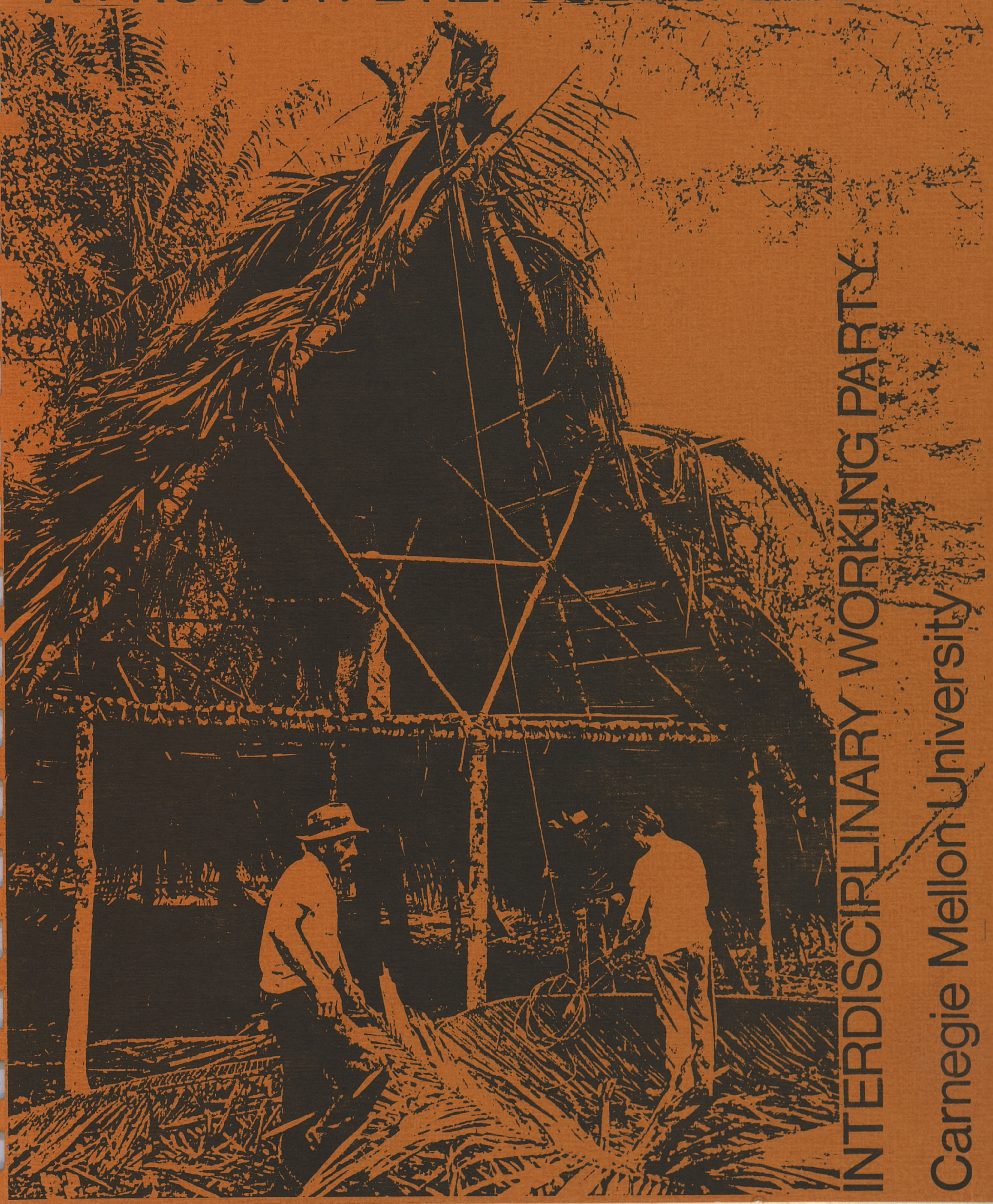
REPORT:

A PROTOTYPE REFUGEE SHELTER



INTERDISCIPLINARY WORKING PARTY

Carnegie Mellon University

I. Introduction

In the fall of 1973, an interdisciplinary team of architects, civil engineers, and chemical engineers was formed at Carnegie-Mellon University to study housing problems in refugee situations in the developing countries and to design ultra low-cost housing prototypes for use in the disaster prone areas of these countries.

This report outlines the development of the first of these prototypes, explains the test program and describes the results of the research. It should be pointed out that the work outlined herein pertains to the unit as a shelter which utilizes only indigenous materials of a tropical environment; other materials and adaptations for other environments will be tested as funding becomes available.

II. Approach

Due to regional variations in climate, topography and culture, no universally acceptable housing prototype is possible. Thus, the Working Party decided to concentrate its initial efforts in three areas: first, the development of a building process and methodology which can be applied to a wide variety of situations; second, the development of a prototype housing unit which could be built throughout large areas of the world with whatever materials were on hand locally; third, the introduction of technological processes to improve indigenous building techniques and construction practices. All were incorporated into a design program to produce an evolutionary shelter, a unit which provides immediate shelter for refugees and, with modifications, can be turned into a long-term house. By concentrating efforts on developing housing for refugees who are traditionally the people on the lowest rung of the housing ladder, the resulting technologies could be applied to the problem of providing housing for the ultra low income urban and rural populations in the third world.

The team decided to concentrate its initial efforts on developing a prototype for tropical environments. Tropical housing was selected for several reasons:

A. The majority of high density refugee situations occur in the tropical regions.

B. Housing in tropical areas worldwide tends to utilize similar shapes, thus providing a strong cultural base from which to begin.

C. Tropical areas have the greatest variety of materials with which to work.

D. There were currently a number of active refugee operations on-going in tropical areas (Bangladesh, Indo-China, Philippines).

III. Design Constraints

A. Cost: An estimated cost of $10 of shelter space per family was derived by utilizing criteria obtained from the U. S. Agency for International Development (AID) and from costs typically allocated by relief organizations in recent operations. For the design to be acceptable, it had to contain the total cost of materials and labor within this limit. Similarly, the unit cost basis of other items such as sanitary facilities, stabilized soil, drainage ditches and water supply facilities, must be viewed as separate costs.

B. Use of Local Materials: The materials indigenous to tropical areas were the only structural materials considered in building the system. The structural flooring and roofing systems were designed so that modification required by material constraints in one system will not affect the details in the other systems. The framing system design for the structural members and the connecting materials had to be adaptable to the various structural strengths and sizes possessed by the materials. The flooring system had to accommodate similar variations in material properties by modification of design detail and not the entire floor framing system. An entire roof system consisting of framing and covering had to be devised for the various materials used due to the extreme difference in the material properties. It was the intent of the program to investigate many of the materials available for construction and document the necessary modifications as dictated by the material constraints. To ensure connection durability, it was necessary to transfer loads through contact of the members and not by the connecting material.

C. Environmental Problems: Many environmental conditions impose the controlling constraints in the design of refugee shelters. Flooding, wind and heat of the tropical zone induce extensive loading and design problems. Many areas of the tropics are at an elevation of only a few feet above sea level with a ground water table 9 to 18 inches below the ground surface. During tropical rains, extensive flooding occurs which must be considered in the shelter system design. The high temperature and humidity of the tropical zones necessitate the need for adequate ventilation. The building design must also consider methods for preventing the building material from rotting under the prevalent conditions of heat, water and moisture. Ultraviolet rays are extremely strong in the tropical zones, thus any synthetic materials introduced in the design must be UV treated.

D. Ease of Administration: With the vast numbers of people in refugee camps, it is imperative that administrative personnel be able to make frequent checks for illness and death throughout all structures. This requires that each living space be adequately lighted and easily accessible. Shelters must also be built to facilitate feeding and medical care for the occupants. The layout of the refugee camp as well as the shelter configuration must not only be acceptable to the administrative personnel but to the social and cultural patterns of the people.

E. Ease of Construction: For a shelter system design to be feasible, a specified number of units must be capable of being produced on a daily basis. Thus, the structural system must utilize a repetitive pattern in the framing. It is desirable to require various repetitive operations so that organized teams with only limited skills can mass produce the components of the building. By using repetitive operations, administrative personnel can set up rigs or patterns in which uniform components can be produced. The erection process must also facilitate the scheduling of continuous work for each team.

F. Behavioral Constraints: While the emotional and physical status of refugees varies greatly according to the nature of the disaster and the time the people have been refugees, certain generalizations may be made concerning their behavioral aspects. In his study, Refugee Camps & Camp Planning,* Frederick Cuny identifies the phases of personal adjustment that refugees undergo in refugee camps. The general improvement of emotional and behavioral aspects is seen to be a function of stability, organization, involvement and improvement of the physical environment. The Working Party addressed these functions in the design program for the prototype. First, the various behavioral aspects of refugees were outlined as design constraints. The constraints were then grouped under the functions outlined above. The results were as follows:

1. Stability: In order to encourage stability, the structure must be of a design similar to existing housing types or familiar to the region. Thus, the constraints identified which would promote stability were familiarity and similarity.

2. Organization: In order to be successful as relief housing, the structure must facilitate refugee organization. This requirement had to be met two ways. First, the unit had to lend itself to encouraging administration by design. In other words, the structure had to be designed from the viewpoint of a refugee camp administrator. Second, the structure itself had to be designed to be part of an organizational effort, i.e., it had to lend itself to mass production by the refugees themselves. To meet this requirement, the prototype had to be easy to understand, simple to build, and able to utilize pre-fabrication techniques.

3. Involvement: To be able to involve the refugees, the prime constraint was to design a structure that could be built with those tools, materials and building techniques with which rural people in the developing countries would be familiar. If the refugees couldn't use their own limited tools, in all likelihood the structure wouldn't be built.

4. Environmental Improvement: This was the most difficult aspect. Not only would the structure have to be able to reasonably withstand a hostile natural environment; it would also have

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* Refugee Camps & Camp Planning, Frederick C. Cuny & Associates - INTERTECT, Dallas, Texas, 1971.

to withstand a high density refugee camp environment with poor sanitation, inadequate health care and other accompanying detrimental factors. Within the camp environment, the structure had to provide a safe sanctuary for families, broken families and individuals alike. Furthermore, the unit had to be flexible enough to allow individual modifications or improvements by the occupants without substantially affecting the strength of the unit or altering any of the other functions of the structure.

These constraints were incorporated into the design program and each was met.

IV. Selection of Materials

It was decided that initial efforts would be concentrated on designing a structure which would utilize bamboo for the frame and palm thatching for the roofing material. The design was to be flexible enough to allow the substitution of unfinished wood (logs) in construction of the frame with only minor modifications. All other components of the structure were to utilize only indigenous materials or materials which could be produced easily in the region with unsophisticated techniques. Specifically, the bamboo structure was to utilize:

A. Frame - bamboo
B. Roof - palm thatch
C. Floor - ground level: earth, dung; first level: bamboo
D. Drainage - earth
E. Binding - twine or ropes
F. Partitions - reeds, dung

The wood structure was to utilize:

A. Frame - logs and sticks
B. Roof - palm thatch
C. Floor - ground level: earth; first level: sticks
D. Drainage - earth
E. Binding - vines
F. Partitions - palm mats

To ensure that the building process was kept at the simplest possible level, the only tool allowed for construction was the machete or bolo.

V. Selection of the Design

A. Research of Existing Structures: An extensive file was compiled by the Working Party on rural housing in the tropical areas and on structures and designs currently in use in relief operations. Various designs were examined with respect to the constraints outlined above in selecting an optimum design. A-frames, domes, pyramids, tension structures and gable frames were analyzed by a computer program. Models of the more promising designs were built, and a loading condition equivalent to a 150 mph wind was simulated by inducing a pushing force on the windward side and pulling force on the leeward side of the various structures. Existing designs were modified for strength and for use with other materials to determine those components which gave the most promise for incorporation in the prototype.

B. Co-ordination with On-going Research: In selecting the design for the prototype, efforts were co-ordinated with the Emergency Shelter Group of the University of Texas. The Texas team, under the direction of Wolf Hilbertz, built full-scale mock-ups of several of the proposed designs and conducted extensive research into bamboo joining techniques. Structures evaluated included triangulated pyramids, bamboo lattice shells and cable tension structures.

The Working Party also co-ordinated its research with relief organizations engaged in housing efforts. Through INTERTECT, consultants for the project, the designs were evaluated from the viewpoint of relief field staff for simplicity, ease of construction, ease of administration and cost.

C. Selection of Basic Design: The shelter consists of three independent systems: the main framing, the flooring, the roof framing and covering systems.

The main framing consists of the A-frames, diagonal bracings, a ridge pole and associated connections. The A-frame itself consists of two large wooden members notched and bound at the top to form a durable joint. The height and spacing of the frames can be modified when required by the structural strength of the members. The diagonal bracing between the A-frames is assembled separate from the roofing system. The connection details for the diagonal bracing resist either compressive or tensile forces depending on the properties of the diagonal members.

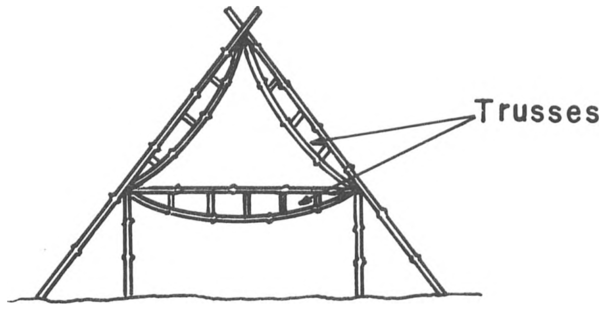
The flooring system consists of the floor and supporting beams and columns. The flooring configuration remains fixed with the construction details varying slightly depending on the material properties.

The beam-column connections for the flooring system do not change but the spacing for the beams and columns vary with material properties. The column height and anchoring system is dependent on the expected local flooding conditions.

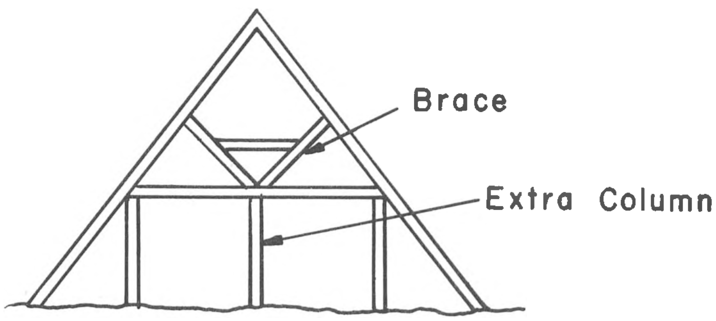
The roof framing and covering system is totally dependent on the properties and utilization of the covering material, thus requiring distinct designs for the various covering materials. A means of venting was devised for the vertex of thatched roofs.

It is felt that the total system is flexible and can be modified to accommodate the various material, environmental, administrative, cultural and technical constraints. The structure resembles the majority of those structures found throughout the tropical areas. It incorporates building features which are common to both wood and bamboo structures. The design is simple enough to be built with no more than a machete.

Additional reinforcement for the elevated floor and A-frame was provided in the form of trusses.



The use of trusses was chosen to meet the requirement that a refugee shelter have access to view throughout its entire length. For wood structures, a brace system crossing the A-frame would be substituted for the trusses.

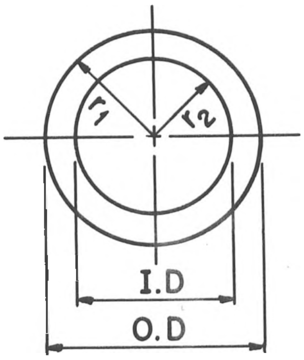


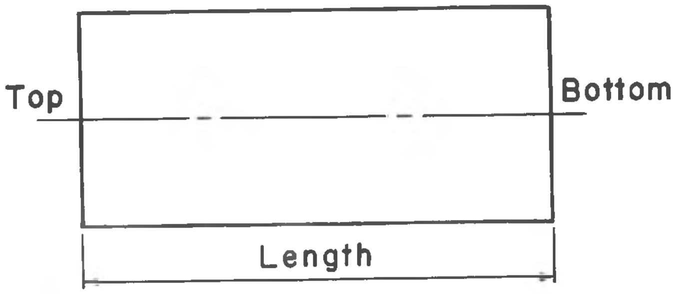
Materials are used to their greatest advantage in this design. Large components are kept to a minimum and rely on smaller pieces for supplementary strength. The flooring, stringers, cross-bracing and trusses are only one and one-half inches in diameter. Only the A-frames and columns are large members. The floor beam is an intermediate size.

VI. Materials Testing

A structural analysis was performed on the materials proposed for the structure under working loads to verify feasibility of their use in the structure and thus finalize the preliminary design. The structural properties of the materials had to be determined first.

A. Bamboo: The tests performed on the bamboo were meant to serve as a guide. Variations in species, age, growth conditions, moisture content, disposition of nodes and position along the culms necessitates approximations.





Sample dimensions were as follows:

Sample #1

Top	Bottom
O.D. = 1.09 in.	O.D. = 1.03 in.
I.D. = .69 in.	I.D. = .69 in.
Wall Thickness = .20 in.	Wall Thickness = .17 in.
Area = $\pi(r_1^2 - r_2^2)$ = .57 in.^{2}	Area = .47 in.^{2}
I = $\frac{1}{4}\pi(r_1^4 - r_2^4)$ = .060 in.^{4}	I = .046 in.^{4}

Length = 4.00 in.

Sample #2

Top	Bottom
O.D. = 1.06 in.	O.D. = 1.06 in.
I.D. = .70 in.	I.D. = .73 in.
Wall Thickness = .18 in.	Wall Thickness = .165 in.
Area = .50 in.^{2}	Area = .453 in.^{2}
I = .050 in.^{4}	I = .047 in.^{4}

Length = 5.94 in.

Sample #3

Top	Bottom
O.D. = .81 in.	O.D. = .84 in.
I.D. = .62 in.	I.D. = .65 in.
Wall Thickness = .095 in.	Wall Thickness = .095 in.
Area = .22 in.^{2}	Area = .21 in.^{2}
I = .014 in.^{4}	I = .019 in.^{4}

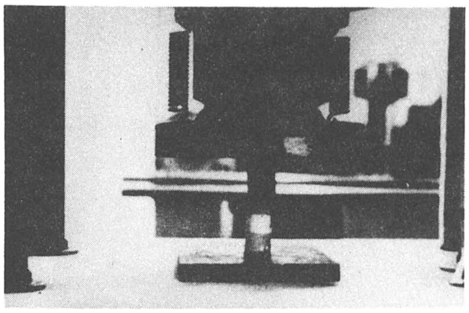
Length = 6.06 in.

Sample #4

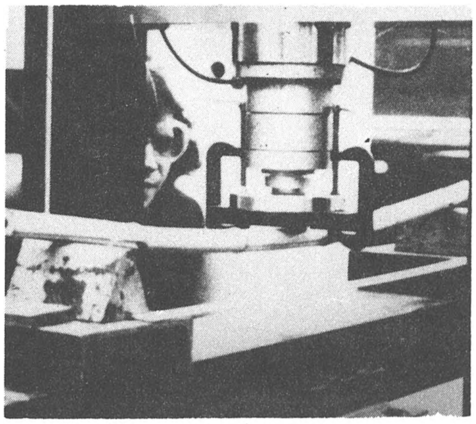
O.D. = 1.00 in.
I.D. = .64 in.
Wall Thickness = .18 in.
Area = .461
I = .037

Length = 42 in.

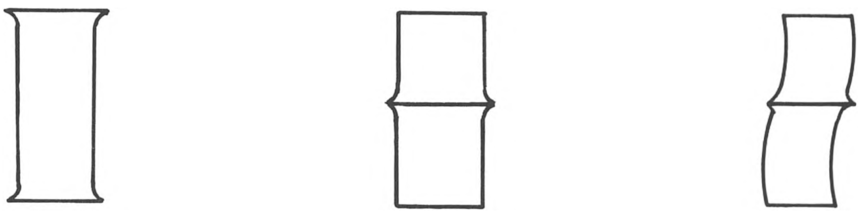
Samples #1, #2 and #3 were tested in compression.



Sample #4 was tested for flexural strength.



Sample #1 had a node at each end as in Figure (a). Sample #2 had a node in the middle, Figure (b), and Sample #3 was slightly irregular, as depicted by Figure (c).



(a) (b) (c)

Sample #1 had an elastic modulus of 85,300 psi. It failed under a stress of 14,600 psi.

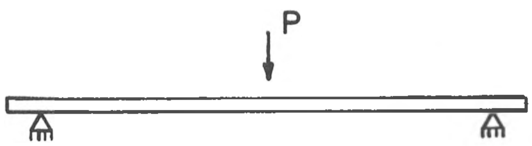
Sample #2 had an elastic modulus of 77,800 psi and was not stressed to failure.

Sample #3 failed at a stress of 10,500 psi.

The tensile strength of bamboo increases greatly from the inside to the outside. Thus, the skin is often peeled off and used as a wrapping material or to make tension joints.

Because the team felt that the specimens used for testing were not representative of field material (these specimens were taken from storage after three or four years), a low modulus of elasticity was chosen from The Use of Bamboo and Reeds in Building Construction* and used for all future calculations. This was the average modulus of elasticity, 1,500,000 psi. This value was chosen because the modulus of elasticity listed for strong, green culms was approximately 1,500,000 psi. After treatment processes, elastic moduli for bamboo as high as 3,000,000 psi have been measured.

Sample #4 was loaded as shown below.



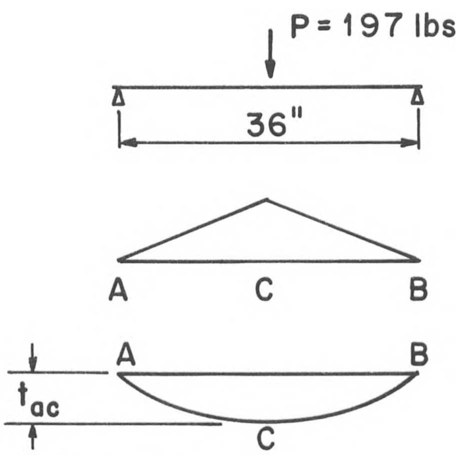
Failure occurred under a load of 197 pounds. This is not representative of the true bending strength of bamboo, though. The speciman crushed before it failed in either tension or compression. But up to crushing:

$$\sigma \text{ max} = \frac{\text{Max c}}{\text{I}}$$

$$\sigma \text{ max} = \frac{295.5\ (.5)}{.037}$$

$$\sigma \text{ max} = 4{,}000 \text{ psi}$$

Using the moment-area method to solve for the elastic modulus:



$$t_{ac} = \frac{\tfrac{1}{2}\ \text{m max}\ (18)(6)}{\text{E I}}$$

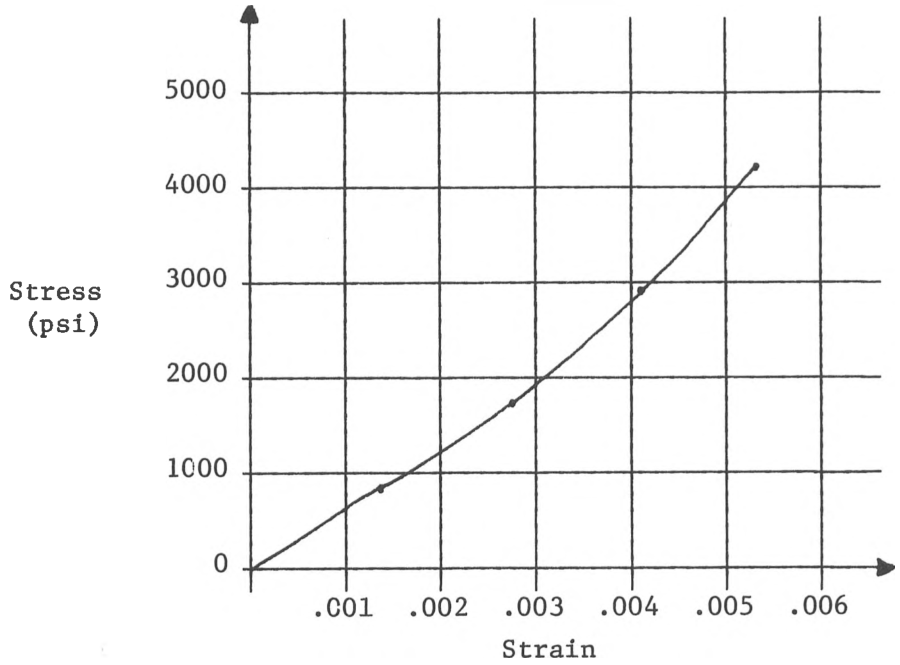
t_{ac} (measured) = 1.56 in.

$$1.56 \text{ in.} = \frac{\tfrac{1}{2}\ (1800)(18)(6)}{\text{E}\ (.037)}$$

$$\text{E} = 1.31 \times 10^{6} \text{ psi}$$

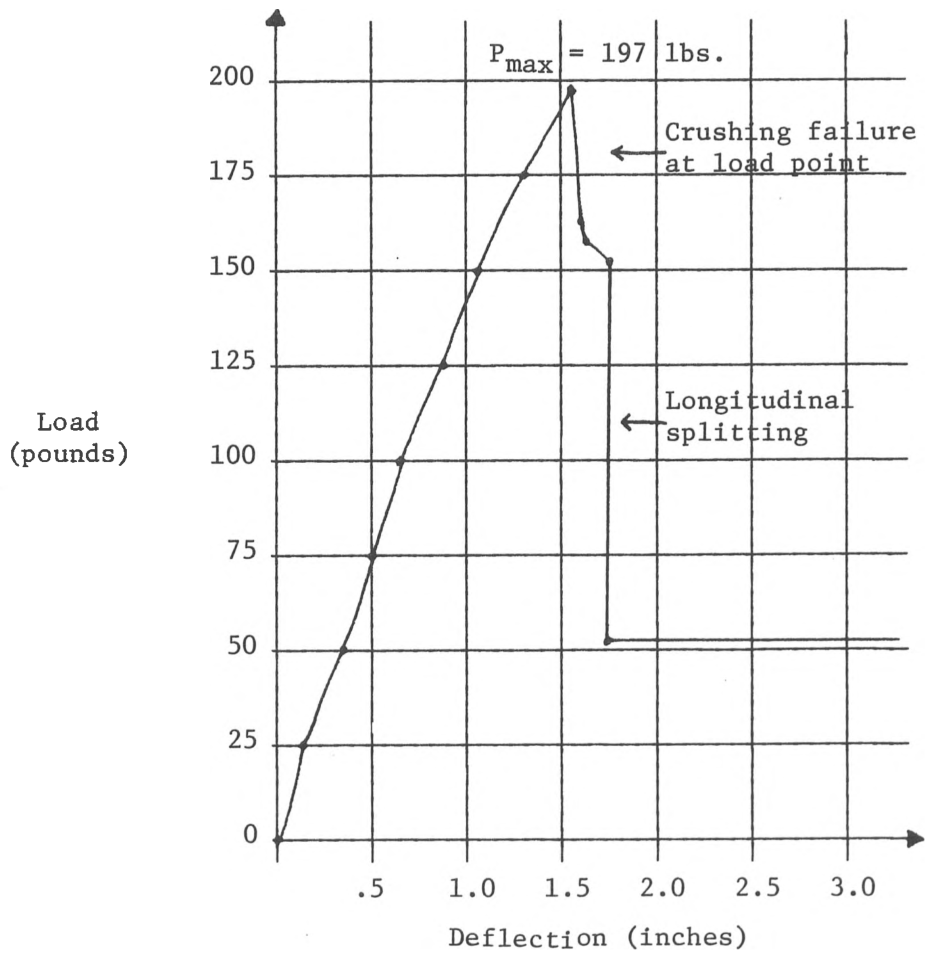
* The Use of Bamboo and Reeds in Building Construction, U.N. Publication #ST/50A/113; page 13.

BAMBOO COMPRESSION TEST
(Sample #2)



Specimen not loaded
to compressive failure

BAMBOO FLEXURE TEST
(Sample #4)



In this case, the calculated modulus of elasticity compares favorably with the value chosen for future use.

In addition, the anchorages were subject to concern:

> ...Examples of the use of bamboo posts instead of a conventional foundation for low-cost houses are available in both hemispheres. Unless they are treated with some effective fungicidal preservative, however, such posts are not expected to last more than two or three years on the average, or five years at most under unusually favourable conditions. Although no experimental data are available, it seems reasonable to expect that the lasting qualities of bamboo culms set in the ground may ultimately be extended appreciably by applying pentachlorophenol in an appropriate form.... Until reliable and economical treatments have been developed for preserving bamboo that is frequently wetted or is constantly in contact with damp earth, it is considered better to use some material that is more durable than untreated bamboo for foundations - concrete, for example, or stone brick, or some durable hardwood.*

It is the hope of the team that a relatively impermeable stabilized soil can be used for the anchorage backfills, thereby protecting the buried portion of the member.

B. Earth: Various experiments were conducted on soils to determine the best means of anchoring the structure, providing a drainage system, and providing other features such as flood protection, partitions and possibly walls or roofing. The test program for soils was divided between the University of Texas and Carnegie-Mellon University, with the University of Texas concentrating on untreated rammed and compacted earth and C-MU testing chemically stabilized earth. Rammed or stabilized earth processes currently in use, such as the CINVA RAM process or the Dicker Stack-Sack process, were investigated but not tested as adequate data is available on those processes.

Soil samples were obtained from the test site in Guatemala and data on soil types in Asia were obtained which allowed tests on soil stabilization to be conducted. The stabilization process explored by the team consists of a mixture of soil and three per cent by weight of a water soluble vinyl monomer. As the chemicals would probably need to be imported in most developing areas, the soil stabilization process was explored as an independent system so the construction of the shelters will not be held up if the chemicals

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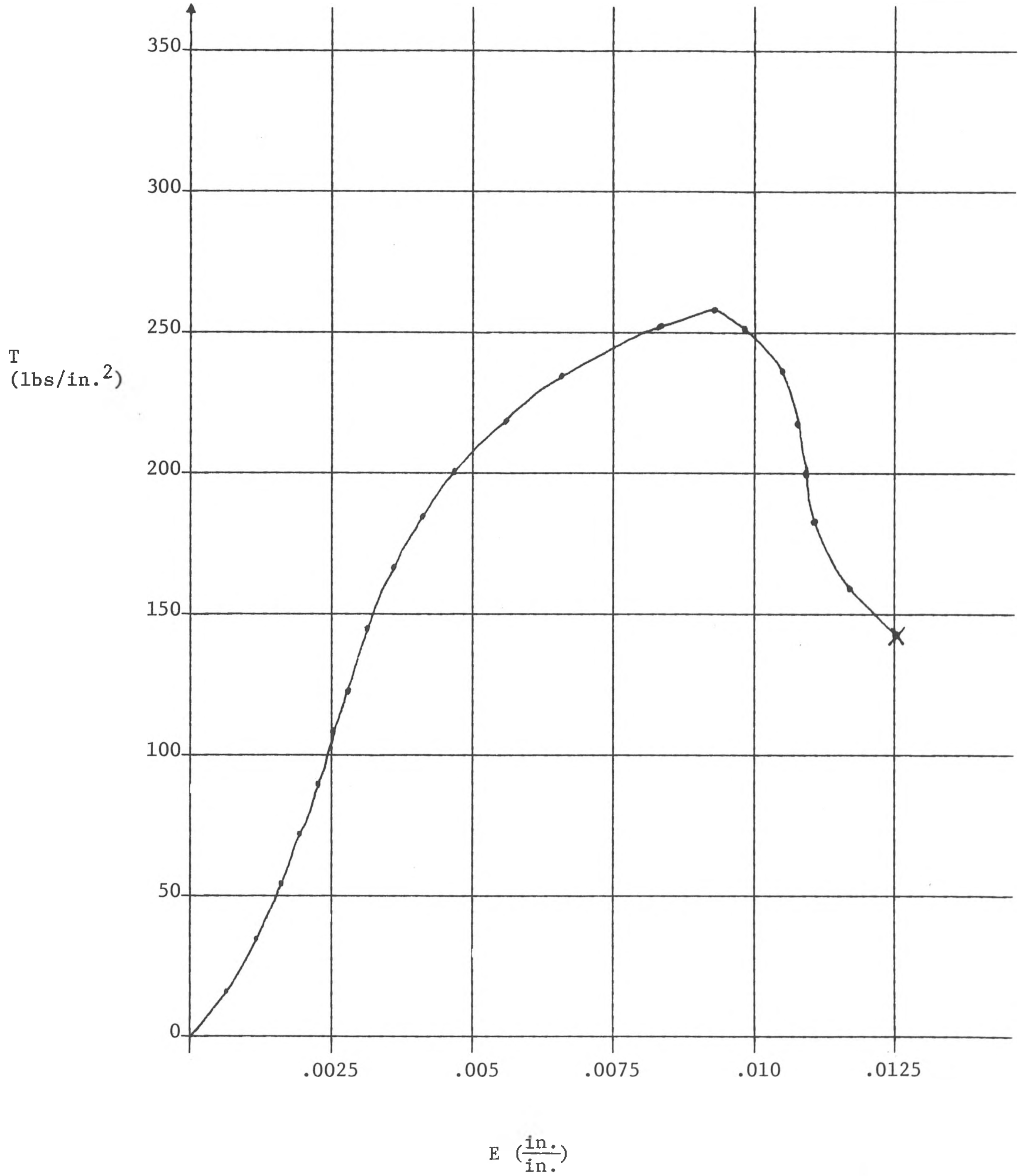
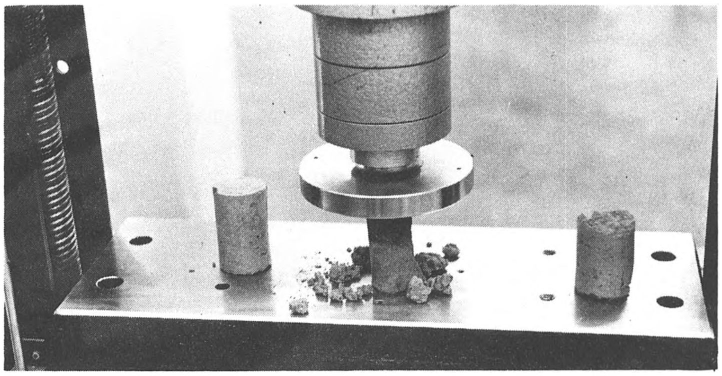
*Ibid., page 40.

COMPRESSION TEST
Stabilized Soil



are delayed or not available. The stabilized soil is analagous to concrete, and being such was tested in compression.



Two cylinders of the following dimensions were used:

Sample #1

Average diameter = 1.875 in.
Minimum diameter = 1.860 in.
Length = 3.25 in.

Sample #2

Average diameter = 1.90 in.
Minimum diameter = 1.875 in.
Length = 3.50 in.

Both samples were capped with Vitribond. Because of certain irregularities in Sample #1, Sample #2 may be considered a "better" specimen.

Specimen #1 failed under a load of 400 lbs, or an ultimate stress of 146 psi.

Specimen #2 failed under a load of 710 lbs, or an ultimate stress of 258 psi.

Both specimens exhibited an elastic modulus of approximately 48,000 psi.

C. Thatching: No lab tests were conducted on thatching as adequate data exists. However, the Working Party is monitoring the efforts of various studies currently being conducted under the auspices of the U.N. Centre for Housing, Building and Planning, and by Monsanto Corporation under contract with the U.S.A.I.D.

D. Wood: No lab tests were conducted on wood as the varieties available are too varied. However, in future test programs, the major species will be tested.

VII. Computer Verification of Design Feasibility

A. Stress Program: The analysis of framed structures deals with forces and displacements, given the makeup and orientation of all the members. The term "framed" structure is used to denote structures composed of slender elements, that is, members that can be represented by their centroidal axis and analyzed as line elements. The structure may extend in two or three dimensions, and at any joint the members may be pinned or rigidly connected.

In order to expedite the analysis phase of this project, a computer programming system known as STRESS (which is an abbreviation for Structural Engineering Systems Solver) was used. In STRESS a problem is described by writing a number of statements specifying the nature and size of the structure, the loads, a solution procedure and the results desired.*

For the program, the joints and members of the structure were numbered as in Figure

The 50 members and 34 joints were completely described by listing:

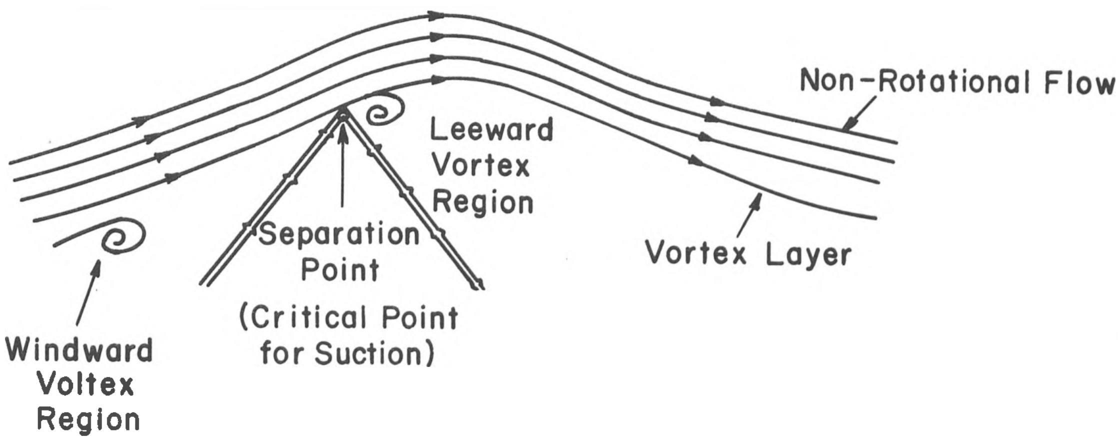
1. All member properties
   a. Elastic modulus
   b. Area
   c. Moment of inertia
2. Joint coordinates
3. Member incidences

Joints 1,26,25,24 and 9 were listed as supports and were considered fixed. Joint 17 was also considered fixed. Members 17-21, 23-25 and 37-46 were assumed to be pinned at both ends. Member 22 was called pinned only at joint 16. Members 18,33,36 and 40 were assumed pinned at joint 2; members 11,26,34 and 50 at joint 8; and members 5,6,43 and 47 at joint 5.

In other words, each half of the A-frame, the floor beam, columns and trusses were listed as continuous members. This is a good description of the true structure, for in reality these are continuous members.

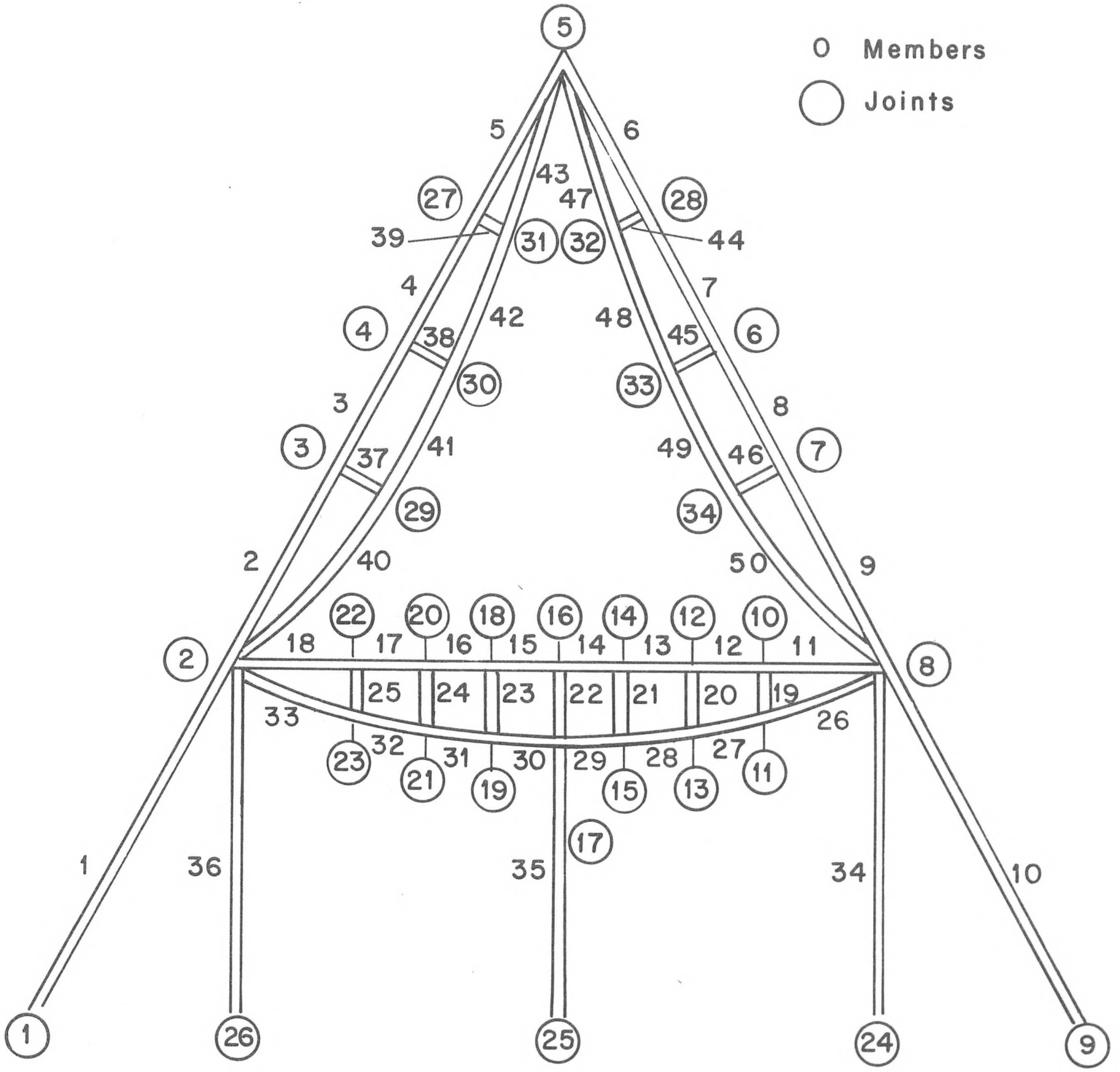
Because long, large diameter bamboo can be expected to have considerable taper from one end to the other, members 1,2,3,4 and 5 were declared to have successively smaller areas and moments of inertia.

To account for wind, a uniform load of 200.4 pounds per foot was placed on one side of the A-frame and a suction, uniform load of 100.2 pounds per foot was placed on the other side. As the structure is less than 66 feet in height, wind pressure variation was not considered. As the structure is sharp-edged, there is a well-defined separation point. It was assumed that there would be no shielding effects. Gust velocity for the test was 140 miles per hour.



*STRESS Reference Manual, S. J. Fenves, R. D. Logcher, S. P. Mauch, the M.I.T. Press, Cambridge, Mass., June 1964.

FIGURE 1



Cs = Shape Factor = 1.0
V = Gust Velocity = 140
$P = .002558\, Cs(V^2)$
$P = (.00256)(1.96 \times 10^4)$
$P = (2.56 \times 10^3)(1.96 \times 10^4)$
$P = 5.02 \times 10^1$
$P_{total} = 50.2$ psf

P(windward) = 33.4 psf
P(leeward) = 16.8 psf

A uniform load of 240 pounds per foot was placed on the floor beam.

The method of solution was the stiffness (displacement) method and the results sought were forces, reactions and displacements.

Three computer runs were conducted, the differences being:

1. Six-inch members assumed for the A-frame;
2. Five-inch members for the A-frame;
3. Three-inch members for the A-frame.

B. Results: The entire output data will not be reproduced here. Instead, it is important to note that at only one point in the structure was a stress induced anywhere within the range of the failure stress. This occurred in the area of joint 2.

The total stress at a point is the sum of the stress due to bending plus the stress due to axial load.

The bending moment computed at joint 2 for member 1 was 29,075 pound-inches. The axial force computed was 2,841 pounds.

Stress due to bending:

$$\sigma_{M\ max} = \frac{MC}{I} = \frac{(29.075)x(3)}{43.5}$$

$$\sigma_{M\ max} = 2{,}010 \text{ psi}$$

Stress due to axial load:

$$\sigma_x = \frac{P}{A} = \frac{2841}{12.4}$$

$$\sigma_x = 230 \text{ psi}$$

Total stress = 2,010 + 230 = 2,240 psi.

$\sigma_{ultimate}$ in compression is 7800 psi, so the induced stress is well below this value.

The bending moment at joint 2 for member 2 was 36,580 pound-inches. The axial force computed was 1,349 pounds. Again:

$$\sigma_{M\ max} = \frac{MC}{I} = \frac{(36,580)x(2.5)}{19.58}$$

$$\sigma_{M\ max} = 4,670 \text{ psi}$$

$$\sigma_x = \frac{P}{A} = \frac{1349}{7.84}$$

$$\sigma_x = 172 \text{ psi}$$

$$\sigma_{total} = T_{M\ max} + T_x = 4,670 + 172$$

$$\sigma_{total} = 4,842 \text{ psi} \ll 7,800 \text{ psi}$$

These results are for the run with the six-inch diameter A-frame. The other two runs cause failure of the A-frame at joint 2.

At this point in the project, preliminary design was completed. For all the dimensions, member sizes, etc., see the construction manual.

VIII. Lab Tests

In order to verify the practicality of the design and gain insight into the techniques of bamboo construction, a 2/3 scale prototype frame was built in the Civil Engineering Laboratory of Carnegie-Mellon University. Originally, the intent was to test the lab prototype at design loads and beyond. However, the bamboo received for the lab work was badly cracked and split due to the relatively dry Pittsburgh air. Bamboo does not split as readily in its natural climates where humidities are higher. However, it was decided to construct the lab prototype in order to familiarize the team with bamboo construction and facilitate supervision and management of the field construction.

The first step was to size and scale. It was decided to build three bents at 2/3 scale (the height of the lab ceiling prohibited a full-scale model), with flooring between two bents and cross-bracing between all three.

From the beginning, attention was focused on making the joints and anchorages as strong as possible, as the literature search had yielded warnings; the Building Material Development Laboratory in Indonesia reported a number of joint failures in their research:

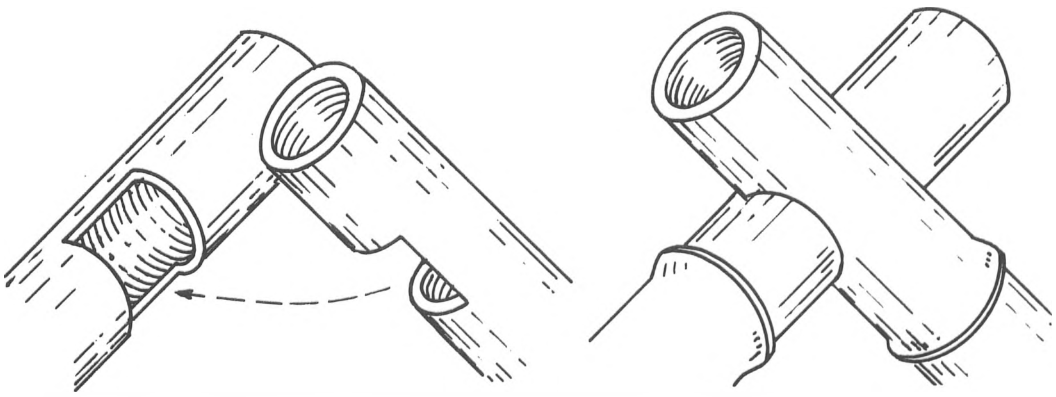
> The structure tested was a bamboo roof truss having a span of 6.0 M and a height of 3.0 M. The bamboo used (Gigantochloa apus) had a tension strength of 1,060 to 2,300 Kg/CM^2, and was about two years old. The truss was of the "Kingpost" type and the members were fastened using bamboo pins and "indjuk" rope with a

6.0 MM diameter and an ultimate tensile strength of 1,000 Kg/CM^2. The load was applied at the three upper joints through 1,000 Kg capacity dyna-mometers. The load was applied in two stages; first up to nominal loading and then to failure.

The conclusions reached by the experimenter on the basis of the tests were: (1) the failure was caused by yielding at the joints due to a low radial resistance rather than tensile or compressive failure; (2) the deflections were considerably greater than those based on theoretical calculations; (3) the location of nodes at joints greatly increased the strength of the truss; and (4) a safety factor related to the ultimate load could not be considered because many defects developed in the members before ultimate load was reached. The author recommends further study to increase the strength at joints.*

By actually building a prototype in the lab, the team gained expertise in fabricating joints. Whenever possible, joints were made to rely on more than friction to provide the binding force. For example, when the end of one member was butted into the side of another member with approximately the same diameter, connection plates were used to provide a protrusion as a tying surface, for transferring the load by the material and not by friction.

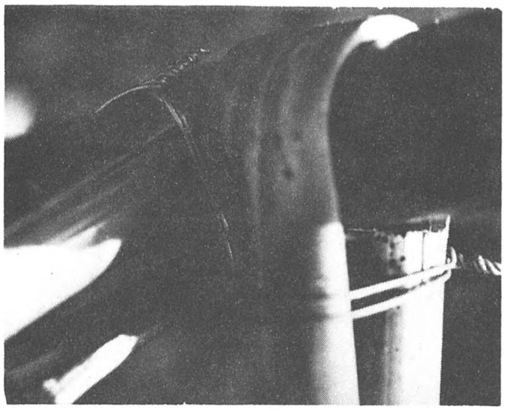
It was also found that the apex joint could best be fabricated by notching both members to the proper angle and tying the joint with cover plates over the notching area. This idea evolved when it was found that a flush-butt apex joint was too difficult to fabricate without measuring devices.



The most serious connection problem encountered was that of fabricating a tension joint. Bamboo is extremely strong in tension, due to its fibrous composition; but a tension member is only as strong as the joint it pulls. Rope-bamboo friction cannot provide an adequate restraining force for a tension joint. Therefore, it was necessary to try to

*The Use of Bamboo and Reeds in Building Construction, U.N. Publication #ST/50A/113; page 57.

split the member and wrap it around the member it was to be joined to. However, the bamboo used was extremely dry and brittle, making wrapping and bending difficult. Steaming the dry bamboo was attempted, with moderate success on smaller members. It was recognized, however, that greener bamboo would be much more workable for tension wrapping.



The construction and fabrication problems occurring during the erection of the prototype required minor modification in some of the design details of the frame. The upper trusses were replaced by triangulating members which were structurally similar to the trusses. The tension members were secured on both sides of the compression struts to provide some protection against lateral buckling of the compression member. The trusses were originally included in the design to keep the upper floor obstruction-free. However, that feature was later superceded by: (1) the desire to create individual living units, each accessible by its own ladder; (2) the desire to experiment with joints which could be used with wood. It should be pointed out that the tying material and connection plates do more than secure the members at a joint; they actually carry a portion of the load. Thus, the importance of well-tied joints cannot be overemphasized.

One of the constraints was to minimize the use of larger diameter members. Consistent with this objective, it was attempted to replace the six-inch O.D. members with various combinations of smaller members bound together. In order to substitute such a combination of smaller members, the composite moment of inertia (I) must be at least as large as the moment of inertia of a single 6" member (typically 43.4 $in.^4$). The modulus of elasticity remains the same as it is a material property which is independent of member size or shape. With three 1.5" O.D. members bound together, the composite (I) was 1.31 $in.^4$ which was much less than the required 43.4 $in.^4$. With three 3" O.D. members, the equivalent (I) was 22.3 $in.^4$, which again was insufficient. With members larger than 3", the plan defeats its purpose, so further experimentation was halted. In addition, composite sections proved hard to work with.

At the conclusion of the lab tests, a model was then constructed representing the final design of the prototype. It was to be used as a visual aid to describe the appearance and construction of the structure.

IX. Field Tests

A field test site was selected in Guatemala enabling the shelter to be constructed and tested in environmental conditions typical of a tropical zone. The selection of this site enabled the team to study thatching techniques first-hand and to learn about various uses of vines. It also enabled the team to have valuable inputs from local workers and people long accustomed to living in thatched dwellings. This site did not have bamboo, and it was selected in part to allow the team to test the structure's adaptability to wood construction.

One of the main objectives of the field tests was to outline the most expedient construction sequence and to determine simple methods of pre-fabricating various components. Thus, preparatory to the field tests, a critical path was developed.

At the test site, the following procedures were followed:

A. A pattern for the A-frame was staked out on the ground and used for fabricating the A-frames, thus ensuring uniformity of the frames. The local workers were asked to build the frames by looking at the model and using the rig. This they were able to accomplish with no further guidance and in very little time.

B. The locations for the supporting members of the structure were laid out using a knotted rope and stakes were placed where holes were to be dug.

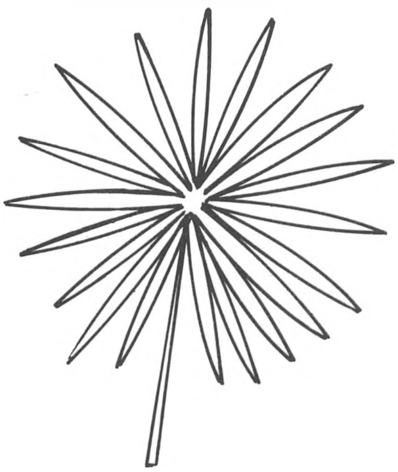
C. The assembled A-frames were erected and secured by cross-bracing.

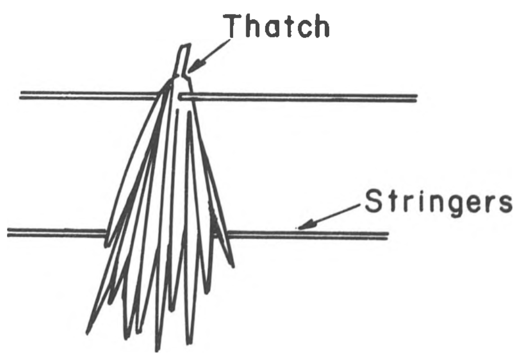
D. Floor columns and beams were then installed and secured to the frame.

E. Interior braces were added to transfer wind loads from the center of the frames to the center floor column. The truss approach was not used due to the inflexibility of the wood used for construction.

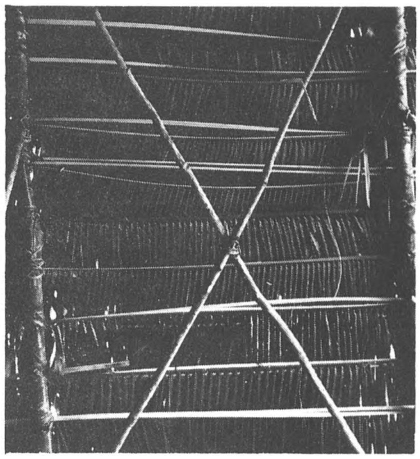
F. End pieces were then added to stabilize the structure.

G. Two types of palm thatching were then installed for roofing. The first type utilizes a fan-shaped palm frond (called guano in Spanish) with leaves which grow from a central point outward. To thatch, the leaves are tucked over and under sticks or stringers attached horizontally to the frame.





The second type of thatch uses a tall spreading palm which grows in clusters from the ground or at the top of palm trees. The plants have a sturdy spine from which leaves grow horizontally in line. To thatch, the plants are split down the center of the spine and are then overlapped and attached. This thatching does not require the addition of stringers.



H. Tests were conducted on the use of local soils with the soil stabilizer. Two soils were tested, one a caliche obtained from ant hills, the other a typical humus-earth mixture. The tests were inconclusive as to the value of the stabilizer and further research will be necessary.

The field tests proved the feasibility of the basic design and construction techniques. However, the tests pointed to several modifications that will be necessary when wood is used instead of bamboo. The main change is the cross-bracing which secures the A-frames vertically cannot be built as compression-tension members and must be triangulated with the base of the brace resting on the ground. The remainder of the changes were in the construction sequence.

X. Conclusion

The Working Party is very pleased with the results of the development program thus far and sees a variety of areas for further research. The two most important areas are:

A. Materials Research: The Working Party will explore a variety of materials, chemicals and compounds to increase the usages of indigenous materials. Among these will be treatments for improving fire and rot resistance properties of bamboo. Research will also continue in stabilizing soil for use as anchoring structures, as a material for lining drainage systems, and for use as a roofing material.

Extending the research one more step, by introducing not only chemical materials but also light machinery, many innovative building systems could be devised. One concept is spraying soil mixed with a chemical compound that will cause the soil to stabilize shortly after contact with a surface. Using this technique, any frame could be used (including inflatable structures) and a cloth or wire mesh could be stretched over the frame to which the spray could be applied.

B. <u>Adaptations of the Basic Design</u>: The present building system consists of a framing, flooring and roofing system which can be easily modified for uses other than housing. Thus far, the structure has been designed to permit an option of variable length. The exterior frames are independent of the interior flooring arrangement; thus the interior is adaptable for other usages such as those outlined below:

1. Medical Facility: Use of the structure as it is now designed would permit a wide variety of hospital and/or clinical uses. Among these are:

Field hospital
Out-patient clinic
Feeding ward
Special purpose clinic (i.e., under 5's clinic, isolation ward, etc.)
Medical staff quarters
Medical warehouse

Use of the design would encourage multi-use facilities and would provide adequate space for waiting, reception, examining, staff and storage measures.

2. Warehousing: The design would be excellent for warehousing, especially in areas of frequent flooding. The second floor would not only be safe from high water, but would provide excellent protection from theft and wandering animals. A program of rodent control would be easy if rat guards similar to those used on mooring lines for large ships were built around the A-frames and floor columns.

3. Administrative Center: The primary advantage of the structure as an administrative center would be its low cost and the availability of space for separate functions. Security would also be facilitated.

4. Food Distribution Centers: The design of the structure enables large numbers of persons to receive food in either sit-down feeding schemes or cafeteria-style.

5. Field Kitchens: The design would enable a large number of food processing activities to be undertaken simultaneously. The ventilation system in the roof also allows the use of open fires for cooking and water heating.

6. Schools: The design would lend itself easily to use as a school. A variety of classroom techniques could be used such as traditional, use-area, or open classroom teaching.

7. Other Uses: Research will be conducted into additional uses of the design as funding is made available.

The Working Party has far to go. In the coming year, we shall monitor the reaction of a wide variety of occupants to the structure. Their comments, their modifications, their alterations, and possibly their rejection of the structure and its components will be analyzed and resulting changes will be incorporated into design revisions as part of the on-going research program.

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