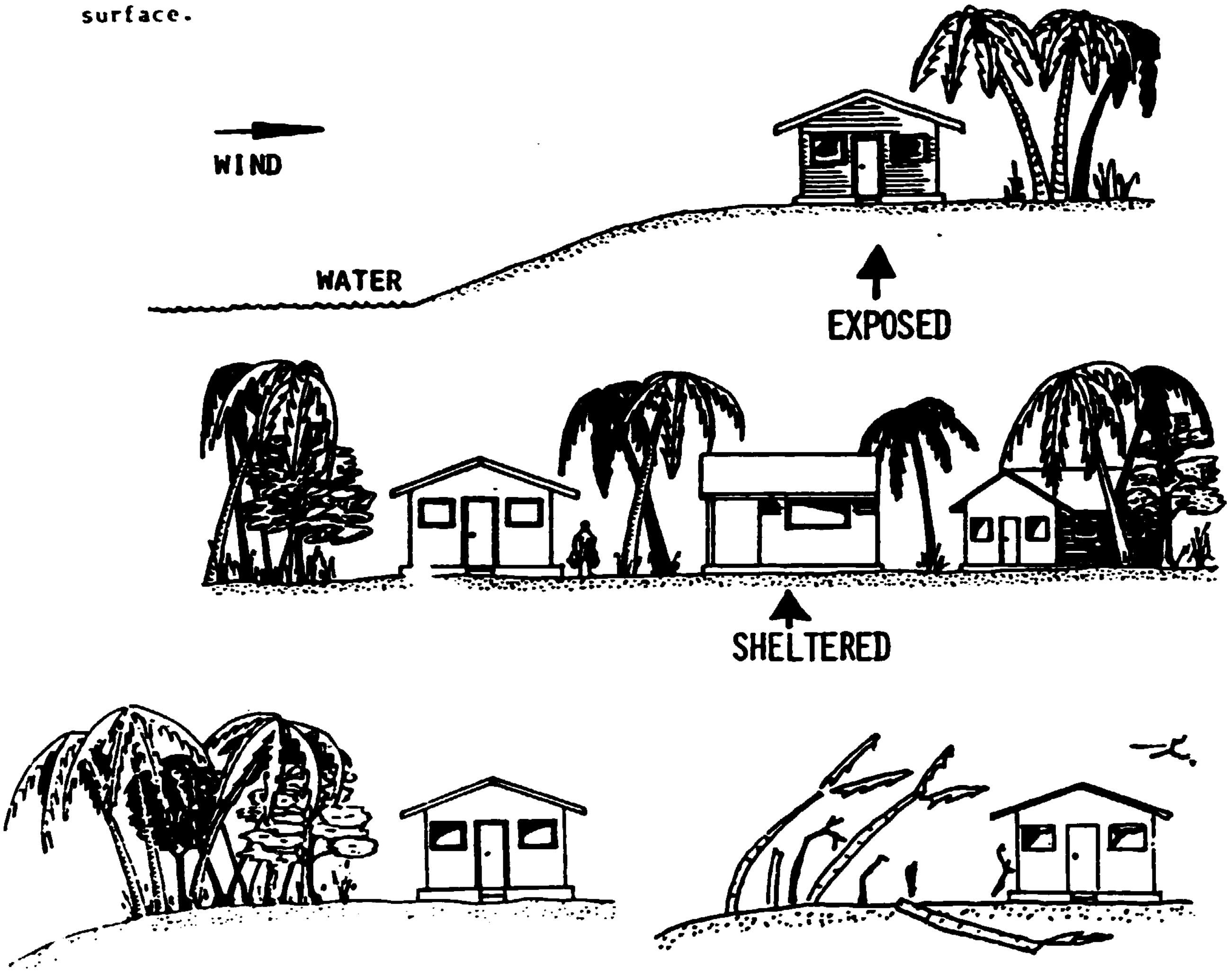
3. THE INFLUENCE OF TERRAIN ON WIND SPEEDS

Buildings are located in a highly turbulent boundary layer of air, and wind speeds at the location of particular buildings are a function of the roughness of the landscape surrounding each location. The passage of wind over many houses such as in a suburban or town setting, can increase the depth of the turbulent boundary layer. This effect reduces the mean wind velocity but increases turbulence. Likewise the passage of wind over a very smooth surface causes a reduction in the height of the boundary layer and a corresponding increase in the mean wind velocity with a reduction in turbulence. Damage to buildings appears to be highly correlated with the approach exposure. This indicates that in the past not enough importance has been placed on the effect of upwind surface characteristics. Figure 1 illustrates sheltered and exposed positions.

In non-cyclonic conditions, trees can afford some protection from high winds, by both sheltering houses directly, and increasing surface roughness. Both effects cause a reduction in the mean wind speed. However, in tropical cyclones, many trees are completely stripped of leaves. Those types that do not readily lose their leaves may be blown over. The long duration of tropical cyclone events means that for much of the period of high winds, the trees can be discounted as either surface roughness or shelter for houses. The effect of defoliation means that surface roughness must be found independently of vegetation considerations. Figure 1 illustrates the effect.

Other complications occur in hilly or undulating country. The aerodynamic effect of a cliff is to increase the wind velocity near the edge of the cliff. The structure eaves height is effectively increased by the height of the cliff, and the convergence of flow over the top of the cliff may cause even higher velocities. Design wind speeds could be between 10 and 20% higher than an equivalent structure in flat locations due to proximity of a small abrupt rise.

Wind that approaches a building over a large stretch of water may have quite turbulent characteristics during tropical cyclones. Under normal conditions, the nearly flat surface of the water causes little turbulence in an air stream that passes over it. However, the winds experienced during the passage of tropical cyclones can cause significant wave action. This has an effect on the airstream that is similar to that caused by a large number of houses. Wave profiles can reduce wind speeds and increase turbulence. Houses located close to the sea shore should be located above the storm surge zone, which can result in increased wind speeds due to topographic effects, offsetting reductions due to the roughness of the sea surface.



EXAMPLE OF A BUILDING SHELTERED BY TREES.

THIS BUILDING WILL BE FULLY "EXPOSED" AFTER LOSS OF TREES IN A CYCLONE.

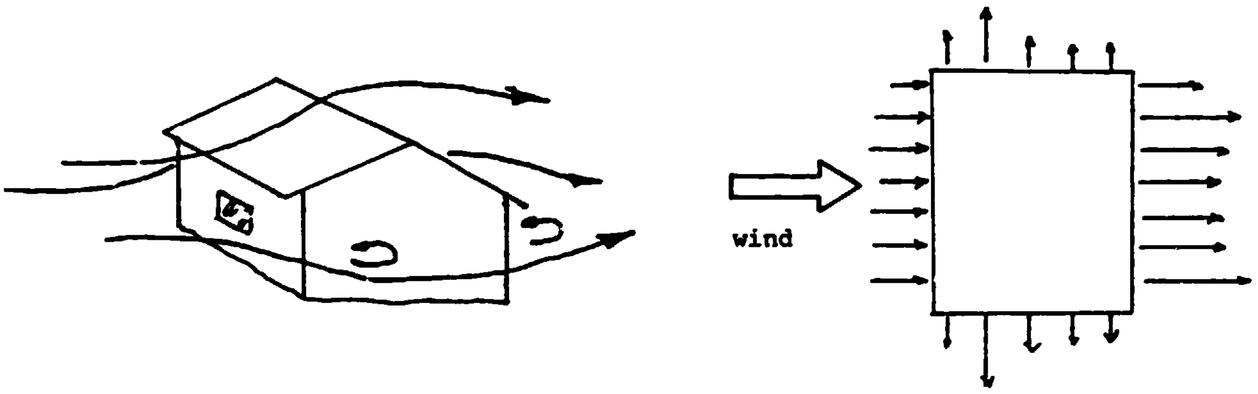
Figure 1 - Exposure Classifications
(from Sri Lanka Govt, 1980)

4. EXTERNAL AND INTERNAL PRESSURES ON BUILDINGS

The action of wind in passing around an obstruction such as a house causes positive and negative pressures to be applied to different external surfaces of the building.

The wall that faces the direction from which the wind is blowing (the windward wall), blocks and redirects the wind stream. It therefore always experiences positive pressure.

The leeward wall is opposite to the wall mentioned above and is affected by the wake of the building. It generally experiences suction, although the turbulent nature of the wakes observed from most common building shapes means that the magnitude of the suction may fluctuate wildly. The other walls of rectangular buildings generally experience fluctuating suctions on their external surfaces. High turbulence in the vicinity of these walls contributes to fluctuations in pressure observed on them as well. The average pressures are shown on figure 2.



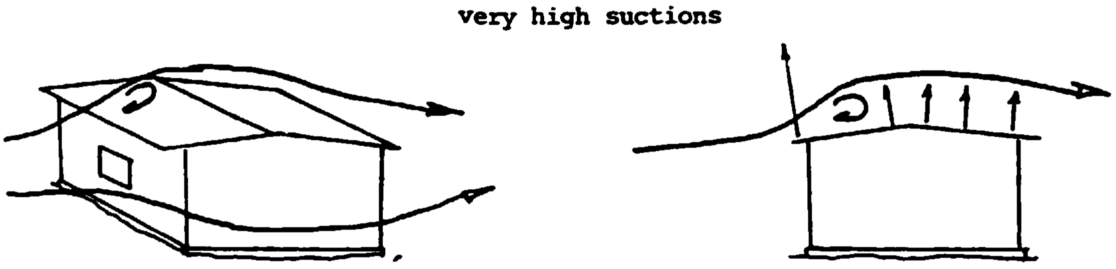
wind flow around house

plan of house showing pressures and suctions

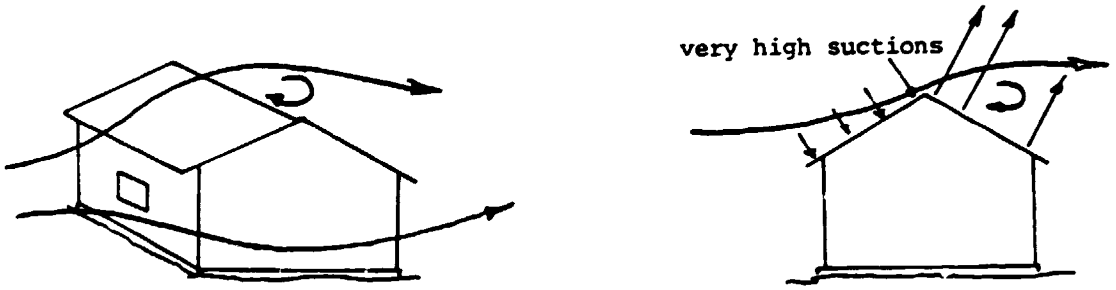
Figure 2 - External wind pressures on walls of houses

The effect of wind on roofs is a complex function of roof slope, house geometry and wind direction. In general houses with low roof slopes experience suction over all parts of the roof. Buildings with steep roofs may experience external pressure on the windward slope and high suctions on the leeward slope. At some points on all roofs and for all wind directions there are very high suctions generated by the separation of the airstream from the roof surface. The external suctions in these locations, which are generally near the edges, are very high and subject to large fluctuations. Roof sheeting failures generally originate in these areas. Figure 3 illustrates the effect.

The numerical value of external wall and roof pressures is a function of the geometry of the building.



(a) Suctions on low-slope roof



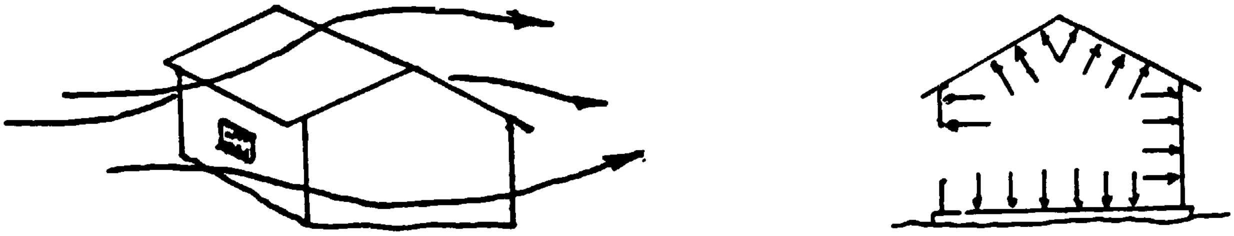
(b) Pressures and suctions on high slope roofs

Figure 3 - External pressures and suctions on roofs

In extreme events, windows and doors are often damaged. Walker and Minor (1985) show that window failure of 5 to 10 percent can be expected due to wind pressure alone. However tropical cyclones are invariably accompanied by flying debris. In rural settings, the debris may originate from branches torn from trees. In villages and towns, unsecured belongings stored outside may be lifted by the wind and hurled at nearby houses. Flying debris can be minimised by mounting clean up campaigns at the commencement of the cyclone season, but even so, parts of damaged houses and other buildings can form airborne debris.

The Australian experience of cyclone Tracy has shown that windows on the windward wall have a very high probability of being broken by debris even if they are strong enough to withstand wind pressure. A large number of broken windows or wall panels on the windward wall will admit the full positive pressure on the external surface of the windward wall to the inside of the building. This can more than double the total net load on surfaces which experience external suctions. Thus after windows have been broken, the total net outward force on the leeward walls, side walls and roof panels all increase significantly.

Special screens can be designed to absorb the impact of flying debris and therefore protect window glass. Alternatively, vents can be designed in buildings to automatically release high internal pressures should windward windows break. Test procedures have been in place in Australia for evaluating the effectiveness of cyclone protection screens, but little work has been performed on the evaluation of vents for the release of internal pressure.



wind flow around house

section of house showing internal pressures

Figure 4 - Internal pressure from openings in the windward wall

For buildings in which the contents represent a high value compared with the structure cost, the use of permanent cyclone debris screens may be warranted, but for all buildings where debris screens are not installed, the structure must be designed for full positive internal pressure.

5. FATIGUE SUSCEPTIBILITY OF HOUSING COMPONENTS

It has been observed in both the previous section of this paper and the paper 'Design Philosophies for Tropical Cyclones' that those panels of buildings which experience external suctions are also subjected to fluctuations in the load due to the structure-induced turbulence in the wake. Some components commonly used in domestic construction are susceptible to metal fatigue under conditions of repeated loading due to fluctuating suctions.

Morgan and Beck (1978) reported failure of sheetmetal roofing systems under repeated loading at loads much lower than their corresponding ultimate load under static loading. As a result of these observations, and those of many other workers, a test procedure (EBS, 1977) was devised in which building materials could be subjected to repeated loading. The procedure ensured that the loads were applied in a manner that was thought to represent loading patterns typical of those experienced in tropical cyclones. This document presents two separate procedures - one for elements associated with walls under external suction and another for elements associated with roofs under external suction. They are presented in Table 1.

At the conclusion of a fatigue test of the type indicated in Table 1, the component is loaded to failure and the ultimate load recorded. This test procedure is currently under review, but nevertheless provides a basis for assessing the fatigue susceptibility of building components under conditions reasonably representative of those experienced in tropical cyclones.

Boughton (1986) has noted that as well as roof sheeting, a number of elements can show susceptibility to fatigue. These include light gauge steel framing in the vicinity of fasteners, light gauge steel straps and steel fasteners.

The work performed to date on fastening systems shows the importance of fatigue testing in the minimisation of significant damage in tropical cyclones.

Table 1 - Wind Loading Fatigue Criteria for Building Components in Tropical Cyclone-Prone Areas

(a)

Wall elements	
Cycles	Load range
800	0 → 0.625 x design load → 0
200	0 → 0.75 x design load → 0
20	0 → 1.0 x design load → 0

(b)

Roof elements	
Cycles	Load Range
8000	0 → 0.625 x design load → 0
2000	0 → 0.75 x design load → 0
200	0 → 1.0 x design load → 0

6. IMPORTANCE FACTORS

Under tropical cyclone conditions, the function of some buildings may give them an increased importance when compared with others. These buildings include emergency shelters, hospitals and essential facilities.

Walker (1985) indicates that these buildings should be designed for wind loads that are 30 tO 50% higher than those used for other buildings. The significance of designing important buildings with higher ultimate loads is that the onset of serious damage could only be expected once most conventionally designed buildings have been very seriously damaged.

For example. in a zone designated as SS3, conventionally designed buildings may start to show some signs of distress when the basic wind speed is 60 m/s - equal to the basic ultimate wind speed used in the design of conventional buildings. A building that is to be used to protect people during the passage of a tropical cyclone should be designed for 1.5 times the load of normal buildings - equivalent to a basic wind speed of 75 m/s in the same zone. Thus in the event of an SS4 event (75 m/s) in the SS3 zone, which would be an extremely rare occurrence, most buildings would exhibit severe damage, but the specially designed building to be used as a shelter designed to 1.5 times the load of conventional buildings, would show little, if any damage.

7. CRITERIA

In determining the loads on a building a number of decisions need to be made. Some are on the basis of meteorological data, others on aerodynamic principles, the physical properties of the construction materials and the importance of the structure.

(i) Zone designation

Cyclone-prone regions need to be zoned to enable a design wind speed for a given location to be determined.

(ii) Terrain designation

The design wind speed at the building site is determined on the basis of terrain characteristics. Rules for determining site exposure and topographic effects must be formulated.

(iii) External pressures

The design ultimate wind speed can be used to calculate appropriate external pressures from aerodynamic information relation to the structure shape. Data for the most common house shapes must be collected and tabulated.

(iv) Internal Pressures

Where cyclone debris screens or effective venting are to be used, very low internal pressures can be utilised in the design, otherwise it must be assumed that some fraction of the full windward wall pressure is available as an internal pressure. The actual internal pressure is a function of wall permeability which will vary with the most common type of housing used.

(v) Design Loads

The sum of internal and external pressures give the total design loads on all portions of the structure. Where the structure has a particular disaster or post-disaster function it may be necessary to apply an importance factor to the design loads determined above. A decision regarding the size of the importance factor must be made.

(vi) Fatigue Effects

Where light gauge metal fasteners or components are to be used in the building, their effective strength under cyclonic repeated loads must be reduced from their static load strength. The reduction is a function of the geometry and form of the component used.

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DESIGN PHILOSOPHIES FOR TROPICAL CYCLONES

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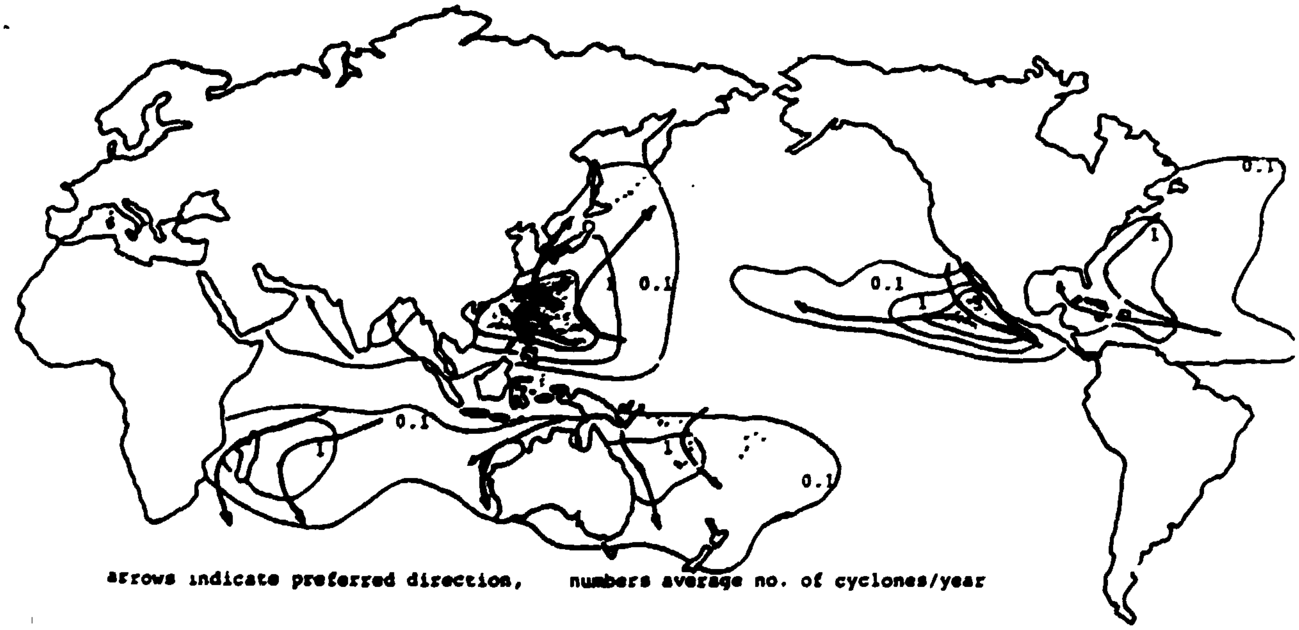
ABSTRACT

Tropical cyclones have historically caused much disruption to households, communities, towns, islands and in some cases to nations. Much of the hardship can be attributed to the high winds which are a significant characteristic of tropical cyclones. While it is generally recognised that it is very expensive to design all buildings to eliminate damage during the passage of tropical cyclones, cyclone-resistant designs can be produced that will minimise the long term cost of cyclone damage to communities. This paper examines the characteristics of tropical cyclones and the damage they produce and indicates a design philosophy that has been successfully implemented in a number of countries to reduce community hardships.

1. INTRODUCTION

Tropical cylcones, also known as typhoons, hurricanes, etc. occur in tropical waters in Asia, Oceania, the Americas and on the east coast of Africa. Figure 1 shows a reproduction of a map giving the location of cyclone prone areas and commonly recorded directions of movement.



arrows indicate preferred direction, numbers average no. of cyclones/year

Figure 1 - World map of natural hazards
(Munich Re, 1978)

Considerable regional variations in tropical cyclone characteristics appear to occur. The size of this meteorological phenomenom tends to vary. Tropical cyclones in Australian waters are generally much smaller in diameter than those elsewhere but their intensity is not diminished. Also, the generally western movement of most tropical cyclones is in contrast with the generally eastern movement of those in the SW Pacific. There are wide variations in frequency of occurrence and intensity of the events both within regions and between regions. This is complicated by global and regional climatic variations and cycles.

In combination with the relatively short history of detailed records of tropical cyclones, these variations can make the estimation of cylcone risk very difficult. The risk varies with the intensity of an expected extreme event. Land crossings of catastrophic cylcones are very rare, but their potential to cause damage is extremently high. Mild and moderate events are much more common but rarely cause major disasters from wind damage.

2. CHARACTERISTICS OF TROPICAL CYCLONES

Tropical cycles are large scale meteorological events that take days to generate over warm water and transfer energy from heat stored in the ocean to wind and wave energy. While a number of aspects of tropical cyclones vary regionally, the thermodynamic principles that determine their formation, and enable their growth are essentially the same in all regions.

Warm sea surface temperatures allow upward movement of moist heated air. Where the latitude of such a column of upward moving air is greater than about 10 degrees , Coriolis forces cause it to spiral. Warm moist air is then generally moved into the centre of the spiral where it rises to add moisture to the cloud layer established in the tropical low pressure cell. When the cloud mass builds up to a sufficient size, rain causes of latent energy of condensation to be released which accelerates the horizontal movement of air in the lower layers. The tropical cyclone therefore forms a high heat engine hundreds of kilometers in diameter that draws energy by lowering the sea surface temperature by between 2 and 5 degrees C, and converts that energy to kinetic energy in the form of air movement.

The centre of a tropical cylone is generally known as the eye, and is relatively calm and free of clouds. It can vary in size from less than ten kilometres to more than fifty kilometres in diameter.

In contrast to the calm of the eye, the strongest winds are experienced in a circular belt immediately surrounding the eye. The wind direction is generally circumferential in this region but the forward motion of the cyclone tends to increase wind speeds on the right hand side of the cyclone in the northern hemisphere and the left and side in the southern hemisphere. The maximum wind velocity measured in tropical cyclones appears to be related to the central pressure of the cyclone. As the central pressure falls, so the pressure gradient driving the wind increase, hence accelerating the wind.

The relationship between central pressure and wind speed is shown in the Saffir-Simpson Scale (Simpson and Riehl, 1981), which has been reproduced as Table 1.

Table 1 - Saffir-Simpson Scale and Tropical Cyclone Intensity

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

Tropical cyclones with low central pressures have very high wind speeds in the band immediately surrounding the eye and thus have potential to do much damage. However, the low central pressure also causes the water level at the centre of the tropical cyclone to rise in the same way that liquids rise in a drinking straw in response to low air pressure in the mouth. The increase in water level at the centre of cyiones is known as storm surge.

The preceding discussion has therefore alluded to the three principal potential sources for damage in tropical cyclones:

(i) high wind velocities
(ii) flooding due to high rainfall associated with the tropical cyclone
(iii) flooding due to storm surge

Each of these has the potential to cause damage to housing in areas known to experience tropical cyclones. Suitable design requirements can be implemented to minimise the risk to housing due to these three effects.

3. DAMAGE TO HOUSING IN TROPICAL CYCLONES

The Bangladesh cyclone of 1970 caused an estimated 300 000 deaths, though the actual toll including starvation following damage to crops and livelihood may have been as high as 500 000. Storm surge caused inundation of heavily populated low lying areas and was the direct cause of the very high death toll. In general, storm surge causes more significant loss of life than wind damage, although the economic loss due to wind damage may be larger.

Two regions prone to storm surge damage have been identified. The wave zone is immediately adjacent to the sea, where breaking waves may be superimposed on top of the surge. These waves have high inertia and are capable of causing significant damage. Oliver and Reardon (1982) reported that a number of substantial front row houses had been swept off their foundations and moved bodily more than 10 metres during the passage of cyclone Isaac in Tonga. Lighter houses have been totally anihilated by wave action in the wave zone.

The second zone lies behind the wave breaking zone and is subjected to inundation by saline water. Flood damage to both houses and contents can be severe in this zone, and the effects of salt on land use can remain for many years after flood waters have subsided.

Flooding by fresh water can also be associated with the passage of tropical cyclones as high intensity rainfall often accompanies the high winds. Recently cyclone Naamu in the Solomon Islands caused much flood damage including the removal of forests, topsoil, and whole villages from fertile river and creek flats. Often flooding can continue to impose a threat to housing for days after the high velocity winds have abated.

Damage by high winds is almost invariably experienced during the passage of a tropical cyclone. The hardship caused by the damage is not completely determined by the structural quality of buildings. Because tropical cyclones are large scale meteorological events, whole communities can be simultaneously affected by the action of strong winds.

The damage caused to Darwin by tropical cyclone 'Tracy' in 1974 is of particular significance as that city was the major population centre, a seat of government and commercial centre for the Northern Territory. More recent experiences in Tonga and Fiji have highlighted the problems experienced by small nations in which most public buildings and facilities are concentrated in one or two communities which are at risk from tropical cyclones.

The involvement of a whole community in the effects of damage by tropical cyclones escalates the cost of the damage. As well as costly physical damage to structures, significant community disruption is caused by diversion of productive effort to cleaning up and re-building. Important personal and community records can be lost making administrative functions difficult for a significant period after the passage of a cyclone. Damage to property and buildings can mean loss of livelihood for many, while rebuilding programmes often draw extra materials and manpower from outside the community which place extra strains on reduced local resources for accommodation. Each of the disruptions mentioned above becomes even more significant if a large provincial centre was damaged by the cyclone.

By contrast, tropical cyclone 'Kathy' caused very significant damage to a small isolated town in the Northern Territory in 1984, but in this case an effective emergency service procedure was implemented in which the entire population of the town took shelter in three strong public buildings. No injuries were sustained during the period of high winds although many houses and other buildings were completely demolished within the town. Power, water and telecommunications were restored within 24 hours to most of the town and temporary accommodation was arranged within days because the area traditionally relied on maintenance services from larger centres elsewhere. These larger centres remained operative and emergency services could be deployed at the damage site expediently.

In most documented damage studies, observations have been made that housing seems to sustain more serious damage from high winds than that observed in industrial and commercial buildings. Studies of cyclone damage to Australian housing has shown a number of recurring damage patterns have occurred.

3.1 Frequently occurring wind damage patterns observed in housing

The action of a high velocity wind stream on a house causes pressure on the windward wall, suction on the roof surfaces and suction on the back and side walls. These principal surface pressures are illustrated in figure 2.

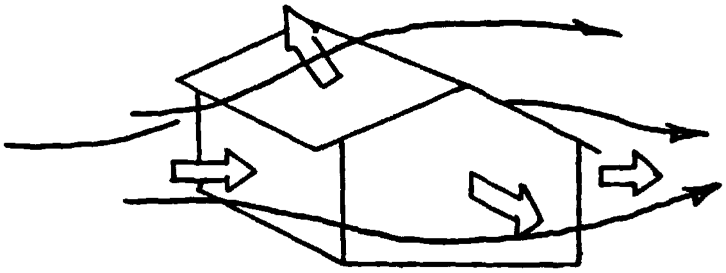


Figure 2 - Wind pressures and suctions on external surfaces of a house

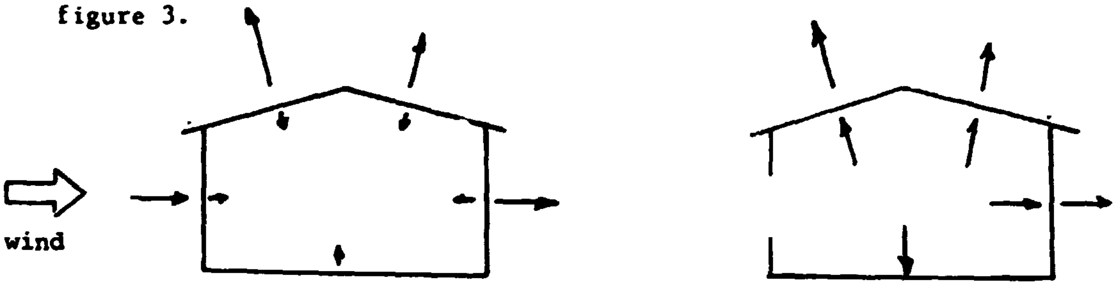
Because housing is situated close to the ground, it is embedded in the turbulent boundary layer of the air moving across the earth's surface. This can cause rapid fluctuation in the speed and direction of the individual wind gusts. This in turn causes changes to wind pressures on wall and roof surfaces. In addition, the structure itself induces turbulence in the wind stream that passes over the leeward part of the house. Thus those areas that experience external suction are also subjected to increased turbulence and highly fluctuating loads due to structure induced turbulence.

One of the major consequences of the investigation of damage from Cyclone Tracy in Darwin in 1974 was recognition of the influence of wind induced fatigue on the failure of light metal roof cladding under the sustained fluctuations in external suction for the duration of a tropical cyclone (Walker, 1975). In Australia, the most common types of roofing material used for domestic housing are roof tiles manufactured from fired clay or cured concrete, or light metal roof cladding fastened by nails or screws. Both these roofing materials have demonstrated inadequacies in resisting cyclonic winds for extended periods. External suctions on tiled roofs can exert uplift forces on the tiles that are larger than their weight. If the tiles are not tied, they will lift under those conditions. Where tiles have been tied with light gauge steel wire, the wire ties themselves may be subjected to repeated loading which may cause failure by metal fatigue. The loss of some tiles will allow the wind to pressurise the roof space and greatly accelerate the loss of other tiles.

Sheet metal roofing generally fails due to metal fatigue near the fasteners.

Under external suction, the roof sheeting is restrained by the heads on the fasteners causing high bearing stresses and flexural stresses immediately adjacent to a hole in the sheeting. During fastener installation radial cracks may be placed in the sheeting immediately adjacent to the holes. This type of cracking is most common with nailed roof sheeting. The action of fluctuating loads causes metal fatigue resulting in propagation of the radial cracks. Failure occurs by pull through of the fastener once the cracks have increased in length so that they extend beyond the fastener head.

Walker (1975) observed that in many cases, the first noticable damage to housing was the loss of some or all roof sheeting. In many cases this was precipitated by window breakage. Figure 2 shows that on the windward wall positive pressure is observed. Also flying debris due to failure of adjacent buildings or tree damage has a higher probability of striking a windward wall surface than any other surface of the house. Thus window or door failures due to either wind pressure or debris impact cause the high external pressure on the windward wall surface to be admitted to the inside of the house. For roofs, which generally have high external suctions, the addition of internal pressure causes extra load on the roof which may lead to premature failure. The effects of internal pressure is illustrated in figure 3.



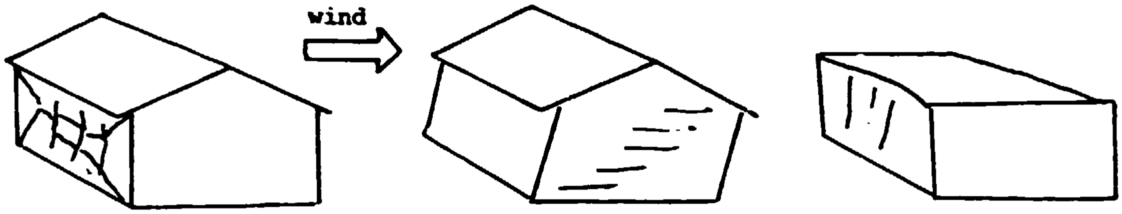
(a) All windows intact

(b) After window breakage on windward wall

Figure 3 - Effect of window breakage on roof loads

Loss of roof sheeting invariably results in damage to other parts of houses. The roof structure generally provides lateral support to the top of walls, so after the roof structure has been damaged, walls can lose their support and as a result are commonly blown in. While observations of wind damage from cyclones have shown that many houses that sustain significant roof damage also have wall damage, few houses are observed that have wall damage alone.

Wall damage is generally precipitated by the combined action of windward wall pressure and leeward wall suction which produces a significant lateral force on the house. Three types of wall failure have been observed and are illustrated in Figure 4.



(a) cladding damage (b) racking damage (c) bending failure due to roof loss

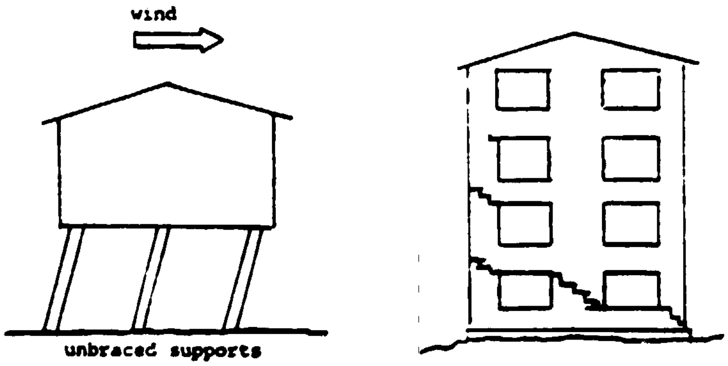
Figure 4 - Types of wall damage

Wall damage may be caused by flying debris, or inability of the wall fabric itself to carry the lateral loads applied by wind. Where wall failures in brick houses are observed, they are generally of this type. Thin plywood sheets may also be prone to failure at the fasteners to wall studs under the action of lateral loads.

Racking damage occurs when walls are deflected out of square and has been observed in houses that make extensive use of louvres or where the cladding has been removed by the action of wind loads or debris. Racking type failures are prevented by the use of large, adequately fastened sheets. These may be fibre cement or plywood panels nailed to a wooden frame.

The bending failure of walls due to roof loss has already been mentioned.

Elevated and multistorey housing have additional problems in that the lateral loads from the top parts of the building must be transferred to ground by lower storeys as indicated in figure 5.



(a) elevated housing (b) multistorey housing

Figure 5 - Damage to elevated and multi-storey

Wind speeds tend to increase with height, applying higher pressures to the upper storeys. The extra cross sectional area of multistorey housing also increases the total lateral load attracted by the complete building. Lower storeys must therefore be designed to carry high lateral loads to ground.

In the case of elevated housing supported on vertical piles, where the piles are not braced, racking displacement of the lower storey can occur as shown in figure 5(a).

Observations of multistorey brick housing after the passage of cyclones have shown that the higher wind velocities at roof level are more likely to cause roof structure damage, and also that the high lateral loads transmitted to ground through the lowest storey may cause cracking of the brickwork as shown in figure 5(b).

In summary a progression of damage through buildings has been observed to be as follows:

(i) window and door damage due to pressure or debris
(ii) roof damage
(iii) roof loss or roof structure damage
(iv) wall damage
(v) wall loss
(vi) elevated and multistorey housing may also be subject to substructure damage.

3.2 Relationship of housing damage to other buildings:

The major cause of disruption following cyclones is the failure of buildings and other facilities to withstand the extreme winds accompanying the cyclone. In most cases some buildings do perform well. In Darwin, cyclone 'Tracy' caused serious structural damage to over seventy percent of housing but the same relative level of damage was sustained by less than five percent of the larger buildings which had been structurally engineered to resist wind loads.

The design of these larger buildings utilised an established technology based on wind tunnel tests, experimental and theoretical studies and structural mechanics. Their performance highlighted the contribution that structural engineers can make to the mitigation of disasters arising from structural damage of which wind and earthquake are the principal examples. Had the housing in Darwin performed as well as the larger engineered buildings, the economic cost would have been reduced by about 80% and the human cost would have been reduced by an even larger factor.

The poor performance of housing in cyclone 'Tracy' was not a unique event. Most of the disasters caused by extreme winds around the world show a similar pattern. In both developed and developing countries, society has tended to regard housing construction as a traditional art for which sufficient experience exists to build safe structures without resort to modern technology. In some locations this rationale is justified as extreme winds occur with sufficient regularity to test out most houses every two or three years. Systematic structural deficiencies can be located and changed before being incorporated in many houses. Wellington (NZ) and Hobart (Australia) are good examples of these locations, as their climate is such that very strong gales associated with winter weather patterns occur each year. However in tropical areas, many years can pass without a given location being subjected to a tropical cyclone. This has two effects.

(i) Complacency within the building industry may lead to a reduction in attention to detail necessary to resist high winds after a long period without damage due to tropical cyclones.

(ii) A large number of new houses may be constructed and incorporate deficiencies prior to the flaws being detected in the next passage of a tropical cyclone.

Both of these effects indicate that for cyclone-prone areas, experience can be a poor guide to the performance of building practices, especially as building techniques are changing relatively rapidly.

However, the recent Australian experiences of tropical cyclones have shown that engineering principles applied through building regulations can play a major role in minimising damage, community disruption and hardship caused by high winds.

4. DESIGN FOR TROPICAL CYCLONES

In the years since tropical cyclone 'Tracy' caused such massive damage in

Darwin, the philosophy of housing design and construction in Australia has changed radically. The benefit of structurally designed components and details in housing has been recognised and as a result structural engineers have played an increasing role in the development of new building techniques and materials. Also, structural engineers have been able to play a vital role in the development of new building regulations for tropical cyclone-prone areas of the country.

The media exposure given to the effects of tropical cyclone 'Tracy' has enabled householders to become aware of the necessity to maintain houses in a structurally safe condition. In most cyclone affected regions of Australia regular seminars are attended by builders, architects, engineers and building supervisors at which changes to building regulations are outlined, reasons for their existence given and the effect of ignoring them presented. While no tropical cyclones of the magnitude of cyclone Tracy have made land fall in Australia in recent times, surveys of damage following tropical cyclone 'Kathy' (Boughton and Reardon, 1984) and tropical cyclone 'Winifred' (Reardon, Walker and Jancauskas, 1986) have shown that the performance of modern housing has been significantly better than housing which was constructed more than ten years ago.

4.1 Design philosophy

The characteristics of cyclonic wind loads are quite different from those of other structural loads. In the case of normal structural loads, we generally ensure that the risk of failure is so low that in practice, failure is extremely unlikely even under the worst combination of loads. This is achieved by the use of adequate load factors or factors of safety, and means that under the normally expected maximum loads, the structures will remain completely serviceable.

However tropical cyclones have a number of characteristics that set them apart from the normal structural loads.

(i) They are discrete events separated by long periods of low wind loads,

(ii) they are generally infrequent in their occurrence, and

(iii) they can be extensive in area. One event may affect an entire community should it be situated within the area affected.

In deciding on the primary objective of cyclone resistant design, it is generally accepted that if a severe natural hazard strikes a community, some damage may occur. The level of protection provided by building standards is derived by weighing up the economic cost of the provision of stronger housing with the social and economic cost of failure. Planners are required to determine the level of damage with which each community can cope without major disruptions. Engineers should then ensure that building standards are set which prevent damage from tropical cyclones exceeding the limit set by the planners. The concept is one of 'cyclone-resistant' design, not 'cyclone-proof' design.

4.2 Consequences of 'cyclone-resistant' design

The design philosophy given above implies that:

(i) the primary concern is the protection of the community as a whole and not individual buildings, and

(ii) the aim is to provide a degree of protection which may vary as a function of the anticipated frequency and level of the event, and not to provide guaranteed protection.

The degree of protection provided will also vary from building to building, and community to community depending on the following factors:

(1) Some buildings may have specific disaster or post-disaster functions. These may include hospitals, health centres, water supply facilities, but may also extend to buildings intended for use as community shelters during an event, or as centres for emergency activities such as administration or communication immediately after an event. These buildings should be designed to be significantly safer than normal buildings. In general, housing does not fall into this category.

(2) Some buildings house contents of high value. For example banks and insurance offices hold titles, records and money. Some warehouses may hold goods whose economic value far exceeds the value of the building structure. Where the contents of these buildings may be at risk from structural failure, a higher degree of structural damage may be warranted. Where water damage presents a risk to the contents as in the case of buildings housing computers or degradeable goods such as

sugar or fertilizer, then a higher degree of safety must be extended to the design of claddings, flashings and window glass. Again, housing generally does not fall into this category.

(3) Some communities house essential administrative and commercial functions which make them more vulnerable to disruption from tropical cyclones. Where surrounding towns or communities rely on a larger centre for warehousing facilities, government functions or financial administration, community disruption to the larger centre will also cause inconvenience and hardship in the surrounding smaller communities even though they were not directly affected by the tropical cyclone. Housing definitely is included in this category, as the reconstruction or repair of housing can divert manpower from essential functions and effectively cripple large centres even though commercial and administrative facilities may have remained largely undamaged.

4.3 **Practical implementation of cyclone-resistant housing design.**

Large commercial, administrative or industrial buildings have traditionally had significant engineering input in their design, in contrast with housing which traditionally has received little, if any structural engineering consideration. However, it is apparent from the previous sections, that if housing is to be regarded as 'cyclone-resistant' then some consideration must be given to engineering principles in design of the structural shell.

The two largest obstacles to the application of structural engineering technology to houses are:

(i) the high cost of the associated design process relative to the cost of individual houses, and

(ii) the traditionally conservative nature of the building industry.

To overcome these obstacles, two basic principles have been incorporated into the Australian approach to the problem. These are standardisation to spread the design costs over many houses, and evolutionary change as opposed to sudden change.

Walker and Eaton (1983) identified the major steps in applying wind engineering technology to domestic buildings:

- identification of risk areas
- zoning
- establishment of design philosophy
- standardisation of wind loads
- standardisation of assessment of structural strength
- standardisation of construction details
- implementation

In Australia, currently all buildings, including houses, in tropical cyclone prone areas have structurally engineered details built in to resist wind loads. In some states 'deemed-to-comply' standards have been prepared. These set out a large number of engineer designed and tested details which can be incorporated within the structural framework of buildings to provide adequate resistance to tropical cyclones.

Similar codes have been developed for Sri Lanka (Sri Lanka Govt, 1980) and are planned for Fiji (Walker, 1985). The Kingdom of Tonga has developed a standard house for use in reconstruction following tropical cyclone Isaac in 1982. This house has been tested for resistance to cyclonic winds and details that were found to be inadequate have been modified to provide adequate resistance (Boughton and Reardon, 1984).

In the development of 'deemed-to-comply' standards, consideration of local availability of materials and expertise needs to be made. The details used need to have been tested adequately to ensure their structural performance under the action of cyclones. These tests may have to take into account:

(i) the complexity of loading, being a combination of uplift and lateral loads,

(ii) the repeated nature of cyclonic loads over a long period causing low cycle fatigue in some details,
and

(iii) the high ambient humidity encountered during tropical cyclones.

5. CONCLUSIONS

Tropical cyclones have the potential to cause wind damage that has high economic and social cost for whole communities.

Studies of damage to housing have revealed systematic failure patterns that indicate weaknesses in many currently used details in tropical buildings. The types of damage observed can indicate the most cost effective structural details to upgrade in cyclone-resistant designs for any given area.

Design and construction of buildings that have sufficient strength to resist tropical cyclones is possible at an extra cost that is frequently less than 10% more than the structural cost of an equivalent building with no cyclone resistant provisions.

The design philosophy to be used for housing is complicated by many practical details relating to the function of the building, the size of community and the availability of materials. It is generally possible to reduce the extra cost of cyclone resistant features by trading off extra capital cost at the time of construction with repair costs should a major wind event occur. The penalty for the trade-off is a slight increase in community disruption following the passage of a tropical cyclone.

Implementation of cyclone resistant housing design will necessarily include testing and structural engineering analyses of locally available materials and building technologies. Standardisation of details where possible will spread the cost of development of adequate structural details over a large number of buildings.

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THE STRUCTURAL RESPONSE OF A TONGAN HURRICANE HOUSE TO SIMULATED CYCLONE LOADING

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ABSTRACT

The hurricane house has been loaded simulating the pressures of cyclone winds. Its elastic response has been measured, and an analysis made to determine load sharing between lateral walls, together with the effect of a roof diaphragm. The cyclic loading regime pinpointed a weakness in construction in respect of light gauge metal hold-down straps. The house was modified and successfully withstood the full complement of load cycles, despite a number of local failures and some resultant excessive deflections.

1. INTRODUCTION

A severe housing shortage was one of the main consequences of cyclone Isaac, after it devasted the Pacific island kingdom of Tonga in 1982 (1). Two thousand families were left homeless. The Tongan Ministry of Works embarked on a reconstruction programme and designed a cyclone resistant house of timber framed panel components. The panels were constructed at Nuku'alofa, the capital and transported either by land or sea to the villages. One set of components was shipped to the Cyclone Testing Station where facilities have been developed to simulate cyclone wind forces on houses, and measure their response and strength.

2. THE TONGAN HURRICAN HOUSE

The structural design of the components was undertaken by Ministry of Works (MOW) engineers in consultation with the Building Research Establishment, U.K. (BRE) who had been involved in a similar exercise at St. Vincent in the Caribbean (2). The results of the combined MOW, BRE design became known as the 'Hurricane House'.

Simplicity was the basic concept of the reconstruction programme. The decision was made to have only one floor plan, Fig. 1, with the possibility of later extension by the owner. The plan is based on modular wall construction 2.4 m long, thus the standard house is three panels long and two panels wide (7.2 m x 4.8 m).

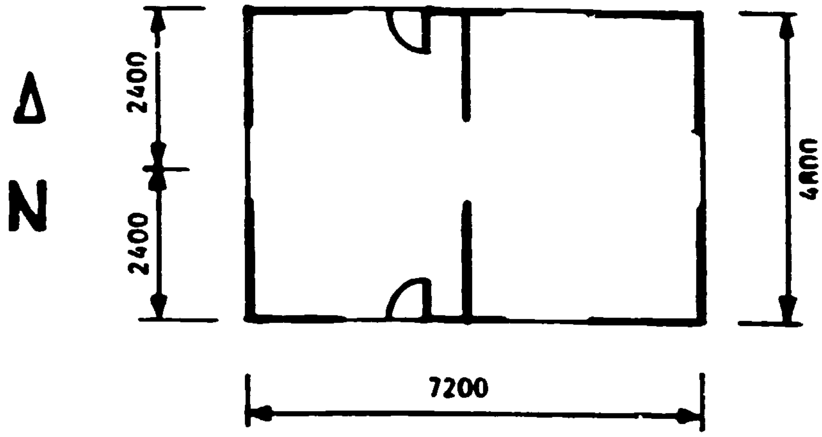


Figure 1 Floor plan of hurricane house

BRE co-operated with MOW to organize a sample set of components to be sent to the Cyclone Testing Station for erection and test. By doing this, the strength of that prototype house under simulated cyclone wind conditions could be determined. Further if there were an unforseen weaknesses in the design they could be pinpointed during the test programme. This would allow modifications to be made to existing houses if necessary, and thus they could be made safer prior to the next cyclone.

To ensure that the components were correctly assembled in Australia, the Tongan Assistant Secretary of Works supervised and participated in the construction of the test house. Thus with Tongan components and construction techniques the house represented as closely as possible a typical hurricane house. Only the foundation conditions were different.

Structural details of the test house nominally were as follows:

200 mm dia. pile stumps on 1200 mm grid
100 x 75 mm bearers at 1200 mm spacing
100 x 50 mm joists at 600 mm spacing
100 x 50 mm wall studs at 600 mm spacing
100 x 50 mm top and bottom plates
4.8 m span roof trusses at 1200 mm spacing
75 x 50 mm battens at approximately 600 mm spacing

The house was clad externally with 8 mm thick plywood and had a corrugated galvanized steel roof. The timber was hem-fir from USA.

The internal partition wall was basically non-structural. The timber framing of that wall was clad on one face with 4.5 mm hardboard fastened with light gauge brads at about 150 mm spacing. There was no other internal lining or ceiling.

3. WIND LOADINGS AND SIMULATION

3.1 Design Wind Loads

Structural engineering calculations for the design of the test house were provided for the Station by the Tongan MOW. They were based on the New Zealand wind loading code (3) and timber code (4). The basic gust wind speed was taken as 66 metres per second which after various modifications yielded a design wind speed of 62 m/s and a quasi static design pressure of 2.36 kPa. Net uplift design pressure on the roof structure was calculated as 2.6 kPa and the wall bracing was designed for 3.5 kPa. A subsequent check of the calculations by the Cyclone Testing Station revealed that the light gauge metal strap securing the trusses would be overstressed by about 60% at design load, but that stress would still be only about 50% of the predicted static failing load.

3.2 Simulated Loading and Measurement

After having determined design loads, forces were applied to the hurricane house in such a manner as to produce the same structural effect as those loads. The mechanics of the force application are illustrated in Fig. 2.

Racking forces were applied to the top of the structure by a hydraulic ram (a) which applied a tension force to a cable. This cable passed over a pulley (b) and through the house to a load spreader (c). Three such loading frames and spreaders distributed lateral loads over the length of the top plate of the house, approximating the uniformly distributed load applied to the walls in high winds.

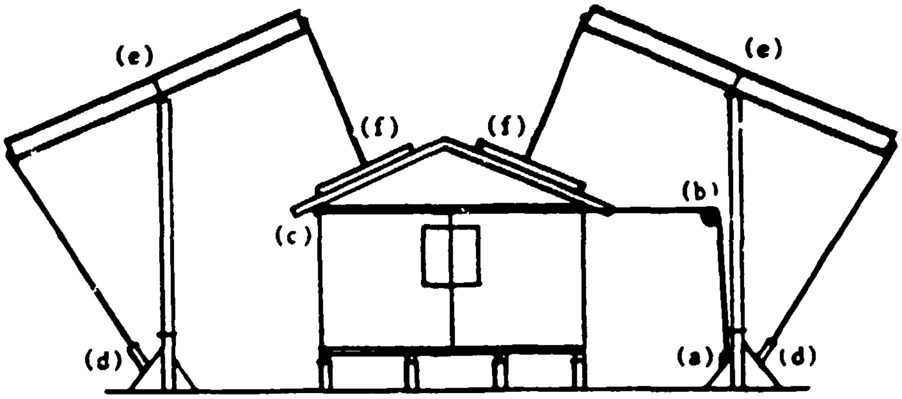


Figure 2 Configuration of loading system

Uplift forces were applied using the hydraulic ram (d) which pulled downwards on one end of a large "see-saw" beam (e). The other end lifted a load spreader (f) which distributed the uplift loads to load spreaders adjacent to the roof battens.

The forces were monitored using strain gauge load cells, and deflections were measured using a computer based instrumentation system (5). Over fifty specially constructed displacement transducers were placed on the house, and they electronically transmitted measurements to a portable computer. The data acquisition system took less than 5 seconds to record readings from 52 transducers, so that creep during the measurement period was minimised. The loads and deflection curves could be viewed as the test was being performed. These curves verified that the house was behaving in a linear fashion during elastic tests and were used to determine modes of failure during the destructive tests.

3.3 Test Programme

There are two separate areas of investigation in the house testing research programme. The first involves stiffness tests on elements of the building during its construction; the second is the determination of strength of the building as an entity and of its components.

3.3.1 Stiffness tests

This test programme necessitates construction of the building in an unusual sequence, whereby the walls are erected and lined prior to the installation of the roofing. By building in this manner, racking tests can be conducted on individual walls to determine their stiffness. Addition of the roofing material may constitute a structural diaphragm, capable of distributing the applied racking force to nearby walls. Roof sheeting can act as an efficient diaphragm, depending upon its fastenings (6). Internal lining materials can also act as structural diaphragms, but this house had no such linings or ceiling.

3.3.2 Strength tests

When testing a house designed to resist tropical cyclones, it is essential to simulate the continual buffetting forces that the house would receive from wind gusts. The sequence and magnitude of application of the forces were in accordance with an industry accepted standard (7). The programme required 10200 cycles of uplift load to be applied to roofing, and 1020 cycles of lateral load to be applied to walls.

For roofs the following sequence is adopted:

8000 cycles	0 - 5/8 design load - 0
2000 cycles	0 - 3/4 design load - 0
200 cycles	0 - design load - 0

For walls one tenth of the number of cycles to each load level is applied.

Racking and uplift forces were applied to the house simultaneously. During the cyclic loading programme this was accomplished by applying nine cycles of uplift only followed by a cycle of combined uplift and racking.

At the completion of the cycling sequence the house was loaded incrementally in both uplift and racking, maintaining the correct ratio of forces, until failure occurred. This was taken as the strength of the hurricane house.

4. RESPONSE OF THE HURRICANE HOUSE

4.1 Elastic Loading

Racking tests were conducted on each transverse wall of the house, with the roof structure in place, but no roof sheeting. The measured racking stiffness of the three transverse walls of the Tongan house was a follows:

West wall	2.02 kN/mm
Internal wall	1.35 kN/mm
East wall	2.03 kN/mm

The end walls show remarkable agreement and the internal wall, which was not designed as a bracing wall, demonstrated that it had the capacity to act as one.

Although the racking force was applied directly to the top of each transverse wall in turn, there was some lateral distribution of that force by the side walls of the house. Table 1 lists the percentage of load carried by each wall. Although the end walls had indentical stiffnesses, they attracted different percentages of the applied load. This is a reflection of the discontinuity provided by the doorways in the external walls (see Fig. 1). It was more difficult for forces to be transferred between the west wall and the internal wall than between the internal and the east wall.

TABLE 1

Racking force distribution in hurricane house without roofing

Racking load applied at top of	Percentage of applied load carried by		
	West wall	Internal wall	East wall
West wall	83	17	0
Internal wall	9	78	13
East wall	2	30	68

After the corrugated steel roofing was installed the racking test on each wall was repeated. The results of the force distribution analysis are listed in Table 2.

The diaphragm effect of the roof sheeting was most pronounced when the west wall was loaded. It negated the effect of the discontinuity, and made the response almost the same as for the case of the loaded east wall. The roofing diaphragm also affected the force distribution for the internal wall, but the effect of the doorways was still evident.

The response of the east wall is interesting in that it shows little effect of the roofing diaphragm. This suggests that, in the elastic range of the house response, the looped strap connecting roof trusses to walls allowed some lateral movement of the walls before the roof diaphragm could act, virtually nullifying the effect of the diagphragm.

TABLE 2

Racking force distribution in hurricane house with roofing

Racking load applied at top of	Percentage of applied load carried by		
	West wall	Internal wall	East wall
West wall	64	32	4
Internal wall	15	52	33
East wall	4	34	62

4.2 Cyclic Loading

4.2.1 Original house

Complete details of the Tongan hurricane house under simulated cyclic loading have been published by Boughton and Reardon (8). A summary is given below.

During application of the proposed 8000 cycles of 5/8 design uplift load, a twisted metal strap securing a truss failed. The strap had been installed in such a way as to attract a disproportionate amount of tensile force to its outer edge. Figure 3 shows the installed strap. A crack started at the edge and propogated until the strap failed in tension, after 2500 cycles of uplift load (hence 250 cycles of lateral load). At about 4000 uplift cycles straps securing three other trusses failed, allowing significant lateral movement of the top of the 'windward' wall.

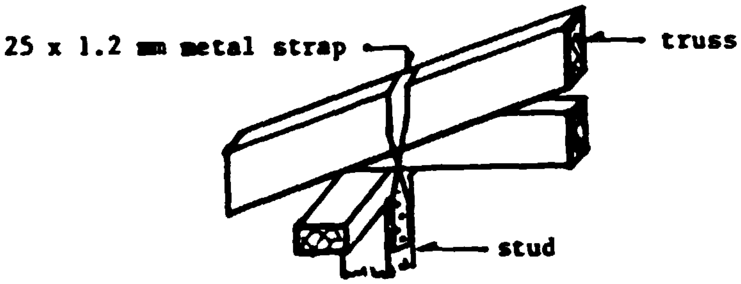


Figure 3 Truss hold-down detail

The test was stopped and the situation assessed.

It was acknowledged that the straps were overstressed by about 57% in uplift. Further, the lateral racking force on the walls caused the trusses to apply an extra force to the straps by means of a wedging action. This may have increased the uplift force to approximately 2.2 times design, and the cycling force to 1.4 times design. But this force is still only about 50% of the anticipated failing load of the strap.

It must be concluded therefore that the strength of the straps had been significantly reduced with application of the loading cycles.

4.3 Modified house

The house was repaired by installing overbattens on top of the trusses and bolting them to the top plate of each wall. Figure 4 demonstrates the principle. This sytem was chosen so that it could easily be implemented on existing houses in Tonga, if necessary.

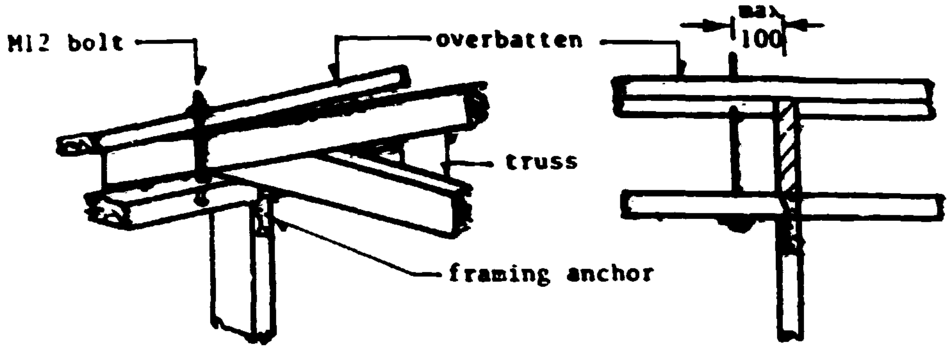


Figure 4 Bolting of overbatten

In order to fully load the new hold-down system it was decided to apply the total 8000 cycles of 5/8 design uplift load to the modified house. However as no modifications were made to the bracing strength of the house only 400 cycles of 5/8 design lateral load were applied, that is, the complement of the original number.

Only minor failures of the internal wall occurred during application of the 8000 uplift cycles. The deflections, however, were quite significant with 20 mm vertical moment at the eaves and 35 mm lateral movement at the top of the windward wall.

Commencement of the 2000 cycles of 3/4 design uplift load, and the corresponding lateral load, caused a significant increase in total movement of the house. The eaves lifted 35 mm and the top of the wall moved 60 mm laterally. These deflections were due in part to the concrete footings lifting by about 15 mm on the windward side of the building.

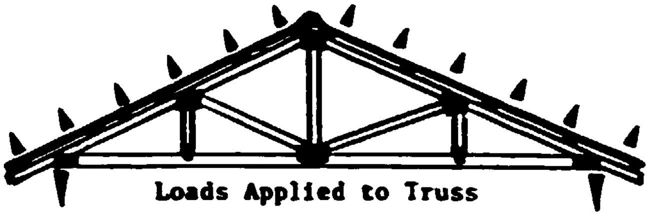
Significant structural damage occurred during this loading sequence. Nails pulled out of batten straps, teeth broke off the truss plates and the hardboard was being sprung off the internal wall.

Despite its overall deterioration the house managed to resist that full complement of load cycles.

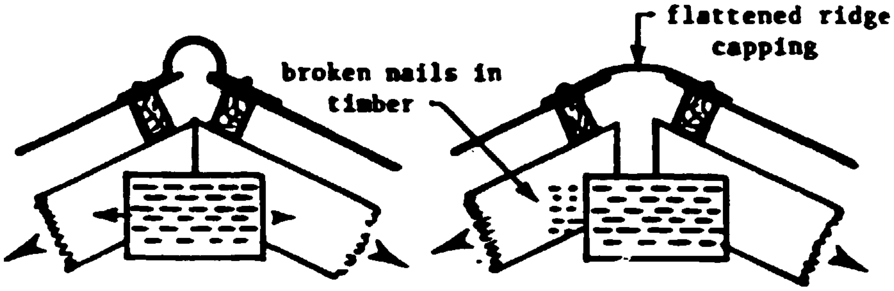
After 50 cycles of design uplift load (5 of design lateral) the internal wall was virtually destroyed, but the house was still resisting the applied loads. The apex joint of two trusses had completely failed, but truss action continued as the ridge capping started to act as link between the two top chords, despite a relative movement of about 30 mm between chords, Fig. 5. This situation prevailed for the rest of the loading sequence, but it resulted in large deflections, beyond the capcity of the measuring equipment.

Subsequent analysis of the forces at the ridge of the truss indicated that the ridge capping had the capacity to resist even higher loads if it acted similar to steel roofing (6).

With the completion of the cycles to design load the full cyclic loading sequency was achieved. The modified hurricane house had been able to resist simulated cyclone wind conditions commensurate with a design wind velocity of 62 m/s. The house had deflected significantly but it had not totally failed.



Loads Applied to Truss



Appex joint intact

Failed apex joint

Figure 5 Load transfer through ridge capping

After the cyclic loading sequence the house was loaded incrementally in uplift and racking until failure occurred. This happened at 1.3 times design load when the top chord of one of the trusses broke at a position near the heel. The very clean break indicated that the failure mode was caused by a combination of shear and tension forces.

The consequences of this 30% reserve of strength should be considered in the light of the Tongan economy.

5. CONCLUSIONS

All transverse walls acted as bracing walls. The roof diaphragm had a greater effect on the western end of the house than on the eastern end, during the elastic response tests. Almost 40% of racking forces applied to a wall can be transferred laterally by the roof diaphragm.

The vulnerability of a traditional method of joining structural components has been highlighted, insomuch as the strength of the light gauge metal straps was significantly affected by the load cycling.

The modified hurricane house resisted the simulated cyclone wind forces based on a design velocity of 62 m/s. Although some joints broke and the house deflected significantly, the structural redundancies allowed it to maintain its integrety.

The authors are of the opinion that the structural principals used in the modified hurricane house could be used as a model for the design of cyclone resistant housing in other countries in the Pacific area. The architecture may need to be changed but the basic concepts could be maintained, especially as they have now been tested by a simulated cyclone. However, traditional jointing materials such as light gauge steel or wire may have to be replaced by bolts and other elements less prone to degredation under cyclic loading.

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