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TECHNICAL REPORT C-69-3

EXPEDIENT REINFORCEMENT FOR CONCRETE FOR USE IN SOUTHEAST ASIA

Report 1

PRELIMINARY TESTS OF BAMBOO

by

F. B. Cox

H. G. Geymayer



February 1969

Sponsored by

Office, Chief of Engineers
U. S. Army

Conducted by

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI

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FOREWORD

A research investigation, "Development and Construction Guides for Bamboo Reinforced Concrete," sponsored by the Office, Chief of Engineers (RDT&E), was authorized by Program Guidance, C.E.O.P.-67, RDTE Annex 2, dated 1 July 1966.

The work was performed during the period September 1966 to July 1968 at the Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) under the direction of Messrs. Bryant Mather, Chief of the Concrete Division, James M. Polatty, Chief of the Engineering Mechanics Branch, Frank B. Cox, and Dr. Helmuth Geymayer, Chief of the Structures Section. The report was prepared by Mr. Cox and Dr. Geymayer.

COL John R. Oswalt, Jr., CE, and COL Levi A. Brown, CE, were Directors of the WES during the investigation and the publication of this report. Mr. J. B. Tiffany was Technical Director.

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NOTATION

- a Depth of rectangular stress block
- A_b Cross-sectional area of bamboo
- C Total compressive force carried by concrete
- d Distance from the center of gravity of reinforcement to the top fiber of the concrete
- E_b Modulus of elasticity of bamboo
- E_c Modulus of elasticity of concrete
- f_b Bamboo stress
- f_c Concrete stress
- f'_c Compressive strength of concrete
- F Anchorage force per culm (12-in. (30.48-cm) minimum anchorage length)
- JD Distance from centroid of compressive force to centroid of tensile force
- kd Distance from NA to the top fiber of concrete (elastic analysis)
- $k_u d$ Distance from NA to the top fiber of concrete (modified ultimate strength analysis)
- M Internal moment of member
- NA Neutral axis
- T Total tensile force carried by reinforcement
- U_1, U_2, U_3 Bond stress values
- V_c Shear stress in concrete
- W Weight of concrete per cubic foot
- ϵ_b Strain of bamboo
- ϵ_c Strain of concrete

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report were converted to metric units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
inches	2.54	centimeters
feet	0.3048	meters
square inches	6.45	square centimeters
cubic feet	0.0283168	cubic meters
pounds	0.45359237	kilograms
pounds per square inch	0.070307	kilograms per square centimeter
pounds per square foot	4.88243	kilograms per square meter
inch-pounds	0.011521	meter-kilograms
inch-pounds per foot	0.037799	meter-kilograms per meter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*
gallons (U. S.)	3.78543	cubic decimeters
short tons (2000 lb)	907.185	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

SUMMARY

This report summarizes the preliminary results of a current U. S. Army Engineer Waterways Experiment Station (WES) study of the feasibility of using bamboo as an expedient reinforcement for temporary, reinforced concrete structures. The report contains an extensive review of the literature, a description of the test procedures, results of an investigation of the most important engineering properties of bamboo, descriptions of tests of 26 bamboo-reinforced structural elements (20 simply supported beams with 6-ft (1.83-m) spans, and 6 simply supported two-way slabs of varying length, width, and depth), and conclusions and tentative recommendations for the design of bamboo-reinforced structures.

The recommended procedures are based on results obtained from tests of local (Mississippi) small cane (*Arundinaria tecta*), and are believed to be conservative when other species of bamboo are used because most of the properties of the small cane were generally inferior to those reported by others for other species.

Some of the principal conclusions are:

- a. Although bamboo has a fairly high tensile strength (values as high as 53,894 psi or 3,789 kg/cm² have been reported), its tensile modulus of elasticity is relatively low (usually less than 1/10 of that of conventional steel reinforcement). This low tensile modulus leads to large deflections and wide cracks when bamboo-reinforced structures are loaded to capacity.
- b. The principal problems associated with bamboo reinforcement are volume changes (i.e. swelling and shrinking) due to moisture variations, low bond strength, and possibly decay. However, if special precautions are taken in preparing and placing the culms (such as splitting, presoaking for 72 hr, coating, etc.), these problems can be minimized.
- c. Bamboo-reinforced members that are designed and constructed according to the tentative recommendations outlined herein can be expected to develop from two to four times the ultimate flexural load-carrying capacity of unreinforced members of equal dimensions.

EXPEDIENT REINFORCEMENT FOR CONCRETE

FOR USE IN SOUTHEAST ASIA

PRELIMINARY TESTS OF BAMBOO

PART I: INTRODUCTION

Background

1. In many areas of the world, standard steel reinforcing bars are frequently scarce, very costly, or, in some cases, unavailable. Therefore, military forces as well as civilian agencies working in these areas need indigenous materials that can be used as expedient reinforcement for temporary or secondary concrete structures.

2. Investigators from several different countries have conducted studies of varying scope on the feasibility of using bamboo as an expedient reinforcement for concrete. These studies have indicated that the major advantages of bamboo lie in its relatively high tensile strength and its availability and inexpensiveness in most tropical, subtropical, and even some temperate countries. The principal problems associated with bamboo reinforcement are bond, volume changes, and possibly decay. However, a review of the literature makes it clear that additional systematic research is needed concerning bond mechanisms, means of improving bond strength, methods of controlling volume changes, decay, and the behavior of bamboo under long-term or repeated loads.

3. Aside from bamboo, several metallic materials (such as barbed and concertina wire, used pierced-steel and aluminum landing mats, wire ropes, and transport tie bars for AM2 landing mats) that are generally available near combat areas appear to be suitable for use as expedient reinforcing materials. However, there is practically no information available on the characteristics of these materials pertinent to their use as reinforcement; again, systematic studies are necessary to determine the most important properties of these materials before their suitability for expedient reinforcement can be evaluated.

4. However, this first interim report is concerned with bamboo and the other materials mentioned will be discussed in subsequent reports.

5. The tentative conclusions drawn from experimental results in this investigation are essentially based on tests conducted with local (Mississippi) small cane (Arundinaria tecta). Since the literature indicates that approximately 550 different species of bamboo have been reported throughout the world, the question arises whether, and to what extent, these conclusions can be applied to other species, particularly to the different native species of Southeast Asia. Obviously, it is impractical to test all, or even a large number, of the different species known to exist.

6. From the data compiled from our review of the literature, it appears that the important engineering properties (such as elastic modulus, tensile strength, and bond strength) of the local small cane are generally somewhat inferior to those reported for other species. Thus, it appears that conclusions and methods based on this lower quality bamboo should be conservative and provide a safe solution for all species.

7. While this interim report was being written, tests were initiated on samples of an Asian species.* To date, the results, which will be published in a later report, do indeed indicate that both the mechanical properties of this species and the strength of structural concrete members reinforced with it are somewhat superior to those obtained on local small cane. This is another indication that design recommendations based on results with local small cane should be conservative.

Purpose and Scope

8. The purpose of this investigation is to compile information concerning the use of bamboo and other indigenous or locally available materials into a design and construction guide for field engineers who use concrete with expedient reinforcement.

9. The investigation covered in this first report was divided into the following four phases.

* Samples of a giant timber bamboo native to China and Southeast Asia, Phyllostachys bambusoides (commonly called Madake), were obtained from a local nursery.

- a. Phase I. This phase of the report is a review of the available literature on the use of bamboo as a substitute reinforcing material.
- b. Phase II. This phase reports a determination of the most important engineering properties of bamboo with particular emphasis on properties not covered sufficiently in the literature. Tests conducted in this phase included determinations of the average tensile strength, elastic modulus, Poisson's ratio in tension, behavior under sustained tensile loads, bond with concrete, coefficient of thermal expansion, dimensional changes due to moisture variations, and decay mechanisms. Methods of improving bond, preventing volume changes, and inhibiting decay were also investigated.
- c. Phase III. During this phase, 26 bamboo-reinforced structural elements (beams and slabs) were cast and tested to supplement available information and to develop suitable reinforcing techniques.
- d. Phase IV. The last part of this report covers tentative conclusions based on the review of the literature and the test results described in the other parts and contains preliminary and tentative design and analysis procedures.

10. Since this is only an interim report in a continuing investigation, it is emphasized that all conclusions and design approaches are preliminary and may be subject to revision as the study continues and new results become available.

PART II: REVIEW OF LITERATURE

General Characteristics of Bamboo

11. Although bamboo has been known and used since the early history of man, its botanical characteristics are still relatively unknown. The principal reason for this lack of information is that most bamboos produce flowers and fruit only at intervals of 30 or more years. Since the identification of bamboo is based largely upon its flower and fruit characteristics, its classification at present is not entirely satisfactory. The situation is further complicated by the fact that many species die soon after flowering.

12. Bamboo is a perennial grass belonging to the class monocotyledoneae, and is found in almost all tropical, subtropical, and many temperate zones with approximately 550 species recorded throughout the world. However, only two species, A. tecta (small cane) and A. gigantea (southern cane), are common in the United States.^{1,2,3} Although most species are from 2 to 4 in.* (5.08 to 10.16 cm) in diameter, some species may be up to 10 in. (25.40 cm) in diameter and 150 ft (45.72 m) high.⁴ In many cases growth is very rapid, with some species elongating as much as 3 ft (0.9144 m) in a single day, and continuing to grow at a rapid rate until their full height is attained.^{3,5,6}

13. The individual bamboo culm is divided into nodes and internodes. The greatest amount of meristematic tissue for the elongation of the internode is found just above the node. As a result, the node, or its upper portion, is generally the weakest part of the culm.⁶ The internodal tissue is made up of parenchymal cells and vascular bundles with the latter consisting of vessels, thick-walled fibers, and sieve tubes.¹ The water movement takes place through the vessels, the fibers being primarily responsible for the strength of the bamboo.¹ The outer and inner surfaces of the bamboo are covered by hard cuticles that offer some resistance to the absorption of water, particularly when the cuticle is dry.

* A table of factors for converting British units of measurement to metric units is presented on page xi.

Engineering Properties

Tensile strength and modulus of elasticity

14. Purushotham,⁷ who has completed a large number of studies on the properties of Indian bamboo, reports that the tensile strength and modulus of elasticity of the individual bamboo culms depend largely on (a) the soil and climatic conditions under which the bamboo is grown, and (b) the age and moisture content of the culms when tested.

15. Shimada,³ in his report on Japanese bamboo, states that (a) culms of the same species may vary in tensile strength due to age, physiological variation of individual culms, habitat, liquid content of soil in the habitat, and the external physical forces; (b) generally, the tensile strength of the individual culm increased from the first node to the center node and then decreased from the center node to the top node; (c) specimens with cylinders (distance between nodes) of the greatest lengths usually had the greatest tensile strengths; and (d) in most cases, the node was the weaker section of a culm due to a large number of soft proliferative cells in the growth zone and liquids being transported from stem to leaf stalk through a number of vessels crossing the nodal area.

16. The Bamboo Research Committee⁶ for the Manila Bureau of Public Highways states that (a) the tensile strength increased with the age of the culm and from the basal to the distal sections of individual specimens, (b) the average tensile modulus of elasticity varied in no consistent manner with the age or the section of the culm, and (c) the node was the weaker section of the culm in most specimens tested.

17. Studies conducted in both the United States² and India¹ indicate that the culms with the greatest tensile strength and modulus of elasticity varied in age from 3 to 4 years or more. It was noted² that these culms can be readily detected in a bamboo grove by the brownish color they generally have at this age compared to a greenish color at earlier ages.

18. Fungal decay,¹ soft rot, and insect attack from borers, termites, and marine organisms can greatly reduce the tensile strength and modulus of elasticity of untreated bamboo. Current U. S. Army Engineer Waterways

Experiment Station (WES) correspondence with other agencies indicates that several studies are being conducted on methods of controlling this type of decay without reducing the bonding strength of the bamboo, but results of these studies are as yet unpublished.

19. Table 1 summarizes average values of the tensile strength and modulus of elasticity of untreated bamboo as reported in the available literature.

Compressive strength and modulus of elasticity

20. Results of tests conducted to determine the compressive strength and modulus of elasticity of bamboo have been reported by Clemson University² and the Bamboo Research Committee.⁶ Results of compressive strength tests (not including compressive modulus) have also been published by the Forest Research Institute⁸ of Dehra Dun, India, and the Bureau of Science,⁹ Manila, Philippines.

21. A summary of the results, shown in table 2, indicates that an average compressive strength of approximately 7000 psi (492 kg/cm²) and an average compressive modulus of elasticity of about 1,900,000 psi (133,583 kg/cm²) may reasonably be expected from seasoned, untreated bamboo. In comparing compressive with tensile properties, it may be noted that the compressive strength of bamboo is considerably lower than the tensile strength and that the compressive modulus is approximately 80 percent of the tensile modulus.

Flexural strength

22. Results of flexural testing of bamboo have been reported by Clemson University,² the Bamboo Research Committee,⁶ and Espinosa.⁹

23. This part of the Clemson study² was conducted primarily to determine the flexural characteristics of bamboo with respect to age and the position of the outer fibers when tested. Tests of 1-, 2-, and 3-year-old culms of various species of the same genus indicated that there was no greater variation in the flexural properties of bamboo culms of different age groups than among individual culms of the same age group. The average extreme fiber stress and modulus of elasticity for seasoned culms were higher than for green, unseasoned culms. However, in many

cases, the green, unseasoned culms had individual stress and modulus values higher than the average of the cured culms.

24. The results of flexural tests conducted on Philippine bamboo⁶ were almost identical with results of the flexural study at Clemson University.² However, one additional statement that "the extreme fiber stress and modulus of elasticity increases from basal to distal sections of the individual culm" was made in this report.

25. Results of flexural tests on split bamboo specimens reported by Espinosa⁹ did not take into account the different age groups, but they did indicate that the extreme fiber stress was greatly influenced by the testing procedure, such as the location of the outer fiber during flexural testing of split specimens.

26. Table 3 lists some results of the flexural characteristics found and reported by the Clemson study,² the Bamboo Research Committee,⁶ and Espinosa⁹ for dry, seasoned American and Philippine bamboo.

Coefficient of thermal expansion of bamboo

27. Mehra, Uppal, and Chadda⁸ indicate that the coefficient of thermal expansion of bamboo is somewhat different from that of concrete by stating that they fear "concrete may leave bamboo in course of time." The authors give no definite values for the coefficient of thermal expansion, but mention that they will conduct a study and publish information at a later date.

28. Purushotham⁷ both supports and disagrees with the beliefs of Mehra et al.⁸ He states that the coefficient of thermal expansion of bamboo varies from (a) 3.00×10^{-6} to $9.00 \times 10^{-6}/^{\circ}\text{F}$ (5.4×10^{-6} to $16.2 \times 10^{-6}/^{\circ}\text{C}$) parallel to the fiber and from (b) 32.00×10^{-6} to $61.00 \times 10^{-6}/^{\circ}\text{F}$ (57.6×10^{-6} to $109.8 \times 10^{-6}/^{\circ}\text{C}$) across the fiber, compared to an average of approximately $6.00 \times 10^{-6}/^{\circ}\text{F}$ ($10.8 \times 10^{-6}/^{\circ}\text{C}$) for concrete.

Volume change due to moisture variation

29. Although no definite volume change is stated for a given moisture variation, several investigators have indicated that volume

instability is one of the greatest drawbacks of using bamboo as a reinforcing material for concrete.

30. The conclusions from the investigations conducted on volume instability of bamboo due to moisture variations are summarized as follows:

- a. Mehra et al.⁸ reported that bamboo encased in concrete will absorb as much as 300 percent of its own weight in water and substantially increase in volume; then it will loose this moisture over a period of time and shrink back to its original volume.
- b. De Simone⁵ indicated that bamboo absorbs water from freshly placed concrete very rapidly, swelling to such an extent that the surrounding concrete may crack. As the curing progresses, the bamboo gives off moisture, and diminishes in volume and bond strength.
- c. Glenn² found, in addition to what has been stated, that the volume change of bamboo, due to either water absorption or drying, was much greater across the fiber than parallel to the fiber.
- d. Current WES correspondence indicates that several rather low-cost methods of maintaining a constant volume for the bamboo during moisture variations have been used, but most methods materially reduce the bonding characteristics of the bamboo. New methods are being studied, and some new information on volume stability should be published soon.

Bond strength

31. It is quite obvious that sufficient bond between the bamboo and the concrete is a prerequisite for the successful use of bamboo as a reinforcing material for concrete.

32. Glenn² concluded that:

- a. When whole, green (unseasoned) culms are used, the bond developed will depend wholly on the protrusions at the nodes and on the tapering and crooks in the culms.
- b. Seasoned culms develop much higher bond values than do green culms. In individual tests the bond value varies greatly from specimen to specimen. The values obtained from the bond test appear to be proportional to the degree of swelling that occurred in the culms due to absorption of water from the concrete and the shrinkage due to gradual moisture reduction in the bamboo after the concrete had hardened.
- c. Seasoned, treated culms develop higher bond values over a period of time than do green or untreated culms, probably as a result of the above-mentioned swelling and shrinking

mechanism. Asphalt emulsion is a good waterproofing agent for seasoned culms as it materially reduces the water absorption, thereby reducing the swelling action that frequently leads to severe cracking of the concrete. However, when an excess of any asphalt-base waterproofing agent is used, it is likely to reduce bond due to a lubricating effect of the asphalt on the outer culm surface.

33. The results of the study conducted on dry, seasoned bamboo specimens by the Bamboo Research Committee⁶ indicated that:

- a. There was no distinct difference between the bond strengths of specimens checked at a concrete age of 14 or 28 days.
- b. The bond strength of specimens brush-coated with either coal tar or asphalt emulsion was approximately the same as that of untreated specimens.
- c. Specimens that contained nodes developed higher bond stresses than those without nodes, with the increase in bond depending on the amount of protrusions of the nodes and the tapering of the specimens.

34. De Simone⁵ concluded that:

- a. The main bond difficulty to overcome is that bamboo absorbs water readily and swells when dampened, frequently leading to early cracks in the surrounding concrete, and subsequently shrinks, losing much of its adherence.
- b. This situation can be greatly improved by soaking and painting the bamboo with suitable mixtures. These mixtures must be compatible with the cement and adhere firmly to both concrete and bamboo. Petroleum and linseed oil are not suitable but a white lead paint diluted with 10 percent varnish appears to work satisfactorily.

35. Mehra et al.⁸ reported that:

- a. Bond strength was probably affected by the difference in the coefficient of thermal expansion of concrete and bamboo and the swelling of the bamboo due to the water in freshly mixed concrete.
- b. Fine sand deposited over wet paint would help the bonding characteristics of bamboo considerably.

36. Referring to work done at the Otto Graf Institute in Stuttgart, Germany, De Simone⁵ indicated that Professor Graf had greatly improved the bond strength by not removing the stumps of the branches when encasing the bamboo culms in the concrete. In some cases, this method was reported to have completely prevented slippage between bamboo and concrete.

37. Mentzinger and Flourde¹⁰ conducted a series of bond tests at Villanova University to verify previously published unit bond stresses, determine the effects of various methods of waterproofing of the bamboo on the bond stress, and attempt to improve the bond characteristics of each method.

38. It was their opinion that the bond strengths of dry, untreated bamboo specimens could be improved as much as 24 percent by treating the specimens with commercial grade varnish. They concluded that the varnish prevented, or at least minimized, the bamboo's tendency to absorb water from the fresh concrete; this resulted in a reduction of the swelling in the bamboo and in a better bond between bamboo and concrete. However, they also stated that upon pulling the bamboo strips out of the concrete, it seemed as if the bamboo was beginning to rot and had lost much of its tensile strength. From these observations, they felt that further study to determine the tendency of bamboo to rot when varnished should be made before any attempts to use varnish-coated bamboo as a reinforcement for concrete.

39. Table 4 gives the different ultimate bond values obtained by the above-mentioned authors.

Fungal decay of bamboo

40. Purushotham^{1,7} indicates that fungal decay, soft rot, and insect attack could be serious problems when using bamboo as reinforcement for concrete.

41. In summary, Purushotham states that:

- a. "Bamboo, when encased in concrete, may decay if the necessary moisture creeps in or fine crevices develop where the bamboo can be attacked by borers, termites, and marine organisms.
- b. Serious damage may be done to a bamboo-reinforced structure (even before completion) if attacked by borers, termites, or marine organisms.
- c. Attempts are being made to correlate the degree of attack by borers, termites, or marine organisms, and the resulting loss in strength, but it may take some time before reliable results are obtained."

Long-term behavior and creep of bamboo

42. The available literature contains very little information on

the behavior of bamboo-reinforced concrete under sustained loads, and information on the creep of bamboo is missing entirely. In fact, the studies by Glenn² and the WES^{11,12} were the only ones that specifically reported the age of the structural elements tested. Therefore, it is hard to estimate the importance of age effects (or the effects of different curing conditions) on the reported results of bamboo-reinforced concrete members. In view of the obvious importance of age and curing conditions on bond and decay, this lack of information appears particularly significant.

Beam and Slab Tests

Bamboo-reinforced concrete beams

43. Results of studies conducted on bamboo-reinforced concrete beams have been reported by Clemson University,² the Bamboo Research Committee of the Manila Bureau of Public Highways,⁶ and the WES.^{4,11,12,13}

44. Clemson study.² In the extensive Clemson study, 32 series of bamboo-reinforced concrete beams were cast and tested. The concrete incorporated into the beams had compressive strengths varying from 2600 to 3500 psi (183 to 246 kg/cm²), but a concrete modulus of elasticity of approximately 3.0×10^6 psi (210,921 kg/cm²) was maintained in the majority of the specimens in the series. The effects of the following were investigated: percentage of bamboo reinforcement, green bamboo, seasoned bamboo, waterproofing, whole culms, split culms, dimensions of rectangular section, diagonal tension, and strength of concrete mixture.

45. Results and conclusions of the Clemson study are summarized below.

a. The following general results and conclusions were obtained:

- (1) Because the modulus of elasticity of bamboo is near that of concrete, bamboo reinforcement in concrete beams does not significantly affect the cracking loads.
- (2) However, bamboo reinforcement in concrete beams does increase the ultimate load-carrying capacity of the member considerably above that of an unreinforced member having the same dimensions and concrete strength.

- (3) The load capacity of bamboo-reinforced concrete beams increases with increasing percentages of the bamboo reinforcement up to an optimum value.
- (4) For a rectangular section, this optimum value occurs when the cross-sectional area of the longitudinal bamboo reinforcement is from 3 to 4 percent of the cross-sectional area of the concrete.
- (5) The load required to cause ultimate failure of concrete beams reinforced with bamboo is from four to five times greater than that required for concrete members having equal dimensions and no reinforcement.
- (6) Concrete beams with longitudinal bamboo reinforcement may be designed to safely carry flexural loads from two to three times greater than those expected for concrete members having the same dimensions and no reinforcement.
- (7) Concrete beams reinforced with unseasoned bamboo showed slightly greater load-carrying capacities than did beams with equal sections reinforced with seasoned, untreated bamboo. This was true only when the unseasoned bamboo had not dried out and seasoned while encased in the concrete before the load was applied.
- (8) When seasoned, untreated bamboo was used as the longitudinal reinforcement in concrete members, the dry bamboo swelled due to the absorption of moisture from the wet concrete; this swelling action often caused longitudinal cracks in the concrete, thereby lowering the load-carrying capacity of the members. The swell cracks were more prevalent in members in which the percentage of bamboo reinforcement was high. This tendency to crack was lessened by using high-early-strength concrete.
- (9) Under a given load, the unit stress in the longitudinal bamboo reinforcement in concrete members decreased with increasing percentages of reinforcement.
- (10) The ultimate tensile strength of the bamboo in bamboo-reinforced concrete members was not affected by changes in the cross-sectional area of the members as long as the ratio of breadth to depth was constant, but was dependent upon the amount of bamboo used for reinforcement.
- (11) Members having the optimum percentage of bamboo reinforcement (between 3 and 4 percent for rectangular sections) were capable of withstanding tensile stresses in the bamboo of from 8000 to 10,000 psi (562 to 703 kg/cm²).
- (12) In designing concrete members reinforced with bamboo, a safe tensile stress for the bamboo of from 5000 to 6000 psi (352 to 422 kg/cm²) may be used.

- (13) Concrete members reinforced with seasoned bamboo treated with a brush coat of asphalt emulsion developed greater load capacities than did beams with equal sections in which the reinforcement was seasoned, untreated or unseasoned bamboo.
- (14) When seasoned bamboo treated with a brush coat of asphalt emulsion was used as the longitudinal reinforcement in concrete members, there was still some tendency for the concrete to develop swell cracks, especially when the percentage of bamboo reinforcement was high.
- (15) Care should be exercised when using asphalt emulsion as a waterproofing agent on seasoned bamboo because an excess of the emulsion on the surface of the culm might act as a lubricant and thereby materially lessen the bond between the concrete and the bamboo.
- (16) Concrete members reinforced with unseasoned sections of bamboo culms, which had been split along their horizontal axes, appeared to develop a greater load capacity than did beams with equal sections in which the reinforcement consisted of unseasoned, whole culms.
- (17) Concrete members reinforced with seasoned sections of bamboo culms that had been split along their horizontal axes and treated with a brush coat of asphalt emulsion developed considerably higher load capacities than did beams with equal sections in which the reinforcement was split sections of seasoned, untreated bamboo.
- (18) When split sections of seasoned, untreated, large-diameter culms were used as the reinforcement in a concrete beam, longitudinal cracks appeared in the concrete due to swelling of the bamboo. This cracking of the concrete was of sufficient intensity to virtually destroy the load-carrying capacities of the members.
- (19) When unseasoned bamboo was used as the reinforcement in a concrete member, the bamboo seasoned and shrank over a period of time* while encased in the concrete. This seasoning action of the bamboo materially lowered the effective bond between the bamboo and the concrete with a resultant lessening of the load-carrying capacities of the members.
- (20) Increasing the strength of the concrete increases the load-carrying capacity of concrete members reinforced with bamboo.
- (21) Concrete members reinforced with seasoned bamboo.

* Beam tests were conducted up to 148 days after casting.

treated with methylolurea did not develop load-carrying capacities any greater than did beams with equal sections in which the reinforcement was seasoned culms treated with a brush coat of asphalt emulsion.

- (22) Load-carrying capacities of concrete members reinforced with unseasoned, seasoned, or seasoned and treated bamboo culms were increased by using split bamboo dowels as the diagonal tension reinforcement along the sections of the beams where vertical shear was high.
- (23) Load-carrying capacities of concrete members reinforced with unseasoned, seasoned, or seasoned and treated split sections of bamboo were increased by using a combination of split dowels and bending up of the upper rows of the split bamboo from the bottom of the beam into the top and covering the sections of the beam with vertical split bamboo dowels where the shear was high.
- (24) Ultimate failure of third-point-loaded bamboo-reinforced concrete members was usually caused by diagonal tension failures even though diagonal tension reinforcement was provided.
- (25) A study of the deflection data for all the beam specimens tested indicated that:
 - (a) The deflections of the beams when tested followed a fairly accurate linear variation until the first crack appeared in the concrete.
 - (b) Immediately following the first crack, there was a pronounced flattening of the load-deflection curve (probably due primarily to a reduction of the moment of inertia, but also due, in part, to bond slippage), followed by another period of fairly accurate linear variation, but at a lesser slope, until ultimate failure of the member occurred. As expected, the flattening of the deflection curve was more pronounced in the members in which the amount of longitudinal bamboo reinforcement was small.
 - (c) As expected, the load-deflection curve had a lesser slope after the appearance of the first crack in the concrete. This was noted in all cases, including those in which high percentages of bamboo reinforcement were used.
- (26) T-shaped, bamboo-reinforced concrete members under flexure were no more effective than were equal rectangular sections, provided the breadth of the stem of the T section was equal to that of the rectangular section and the effective depths of both were the same.

b. Conclusions reached with regard to design, analysis, and construction were as follows:

- (1) In important concrete members, the use of whole culms of green, unseasoned bamboo is not recommended. However, in concrete slabs and secondary members, whole, green, unseasoned culms may be successfully used when the diameter of the culms does not exceed $3/4$ in. (1.91 cm).
- (2) When possible, the bamboo to be used as reinforcement in concrete members subject to flexure should be cut and allowed to dry and season for 3 to 4 weeks.
- (3) Bamboo culms cut in the spring or early summer are not recommended as reinforcement in concrete. To ensure better results, only seasoned culms that are at least 3 years old should be used. The culms of this age can be readily detected in a bamboo grove by their pronounced brownish color.
- (4) Some type of waterproofing is recommended when thoroughly seasoned, whole bamboo culms are used in important flexural concrete members.
- (5) When sections of seasoned bamboo split from large-diameter culms are used as reinforcement in flexural concrete members, some type of waterproofing is recommended. However, for slabs and secondary members where the concrete sections are of sufficient size to allow the placement of the bamboo with a clear distance of $1-1/2$ to 2 in. (3.81 to 5.08 cm) between the individual split culms and between successive layers, the use of unseasoned bamboo is recommended, provided high-early-strength cement is used. In no case is a split-bamboo section with a width greater than $3/4$ in. (1.91 cm) recommended for slabs or secondary members.
- (6) When it is impractical to bend the main longitudinal reinforcement up, vertical split sections of bamboo are recommended for resisting diagonal tension stresses. In continuous members, and where otherwise practical, the practice of bending up the main longitudinal reinforcement at points of heavy shear is suggested. Also, if feasible, a combination of the two methods may be used.
- (7) Proper spacing of the bamboo reinforcement is very important. Most tests indicate that when the bamboo reinforcement is placed too closely, the flexural strength of the member is adversely affected.
- (8) In placing the bamboo reinforcement, care should be taken to alternate the basal and distal ends of the culms. This will ensure a fairly uniform cross-sectional area and introduce a wedging effect that

will materially increase the bond between the concrete and bamboo.

- (9) Since bamboo-reinforced members subjected to flexural loads develop large deflections, the design of the concrete members will usually depend on the allowable deflection. If the deflection of the member is to be less than $1/360$ of the length of the span, a design tensile strength of 3000 to 4000 psi (211 to 281 kg/cm²) is recommended for the bamboo.
- (10) The same procedure as used for the design of structural concrete members reinforced with conventional steel is recommended for bamboo-reinforced concrete. Also, T-beams are recommended to be designed as regular beams ignoring the flange widths in the calculations.

46. Bamboo Research Committee study. Eighteen series of bamboo-reinforced concrete beams were cast and tested by the Bamboo Research Committee.⁶ The procedures followed in conducting these tests were almost the same as those described for the Clemson study. Similar, if not identical, results were obtained.

47. WES studies. Two previously reported, less extensive studies were conducted at the WES.^{11,12} The objectives were to:

- a. Either verify or determine the most important physical characteristics of bamboo.
- b. Determine the feasibility of using bamboo as a reinforcement for concrete.
- c. Modify current ultimate strength design and area moment procedures as necessary so that the ultimate moment and deflection of bamboo-reinforced concrete can be estimated.
- d. Determine the load-carrying capabilities and deflections of precast concrete flexural elements with bamboo reinforcement under both short-term loads and sustained loads.

48. The conclusions reached by the authors of these two reports are listed below.

- a. The general conclusions were:
 - (1) The use of bamboo as a reinforcing material in light, semipermanent concrete structures is practical.
 - (2) The maximum-size aggregate should be small so that the concrete can be easily consolidated around the bamboo.
 - (3) Tensile cracks with associated large deflections would probably occur in bamboo-reinforced concrete. However,

if large deflections could be tolerated, the members would apparently maintain sufficient structural integrity for light-loading conditions.

- (4) No unusual difficulties should arise in fabricating and curing precast concrete elements with bamboo reinforcement under field conditions.

b. The conclusions concerning analysis, design, and construction were:

- (1) Ultimate strength design procedures, modified to take into account the characteristics of the bamboo reinforcement, can be used to estimate the ultimate load-carrying capacity of precast concrete elements with bamboo reinforcement.
- (2) As the percentage of bamboo used in the beam increases, the estimate of the ultimate load-carrying capacity of the beam becomes less accurate.
- (3) Short- and long-term deflections of bamboo-reinforced concrete beams cannot be accurately estimated by using the moment of inertia of either the cracked or the uncracked transformed sections of the beams.
- (4) To maximize the load-carrying capability of a bamboo-reinforced concrete beam, as much bamboo should be used as can reasonably be placed in the beam.
- (5) To minimize long-term deflections, a minimum thickness of 4 in. (10.16 cm) is recommended for flexural members.

Bamboo-reinforced soil-cement slabs

49. Mehra, Ghosh, and Chadda¹⁴ compared a 6- by 111- by 111-in. (15.24- by 281.94- by 281.94-cm) soil-cement slab reinforced one way with 1.5 percent bamboo and overlaid with a 3-in. (7.62-cm) cement-concrete wearing course with an unreinforced soil-cement slab with exactly the same dimensions overlaid by an identical cement-concrete wearing course. The following conclusions resulted from this study:

a. The general conclusions were:

- (1) The bamboo needed some type of treatment to prolong its useful life.
- (2) Detrimental swelling of bamboo when used as reinforcement could be reduced by first soaking the culms in water and then applying, serially, one coat each of a resin-alcohol mixture and a white paint.

- (3) A bamboo-reinforced soil-cement base under a thin, concrete pavement surfacing was likely to effect a saving in the order of 30 percent over normal, plain cement-concrete pavement.
- b. The conclusions concerning analysis, design, and construction were:
- (1) With proper construction procedures, it was possible to increase the flexural strength of soil-cement by approximately 2.5 times by reinforcing it with bamboo at an extra cost of about 40 percent.
 - (2) A bond strength of 150 to 180 psi (10.5 to 12.7 kg/cm²) could be obtained between bamboo and soil-cement after 4 weeks of curing.
 - (3) Elastic theory was not suitable for design purposes because tests indicated that the safe design load was approximately four times greater than the calculated allowable load, using said elastic theory.
 - (4) Design based on ultimate strength theory and bond failure was in good accord with results; therefore, this method was recommended for design.

Field Applications of Bamboo-Reinforced Concrete

50. The literature and some WES correspondence indicate that a limited number of bamboo-reinforced concrete and soil-cement structures have been constructed and observed under field conditions for periods up to 15 years. Currently available information on the design and construction procedures used and the conclusions reached from observations of the structures over a period of several years are summarized below.

Information from the Clemson study²

51. The previously mentioned Clemson study included the design and construction of three bamboo-reinforced structures for the purpose of checking the accuracy of design data and construction principles recommended as a result of the laboratory work. These structures included a planer building, a press box, and a five-room residence. The following is a condensed description of the construction methods used and the conclusions reached from each individual structure.

52. Planer building. Floor plans and dimensions are shown in

figs. 1 and 2.

- a. The following design and construction procedures were used in this structure.
- (1) Several different concrete mixtures were used in construction of this building but, unfortunately, no information on the variation of concrete strength was given.
 - (2) The slabs were reinforced with whole, untreated culms; whole, treated (asphalt emulsion), seasoned culms; or whole, green culms.
 - (3) Continuous beams were reinforced with the same size and type of bamboo in both the tensile and the compressive zones. Vertical stirrups consisting of cut bamboo culms were used as shear reinforcement when needed.

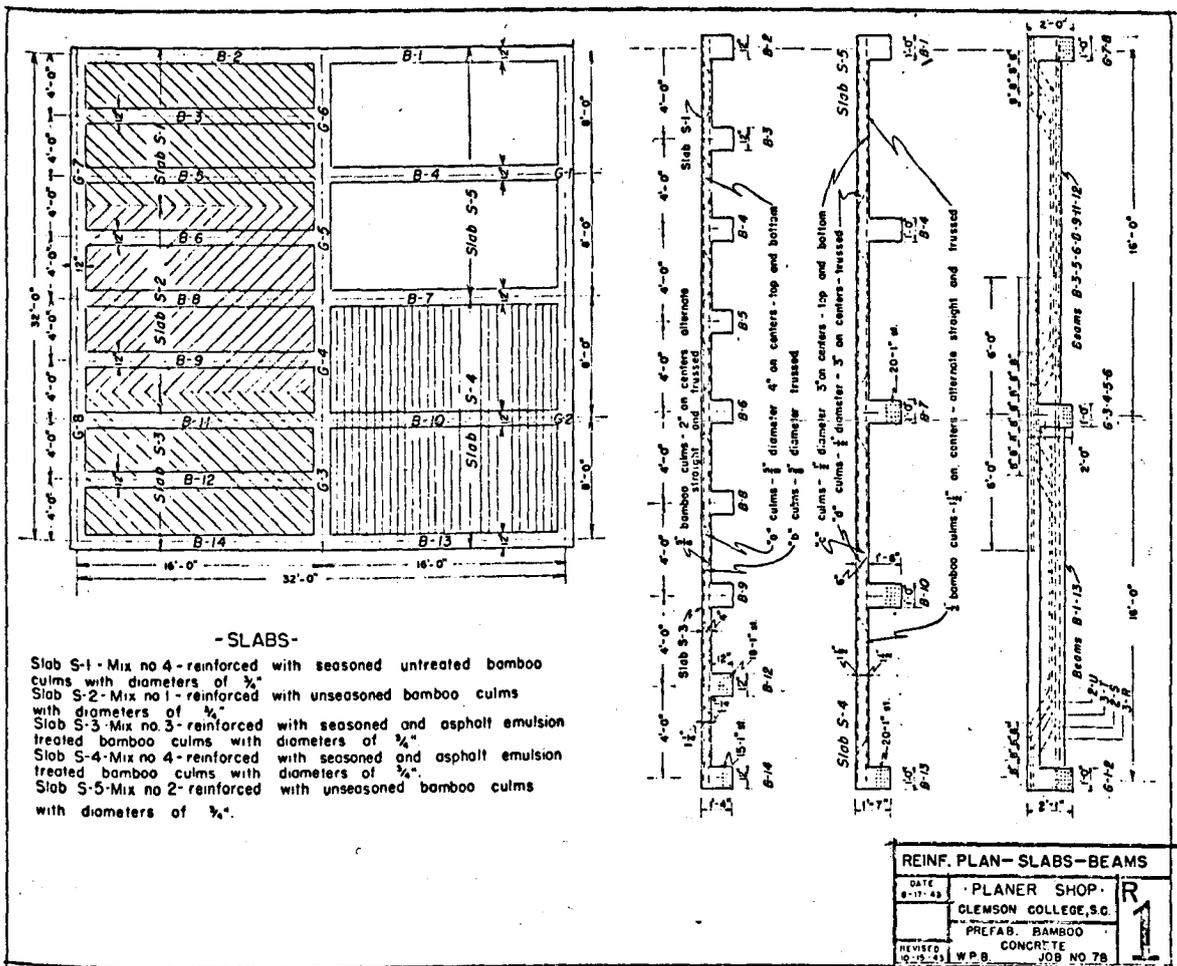


Fig. 1. Reinforcing plans for slabs and beams of bamboo-reinforced concrete planer shop constructed at Clemson University

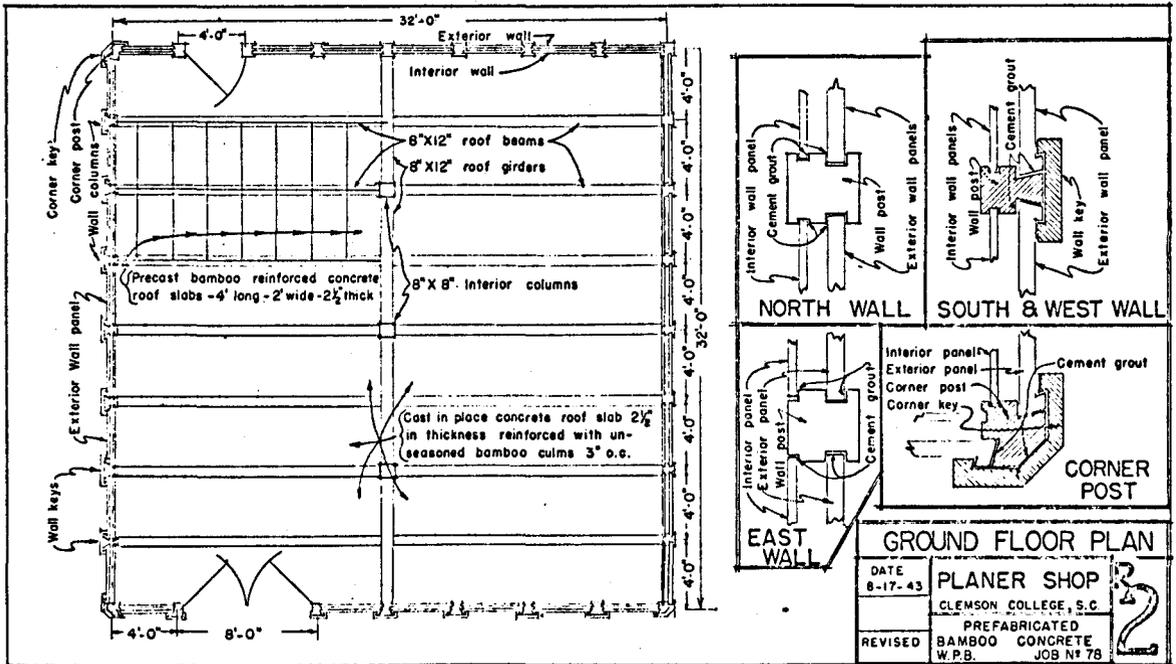


Fig. 2. Ground-floor plan for bamboo-reinforced concrete planer shop constructed by Clemson University

(4) The roof consisted of 2-1/2-in. (6.35-cm) by 4-ft (1.22-m) by 16-ft (4.88-m) slabs supported by 8- by 12-in. (20.32- by 30.48-cm) beams.

b. The following conclusions were reached from observations of the planer building for approximately 3-1/2 years.

- (1) There were no apparent differences in the load-carrying capacities of members reinforced with green, unseasoned bamboo or seasoned bamboo. (It was noted that bamboo classified as green, unseasoned was actually cut approximately 6 weeks before using; therefore, some degree of curing was evident.)
- (2) The footings, columns, girders, floor slabs, and roof slabs were all in good condition; however, the beams supporting the roof slab were entirely unsatisfactory. These beams developed cracks within 2 weeks, and additional reinforcement consisting of steel channels and shore columns were necessary within 6 months.
- (3) The failure of the beams was credited to:
 - (a) Insufficient control of concrete mixture proportions (an error was made in weighing the materials).
 - (b) Improper placing of the tensile reinforcement (some cracked sections indicated the bottom layer of

bamboo was 4 in. (10.16 cm) instead of 1 in. (2.54 cm) above the lower face).

(c) A faulty design (the author states that the beam should have been 10 by 12 in. (25.40 by 30.48 cm) instead of 8 by 12 in. (20.32 by 30.48 cm)).

53. Press box. The plans and dimensions are shown in figs. 3 and 4.

a. This particular test structure involved typical elementary design and construction problems representative of almost any type of building, such as:

- (1) Flat slabs with both continuous and noncontinuous spans.
- (2) Rectangular beams with both continuous and noncontinuous spans.
- (3) Partial and full T-beams with both continuous and noncontinuous spans.
- (4) Load-bearing walls with sections supported by spread footings.
- (5) Walls and girders supported by columns.

b. The following conclusions were reached from observations of the press box conducted for approximately 5-1/2 years.

- (1) Several cracks had developed, but most, if not all, were attributed to concrete shrinkage.
- (2) Deflection measurements made on the beams and slabs that had cracked indicated that the deflection was less than anticipated.
- (3) The structure had been loaded to design capacity on many occasions with no visible weakening of the members.
- (4) The structure had been entirely satisfactory for 5 years.

c. Recent correspondence indicates that the press box was demolished in 1959 to allow enlargement of the seating capacity of the stadium. An inspection of the structure at this time (approximately 15 years after construction was completed) revealed that: generally, the concrete was in very good condition; some bamboo that had been subjected to air and moisture due to shrinkage cracks in the concrete had completely deteriorated, but most of the bamboo was still green and in very good condition; no cracks were believed to be caused by flexural stresses; and generally, the press box was in excellent condition and was demolished only to enlarge the stadium.

54. Five-room residence. Drawings of main floor, basement, foundation, roof, and wall framing plans are given in figs. 5 and 6.

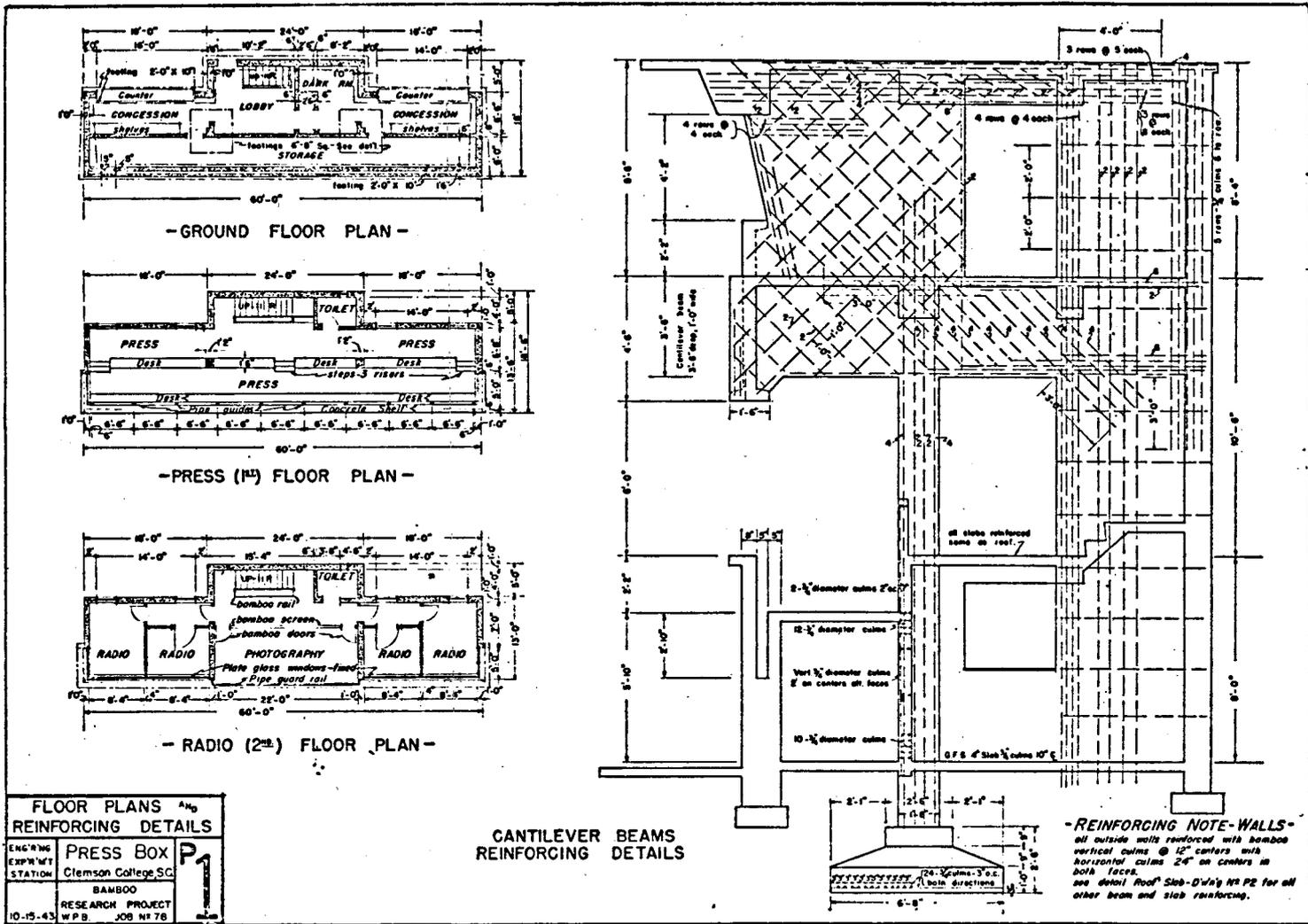


Fig. 3. Floor plans and reinforcing details for bamboo-reinforced concrete press box constructed by Clemson University

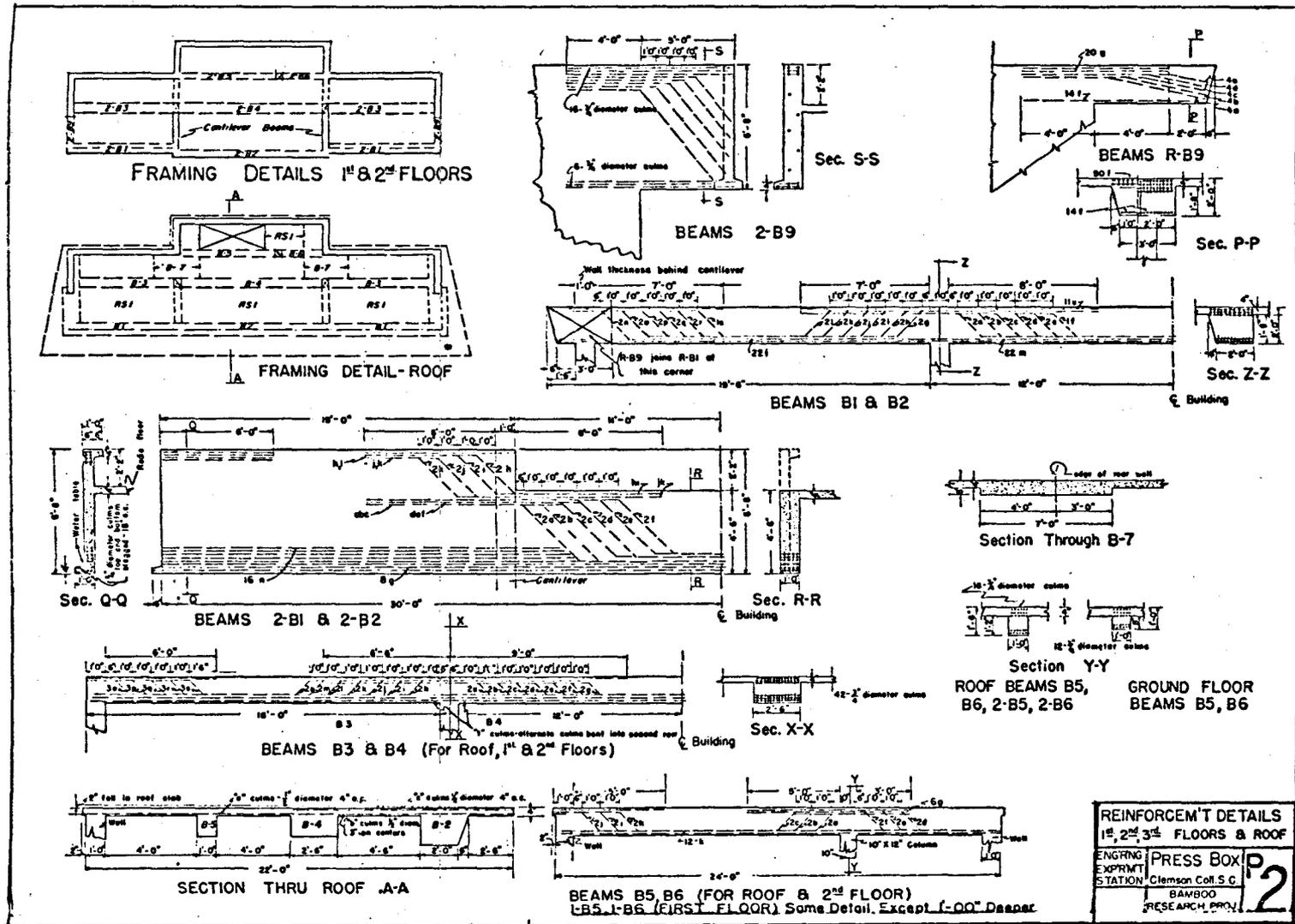


Fig. 4. Reinforcing details (ground, first, and second floors and roof) for bamboo-reinforced concrete press box constructed by Clemson University

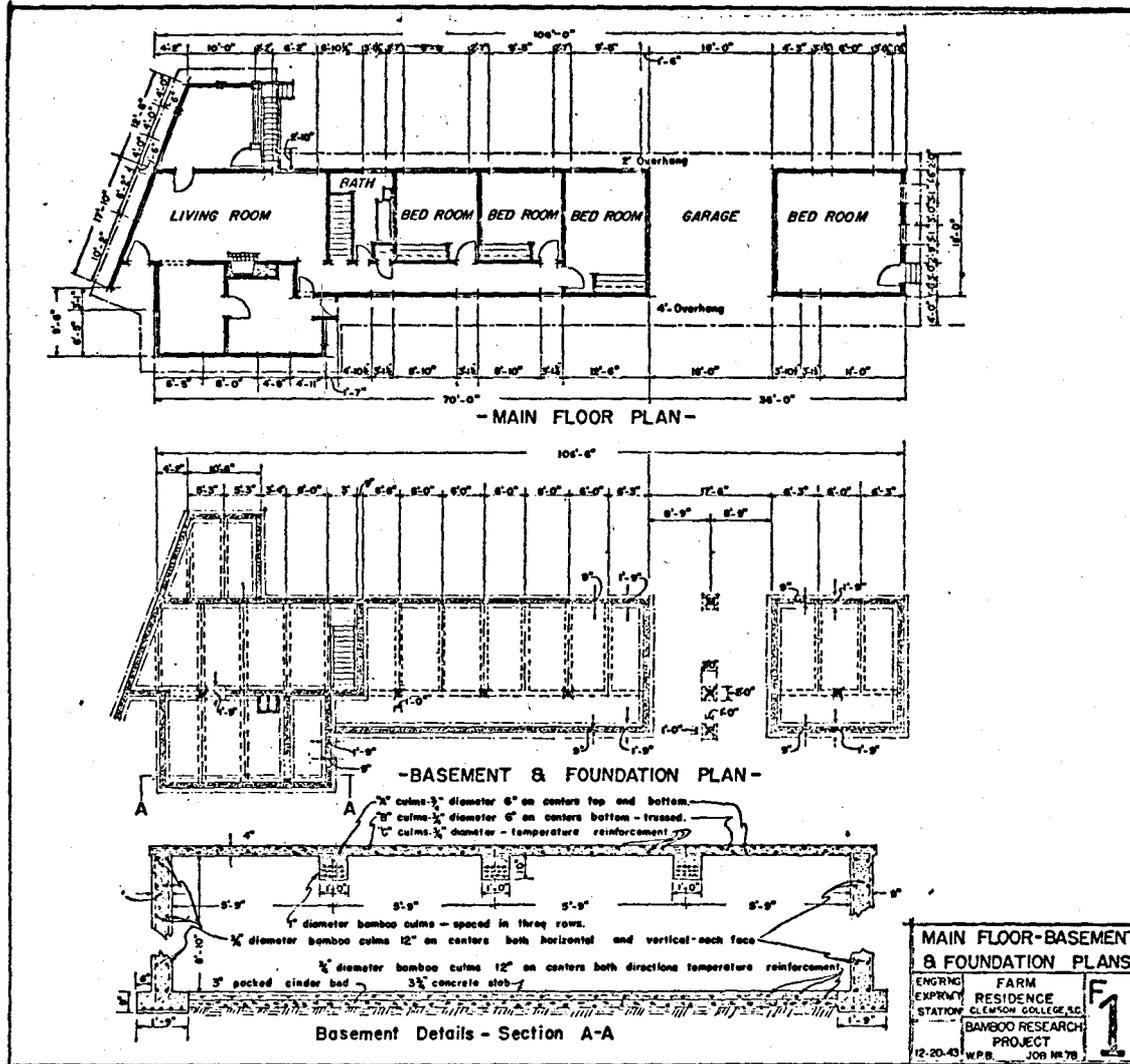


Fig. 5. Main floor, basement, and foundation plans of bamboo-reinforced concrete five-room residence constructed at Clemson University

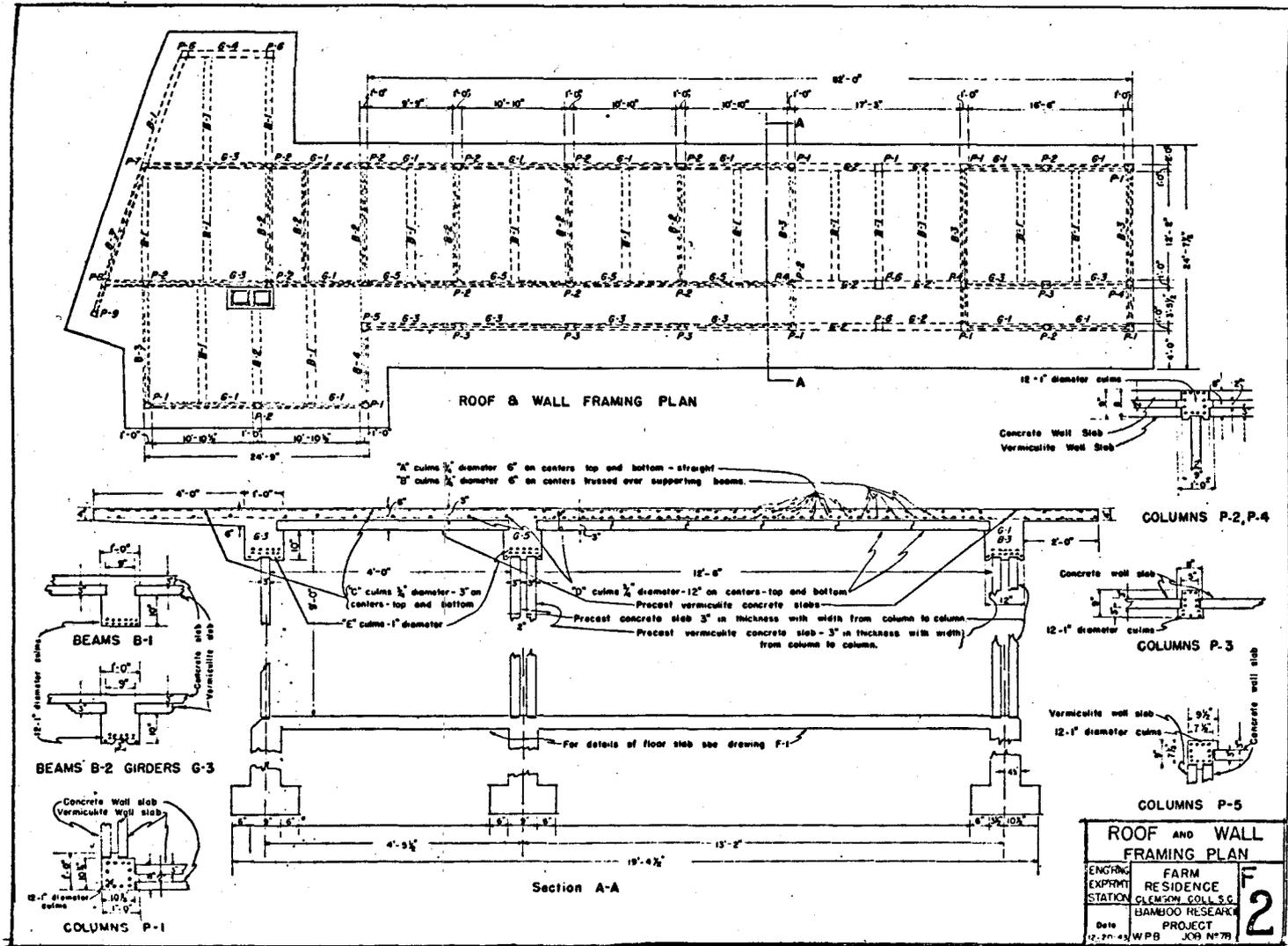


Fig. 6. Roof and wall framing plan of bamboo-reinforced concrete five-room residence constructed at Clemson University

- a. The following design and construction procedures were used in the structure:
- (1) All structural components were prefabricated bamboo-reinforced concrete members.
 - (2) In most cases, the bamboo was an unseasoned, native variety.
 - (3) Where structurally possible, all members were cast in units that could be handled by two men.
- b. The following conclusions were reached from observations of the structure made for approximately 4-1/2 years.
- (1) All structural members, except the roof beam and girders, were performing satisfactorily.
 - (2) The roof beam and girders required additional reinforcement with steel channels within 1 year.
 - (3) The only change in design deemed necessary is that roof beams and girders need a greater safety factor than other structural members.
 - (4) With modifications and improvements, bamboo-reinforced concrete may offer great opportunities in the low-cost housing field.

Information from India on
bamboo-reinforced soil-cement¹⁴

55. A 900-ft-long (274-m-long) soil-cement test base overlaid with rigid and flexible pavement has been constructed on a busy section of roadway in the state of Punjab. No specific dates or measurements (other than the length) were given; however, the authors indicated that the roadway was performing satisfactorily after a short period of use. Also, it was noted that more field findings must be considered before reaching any conclusions on this type of design or construction.

Additional information
from WES correspondence

56. Some of the recent WES correspondence indicates that several bamboo-reinforced concrete gun mounts and warehouses were constructed by U. S. forces in the Aleutian Islands during 1942.

57. These structures were designed with a 10 percent safety factor and a life expectancy of 3 years. It is not known what the actual useful life was, but the correspondence states that the bamboo did solve a temporary but critical reinforcement problem.

58. Also, it has been reported that the Japanese Imperial Navy made large-scale use of bamboo-reinforced concrete in expedient field construction during World War II. Unfortunately, all data and reports of this construction seem to be lost or misplaced.

The economy of using
bamboo-reinforced concrete
and soil-cement structures

59. The Clemson study² indicated that their final cost should not be considered when studying the economy of their structures because their design and construction procedures were of a pioneering nature, and many changes were made during the actual construction phase.

60. Mehra et al.¹⁴ indicated that should bamboo-reinforced soil-cement prove satisfactory in further field tests, one might reasonably expect an increase in flexural strength of up to 250 percent with an increase in cost of approximately 40 percent as compared with conventional methods of soil-cement construction.

61. Based on the currently available information, it seems that very little is now known about the economy of bamboo-reinforced concrete or soil-cement structures.

PART III: TEST RESULTS CONCERNING THE ENGINEERING
PROPERTIES OF BAMBOO

62. As noted in Part II, all available literature indicates that considerable variation exists in almost all of the reported engineering properties of bamboo and that some of the most important properties (such as the magnitude of moisture-induced volume changes, Poisson's ratio, creep behavior, strength under sustained loads, etc.) are still unreported. Consequently, it was deemed necessary to determine or verify all important design data before any designing or testing could begin on bamboo-reinforced structural elements.

63. The following is a summary of the engineering properties of bamboo obtained during this phase of the investigation. All properties shown are results of tests conducted on local bamboo; A. tecta, commonly called "small cane."

Tensile Strength and Modulus of Elasticity

64. Twenty-five specimens were tested to determine their ultimate static tensile strength and modulus of elasticity. Also, nine additional specimens were tested to determine ultimate tensile strength only. These specimens were selected, prepared, and tested as follows.

- a. Whole culms with varying degrees of seasoning (i.e. moisture content) were selected for these tests.
- b. To prevent crushing of the bamboo by the grips of the testing machine, gripping-type Chinese pullers were used to transfer the load from the machine to the bamboo (fig. 7).
- c. Diametrically opposed SR-4 strain gages were mounted near the center of the specimens, either at the node (1-in. (2.54-cm) gage lengths) or in the internodes (3-in. (7.62-cm) gage lengths) or both to measure bamboo strains at various increments of load.
- d. A uniform loading rate of 1000 psi (70.3 kg/cm^2) per minute was used in each test.

65. The results of individual tests are shown in table 5. It is apparent from these results that:

- a. Values of tensile strength and modulus of elasticity ranged



Fig. 7. Test arrangement used in determining the tensile strength and elastic modulus of bamboo

from 6870 to 25,030 psi (485 to 1760 kg/cm²) and from 1.26×10^6 to 4.01×10^6 psi (88,590 to 281,930 kg/cm²), respectively. Average values of tensile strength and modulus of elasticity were 15,410 psi and 2.62×10^6 psi (1083 and 184,200 kg/cm²), respectively. Whereas the range of values and the average for the tensile modulus agree well with those quoted in the literature, the maximum and average values of the tensile strength obtained in this program are lower than those reported by other investigators.

- b. In almost all cases, the specimens that had a high modulus of elasticity had a high tensile strength; the average ratio between tensile modulus and strength was approximately 166.
- c. Even though the average tensile strength* of specimens failing at the nodes was slightly higher than that obtained for specimens failing between the nodes, the node appeared to be the weaker section of the bamboo, because 76.5 percent of the failures occurred at the nodes.
- d. The degree of seasoning (the percentage of moisture or the

* All stresses were computed by dividing the total test load by the average internodal cross-sectional area of the culm.

age after cutting) did not clearly affect either the ultimate tensile strength or the tensile modulus of elasticity. However, most of the very high tensile strength values were obtained on seasoned specimens. Thus, while there is no clear relation between strength and moisture content, it appears that the strength tends to increase with decreasing moisture content (plate 1), a conclusion that is supported by the findings of other investigators.⁷

- e. Bamboo has an essentially linear stress-strain curve in tension up to its (brittle) failure (see plate 2).

66. Additional tests are now under way to determine the effect of the harvesting season on the tensile strength of bamboo culms.

Poisson's Ratio

67. The Poisson's ratio of bamboo was obtained from tests conducted on 11 tensile specimens. For measuring the axial elongation and transverse contraction, diametrically opposed standard SR-4 strain gages were placed both parallel to (3-in. (7.62-cm) gage) and across the fibers (1/4-in. (0.635-cm) gage length).

68. Results of these tests, shown in table 6, indicate that:

- a. In the small number of specimens tested, there were no significant differences between the Poisson's ratios for green or for seasoned bamboo culms.
- b. The range for all specimens was 0.250 to 0.409, with the average being 0.317.
- c. The average of 0.317 agrees closely with the commonly used value for steel. However, in evaluating bond problems, it must be realized that the diameter reduction in a bamboo culm under a given stress will be about ten times greater than the change in a steel reinforcing bar under the same stress due to the approximately 1:10 ratio between the elastic moduli.

Bond Between Bamboo and Concrete

69. Realizing that a good bond between bamboo and concrete is a prerequisite for the successful utilization of bamboo as a concrete reinforcement, particular emphasis was placed throughout this phase of the

investigation on determining bond strength under various conditions and finding practical ways of improving bond.

70. Specimens used during these tests consisted of:

- a. Whole, untreated, green culms.
- b. Whole, untreated, seasoned culms.
- c. Split, untreated, seasoned culms.
- d. Split, untreated culms with scratched contact areas.
- e. Split, untreated culms with shredded ends.
- f. Split, seasoned culms with fine sand sprinkled on a fresh brush coat of epoxy resin.
- g. Split, seasoned culms with fine sand sprinkled on a fresh brush coat of polyester resin.
- h. Split, untreated culms with the contact area wrapped with 0.05-in.-diam (1.3-mm) steel wire.
- i. Split, seasoned culms with ends consisting of whole culms.
- j. Split, seasoned culms treated with a solution containing 4 lb (1.81 kg) of Super Premium Penta Concentrate.*
- k. Split, seasoned culms soaked in water for 3 days prior to embedment in concrete.

71. All specimens were prepared and cured as follows:

- a. Method CRD-C 24-65 of the "Handbook for Concrete and Cement"¹⁵ was used as a guide in preparing the bond test specimens (fig. 8). However, it was found that after the initial slippage of the bamboo, very little residual bond remained and displacement measurements at both the loaded and the free end of the culms were discontinued.
- b. All 7-day specimens were moist cured in a fog room until tested.
- c. The remaining specimens were removed from the fog room after 14 days and were then dry-room cured (approximately 74 F (23.3 C) and 50 to 70 percent relative humidity (RH)) until tested.
- d. The concrete mixture used throughout this program had a design strength of 3000 psi (210.9 kg/cm²) at 28 days; the actual strength at the time of testing (7 to 90 days) varied between 1487 and 3710 psi (104.8 and 260.8 kg/cm²).

* Four pounds of technical Pentachlorophenol per gallon of special solvents and antibloom agents; manufactured by Vulcan Materials Company, Wichita, Kansas.

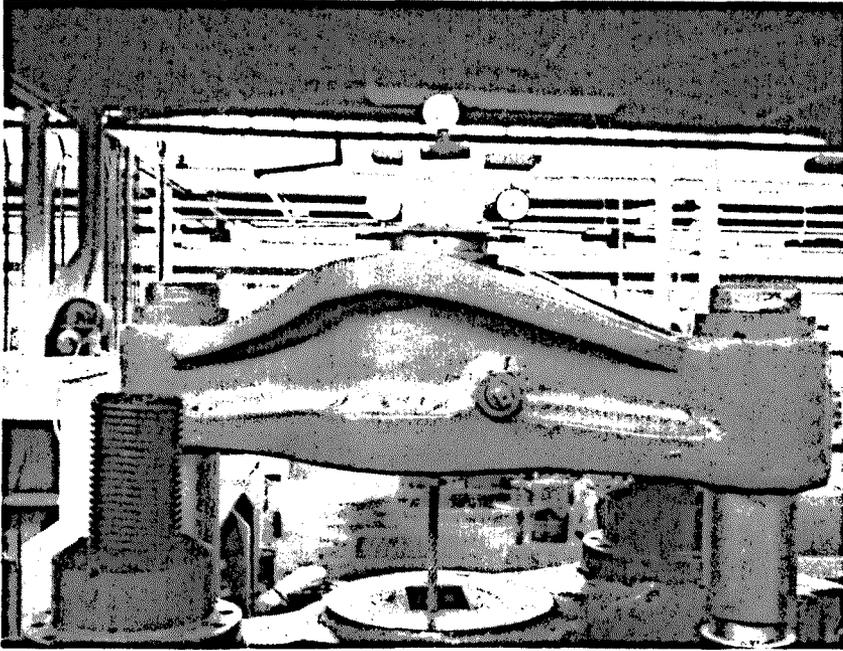


Fig. 8. Typical pullout test arrangement used in checking the bond developed between bamboo and concrete

72. Results of the tests, shown in table 7, were as follows:
- a. There appears to be no significant difference between green culms and seasoned culms; however, the use of seasoned, untreated culms as reinforcement was considered unsatisfactory because they tend to cause cracks in the concrete cover.
 - b. The bond strengths per unit of contact area of split and whole culms are approximately the same; however, the contact areas are almost doubled when the culms are split.
 - c. Most specimens tested at 7 days developed a higher bond strength than specimens tested at greater ages. This was probably due to a loss of moisture from the bamboo and resultant shrinkage of the culms during the dry-room curing period of the older specimens; the 7-day specimens remained in the fog room until tested. However, a limited number of 90-day tests showed no further reduction in bond after 28 days. Additional tests to verify this and to evaluate bond strength at intervals of dry curing up to 1 year have been initiated.
 - d. Specimens of split bamboo with fine sand sprinkled over a fresh brush coat of polyester or epoxy resin and split bamboo with the encased ends consisting of whole culms exhibited the greatest bond strength. It is questionable,

however, whether these methods are feasible for field construction since both require either special materials or excessive labor.

- e. In general, the bond strength values determined in this program resemble the values reported in the literature.

Approximate Coefficient of Thermal Expansion

73. Bamboo, like wood, tries to stay in hygrothermal equilibrium with its environment at all times; therefore, it will undergo dimensional changes because of its tendency to absorb or lose moisture whenever the RH of the environment changes. Since under the test conditions described in the following paragraphs, as in actual practice, the RH of the environment is a function of the temperature, it appears that temperature changes must doubly affect the dimensions of a bamboo specimen. Temperature changes exert a primary effect due to regular thermal expansion and a secondary effect due to temperature-induced moisture changes. For this reason, and because of the small number of tests conducted, the investigation was not considered a means of obtaining a reliable and accurate value for the coefficient of thermal expansion; therefore, the term "approximate coefficient of thermal expansion" was adopted.

74. In an attempt to minimize the above-mentioned temperature-induced moisture effects, three separate test methods were used with a maximum temperature of 100 F (37.7 C) for each test.

Test methods

75. Method I. Three seasoned culms, approximately 3/4 in. (1.91 cm) in diameter, were prepared by:

- a. Mounting pairs of diametrically opposed standard measuring disks for mechanical (Demec) strain gages 8 in. (20.32 cm) apart parallel to the fibers.
- b. Completely coating each specimen with wax to provide a vapor barrier to minimize volume changes due to moisture variation.

Readings were taken with a mechanical strain gage when the temperature reached approximately 100 F (37.7 C) inside a constant-temperature room and at approximately 28 F (-2.2 C) in the open air outside the laboratory. The

test consisted of a full temperature cycle (100 to 28 to 100 F (37.7 to -2.2 to 37.7 C)) with approximately 3 hours exposure to each environment and temperature. No reliable measurement could be taken across the fibers during this particular method of testing.

76. Method II. Four seasoned culms of essentially the same dimensions as those described in Method I were prepared by:

- a. Mounting diametrically opposed, moisture-proofed, temperature-compensating, SR-4 strain gages both parallel to (3-in. or 7.62-cm gages) and across the fibers (1/4-in. or 0.64-cm gages).
- b. Completely coating the specimens with wax as described in Method I.

The specimens were placed in a temperature-controlled oil bath (fig. 9) and

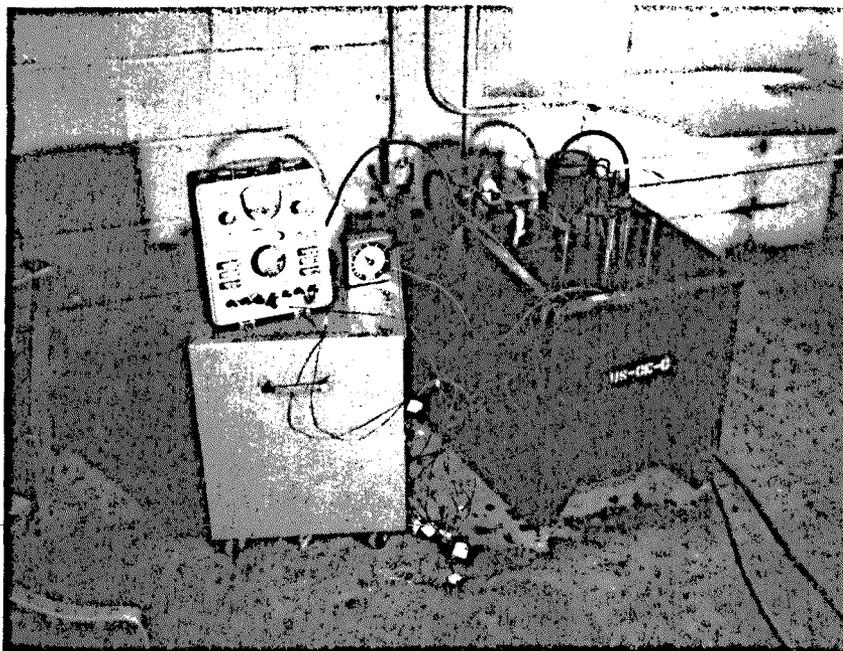


Fig. 9. Testing apparatus used in Methods II and III of coefficient of thermal expansion tests

readings were taken at 50 and 100 F (10 and 37.7 C). As in Method I, the specimens were exposed to a full temperature cycle with each temperature being maintained for several hours.

77. Method III. Five seasoned culms with essentially the same dimensions as those previously described were used in this series. The

culms were prepared exactly as those in Method II. In addition, the culms were hermetically sealed in steel tubes to keep them straight and eliminate warping, which was suspected to have occurred during Methods I and II, and to provide an additional vapor barrier, thus further reducing the secondary temperature effects. Readings were then taken as described in Method II.

Results

78. The results of these tests, table 8, show that:

- a. Between individual specimens, there is a pronounced variation in the coefficient of thermal expansion when measurements are made either parallel to or across the fibers.
- b. In Methods II and III, the coefficients of thermal expansion measured across the fibers agree reasonably well.
- c. In Methods I and II, the average coefficients of thermal expansion parallel to the fibers agree very closely.
- d. In Method III, some individual results for the coefficient of thermal expansion measured parallel to the fibers agree reasonably well with average and individual results found in Methods I and II.
- e. Approximate values of $26.00 \times 10^{-6}/^{\circ}\text{F}$ and $2.00 \times 10^{-6}/^{\circ}\text{F}$ ($46.8 \times 10^{-6}/^{\circ}\text{C}$ and $3.6 \times 10^{-6}/^{\circ}\text{C}$) can be expected for the coefficients of thermal expansion measured across and parallel to the fibers, respectively, for the temperature range shown.

79. As is rather common for woods, the coefficient of thermal expansion was much greater across the fibers than parallel to the fibers, by a factor of approximately 13. This, of course, means that the coefficient for a bamboo culm longitudinally is only about one-third of that of concrete, and radially about four times that of concrete.

Dimensional or Volume Changes of Bamboo Due to Moisture Variations

80. As stated earlier, the review of the literature did not reveal quantitative data concerning the length and diameter changes of bamboo caused by variations of its moisture content; however, several investigators have indicated that the swelling and shrinking process is one of the greatest disadvantages in using bamboo as a reinforcement material for

concrete. Therefore, the objective of the test series described below was to determine the magnitude of the dimensional changes to be expected when bamboo is exposed to environments of varying RH.

Methods

81. Twelve seasoned, whole culms (68 days after cutting) were selected for the first test series. To allow measurements of length and diameter changes, four standard measuring disks were mounted in diametrically opposed pairs 8 in. (20.32 cm) apart on each specimen. The following measurements were made:

- a. Original specimen weights and weight changes were determined to the nearest 0.01 g.
- b. Specimen diameter changes were measured with a micrometer accurate to 0.001 in. (0.025 mm).
- c. Specimen length changes were recorded to the nearest 0.0001 in. (0.0025 mm) with an 8-in. (20.32-cm) mechanical (Demec) strain gage.

82. After taking the original measurements as described above, continuous measurements were made on a total of 12 specimens; of the 12, six were allowed to dry for 49 days in the laboratory at a temperature of approximately 75 F (24 C) and an RH of 50 to 85 percent, and the remaining six were completely submerged in water for the same period.

83. At the end of the 49-day test period described above, the specimens were reversed (i.e. specimens that had been drying were submerged in water and those that had been submerged were allowed to room-dry). These reversal tests were conducted in the same manner as the other tests except they were conducted for a 140-day test period.

Results

84. Results of these tests, plate 3, were as follows:

- a. The submerged specimens swelled approximately 11×10^{-5} in./in. longitudinally, with practically all of this change occurring within the first 3 days of the test.
- b. The curve for longitudinal changes of the drying specimens was rather erratic (obviously due to changes in the RH in the storage area, which may have caused some warping in addition to true length changes of the specimens); however, the curve does indicate an average longitudinal shrinkage in the order of 15×10^{-5} in./in. to 20×10^{-5} in./in., with maximum values as high as 32×10^{-5} in./in.

- c. The submerged specimens gradually gained 30 percent in weight, indicating a considerable increase in moisture content.
- d. The drying specimens lost about 30 percent in weight, with the greater part of the moisture loss occurring during the first 7 days of the test.
- e. Submerging the specimens resulted in a diameter increase of approximately 2 percent during the first 3 days of the test. This increase remained essentially constant throughout the remainder of the test.
- f. The drying specimens decreased in diameter by approximately 5 percent, with practically all of the change occurring within the first 14 days of the test.

85. Results of the reversal tests, also shown in plate 3, were as follows:

- a. The submerged specimens showed maximum increase in length of approximately 19×10^{-5} in./in., with the majority of this increase occurring during the first 3 days.
- b. Again the longitudinal shrinkage curve of the drying specimens seemed rather erratic, which was again suspected to be partially caused by warping due to the changing RH of the environment.
- c. The submerged specimens gradually gained approximately 108 percent in weight (related to the weight at the end of the previous 49-day test period). However, a part of this additional weight was due to the bamboo absorbing and trapping water in the hollow internodes.
- d. A decrease of approximately 40 percent occurred in the weight of the drying specimens (after they were taken out of the water), with practically all of the decrease occurring within the first 7 days.
- e. The diameters of the submerged specimens increased approximately 5 percent, with the increase occurring primarily within the first 3 days.
- f. The diameters of the drying specimens decreased by approximately 5 percent, with approximately 80 percent of the change being recorded within the first 7 days.

Additional test

86. Method. Since it was suspected that the drying specimens had a tendency to warp and indicate erratic strain readings during periods of varying RH, a supplementary test was conducted on four whole, seasoned (70 days after cutting) bamboo culms that were placed in closely fitting,

perforated-steel tubes, thus eliminating any warping. Each culm was fixed to one end of the steel tube with the other end free to move. The movement was measured by a dial gage accurate to 0.0001 in. (0.0025 mm), fig. 10. Readings were made after 1, 2, 3, and 7 days, and on a weekly basis thereafter.

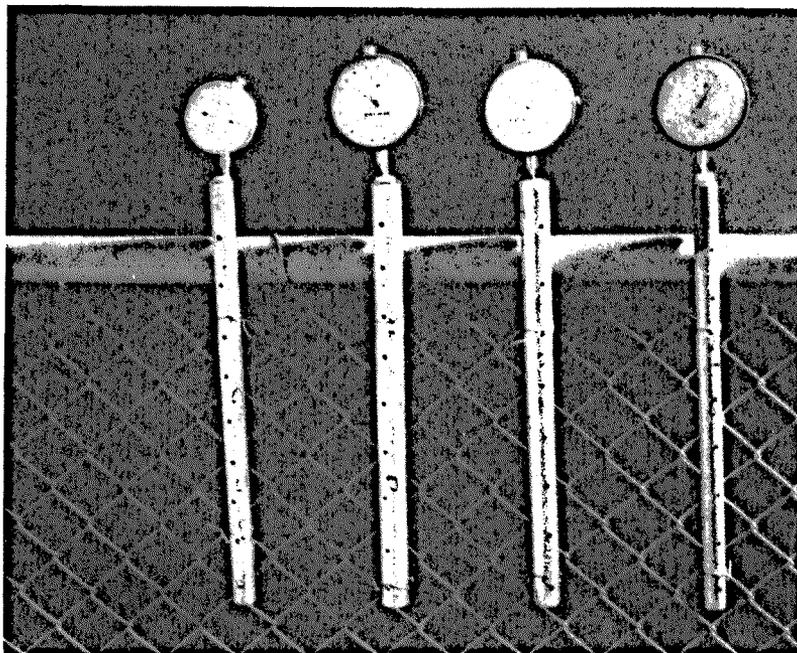


Fig. 10. Method used to eliminate warping when checking bamboo dimensional changes due to changing RH

87. Results. The results of these tests, plate 4, show that:

- a. RH readings between approximately 20 and 80 percent resulted in total length change of approximately 52×10^{-5} in./in.
- b. Readings taken during extended periods of high RH (above 50 percent) usually indicated swelling, whereas readings taken during extended periods of low RH (under 50 percent) showed shrinkage.
- c. A change in RH usually resulted in a corresponding length change in the bamboo; however, no consistent quantitative relation could be determined.
- d. The maximum positive strain (swelling) recorded was approximately 23.5×10^{-5} in./in. at a RH of approximately 78 percent, while the maximum negative strain (shrinkage) was 28.3×10^{-5} in./in. and occurred at a RH of 24 percent.
- e. The suspicion that warping caused major errors in the

measurement of length changes of unconfined specimens appears to be unjustified since overall length changes for RH variations of approximately 50 percent were almost the same (approximately 52×10^{-5} in./in.) in both the specimens that were free to warp and the specimens for which warping was minimized.

Strength and Deformations Under Sustained Loads

88. Since the literature lacks any information concerning the strength and deformation characteristics of bamboo under sustained loads, a number of sustained load and creep tests were conducted on whole, seasoned culms (109 days storage in laboratory rooms after cutting) 4 ft (1.22 m) long by approximately $3/4$ in. (1.91 cm) diameter.

Description of procedures

89. A system of levers and deadweights (fig. 11) was used to

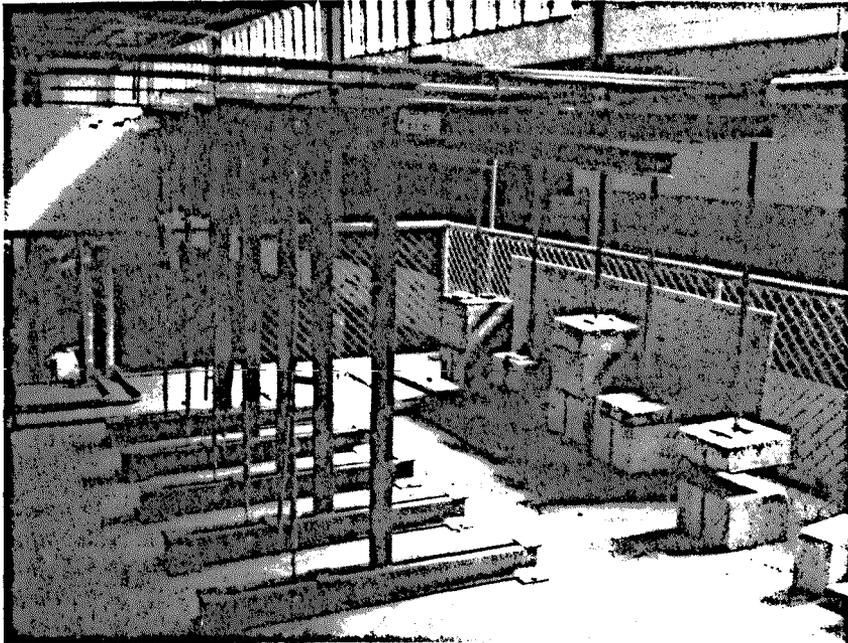


Fig. 11. System of levers and deadweights used in checking bamboo strength and deformation under sustained loads

maintain a stress level of 8250 and 4000 psi (580.0 and 281.2 kg/cm²) on two groups of three specimens each. Again, as in some of the previous

tests (tensile, modulus of elasticity, etc.), Chinese pullers transferred the loads to the specimens. All test rigs were located in rooms without climate control, resulting in temperature variations of about 80 ± 7 F (26.6 ± 3.9 C) and RH changes between 24 and 75 percent. Several specimens loaded to 8250 psi (580.0 kg/cm^2) failed in tension after loading periods between 10 min and 188 days, and were subsequently replaced by new specimens.

90. To allow strain measurements, four diametrically opposed standard measuring disks for mechanical strain gages (Demec) were mounted on each specimen, 8 in. (20.32 cm) on center. Strain readings were taken before and immediately after application of loads; after 6 hr of loading; and after 1, 3, and 7 days of loading, and weekly, thereafter.

Test results

91. The results of the above tests (plate 5) show that:

- a. Six of the nine specimens loaded to 8250 psi (580.0 kg/cm^2) failed after sustained loading periods ranging from 10 min to 188 days with four of the six failing within 1 hr after application of the load (these six specimens were replaced after failure). This indicates that the tensile strength of bamboo under sustained loads is considerably lower than its short-term static tensile strength.
- b. None of the three specimens loaded to 4000 psi (281.2 kg/cm^2) failed during the 1-yr test period.
- c. After a loading period of almost a year, the specimens had undergone creep deformations of about 0.12 to 0.14×10^{-6} in./in./psi. The average creep factor (i.e. ratio of creep to elastic strain) at the end of the test period was about 0.4 for both stress levels, indicating a near linear relation between creep and stress.
- d. The creep curves in plate 5 show the effect of RH changes on the measured strains of the specimens loaded to 4000 and 8250 psi (281.2 and 580.0 kg/cm^2). Specimens under 8250-psi (580.0-kg/cm^2) stress were much less affected by environmental changes.

PART IV: BEAM AND SLAB TESTS

Objectives

92. To date, eleven groups of bamboo-reinforced concrete beams and slabs totaling 26 specimens have been cast and tested to determine:
- a. The effect of the degree of seasoning of the bamboo on the load-carrying capacity of beams and slabs.
 - b. Methods for controlling cracks in the concrete cover due to swelling of the bamboo in fresh concrete.
 - c. Practical techniques for preparing culms (splitting, soaking in water, chemical treatment, coating, etc.) to improve bond and obtain increased load-carrying capacity.
 - d. Practical methods for placing culms in beams and slabs.
 - e. The effect of the percentage of bamboo reinforcement on the flexural strength of beams and slabs.
 - f. A suitable method for analyzing and designing bamboo-reinforced concrete structural members.

Concrete Materials and Mixture Proportions

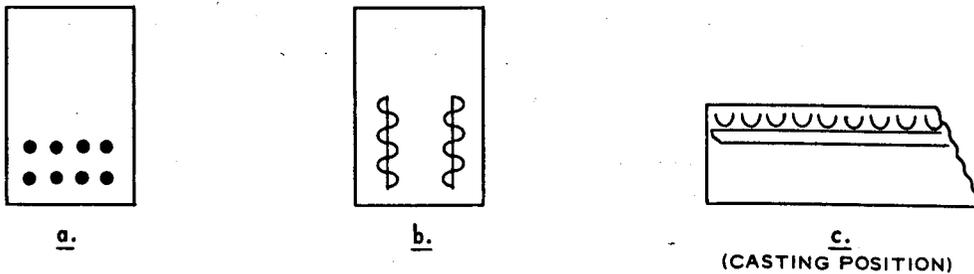
93. The materials used in the concrete mixture were type II portland cement manufactured in Alabama and fine and coarse crushed limestone aggregate from Tennessee.

94. A concrete mixture (table 9) was proportioned with 3/8-in. (9.5-mm) maximum-size aggregate to have a slump of $2 \pm 1/2$ in. (5.08 ± 1.27 cm) and a 28-day compressive strength of 3000 psi (210.9 kg/cm^2). The 3/8-in. (9.5-mm) maximum aggregate size was chosen to minimize difficulties in placing and compacting the concrete where high reinforcement ratios required very close spacing of the bamboo culms. A constant ratio of cement, aggregate, and water was maintained for all batches of concrete. Compressive strengths of the various batches of concrete are included in tables 10 and 11.

Fabrication and Curing of Specimens

95. The following methods of placing the bamboo reinforcement were used (see fig. 12):

- a. Arrangement of whole culms in horizontal layers (fig. 12a).
- b. Arrangement of split culms in vertical planes, with the concave sides facing sideways, and tied to short vertical splints (fig. 12b).
- c. Slabs only (fig. 12c): (1) split culms placed orthogonally in two horizontal planes with concave sides facing upward at casting (since the slabs in this investigation were cast upside down, this resulted in the concave sides facing downward at testing); and (2) same as (1) but orthogonal culms partially interwoven.



NOTE: IN ALL CASES BASAL AND DISTAL ENDS OF CULMS WERE ALTERNATED TO ENSURE FAIRLY UNIFORM REINFORCEMENT AREA.

Fig. 12. Arrangement of reinforcement in specimens

96. Beams and slabs were cast in plywood forms. The concrete was consolidated in three layers with a 3/4-in.-diam-head (1.91-cm) electric vibrator (frequency 7000 vpm). Each beam was then placed on a vibrating table and vibrated briefly.

97. All beams, slabs, and associated cylinders were finished with a wooden float, stripped at 24 hr age, and placed in a fog room for 13 days. On the fourteenth day the specimens were removed from the fog room and allowed to dry cure (approximately 74 ± 10 F (23.3 ± 5.5 C) and 50 to 80 percent RH) until testing.

Beam Tests

Equipment

98. Eight groups of bamboo-reinforced beams, involving a total of 20 simply supported beams (4 by 9 by 78 in. or 10.16 by 22.86 by 198.12 cm), were tested to failure under third-point loads. The beams were supported on a full-rocker system on one side and a half-rocker system on the other side that provided a span of 6 ft (1.83 m). A hydraulic system consisting of two 20-ton (18,144-kg) jacks, a control panel, and a 2500-psi (175.7-kg/cm²) precision pressure gage (calibrated before and after the test series) was used to apply and measure the third-point loads. Pads, 1 in. (2.54 cm) wide, between the rollers and the beams served to distribute loads and support reactions.

99. Three independently supported dial gages, thus unaffected by possible deformation of the testing frame, were used to measure beam deflections.

Methods

100. Loads were applied in increments of 500 lb (226.8 kg) (total load*) and beam deflections were read at each increment. Occasionally, loads were removed completely to check the nonelastic deflections of the beam.

101. Cracks were observed visually throughout the test, and all were marked as they appeared. The crack patterns were photographed (photographs 1-20) when significant changes occurred.

Results

102. Results of tests on individual groups are summarized in table 10 and briefly discussed below.

103. Group 1. This group consisted of three beams (1-3) reinforced with whole, green culms placed as shown in fig. 12a. The reinforcement ratios (ratio of bamboo cross-sectional area to total cross-sectional area) for these three beams were 1.96, 2.96, and 4.53 percent. The principal results of tests on this group were:

* Total load equals two times the load per ram.

- a. All three beams developed horizontal cracks at the level of the reinforcement shortly after casting (photographs 1, 2, and 3). Obviously these cracks were caused by swelling of the bamboo culms due to absorption of water from the fresh concrete.
- b. All three beams failed as a result of loss of bond at low loads. The calculated average bond stresses at failure for the bottom layer of culms were in the order of 12 to 16 psi (0.84 to 1.12 kg/cm²), considerably below the bond strength of whole, green culms obtained in pullout tests at 28 days. It is believed that the cracking of the concrete was a major factor in reducing the bond strength.
- c. The computed average tensile stress at failure in the bamboo reinforcement ranged from 2790 to 4310 psi (195 to 305 kg/cm²) using an approximate elastic analysis (Appendix A) and from 2660 to 4300 psi (185 to 300 kg/cm²) based on a modified ultimate strength analysis (Appendix B). The maximum tensile stress in the bottom layer of bamboo (approximate elastic analysis) was computed to range between 2790 and 4700 psi (195 to 330 kg/cm²) for the three beams, or less than 30 percent of the average tensile strength of bamboo.
- d. Midspan beam deflections under maximum load for beams 1 to 3 were 0.10, 0.33, and 0.40 in. (0.254, 0.838, and 1.016 cm) (plate 6a), respectively.
- e. The three beams developed ultimate moments of 13,920, 30,000, and 33,000 in.-lb (160.4, 345.6, and 380.2 m-kg), whereas the ultimate moment of an equivalent unreinforced beam in this group is estimated to be approximately 20,000 in.-lb (230.4 m-kg) (assuming the tensile strength of concrete to be 1/10 of its compressive strength). Thus, the use of green, whole culms as reinforcement must be considered a failure since it led to serious cracking of the beams before loads were applied and did little to enhance the flexural strength (in the case of beam 1, it even decreased it).

104. Group 2. The principal problem evident from group 1 tests was the low bond strength, probably caused, in part, by the cracking of the concrete cover. The first step in attempting to overcome the bond problem was to increase the contact area between the concrete and the bamboo by using split culms. Two beams (4 and 5) were cast using split, seasoned culms and the smaller reinforcement ratios, i.e. 1.96 and 2.96 percent, used in the first group. Since split culms were used, the number of reinforcing members was doubled (as was the contact area between the bamboo

and concrete). This presented a problem in placing the reinforcement in the lower portion of the cross section with sufficient spacing to place and consolidate the concrete and provide adequate cover for the culms. The arrangement of the reinforcement used in group 1 specimens was found to be impractical for the increased number of reinforcing members; therefore, a new arrangement (see fig. 12b and fig. 13) was adopted for split-bamboo reinforcement in rectangular-cross-section beams for this and subsequent test groups.

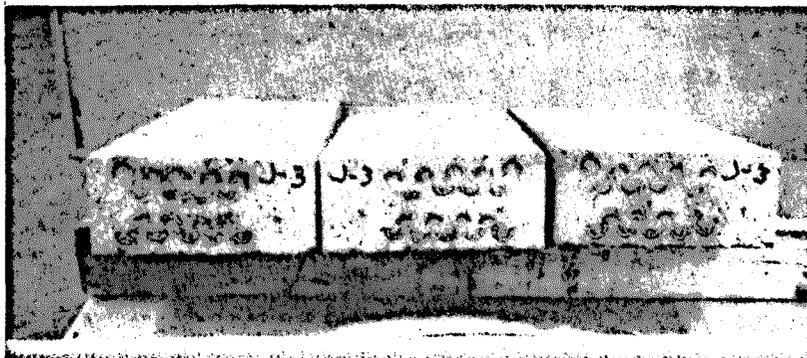


Fig. 13. Typical cross section of beam showing placement of split culms

105. Results of the two beam tests in this group showed that:
- a. The use of seasoned split bamboo resulted in the formation of cracks in the concrete cover due to swelling of the culms; however, the cracks were smaller than those in the first group of beams.
 - b. The ultimate moments developed by the two beams in this group were higher than those of corresponding beams in group 1; however, the beams were still considered unsatisfactory and failure again resulted from premature loss of bond. The calculated average bond strength for the bottom layer of split culms was in the order 19 to 20 psi (1.3 to 1.4 kg/cm²), still considerably below the values obtained in pullout tests.
 - c. The average tensile stress in the bamboo reinforcement was between 5400 and 6420 psi (380 and 450 kg/cm²) (elastic analysis) and 5610 and 6610 psi (395 and 465 kg/cm²) (modified ultimate strength analysis). Computed elastic stresses in the bottom culms were 7820 and 7020 psi (550 and 495 kg/cm²).
 - d. Initial flexural cracks developed in each beam at moments

between 15,600 and 18,000 in.-lb (179.7 and 207.4 m-kg), or approximately the failure moment expected for a comparable unreinforced beam.

- e. Deflections at ultimate load were in the order of 0.35 in. (0.889 cm) (plate 6b), and each beam gave considerable warning of imminent failure by developing large cracks (photographs 4 and 5).

106. Group 3. Bonding was improved considerably by using split bamboo instead of whole culms; however, the problem of cracks in the concrete cover due to swelling of the culms was still evident in group 2. Thus, in group 3, three beams were fabricated with split-bamboo reinforcement that was soaked either in water (beam 6) or in a Super Premium 4-lb (1.81-kg) Penta compound (beams 7 and 8) for 72 hr prior to embedment in concrete. Since culms immersed for 72 hr are essentially saturated, it was hoped that no swelling due to water absorption would occur after embedment in concrete, thus reducing any cracking of the concrete cover. Reinforcement ratios of 4.53, 1.96, and 4.53 percent were used in the three beams. The split culms were arranged as shown in fig. 12b.

107. Results of the three beam tests (photographs 6, 7, and 8 and plate 6c) in this series showed that:

- a. Cracking of the concrete cover was eliminated by pre-soaking the culms for 72 hr prior to embedment in the concrete.
- b. The calculated average bond stress at failure for the bottom bamboo culms was still approximately 20 psi (1.4 kg/cm²), or less than 30 percent of the bond strength obtained in pullout tests; all beams still failed exclusively in bond.
- c. The average tensile stress in the bottom reinforcement culms at failure ranged between 7180 and 8410 psi (505 and 590 kg/cm²) (elastic analysis) or approximately 50 percent of the average bamboo tensile strength.
- d. The treatment of split culms with a wood preservative (as compared to soaking in plain water) did not increase the flexural strength at 28 days; in fact, beam 8, reinforced with split culms soaked in Penta solution, exhibited a lower strength than a similar beam (beam 6), whose culms had been soaked in plain water. This does not, of course, preclude a beneficial effect of the wood preservative on the durability of bamboo reinforcement, particularly under field conditions.

108. Group 4. Since the results of tests on beam 6 indicated that presoaking of the bamboo in water for 72 hr reduced the swelling of the bamboo when embedded in fresh concrete sufficiently to eliminate cracking of the concrete cover, further tests were conducted in group 4 on three beams (9-11) to verify this finding. Seasoned, split-bamboo reinforcement, presoaked in water for 72 hr prior to embedment in concrete, and representing reinforcement ratios of 1.96, 2.96, and 4.53 percent, was used for the beams of this series. In addition, one beam (12) was cast that contained 2 percent presoaked split-bamboo culms with 8-in.-long (20.32-cm) end sections (fig. 14) of whole culms. It was hoped that these whole ends

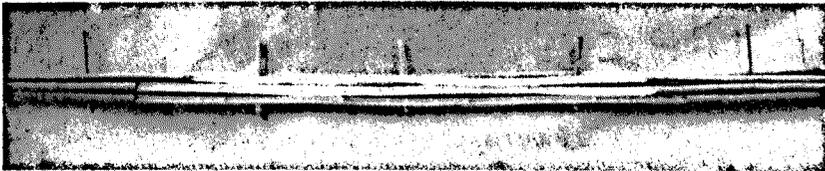


Fig. 14. Split-bamboo beam reinforcement with ends (approximately 8 in. or 20.32 cm) consisting of whole culms

would act as end hooks. Obviously, such reinforcement is hardly practical in actual field construction, since considerable time is required to prepare individual culms; however, pullout tests, described in Part III, showed this to be the only effective system to improve bond that did not require special materials. Thus, it was deemed worthwhile to try it in a beam.

109. The results of this group of tests allowed the following conclusions:

- a. Presoaking of the bamboo in water for 72 hr is a simple and reliable method of preventing cracking in the concrete cover.
- b. Split, presoaked bamboo culms can develop sufficient bond with concrete to allow utilization of up to two-thirds of the average tensile strength of bamboo. Some of the individual reinforcing culms in beams 9 through 11 were observed to fail in tension as the beams underwent failure; however, the principal failure mechanism for these three beams was still loss of bond.
- c. The use of split culms with 8-in.-long (20.32-cm), whole end sections to provide mechanical anchorage proved to be

an effective, though rather impractical, means to overcome the bond problem. The culms in this beam failed in tension, without noticeable slippage, at an ultimate moment some 50 percent higher than the ultimate moment of comparable beams reinforced with split, presoaked culms without such end anchorage. The calculated stress in the bottom culms at failure for beam 12 was 12,500 psi (880 kg/cm²), compared to stresses between 7940 and 9600 psi (560 and 675 kg/cm²) for beams 9 through 11.

- d. Initial flexural cracks were observed in all beams at moments between 12,000 and 16,000 in.-lb (138.3 and 184.3 m-kg), which, for this group, is about the range in which failure of an unreinforced concrete beam would have been expected, the concrete strength in group 4 being considerably lower than in all other groups. Consequently, it can be reiterated that the bamboo reinforcement did not increase the cracking load; in fact, with increasing reinforcement ratios the cracking moment appeared to decline slightly. Theoretically, such an effect is to be expected since the tensile modulus of bamboo is less than that of concrete. The ultimate moments of bamboo-reinforced beams in this group, however, were between about 100 and 300 percent higher than those of unreinforced beams (depending on the type and amount of reinforcement), and contrary to unreinforced beams, gave ample warning of imminent failure by gradually developing large cracks and deflections (photographs 9-12).
- e. From a practical standpoint, a reinforcement ratio between 3 and 4 percent appeared to be an optimum for rectangular-cross-section beams.
- f. Midspan deflections, at maximum load, ranged between 0.75 and 1.10 in. (1.905 and 2.794 cm) for the four beams in this series (plate 7).

110. Group 5. Since previous tests had shown that the use of split, presoaked culms is an expedient method of increasing bond and preventing the cracking of the concrete cover, the important question arose whether subsequent shrinkage of the originally saturated culms will reduce the bond and result in lower flexural strength at later ages and/or whether rapid decay of the bamboo may have a similar effect. Thus, the first three beams of group 4, reinforced with 1.96, 2.96, and 4.53 percent split, presoaked culms, were duplicated and the three beams (13-15) were tested at 90 days instead of 28 days.

111. Results of these tests (photographs 13, 14, and 15) were as follows:

- a. The flexural strength of beams at 90 days age (14 days moist curing and 76 days laboratory-room storage) was about 10 to 20 percent higher than at 28 days, indicating that shrinkage or decay of the bamboo, if it occurred at all, had not affected the 90-day flexural strength.
- b. Obviously, it is necessary to repeat the tests at 180 and 360 days before even a tentative conclusion can be drawn. But, based on the preliminary test results described above and on some observations reported in the literature concerning field structures, the authors are inclined to believe that shrinkage and decay of the embedded bamboo (particularly in the case of split bamboo) may not be quite as serious a problem as it is generally feared to be. At any rate, more tests are necessary. It should be added that the environment of use, the thickness of the concrete cover, and the degree of cracking (i.e. the degree of loading of the member) will obviously be factors in determining the seriousness of the decay and shrinkage problem. Consequently, experience in the field rather than laboratory tests will have to provide the final answer.
- c. In order to secure more information on this vital question, it is important to conduct tests after 180 and 360 days exposure to laboratory and field environments for similar beam series and to verify results by field tests on an experimental structure.
- d. The shape of the load-deflection curve of beam 13 (plate 8a) indicates that the beam was cracked (perhaps due to rough handling) before any test loads were applied. However, no cracks were observed until a total load of 500 lb (226.8 kg) was reached. In contrast, beams 14 and 15 showed rather high cracking loads, presumably due to the higher strength of concrete at 90 days. However, following the formation of cracks and the transfer of tensile stresses to the bamboo reinforcement, midspan deflections in this group were about the same as those of equivalent beams in the previous group (plate 8a).

112. Group 6. Since the predominant failure mechanism in all previous groups (except beam 12) was the loss of bond, it was decided to further investigate methods of increasing the bond strength between bamboo and concrete, even though most of the conceivable techniques appear rather impractical for application under field conditions. Pullout tests had shown that of all the methods tested only two were effective in increasing

bond. These were (a) brush coating the seasoned culms with epoxy resin or polyester resin and applying sand and (b) providing some degree of mechanical end anchorage by leaving whole ends on the split culms.

113. Since the first method requires special materials not normally available in the field and the latter method is rather complicated and involves considerable labor, both methods appear of limited value for military field applications. To determine the capability of these methods in solving the bond problem and to determine what flexural strength could be achieved if the bond problem were eliminated, two beams (16 and 17) containing 3.5 percent epoxy- or polyester-coated, seasoned, split culms* were cast in this series. Again, the bamboo reinforcement was in accordance with fig. 12b.

114. Tests on these two beams yielded the following results:

- a. In spite of the resin coat, the seasoned split culms still absorbed water from the fresh concrete and swelled, causing longitudinal hairline cracks in the concrete cover (photographs 16 and 17).
- b. Though these cracks probably reduced the strength of the beams somewhat, both beams developed higher ultimate moments than all previously tested beams. The (elastic) stress in the bottom bamboo culms at failure was computed to be in the order of 12,000 to 13,000 psi (845 to 915 kg/cm²) for both beams, or about 85 percent of the average tensile strength of bamboo. Failure of both beams was caused by a combination of bond and tensile failure of the bamboo reinforcement, eventually resulting in extreme beam curvatures that caused crushing of the concrete in the small remaining compression zone.
- c. The calculated bond stress at failure in the bottom culms was approximately 32 psi (2.2 kg/cm²), or about 50 percent higher than in beams reinforced with presoaked, split culms without a resin coating.
- d. Although the bamboo reinforcement again had little, if any, influence on the cracking loads, it did increase the ultimate load-carrying capacity by a factor of almost four.
- e. Midspan deflections at the maximum load were in the order

* Split, seasoned culms were dipped in a two-component, polysulfide-epoxy compound or in a polyester resin-methyl ethyl ketone peroxide catalyst system. Quartzite sand was sprinkled on the wet resin coat. The resins were allowed to cure 3 days before embedment of the culms.

of 0.88 to 1.00 in. (2.235 to 2.540 cm). The load-deflection curves (plate 8b) had a considerably steeper slope than in all previous groups, another indication of improved bond.

115. Group 7. This was essentially a repetition of group 6; however, the resin-coated, split, seasoned culms were soaked for 72 hr in plain water in order to reduce their swelling after embedment in the concrete and thus eliminate the cracking problem. The ends of two bottom reinforcement culms were left sticking out of both beam ends and four dial gages were used to monitor slippage of these culms (photographs 18 and 19).

116. The results of these tests showed that:

- a. Presoaking of the resin-coated, seasoned, split culms prevented cracking of the concrete cover and resulted in about 10 percent higher ultimate moments.
- b. The beneficial effect of presoaking is also evident in the load-deflection curves (plate 9a), which show that beams reinforced with presoaked, resin-coated, split culms deflected less under a given load than equivalent beams reinforced with nonpresoaked, resin-coated, split culms.
- c. The calculated average bond stress in the bottom culms at failure was approximately 35 psi (2.5 kg/cm^2), and calculated maximum elastic tensile stresses in those culms ranged between 13,210 and 14,310 psi (930 and 1005 kg/cm^2), or around 90 percent of the average tensile strength of bamboo.
- d. Beam failure was caused by a combination of bond failure and tensile failure of the bamboo reinforcement. Dial gages at the ends of beam 18 indicated some slippage of one of the two instrumented culms at loads exceeding 90 percent of the ultimate, whereas the two bottom culms monitored in beam 19 did not slip.
- e. Midspan deflections of the two beams (plate 9a) under maximum loads were 0.77 and 1.10 in. (1.956 and 2.794 cm) with cracks opening up to 0.2 in. (0.51 cm) before failure.

116. Group 8. The last group described in this report consisted of one beam, 20, reinforced with 3.5 percent presoaked, split culms with whole end sections 8 in. (20.32 cm) in length.

117. The principal results of this test were:

- a. The technique of using split culms with whole end sections again proved to be most effective in overcoming the bond problem. Beam 20 developed an ultimate moment of 78,000 in.-lb (898.6 m-kg), which was more than four times its

cracking moment. Failure was caused by tensile failure of the reinforcing culms. Good bond (or end anchorage) was also indicated by the steep load-deflection curve (plate 9b).

- b. Calculated tensile stresses in the bottom culms at failure were approximately 14,120 psi (995 kg/cm²) (elastic analysis), or more than 90 percent of the average tensile strength of bamboo.
- c. Midspan deflection at maximum load (plate 9b) was 0.60 in. (1.524 cm) and the maximum crack width before failure was about 0.16 in. (0.41 cm) (photograph 20).

Slab Tests

Methods and equipment

118. Three groups of test slabs consisting of six simply supported, two-way, concrete slabs reinforced with presoaked, split bamboo were tested. The rectangular slabs (group 1) had short and long clear spans of 44 and 66 in. (111.76 and 167.64 cm), respectively. The square slabs (groups 2 and 3) had clear spans of 62 in. (157.48 cm).

119. Split culms with an average diameter of approximately 1 in. (2.54 cm) tied together in mats (figs. 15 and 16) and presoaked for 72 hr prior to embedment were used for reinforcement.

120. All slabs were cast in an inverted position; the concrete in what was to be the upper section of the slab was placed and consolidated; then the prepared reinforcing mats were inserted (figs. 17 and 18); and finally the 1/2-in. (1.27-cm) concrete cover was cast, consolidated, and finished.

121. The pneumatic slab tester seen in photograph 22a was used to apply uniformly distributed loads. The corners of all slabs were restrained against vertical translation. Rubber bags were inflated to apply uniform loads at a rate of approximately 15 psf/min (73.24 kg/m²/min). A mercury manometer and a precision pressure gage were used to measure loads. Midspan and quarterspan (long span) deflections were determined by mechanical dial gages. Cracks were marked and significant changes in the crack pattern were photographed.

122. The stresses presented in table 11 and discussed in the

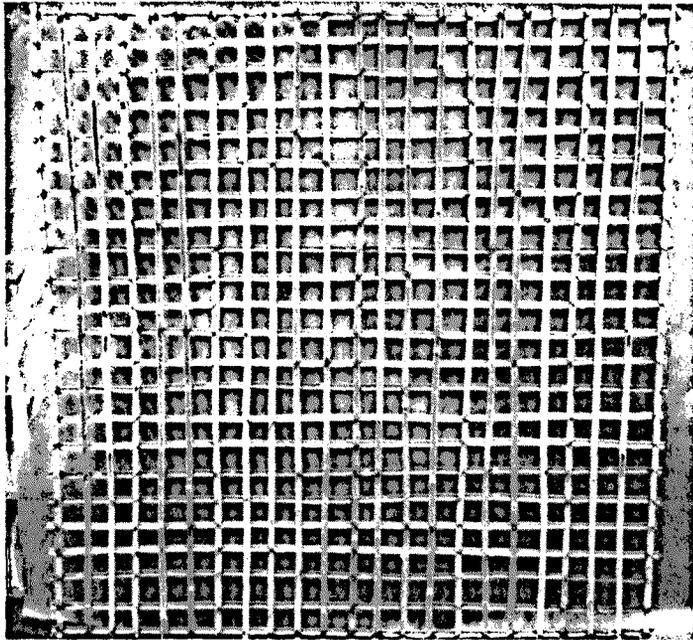


Fig. 15. Typical slab reinforcement (3 in.
or 7.62 cm on center)

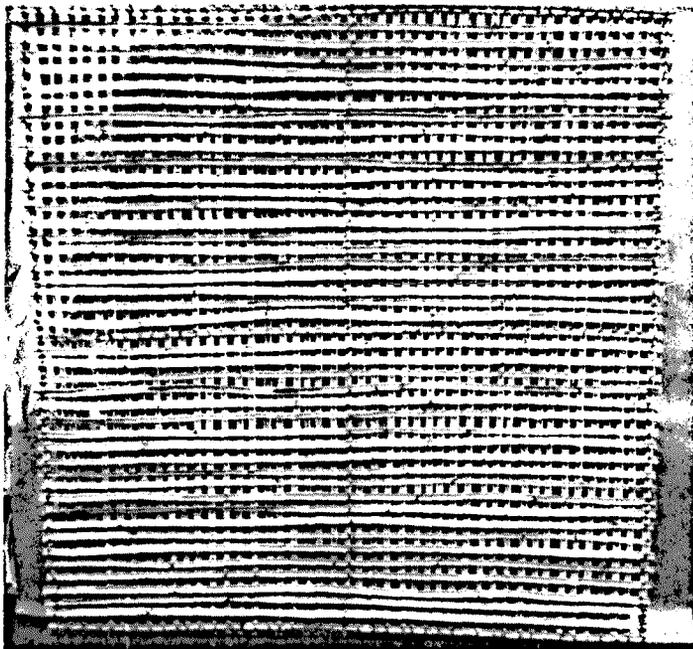


Fig. 16. Typical slab reinforcement (1-1/2 in.
or 3.81 cm on center)

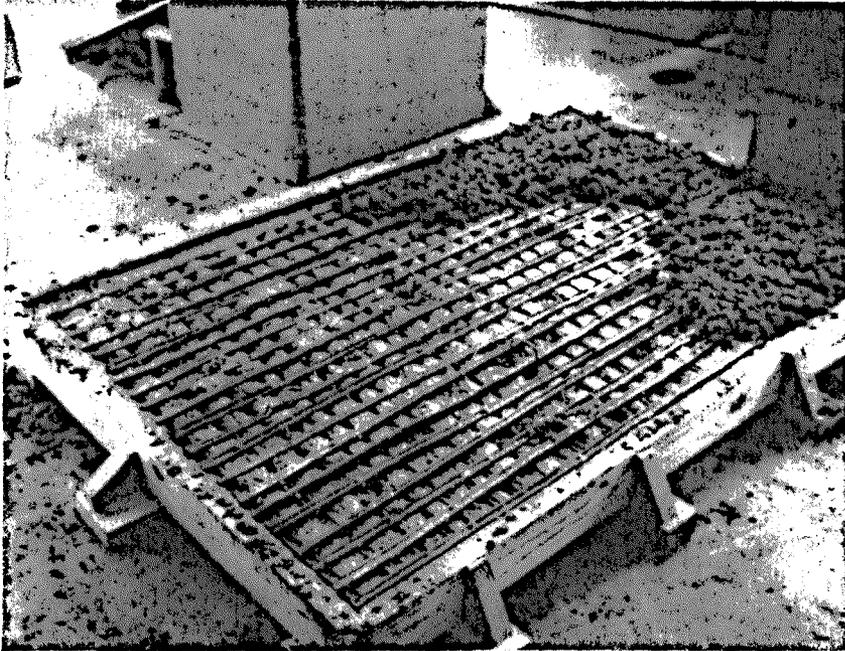


Fig. 17. Typical method of casting slabs in an inverted position during this investigation

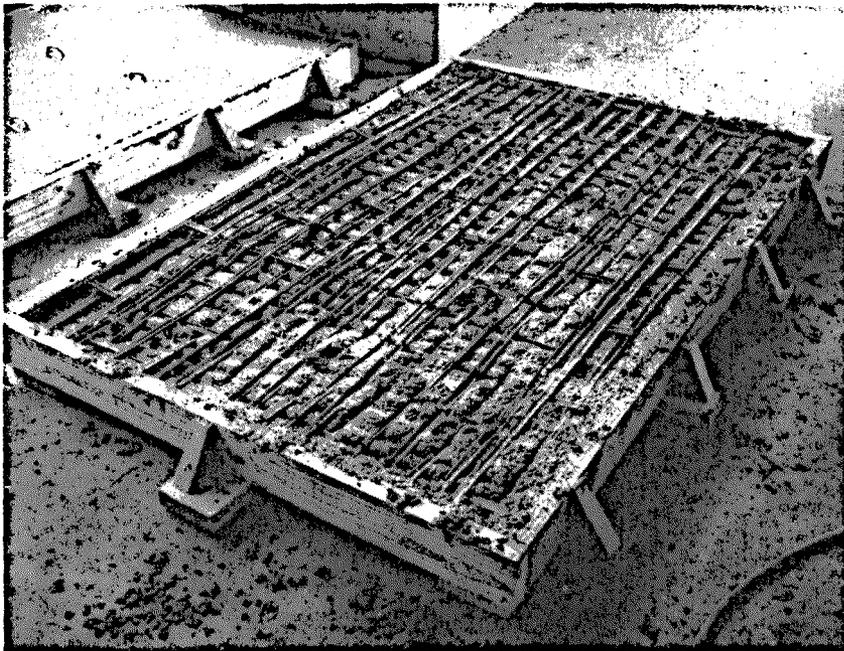


Fig. 18. Split-bamboo reinforcement with culms interwoven on approximately 5-in. (12.70-cm) centers

following paragraphs were obtained from an elastic analysis of the slabs under failure load, i.e. maximum slab moments were derived from Method 2 from ACI 318-63,¹⁶ and maximum tensile stresses in the cross section were obtained by a straight-line elastic analysis, similar to the working stress design (WSD).¹⁶

Results

123. Group 1. This group consisted of two 6-ft by 4-ft by 4-in. (1.83-m by 1.22-m by 10.16-cm) slabs, isotropically reinforced with split, presoaked culms 2-1/3 in. (5.93 cm) on center, resulting in a reinforcement ratio of 1.125 percent in each direction (percent of total concrete cross-sectional area). The reinforcement in slab 1 was placed in two horizontal planes (short-span reinforcement in the lower plane) with the concave sides of the culms facing upward at casting and alternating distal and basal ends. Slab 2 contained the same amount of reinforcement; however, in an effort to improve bond the culms of the two layers were partially interwoven on approximately 5-in. (12.70-cm) centers.

124. Results of this group of tests, summarized in table 11, were as follows:

- a. Interweaving of the culms did not significantly affect the flexural strength or the ductility of the slabs. However, slab 2 with interwoven culms had a considerably higher cracking load and, consequently, smaller deflections between about 900 and 1300 psf (4394.2 and 6347.2 kg/m²) than slab 1 (plate 10a). On the basis of just two tests, it is difficult to conclude whether the higher cracking load was coincidental or a direct result of the partially interwoven culms. In any case, the marginal benefits that may result from interweaving do not appear to justify the additional cost of mat preparation.
- b. The computed stresses at failure in the short-span culms of the two slabs were nearly the same--12,180 and 12,750 psi (855 and 895 kg/cm²). The culms ultimately failed in tension, or rather a combination of tension and kinking, since the large local curvatures at the cracks added considerable flexural stresses to the tensile stresses already present in the bamboo culms. However, slippage or partial bond failure of the culms became evident in slabs 1 and 2 at loads of approximately 1100 and 1300 psf (5370.7 and 6347.2 kg/m²), respectively, or long before failure.

- c. Under uniform loads of about 900 psf (4394.2 kg/m^2) (slab 1) and 1300 psf (6347.2 kg/m^2) (slab 2), the slabs began to develop a crack pattern similar to the yield-line pattern predicted by Johanson's yield-line theory for rectangular slabs under uniform loads (see photographs 21 and 22). As loading continued, the cracks gradually widened, reaching a maximum of about 1/2 in. (1.27 cm) at about 1300 psf (6347.2 kg/m^2) and approximately 1 in. (2.54 cm) immediately preceding failure.
- d. Deflections were predictably small prior to the formation of a hinge-line (i.e. yield-line) pattern, but increased rapidly after this pattern developed and culms began to lose bond. Midslab deflections at maximum load were 1.20 and 1.32 in. (3.048 and 3.353 cm) (plate 10a).

125. Group 2. The second group consisted of two 5-ft 10-in. by 5-ft 10-in. by 3-in. (177.8- by 177.8- by 7.62-cm) slabs reinforced in both directions with split, presoaked culms placed on 3-in. (7.62-cm) (slab 3) and 1-1/2-in. (3.81-cm) (slab 4) centers. This spacing resulted in reinforcing ratios of 1.21 and 2.42 percent for slabs 3 and 4, respectively. Since interweaving was rather difficult to achieve and results of the previous tests indicated that it did not materially enhance the load-carrying capacity, the orthogonal reinforcing mesh was not interwoven and the culms were placed in two separate horizontal planes, concave sides upward (at casting).

126. Results of tests on slabs 3 and 4 (also summarized in table 11) were:

- a. Doubling the reinforcement ratio (1.21 to 2.42 percent) resulted in approximately a 50 percent increase in the load-carrying capacity from 576 to 835 psf (2812.3 to 4076.8 kg/m^2). However, the calculated elastic stresses in the reinforcing culms at failure were lower for slab 4 with the higher reinforcing ratio (8260 psi (580 kg/cm^2) compared to 11,170 psi (785 kg/cm^2)).
- b. The low reinforcing ratio of slab 3 was too small to substantially increase the load-carrying capacity; therefore, the slab failed at essentially the same load as that predicted for an unreinforced slab with the same dimensions and the same concrete, assuming the most favorable conditions. As the concrete cracked (plate 10b) and tensile forces were transferred to the bamboo, the culms began to slip; and the slab kept deflecting under a constant load until some culms finally failed in tension and kinking (photographs 23 and 24). The beneficial effect of the

small amount of bamboo reinforcement in this relatively thin slab was not to increase strength, but primarily to improve ductility and prevent a brittle or premature failure.

- c. The statement that the lower reinforcement ratio (slab 3) was too small to substantially increase the load-carrying capacity perhaps needs further clarification. It is true that an unreinforced slab under very favorable conditions could probably carry the same load; however, if the conditions to which the slab is exposed prior to and during loading are unfavorable (involving, for instance, appreciable shrinkage, thermal gradients, and boundary restraints) the load-carrying capacity of the slab might actually approach zero. For this reason, the ACI and other codes do not allow concrete to take any tension in flexural members. In this light, even the relatively small amount of bamboo reinforcement will have a beneficial effect, in that it appears to ensure that the slab will develop at least the load-carrying capacity that an unreinforced slab would develop under the most favorable conditions.
- d. Slab 4 with a reinforcement ratio of 2.42 percent began to crack at a load lower than slab 3 (430 psf (2099.4 kg/m²) compared with 576 psf (2812.3 kg/m²)), which contained 50 percent less bamboo reinforcement. However, cracking of the concrete did not signify that slab 4 had reached its maximum load-carrying capacity. As the tensile forces were transferred from the concrete to the reinforcement at cracking, the slab rapidly developed a midspan deflection of about 1 in. (2.54 cm), but as loading continued the slope of the load-deflection curve (plate 10b) again became rather steep. The curve continued in this manner up to a load of about 750 psf (3661.8 kg/m²). Apparently the reinforcement started to slip at this point, as indicated by the flattening slope of the load-deflection curve. Again, final failure was caused by rupture of the culms due to tension and kinking.
- e. Midspan deflections of the two slabs upon reaching their ultimate load-carrying capacity were between 2 and 2-1/2 in. (5.08 and 6.35 cm). Excessive cracking (maximum crack width preceding failure, 3/4 to 1 in. (1.91 to 2.54 cm)) gave ample warning of imminent failure (plate 10b).

127. Group 3. Group 3 was essentially a repetition of group 2, except the slab thickness was increased from 3 to 4 in. (7.62 to 10.16 cm). Using the same number and sizes of split culms as in the preceding series resulted in reinforcing ratios of 1.5 (slab 5) and 0.75 (slab 6) percent.

128. Results obtained in this group (table 11) showed that:

- a. The yield-line pattern again started to form earlier in the slabs with the larger amount of bamboo reinforcement (photographs 25 and 26); therefore, it appears that the close spacing of the bamboo culms causes premature cracking of the concrete.
- b. As in the previous tests, the smaller amount of bamboo reinforcement was insufficient to greatly increase the ultimate load-carrying capacity of the slab. The slab showed only a modest reserve in load-carrying capacity after the initial yield-line pattern had formed and failed under a load some 25 percent higher than the expected failure load for an equivalent unreinforced slab (see discussion in paragraph 126c). However, while an unreinforced slab would certainly have failed in a sudden, very brittle mode, even the small amount of bamboo reinforcement prevented this type of failure and allowed the slab to undergo large deformations (up to 6 in. (15.24 cm)) without losing its load-carrying capacity. The load-deflection curve resembled that of very ductile (elasto-plastic) members, yet the effect was, of course, not caused by plastic deformations but by slippage of the culms (plate 10c).
- c. Doubling the reinforcement ratio from 0.75 to 1.5 percent in slab 5 resulted in an approximately 25 percent increase in the load-carrying capacity; or in other words, slab 5 carried about 50 percent more load than an unreinforced slab could have carried under optimal conditions.
- d. Calculated average elastic stresses in the reinforcement at failure (assuming perfect bond) were again higher in the slab with the lower reinforcement ratio (6) where they reached a value of 16,620 psi (1170 kg/cm²) (compared to 10,400 psi (730 kg/cm²) for slab 5). Although this theoretical value was in excess of the average tensile strength of bamboo, it is felt that the failure mechanism of slab 5 was still the same as in all other slabs, starting with a partial loss of bond, followed by a limited slippage of the culms that gradually caused very large curvatures along the hinge lines. Due to the large curvatures, considerable flexural stresses built up in the culms (kinking), which, superimposed on the already high tensile stresses, finally caused culm failures.
- e. In both slabs, midspan deflections upon reaching the maximum load were in excess of 1-1/2 in. (3.81 cm), and cracks greater than 1 in. (2.54 cm) in width preceded failure.

PART V: CONCLUSIONS

129. On the basis of the review of the literature and the test results described in the foregoing parts of this report, the following tentative conclusions were drawn. It should be emphasized, however, that these are preliminary conclusions only and are subject to revisions as the investigation continues and new results become available.

Engineering Properties of Bamboo

Tensile strength and deformations

130. The tensile strength of bamboo varies greatly with the type and the condition of the specimen tested. Values as high as 53,894 psi (3789.1 kg/cm²) and as low as 5550 psi (390.2 kg/cm²) have been reported for individual culms.³ The average tensile strength for various bamboo species, as given in the literature, varies between about 9500 and 45,500 psi (667.9 and 3198.7 kg/cm²). An average of 15,410 psi (1083.4 kg/cm²) was found for the indigenous small cane used in this investigation.

131. It appears that the species, the age, and the harvesting season have a more pronounced influence on the tensile strength than any other parameter (such as moisture content or degree of seasoning, diameter, distance from the basal end, etc.). If at all possible, it is recommended that the culms not be cut during their main growing season (i.e. spring and early summer) when they seem to have a much lower strength, and that only those culms that show a pronounced brownish color be selected for use as reinforcement.

132. The tensile strength of bamboo under sustained loads is considerably lower than its static strength, as much as about 50 percent lower for local, small cane.

133. The creep of specimens of seasoned, indigenous (Mississippi), small cane after a 1-yr testing period under tensile stresses of 4000 and 8250 psi (281.2 and 580.0 kg/cm²) amounted to about 40 percent of the elastic elongation.

134. The weakest parts of a bamboo culm are the nodes. It appears

that the strength of the node varies more with different species and harvesting seasons than does the strength of the internodes. The literature also indicates an increase in strength from the basal to the distal end of the culms.¹²

135. The safe, allowable tensile strength of bamboo should not exceed 5000 psi (351.5 kg/cm²). Further reductions may be necessary for flexural members that are not allowed to exceed conventional deflection limits.

136. Culms with a high tensile strength generally also have a high elastic modulus. Data from the literature on the elastic modulus in tension indicate that the modulus of individual culms varies between 1.5 and 4.5×10^6 psi (105,461 and 316,382 kg/cm²); average values range between 1.78 and 2.78×10^6 psi (125,147 and 195,453 kg/cm²). An average elastic modulus for indigenous small cane of 2.6×10^6 psi (182,798 kg/cm²) was observed in this investigation.

137. For the design of bamboo-reinforced concrete members, a value for the elastic modulus of 2.0×10^6 psi (140,614 kg/cm²) is tentatively suggested. However, for deflection calculations, it appears advisable to use a reduced modulus (tentatively 1.5×10^6 psi (105,860 kg/cm²)).

138. Poisson's ratios of whole, indigenous, small cane culms ranged between 0.25 and 0.41, the average being about 0.32, very close to the values assumed for most other construction materials.

Dimensional changes

139. Bamboo culms can be expected to undergo diameter changes up to about 5 percent and length changes up to about 0.05 percent with varying moisture content. The great diameter changes can result in serious cracking of the concrete cover. Almost complete loss of bond can occur if embedded culms are allowed to absorb or lose large amounts of moisture.

140. The coefficients of thermal expansion of bamboo are not compatible with that of concrete. Tests on local small cane (averaging approximately $26.00 \times 10^{-6}/^{\circ}\text{F}$ ($46.8 \times 10^{-6}/^{\circ}\text{C}$) across the fibers and $2.00 \times 10^{-6}/^{\circ}\text{F}$ ($3.6 \times 10^{-6}/^{\circ}\text{C}$) parallel to the fibers) show that the thermal expansion or contraction of bamboo may be as low as about one-third that of concrete lengthwise and as much as about four times that

of concrete diameterwise. Purushotham,⁴ reporting on tests of Indian bamboo, quotes a range from 3×10^{-6} to $9 \times 10^{-6}/^{\circ}\text{F}$ (5.4×10^{-6} to $16.2 \times 10^{-6}/^{\circ}\text{C}$) lengthwise and from 32×10^{-6} to $62 \times 10^{-6}/^{\circ}\text{F}$ (57.6×10^{-6} to $111.6 \times 10^{-6}/^{\circ}\text{C}$) diameterwise. Obviously, the large difference in coefficients of thermal expansion between bamboo and concrete will also contribute to cracking of the concrete cover and to loss of bond, particularly if the member is exposed to great temperature variations.

Bond and decay

141. Bond and possibly decay are the principal and least understood problems associated with the use of bamboo as a reinforcing material.

142. Individual bond strength values given in the literature for different bamboo specimens obtained in pullout tests on whole, seasoned and unseasoned, treated and untreated culms vary between 0 and 350 psi (24.61 kg/cm^2), with averages ranging between 35 and 168 psi (2.5 and 11.81 kg/cm^2). Pullout tests on local, small cane culms, split or whole, seasoned, green, or presoaked, with and without treatment, after 0 to 76 days of dry curing yielded bond strengths from 22 psi (1.55 kg/cm^2) to over 166 psi (11.67 kg/cm^2). Presoaked, split culms tested at 90 days (after 76 days of dry curing) gave an average bond strength of 77 psi (5.41 kg/cm^2) (6-in. (15.24-cm) embedment length, 3000-psi (210.9-kg/cm^2) concrete). These pullout tests showed the following to be the principal factors influencing the calculated average bond strength per unit of contact area:

- a. The treatment of culms prior to embedment.
- b. The type of culms, particularly the amount, type, and size of protrusions (nodes), and culm tapering.
- c. The age and curing conditions of the pullout specimen (after casting of concrete).
- d. The embedment length.
- e. The concrete strength.

143. While the literature indicates that untreated, green, or presoaked culms experience a drastic loss of bond in continuously dry-cured specimens (due to shrinkage of the embedded culms), to date this has not

been verified in our tests. The extent of such a bond loss would, of course, primarily depend on:

- a. The degree of saturation of the culm upon hardening of the concrete.
- b. The extent and rate at which the embedded culm is able to dry and shrink.
- c. The surface condition and protrusions of the culm or the extent to which bond is ensured by interlocking (for instance, at the nodes).
- d. The relative roughness of the culm or the protrusion/diameter ratio.
- e. Range of temperature fluctuations in the member.

144. There appear to be six basic approaches to overcoming the shrinkage-bond problem.

- a. Use seasoned culms that will continue to swell after the concrete has set up, in the hope that this swelling will compensate for subsequent shrinkage. Although this method is repeatedly suggested in the literature, it is not recommended here because it frequently results in intolerable cracking of the concrete cover. A considerable reduction and sometimes complete elimination of cracking are possible¹⁰ through the combined use of high-early-strength cement, small-diameter culms, thick concrete covers, and large spacing of culms. However, in view of the necessity for expediency and for reasonably slender cross sections, this modification is not considered suitable for field application.
- b. Coat seasoned culms with some type of moisture barrier (e.g. varnish, asphalt emulsion,² paint, etc.) to slow the rate of moisture changes in the culms. This method appears valuable (provided the coating has no lubricating effect) and should be used if suitable materials are at hand. However, proper attention must be given to the fact that coatings slow but do not completely stop the exchange of water between bamboo and concrete; therefore, some swelling and shrinkage will still usually occur. Pre-soaking of coated culms for 2 to 3 days seems a wise precaution to reliably prevent cracking of the concrete cover. Some investigators^{2,5} have also warned that coatings may aggravate the decay problem.
- c. Coat seasoned culms with a material such as epoxy or polyester resins that firmly adheres to the bamboo surface. To ensure positive bond with concrete, sand should be sprinkled on the fresh resin coat to produce a rough

surface. The resin coat will, of course, also act as a vapor barrier. This method is definitely an improvement on the method in paragraph 144b, and should be used if suitable resins are available. The comments in paragraph 144b apply where volume instability and decay are concerned.

- d. Saturate seasoned culms with a liquid that will neither evaporate nor adversely affect bond or treat them with a hydrophobic substance. Both methods are again designed to prevent absorption of water from the fresh concrete in order to eliminate swelling and subsequent shrinkage. As in the two foregoing methods, it appears questionable that suitable material will be available in the field. Preferably, all treatment materials should contain a fungicide. Another alternative is saturation with a hygroscopic liquid. Presently a 3-day immersion in a concentrated solution of sodium chloride is being evaluated. Since sodium chloride is hygroscopic, readily available almost everywhere, and should discourage fungal growth, it may prove to be an expedient solution.*
- e. Rely on mechanical interlocking between bamboo and concrete through protrusions that are large enough to be relatively unaffected by shrinkage. In this context, the most important characteristic of a culm is its relative roughness or protrusion/diameter ratio. In order to keep this ratio large, only split, small-diameter culms should be used (maximum diameter about 3/4 in. (1.91 cm)). The use of split culms rather than whole culms is strongly recommended (in addition to any other bond improvement method that may be used) since splitting results in a much higher contact area between concrete and bamboo and is thought to afford better decay protection. Also, the protrusion/diameter ratio is generally larger for split sections of large culms than for whole, small culms.
- f. Neglect the effect of shrinkage on bond if it is reasonable to assume that the culms will not experience large moisture losses because the conditions are such that an uncracked, dense concrete cover (minimum thickness 1-1/2 in. or 3.81 cm) can be expected throughout the service life of the member or that the environmental humidity will remain sufficiently high (above 80 percent) so that large shrinkage is not induced.

145. In attempting to specify allowable bond stresses, we must

* Tests completed during the editing of this report have not verified this expectation.

remember that the concept of an average bond strength (as determined in pullout tests) is a crude oversimplification even for steel, and is much more so for bamboo. The total anchorage force of a culm will certainly not increase linearly as the embedment length increases, as is usually assumed. (A systematic investigation is presently under way.) In fact, it might be more realistic to assume that beyond a certain embedment length the pullout force is fairly constant; if it were not for the protrusions (nodēs) on the culm, this could be a rather short length. For instance, take a culm with 30-in. (76.20-cm) embedment length under a tensile stress of 15,000 psi (1054.6 kg/cm^2) and apply the average bond stress concept. It is obvious that the loaded end of the culm will have slipped more than 0.10 in. (0.254 cm) when the tensile stress of 15,000 psi (1054.6 kg/cm^2) is reached. After slippage of 0.10 in. (0.254 cm), it is hardly realistic to expect that much (if any) bond will remain at the loaded end of the culm. Thus, in view of the low elastic modulus of bamboo, its average Poisson's ratio, and the poor bond developed between the culm and the surrounding concrete, it is conceivable that a smooth bamboo culm (particularly a large culm) could be pulled out of concrete regardless of the embedment length in much the same manner as a smooth rubber hose. Usually only the protrusions will prevent this occurrence in actual practice.

146. It is believed that the mechanism mentioned above explains the large discrepancy between the bond strength found in pullout tests (embedment length 6 in. (15.24 cm)) and beam tests (embedment length about 24 in. (60.96 cm)). The bond strength observed in pullout tests was generally about four times greater than the maximum bond stresses calculated from the beam tests. This reflects the 1 to 4 ratio of the embedment lengths. Consequently, the concept of an allowable average bond stress should perhaps be abandoned altogether, or at least modified considerably. It could be replaced, for instance, by the concept of an allowable total anchorage or pullout force based on a specified minimum embedment length and on the area of the culm in contact with the concrete. Proper allowances could be made for special bond improvement methods or different species of bamboo. A little more complicated but possibly even more realistic is the

concept of a graduated allowable bond stress, such as allowing a relatively high bond stress value, U_1 , for the first 6 in. (15.24 cm) of embedment length, a lower bond stress, U_2 , for the next 6 in. (15.24 cm), and a very low value, U_3 , for the remainder (if any) of the embedment length up to about 3 ft (0.9144 m).

147. An allowable (conservative) total anchorage force of 250 lb (113.40 kg) per square inch (6.45 sq cm) of contact area between bamboo and concrete for 1-in. (2.54-cm) culm length is very tentatively suggested, provided a minimum embedment length of at least 12 in. (30.48 cm) is exceeded.* If the bamboo (split) has large protrusions at the nodes, or if special measures to effectively improve bond (such as the two methods described under beam tests) are utilized, the allowable pullout force may tentatively be raised to 400 lb (181.44 kg) per square inch (6.45 sq cm) of contact area for 1 in. (2.54 cm) of culm length. At this stage no values are suggested for the graduated allowable bond stress concept.

148. No meaningful conclusions concerning the decay behavior of bamboo can be arrived at now. The literature is rather contradictory on the subject of bamboo decay. Decay was repeatedly observed in laboratory studies of whole, embedded culms. However, the limited number of field trials apparently were not plagued by serious decay problems. To date no signs of serious decay of embedded, split culms have been observed during this investigation.

Beam and Slab Tests

Volume stability, bond, and decay

149. In an effort to improve the critical bond situation associated with bamboo reinforcement, it is definitely advantageous to use split culms rather than whole culms since split culms provide about twice the contact area and, thus, double the bond capacity. Also, it is believed that a continuous concrete cover around all surfaces of the bamboo culms will provide

* A culm with a contact area of 2 sq in. (12.90 sq cm) would have an allowable pullout force of 500 lb (226.8 kg) provided the embedment length is 12 in. (30.48 cm) or greater.

increased rot protection, fungal and insect attack protection, and a reduction in the rate of shrinkage and its adverse effect on bond.

150. When using split bamboo culms as reinforcing members, the concave side of the culms should be oriented so that no air will be entrapped and so that continuous contact between the concrete and the culm is assured.

151. Since the bulk specific gravity of bamboo is much lower than that of fresh concrete, the culms have a tendency to float toward the top of the member. This condition is particularly evident during vibration of the concrete; therefore, special precautions (such as tying the bamboo down) are necessary to assure proper positioning of the reinforcement.

152. The maximum-size aggregate in the concrete should be restricted to about 3/8 in. (9.53 mm) to avoid difficulties in placing and consolidating the concrete in members with high reinforcement ratios.

153. Special measures are definitely necessary to prevent or reduce the absorption of water from the fresh concrete by the bamboo culms, a mechanism that can lead to considerable swelling of the culms and cause extensive cracking of the concrete cover. If suitable organic materials* (such as varnish, lead-based paint, resins, etc.) are available, they may be used advantageously as a moisture barrier to reduce the moisture exchange between the bamboo and concrete, thus helping to eliminate the swelling-shrinking problem. Preference should be given to materials that harden and firmly adhere to the bamboo, such as epoxy and polyester resins, since a substantial increase in bond can be achieved by using such resin coats. It should be realized that even the use of these coatings will not completely prevent the migration of moisture if an appreciable difference exists between the moisture content of the concrete and the moisture content of the culms. Consequently, swelling and shrinking of the bamboo may still pose some problems under these conditions. Also, the effect of coatings on the bamboo decay mechanism requires further investigation.

154. An expedient method of eliminating the swelling (but not the

* Caution is necessary with regard to materials that may have a lubricating effect.

shrinkage) problem is to soak the bamboo culms (coated or uncoated) in water for 2 to 3 days prior to their embedment in the concrete.

155. The important question of whether the use of presoaked (split) culms eventually causes aggravated shrinkage or decay problems cannot be satisfactorily answered now. Glenn² and others concluded that unseasoned culms will shrink and lose bond in the course of time while seasoned culms may swell and cause intolerable cracking. Their answer to this dilemma was special treatment of the culms; however, it appears very questionable whether the special materials necessary for effective treatment of the culms will normally be available under field conditions.

156. Our preliminary test results and theoretical considerations lead us to believe that the shrinkage of embedded, split culms will be a very slow process as long as a sufficiently thick, uncracked cover protects the culms from the environment or as long as the humidity of the environment stays above about 80 percent. However, if the concrete develops large cracks, as it will if the member is heavily loaded or if the environment is constantly at a low humidity, shrinkage of the bamboo could become a very serious problem.

157. Additional studies concerning the shrinkage and decay mechanisms are clearly necessary. Although a number of laboratory tests are now under way that, hopefully, will allow a better understanding, it is felt that actual field experience will have to provide the final answers.

158. The use of some wood preservative (if available) rather than plain water to presoak the culms would appear to be desirable from the viewpoint of decay, but attention must be given to the influence of the preservative on bond (i.e. lubricating effect).

159. Of all the methods tested to date only two (other than splitting) were effective in increasing the bond between bamboo and concrete. Unfortunately, both have only limited value for field application, since they either require special materials or excessive work. The two methods were:

- a. The use of presoaked, split culms with about 8-in.-long (20.32-cm), whole end sections to provide end anchorage. This technique is very effective but requires some type of power saw to prepare the culms. Even when using such

equipment, the preparation time greatly exceeds that of conventional splitting.

- b. The use of seasoned, split culms brush-coated with an epoxy or polyester resin that firmly adheres to the bamboo. To improve bond, sand was sprinkled on the fresh resin coat. After curing of the resin coat for several days, the coated culms were immersed in water for 72 hr prior to embedment in the concrete to reduce swelling. This method is rather simple and effective but requires resins not normally available under field conditions.

Flexural strength, cracking, and deflections

160. For rectangular beam sections the optimum reinforcement ratio (i.e. area of bamboo to total beam cross-sectional area) appears to be between 3 and 4 percent. Higher percentages result in overcrowded cross sections, and lower percentages give unsatisfactory strengths and large deformations.

161. Rectangular beams reinforced with presoaked split bamboo (about 3.5 percent) are capable of developing about three times the flexural strength of unreinforced beams with identical cross sections. If either of the above-mentioned methods of increasing the bond are used, the flexural strength can be more than four times that of unreinforced beams.

162. In comparing the load-carrying capacity of bamboo-reinforced members with that of unreinforced members, it should be kept in mind that the values given for unreinforced members can be expected only under the most favorable conditions and certainly could not be relied upon in practice. Since the strength of an unreinforced member is entirely dependent on the tensile strength of the concrete, which in turn is influenced by many parameters and is particularly sensitive to shrinkage effects, it is indeed questionable whether one should expect an unreinforced member to have any flexural strength at all. Significantly, the ACI Code¹⁶ does not allow for any tensile strength of concrete in flexural members.

163. Bamboo reinforcement does not significantly affect the cracking load of flexural members, i.e. bamboo-reinforced members will crack at about the same (or a slightly lower) load at which unreinforced members of identical dimensions would have cracked and failed.

164. Upon cracking and the transfer of tensile forces to the bamboo reinforcement, flexural members develop large cracks and high deflections. Due to the poor bond, cracks are usually not numerous but are wide, extending close to the compression face of the member, thus showing the very high position of the neutral axis.

165. In placing the bamboo reinforcement, care should be taken to alternate the basal and distal ends of the bamboo culms. This practice will ensure a fairly uniform cross section for the bamboo reinforcement throughout the length of the member.

Beam Design

Expedient field design

166. For an expedient design of bamboo-reinforced beams, the simplest procedure, and the one now tentatively recommended for use by field engineers, is:

- a. Neglect the bamboo reinforcement, and design the beam (or one-way slab) as an unreinforced beam, using

$$f_{c\text{tension}} = 8 \sqrt{f'_c} \text{ for British units of tension (psi) or}$$

$$f_{c\text{tension}} = 2.12 \sqrt{f'_c} \text{ for metric units (kg/cm}^2\text{) for the}$$

allowable concrete tensile stress (for allowable shear stresses, Elastic Design, Appendix A).

- b. Use 3 to 4 percent split, presoaked culms (preferably treated) as tensile reinforcement to ensure an overall safety factor of 2 to 2.5, which, in view of the wide variation in material properties of bamboo, bond shrinkage, and decay problems, appears reasonable even for temporary military structures.

More refined design procedures

167. For a more refined flexural design of beams reinforced with 3 to 4 percent split bamboo, there tentatively appears to be two suitable methods. Both methods (paragraphs 168-172) are rather approximative, but are straightforward and probably accurate enough considering the widely varying material properties of bamboo and the complex bond situation.

168. Elastic design. This method is a regular straight-line elastic

design according to the working stress design procedures of ACI Code 318-63,¹⁶ but using the following allowable stresses:

Elastic modulus of bamboo* $E_b = 2.0 \times 10^6$ psi (140,614 kg/cm²)
(in tension)

or $E_b = 1.25 \times 10^6$ psi (87,884 kg/cm²) for deflection analysis

Elastic modulus of concrete (normal weight concrete)

$E_c = 57,500 \sqrt{f'_c}$ for psi or
 $15,246 \sqrt{f'_c}$ for kg/cm²

Extreme fiber stress of concrete (in compression)**

$f_c = 0.8f'_c$

Tensile stress in bottom bamboo culms*

$f_{b_{max}} = 5000$ psi (351.54 kg/cm²)

Shear stress in concrete†

$V_c = 1.1 \sqrt{f'_c}$ for psi or
 $0.292 \sqrt{f'_c}$ for kg/cm²

Anchorage force per culm for a minimum anchorage length of 12 in. (30.48 cm)

$F = 250$ psi (17.58 kg/cm²) per square inch (6.45 sq cm) of contact area for 1 in. (2.54 cm) of length (6.92 kg/cm²/cm)††

* Tentative values only; will be revised as current tests yield further information.

** Allowance for higher stresses than given in the ACI Code¹⁶ is made due to large strain gradients in bamboo-reinforced beams.

† For the computation of shear stresses $\frac{V}{bh}$ rather than $\frac{V}{bd}$ shall be used.

†† This corresponds to an average bond strength of less than $\frac{250}{12} = 20.83$ psi (1.46 kg/cm²).

169. Ultimate strength design. This method is an elastoplastic design similar to ultimate strength design procedures specified by ACI Code 318-63¹⁶ and described by Ferguson.¹⁷ This design is based on the concept that the bamboo will gradually lose bond and slip when the bond stress approaches the bond strength. This mechanism produces

results similar to yielding of the reinforcement.

170. The difficulty in this elastoplastic approach lies in predicting the stress at which slippage will actually start because this stress is a function of the ratio of contact area to the cross-sectional area of the culms, the bond strength, and, to some extent, the anchorage length.

171. Again using the concept of an average pullout force (rather than average bond strength), it might be tentatively assumed that slippage will start if the total tensile force in the (presoaked) culm exceeds 400 lb (181.4 kg) per square inch (6.45 sq cm) of contact area for a 1-in. (2.54-cm) culm length (based on a minimum embedment length of 12 in. (30.48 cm)).

172. Using an average outside culm diameter of 0.67 in. (1.70 cm) and an average wall thickness of 0.11 in. (0.279 cm) (representative of the split culms used in this program), this approach leads to an average culm tensile stress at slippage of roughly 8000 psi (562.5 kg/cm²). Assuming the bamboo reinforcement behaves in a linearly elastic manner up to 8000 psi (562.5 kg/cm²) and that it slips (or yields) gradually at a constant tensile stress of 8000 psi (562.5 kg/cm²), the analysis can then proceed on the usual assumptions (ultimate concrete strain 0.003, Whitney stress block, etc.). A minimum load factor of 1.7 (for live load and dead load) should be used if this is chosen.

Two-Way Slab Design

Expedient field design

173. Since, in two-way slabs, it is generally impractical to place 3 to 4 percent bamboo reinforcement in each direction, the following slightly modified expedient field design procedure is tentatively suggested for slabs containing less than 3 percent reinforcement:

- a. Use a minimum slab thickness of 3 in. (7.62 cm), to ensure sufficient cover and efficiency of the bamboo reinforcement.
- b. Neglect the contribution of the bamboo to the strength, and design the slab as an unreinforced slab, using $6 \sqrt{f'_c}$ psi (equivalent to $1.59 \sqrt{f'_c}$ kg/cm² in the metric system) as the allowable concrete tensile stress, provided the

requirements listed under a, c, and d are met. (For allowable shear stress see ACI Code 318-63 WSD.)

- c. Maintain a minimum reinforcement ratio (relative to the total cross-sectional area) of 1.5 percent (for slabs with thicknesses of 4 in. (10.16 cm) and greater) to 2.5 percent (for slabs with 3- to 3-1/2-in. (7.62- to 8.89-cm) thicknesses) to ensure a safety factor of approximately 2. Culms should be split and presoaked (and preferably treated).
- d. Provide additional corner and/or negative reinforcement where necessary.

More refined design procedures

174. The more refined tentative design procedures outlined for beams (paragraph 167) also appear suitable for two-way, bamboo-reinforced slabs.

Future Plans

175. Efforts in the advanced stages of this investigation concerning bamboo reinforcement will concentrate on:

- a. A better understanding of the bond mechanism and how it is affected by shrinkage and splices.
- b. Expedient methods to improve bond.
- c. Factors influencing decay and expedient decay protection.
- d. Tests of larger flexural members (up to 12-ft or 3.66-m span).
- e. Evaluation of more efficient beam cross sections (inverted T sections and others).
- f. Shear reinforcement.
- g. Development of complete structural systems for expedient bamboo-reinforced structures.
- h. Behavior of bamboo-reinforced members under sustained loads.
- i. Field tests of small bamboo-reinforced structures.
- j. Behavior of bamboo-reinforced members under dynamic loads.
- k. Formulation of final design and construction procedures.

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Table 1

Reported Tensile Strength and Tensile Modulus of Elasticity of Untreated Bamboo
Short-Time Static Tests

Source of Information	Location	Species or Origin of Bamboo	Age After Cutting days	Moisture Content	No. of Tests Repre- sented	Range of Tensile Strength		Average Tensile Strength		Range of Tensile Modulus of Elasticity		Average Tensile Modulus of Elasticity	
						psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²
H. E. Glenn ²	Clemson, S. C.	<u>A. gigantea</u> and <u>phyllostachys</u>	Unknown	Green and seasoned	235	26,000 to 50,000	1,828 to 3,515	37,500* 2,637* 32,500** 2,285**		2,000,000 to 4,500,000	140,614 to 316,382	2,783,800	195,721
E. F. Smith and K. L. Saucier ^{4,11}	Jackson, Miss.	<u>A. tecta</u>	1	Green	4	8,160 to 10,600	574 to 745	9,480 667		1,520,000 to 2,220,000	106,867 to 156,082	1,860,000	130,771
R. J. Mentzinger and R. P. Flourde ¹⁰	Villanova, Pa.	Unknown	Unknown	Seasoned	3	17,050 to 18,930	1,199 to 1,331	17,910 1,259		1,870,000 to 2,180,000	131,474 to 153,269	1,780,000	125,147
A. Purushotham ⁷	India	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	22,000† 45,500††	1,547† 3,199††	Unknown	Unknown	2,070,000	145,536
Dr. D. de Simone ⁵	Germany	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	28,250	1,986	Unknown	Unknown	2,550,000	179,283
Hazine Shimada ³	Japan	<u>Madake of the</u> <u>Shiudosasa</u> <u>Genus</u>	Unknown	Unknown	43	5,550 to 53,894	390 to 3,789	41,350* 26,150**	2,907* 1,839**	Unknown	Unknown	Unknown	Unknown
V. A. Purugganan, et al. ⁶	Manila, Philippines	Probably <u>Bambusa</u> <u>spinosa</u>	50	Seasoned	72	20,000 to 41,770	1,406 to 2,937	33,720* 23,803**	2,371* 1,674**	2,010,000 to 2,805,000	141,317 to 197,211	2,543,300* 2,223,300**	178,812* 156,314**

* Average internode failure.

** Average node failure.

† Average of inner layers.

†† Average of outer layers.

Table 2
Reported Compressive Strengths and Compressive Moduli of Elasticity of Seasoned, Untreated Bamboo
Short-Time Static Test

Source of Information	Location	Species or Origin of Bamboo	Age	Moisture Content	No. of Strength Tests Represented	Range of Compressive Strength		Average Compressive Strength		No. of Modulus Tests Represented	Range of Compressive Modulus of Elasticity		Average Compressive Modulus of Elasticity		
						psi	kg/cm ²	psi	kg/cm ²		psi	kg/cm ²	psi	kg/cm ²	
J. C. Espinosa ⁹	Manila, Philippines	<u>B. spinosa</u>	Seasoned	Unknown	Unknown	5,000 to 10,650	350 to 750	7,600	530	Unknown	Unknown	Unknown	Unknown	Unknown	
S. Mehra, et al. ⁸	India	<u>B. balcooa</u>	Seasoned	Unknown	Unknown	Unknown	Unknown	6,500	460	Unknown	Unknown	Unknown	Unknown	Unknown	
H. E. Glenn ²	Clemson, S. C.	Probably <u>Phyllostachys bambusoides</u>	Seasoned	Unknown	6	4,440 to 10,880	310 to 760	8,640	610	4	772,300 to 2,542,000	54,300 to 178,700	2,146,000	150,900	
V. A. Purugganan, et al. ⁶	Manila, Philippines	Probably <u>B. spinosa</u>	Seasoned	Unknown	6	6,550 to 8,600	460 to 600	7,010	490	6	1,356,000 to 2,120,000	95,300 to 149,100	1,626,000	114,300	
								Average						1,886,000	132,600

Note: To prevent buckling, all tests were conducted on specimens with a relatively small L/D ratio.

Table 3
Flexural Characteristics of Dry, Seasoned American and Philippine Bamboo

Source of Information	Location	Species	Moisture Content	No. of Tests	Ultimate Fiber Stress				Modulus of Elasticity						
					Exterior Side Up		Exterior Side Down		Exterior Side Up		Exterior Side Down				
					No. of Tests	Average	No. of Tests	Average	No. of Tests	Average	No. of Tests	Average			
					psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²	
H. E. Glenn ²	S. C.	<u>Phyllostachys</u>	Seasoned	19	20,700	1460	15	20,400	1430	19	2,111,000	148,420	15	2,039,000	143,360
J. C. Espinosa ⁹	Manila, Philippines	<u>B. spinosa</u>	Seasoned	Unknown	20,340	1430	--	16,070	1130	--	Not reported	Not reported	--	Not reported	Not reported
V. A. Purugganan, et al. ⁶	Manila, Philippines	Probably <u>B. spinosa</u>	Seasoned	18	27,150	1910	18	22,300	1570	18	1,840,000	129,360	18	1,487,000	104,550
Average					22,730	1600		19,590	1377		1,975,500	138,890		1,763,000	123,955

Table 4

Reported Ultimate Bond Strength of Bamboo

Source of Information	Location	Species or Origin	No. of Tests	Age of Concrete When Tested days	Concrete Curing Conditions Before Testing	Concrete Strength When Tested		Bamboo Embedment Length	Range of Bond Strength		Average Bond Strength		Type of Bamboo Tested
						psi	kg/cm ²		psi	kg/cm ²	psi	kg/cm ²	
H. E. Glenn ²	Clemson S. C.	Probably <u>A. gigantea</u>	12	21 to 155	Majority of specimens moist cured 21 days, then dry-room cured 7 days; however, some specimens moist cured (21 days) until tested, and some moist cured only 7 days, then dry-room cured 148 days	Unknown	Unknown	12 in. (30.48 cm) given for one series; not specified for remaining series	0	0	100.0	7.03	Dry, untreated culms Green, untreated culms Coat of asphalt emulsion on dry culms
			40								72.6	5.10	
			26								168.0	11.81	
S. Mehra et al. ⁸	India	<u>B. balcooa</u> and <u>Dendrocalamis strictus</u>	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	90.4	6.36	Dry bamboo, fine sand sprinkled over wet paint	
Dr. D. de Simone ⁵	India	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	49.4	3.47	Dry, varnished	
S. Mehra et al. ¹⁴	India	Unknown	Unknown	28	Unknown	Unknown	Unknown	Unknown	150 to 180	10.5 to 12.7	165.0 (Reinforcement for soil-cement)	11.60	Previously soaked in water, one coat of resin-alcohol and white paint
R. J. Mentzinger and R. P. Flourde ¹⁰	Villanova, Pa.	Unknown Unknown	6	7	Moist cured for 7 days	4500	316.4	Unknown	13.5 to 46.2	0.9 to 3.2	35.0	2.46	Dry, untreated Dry, varnished
			Unknown		Moist cured for 7 days	4500	316.4	Unknown			43.3	3.04	
V. A. Purugganan et al. ⁶	Manila, Philippines	Probably, <u>B. spinosa</u>	16	14 to 28	Moist cured for either 7 or 21 days, then dry-room cured for 7 days	Unknown	Unknown	Unknown	58.3 to 222.0	4.1 to 15.6	117.5	8.26	Seasoned culms, coal tar treated Seasoned culms, asphalt emulsion treated Seasoned culms, untreated
			16								90.5	6.36	
			16								96.4	6.78	
									Average	93.5	6.57		

Table 5

Tensile Strength and Modulus of Elasticity of Untreated, Whole Bamboo Culms
Short-Time Static Test

Specimen No.	Species	Age After Cutting days	Moisture Content % (Wt Water/Dry Wt Bamboo)	Location of Failure	Tensile Strength		Tensile Modulus			
					psi	kg/cm ²	Node		Between Nodes	
							psi × 10 ⁶	kg/cm ²	psi × 10 ⁶	kg/cm ²
1	<u>A. tecta</u> (small cane)	4	Not recorded	Node	22,000	1,545	Not recorded	Not recorded	Not recorded	Not recorded
2		4	110.9	Node	14,050	990	Not recorded	Not recorded	Not recorded	Not recorded
3		4	95.3	Node	9,960	700	Not recorded	Not recorded	Not recorded	Not recorded
4		4	89.0	Node	15,960	1,120	Not recorded	Not recorded	Not recorded	Not recorded
5		4	193.7	Between nodes	14,340	1,010	Not recorded	Not recorded	Not recorded	Not recorded
6		4	73.6	Between nodes	11,430	805	Not recorded	Not recorded	Not recorded	Not recorded
7		4	46.6	Node	22,340	1,570	Not recorded	Not recorded	Not recorded	Not recorded
8		4	190.1	Node	9,330	655	Not recorded	Not recorded	Not recorded	Not recorded
9		4	149.7	Node	16,520	1,160	Not recorded	Not recorded	Not recorded	Not recorded
10		3	120.2	Between nodes	10,730	755	1.26	88,590	1.45	101,950
11		3	56.4	Node	20,330	1,430	2.50	175,770	2.84	199,670
12		3	37.8	Node	20,090	1,410	2.27	159,600	2.59	182,100
13		3	55.4	Node	15,160	1,065	3.22	226,390	3.01	211,620
14		3	58.9	Node	13,070	920	2.10	147,640	1.92	134,990
15		3	49.1	Between nodes	24,030	1,690	2.97	208,810	2.86	201,080
16		4	50.4	Node	15,110	1,060	Not recorded	Not recorded	1.87	131,470
17		4	64.8	Node	10,080	710	Not recorded	Not recorded	2.80	196,860
18		4	175.8	Node	10,160	715	Not recorded	Not recorded	1.51	106,160
19		142	10.0	Node	12,150	855	2.15	151,160	2.09	146,940
20		142	10.3	Between nodes	11,680	820	3.24	227,790	3.34	234,830
21		142	9.9	Between nodes	17,270	1,215	2.97	208,810	3.22	226,390
22		142	10.2	Nodes	17,120	1,205	2.83	198,970	3.07	215,840
23		142	10.1	Nodes	6,870	485	2.45	172,250	2.55	179,280
24		20	18.7	Nodes	25,030	1,760	Not recorded	Not recorded	2.70	189,830
25		20	17.6	Between nodes	11,100	780	Not recorded	Not recorded	2.52	177,170
26		20	19.3	Node	19,290	1,355	2.49	175,060	Not recorded	Not recorded
27		20	18.1	Node	20,500	1,440	4.01	281,930	Not recorded	Not recorded
28		20	17.4	Node	15,310	1,075	2.61	183,500	Not recorded	Not recorded
29		20	16.6	Node	17,740	1,245	Not recorded	Not recorded	2.91	204,590
30		20	18.7	Node	15,480	1,090	Not recorded	Not recorded	2.54	178,580
31		20	12.8	Node	14,760	1,040	Not recorded	Not recorded	2.73	191,940
32		20	14.5	Node	14,910	1,050	2.73	191,940	Not recorded	Not recorded
33		20	15.4	Node	12,820	900	Not recorded	Not recorded	2.95	207,410
34		20	15.9	Between nodes	17,370	1,220	Not recorded	Not recorded	2.97	208,810

Note: Average tensile strength of all specimens tested = 15,410 psi = 1083 kg/cm².
Average tensile strength of specimens failing at nodes = 15,620 psi = 1098 kg/cm².
Average tensile strength of specimens failing at internodes = 14,740 psi = 1035 kg/cm².
Percent of node failures = 76.5%.
Percent of internode failures = 23.5%.
Range of all specimens tested for tensile strength = 6870 to 25,030 psi = 485 to 1760 kg/cm².
Average tensile modulus of elasticity of all specimens tested = 2,620,000 psi = 184,200 kg/cm².
Average tensile modulus of elasticity of specimens at nodes = 2,650,000 psi = 186,310 kg/cm².
Average tensile modulus of elasticity of specimens at internodes = 2,590,000 psi = 182,100 kg/cm².
Range of tensile modulus of elasticity of all specimens tested = 1,260,000 to 4,010,000 psi = 88,590 to 281,930 kg/cm².

Table 6

Poisson's Ratio of Whole, Untreated Bamboo Culms

Short-Time Static Test

Specimen No.	Species	Age After Cutting days	Moisture Content % (Wt of Water / Dry Wt of Bamboo)	Poisson's Ratio Between Nodes	Remarks	
1	<u>A. tecta</u> (small cane)	4	50.4	0.393	Green culms	
2	↓	4	64.8	0.250	Green culms	
3		4	175.8	0.277	Green culms	
4		20	18.7	0.283	Seasoned culms	
5		20	17.6	0.333	↓	
6		20	19.3	0.362		
7		20	16.6	0.307		
8		20	18.7	0.409		
9		20	12.8	0.315		
10		20	15.4	0.295		
11		20	15.9	0.263		
				Average		0.317

Table 7

Ultimate Bond Strength of Bamboo and Concrete

Specimen No.	Probable Species	Age of Concrete When Tested days	Method of Curing Concrete	Strength of Concrete When Tested		Type of Bamboo Tested	Age of Culm After Cutting When Cast days	Approximate Moisture Content of Culm When Cast, %	Average Bond Strength		Remarks
				psi	kg/cm ²				psi	kg/cm ²	
1	<i>A. tecta</i> (small cane)	7	Moist cured 7 days	1487	104.55	Untreated, split culms	42	12	96.3	6.77	Seasoned culms
2		7		1487	104.55	Untreated, split culms	42	12	91.5	6.43	
3		7		1970	138.50	Untreated, whole culms	22	18	94.2	6.62	
4		7		1970	138.50		22	18	97.0	6.82	
5		7		1970	138.50		22	18	28.0	1.97	
6		7		1970	138.50		22	18	41.9	2.95	
7		7		1970	138.50		22	18	35.3	2.48	
8		7		1970	138.50		22	18	44.0	3.09	
9		7		1970	138.50		22	18	65.5	4.61	
10		7		2077	146.03		2	105	98.0	6.89	Green culms
11		7		2077	146.03		2	105	93.5	6.57	Green culms
12		7		2256	158.61	Split culms soaked 3 days in Super Premium 4-lb. Penta Concentrate	28	16	87.5	6.15	Seasoned culms
13		7		2256	158.61		28	16	82.9	5.83	
14		7		2256	158.61		28	16	113.5	7.98	
15		28	Moist cured 14 days and dry-room cured 14 days	2843	199.88	Untreated, split culms	42	12	48.7	3.42	
16		28		2843	199.88	Untreated, split culms	42	12	55.0	3.87	
17		28		2962	208.25	Untreated, whole culms	22	18	33.2	2.33	
18		28		2962	208.25		22	18	63.3	4.45	
19		28		2962	208.25		22	18	79.6	5.60	
20		28		2962	208.25		22	18	71.7	5.04	
21		28		2962	208.25		22	18	40.0	2.81	
22		28		2962	208.25		22	18	54.9	3.86	
23		28		2962	208.25		22	18	39.7	2.79	
24		28		2962	208.25		22	18	59.3	4.17	
25		28		2962	208.25		22	18	42.7	3.00	
26		28		2962	208.25		22	18	55.8	3.92	
27		28		3616	254.23		2	105	72.4	5.09	Green culms
28		28		3616	254.23		2	105	67.6	4.75	Green culms
29		28		2683	188.63	Untreated split culms, scratched contact area by chopping surface	73	10	22.3	1.57	Seasoned culms
30		28		2683	188.63	Untreated split culms, scratched contact area by chopping surface	73	10	51.8	3.64	
31		28		2683	188.63	Untreated, split culms with shredded ends	73	10	33.6	2.36	
32		28		2683	188.63	Untreated, split culms with shredded ends	73	10	38.3	2.69	
33		28		2683	188.63	Split culms with a coat of epoxy sprinkled with sand	73	10	>165.9*	>11.66*	
34		28		2683	188.63	Split culms with a coat of polyester resin sprinkled with sand	73	10	>80.6*	>5.67*	
35		28		2683	188.63	Split culms with bond area wrapped with 0.05-in.-diam steel wire	73	10	73.9	5.20	
36		28		2683	188.63	Split culms with ends consisting of whole culms	73	10	>50.9*	>3.58*	

(Continued)

Note:

	Average Bond Strength	
	psi	kg/cm ²
Untreated, whole, green culms tested at 7 days	95.8	6.74
Untreated, whole, seasoned culms tested at 7 days	58.0	4.08
Untreated, split, seasoned culms tested at 7 days	93.9	6.60
Penta treated, split, seasoned culms tested at 7 days	94.6	6.65
Untreated, whole, green culms tested at 28 days	70.0	4.92
Untreated, whole, seasoned culms tested at 28 days	54.0	3.80
Untreated, split, seasoned culms tested at 28 and 30 days	51.9	3.65
Penta treated, split, seasoned culms tested at 28 days	67.9	4.77
Untreated, split culms with a scratched bond area tested at 28 days	37.1	2.61
Untreated, split culms with shredded ends tested at 28 days	36.0	2.53
Untreated, split culms with the bond area wrapped with small-diameter wire tested at 28 and 31 days	71.9	5.06
Penta treated, split, seasoned culms tested at 90 days	62.4	4.39
Split, seasoned culms soaked in water tested at 90 days	77.1	5.42

* Specimen failed in tension; ultimate bond strength not reached.

Table 7 (Concluded)

Specimen No.	Probable Species	Age of Concrete When Tested days	Method of Curing Concrete	Strength of Concrete When Tested		Type of Bamboo Tested	Age of Culm After Cutting When Cast days	Approximate Moisture Content of Culm When Cast, %	Average Bond Strength		Remarks
				psi	kg/cm ²				psi	kg/cm ²	
37	A. tecta (small cane)	28	Moist cured 14 days and dry-room cured 14 days	2680	188.42	Untreated, split culms	73	10	63.6	4.47	Seasoned culms
38		28		3550	249.59	3 days in a solution of Super Premium 4-lb Penta Concentrate	28	16	60.5	4.25	
39		28		3550	249.59		28	16	74.7	5.25	
40		28		3550	249.59		28	16	68.4	4.81	
41		31		2680**	188.42	Same as No. 33	28	16	162.9	11.45	
42		31		2680**	188.42	Same as No. 34	73	10	117.1	8.23	
43		31		2680**	188.42	Same as No. 35	73	10	69.9	4.91	
44		31		2680**	188.42	Same as No. 36	73	10	>84.4*	>5.93*	
45		31		2680**	188.42	Untreated, split culms	73	10	79.1	5.56	
46		90		3710**	260.84	Split culms soaked for 3 days in a solution of Super Premium 4-lb Penta Concentrate	72	10	75.7	5.32	
47		90	Moist cured 14 days and dry-room cured 76 days	3710**	260.84		72	10	41.0	2.88	
48		90		3710**	260.84		72	10	69.0	4.85	
49		90		3710**	260.84		72	10	63.7	4.48	
50		90		3710**	260.84	Untreated, split culms soaked in water 3 days	70	10	78.1	5.49	
51		90		3710**	260.84		70	10	68.8	4.84	
52		90		3710**	260.84		70	10	73.5	5.17	
53		90		3710**	260.84		70	10	88.1	6.19	

* Specimen failed in tension; ultimate bond strength not reached.
 ** 28-day-cylinder strength of specimen.

Table 8

Approximate Coefficient of Thermal Expansion of Bamboo; Seasoned Culms

Test Method	Specimen No.	Moisture Content % (Wt Water/Dry Wt Bamboo)	Minimum Temperature		Maximum Temperature		Approximate Coefficient of Thermal Expansion Across Fibers/°F	Approximate Coefficient of Thermal Expansion Parallel to Fibers/°F
			°F	°C	°F	°C		
I	1	13.82	28	-2.2	100	37.7	Not recorded	2.29×10^{-6}
I	2	10.91	↓	↓	↓	↓	Not recorded	2.56×10^{-6}
I	3	11.82	↓	↓	↓	↓	Not recorded	2.02×10^{-6}
							Average	2.29×10^{-6}
II	1	14.50	50	10	100	37.7	28.60×10^{-6}	1.98×10^{-6}
II	2	14.86	↓	↓	↓	↓	31.90×10^{-6}	2.40×10^{-6}
II	3	13.90	↓	↓	↓	↓	Not recorded	2.87×10^{-6}
II	4	14.91	↓	↓	↓	↓	Not recorded	1.80×10^{-6}
							Average	30.30×10^{-6}
							Average	2.26×10^{-6}
III	1	14.55	50	10	100	37.7	20.74×10^{-6}	2.28×10^{-6}
III	2	12.43	↓	↓	↓	↓	26.39×10^{-6}	1.53×10^{-6}
III	3	13.79	↓	↓	↓	↓	24.80×10^{-6}	Not recorded
III	4	13.54	↓	↓	↓	↓	22.97×10^{-6}	1.08×10^{-6}
III	5	14.32	↓	↓	↓	↓	23.60×10^{-6}	0.80×10^{-6}
							Average	23.70×10^{-6}
							Average	1.42×10^{-6}
							Approximate overall average = $26.0 \times 10^{-6}/^{\circ}\text{F}$ ($46.8 \times 10^{-6}/^{\circ}\text{C}$)	Approximate overall average = $2.0 \times 10^{-6}/^{\circ}\text{F}$ ($3.6 \times 10^{-6}/^{\circ}\text{C}$)

Table 9

Concrete Mixture Data for a One-Bag Batch

Material	Volume		Weight	
	ft ³	m ³	lb	kg
Type II cement	0.479	0.0136	94	42.64
Fine limestone aggregate	2.154	0.0610	358.3	162.53
Coarse limestone aggregate (3/8-in. or 0.955-cm max)	2.069	0.0586	349.4	158.49
Water	1.297	0.0367	80.8	36.65

Admixtures	None
Water-cement ratio by weight	0.86
Slump	2 ± 1/2 in. (5.08 ± 1.27 cm)
Cement content	4.5 bags/cu yd (250 kg/m ³)

Note: See tables 10 and 11 for results of tests conducted on bamboo-reinforced concrete beams and slabs and for the strength data of each individual batch.

Table 10

Results of Flexure Tests of 76-in. (198.1-cm) by 9-in. (22.86-cm) by 4-in. (10.16-cm) Bamboo-Reinforced Concrete Beams

Group No.	Beam No.	Age of Concrete When Tested days	Concrete Cylinder Strength (Average of Three 28-Day Tests on 3- by 6-in. (7.62- by 15.24-cm) Cylinders)		Age of Culm After Cutting When Cast days	Type of Reinforcement	Bamboo Reinforcement (Percent of Total Cross-Sectional Area of Beam)	Beam Cracking Moment		Ultimate Moment		Approximate Average Stress in Bamboo Reinforcement				Approximate Average Stress in Lower Culm of Bamboo at Failure (Elastic Analysis)		Outer Fiber Concrete Stress at Failure (Working Stress Analysis)		Deflection at Maximum Load		Type of Failure	Remarks
			psi	kg/cm ²				in.-lb	m-kg	in.-lb	m-kg	psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²		
1	1	28	3620	255	2	Whole, green culms	1.96	12,500	144.0	13,920	160.4	2,660	185	2,790	195	2,790	195	770	55	0.10	0.254	Bond	Initial beam cracking due to culms absorbing a part of concrete mixing water
	2	28	3620	255	2	Whole, green culms	2.96	12,000	138.3	30,000	345.6	4,300	300	4,310	305	4,700	330	1550	110	0.33	0.838	Bond	
	3	28	3620	255	2	Whole, green culms	4.53	12,000	138.3	33,000	380.2	3,100	220	3,410	240	4,130	290	1620	115	0.40	1.016	Bond	
2	4	28	2840	200	63	Split, seasoned culms	1.96	15,600	179.7	29,520	340.1	6,420	450	6,610	465	7,820	550	1810	125	0.32	0.813	Bond	Initial beam cracking due to culms absorbing a part of concrete mixing water
	5	28	2840	200	63	Split, seasoned culms	2.96	18,000	207.4	36,000	414.8	5,400	380	5,610	395	7,020	495	1990	140	0.35	0.889	Bond	
3	6	28	3710	260	101	Split, seasoned culms presoaked in water	4.53	17,600	202.8	53,400	615.2	5,830	410	6,010	425	8,410	590	3010	210	0.75	1.905	Bond	No initial cracking
	7	28	3710	260	101	Split, seasoned culms presoaked in Penta	1.96	17,600	202.8	33,600	387.1	7,250	510	7,060	495	8,320	585	2060	145	0.38	0.965	Bond	
	8	28	3710	260	101	Split, seasoned culms presoaked in Penta	4.53	17,600	202.8	45,600	525.4	4,930	345	5,130	360	7,180	505	2570	180	0.58	1.473	Bond	
4	9	28	2680	190	76	Split, seasoned culms presoaked in water	1.96	15,000	172.8	30,000	345.6	6,500	455	6,710	470	7,940	560	1830	130	0.75	1.905	Bond and some culms in tension	
	10	28	2680	190	76	Split, seasoned culms presoaked in water	2.96	12,000	138.3	48,000	553.0	7,400	520	7,490	525	9,370	660	2620	185	0.80	2.032	Bond	
	11	28	2680	190	76	Split, seasoned culms presoaked in water	4.53	12,000	138.3	60,000	691.3	6,800	480	6,800	480	9,600	675	3160	220	1.10	2.794	Bond, shear, and some culms in tension	
	12	28	2680	190	76	Split, seasoned culms presoaked in water with ends consisting of whole culms	2.00	16,000	184.3	48,000	553.0	10,530	740	10,560	740	12,500	880	2900	205	0.85	2.159	Tension	
5	13	90	3190	225	11	Split, green culms presoaked in water	1.96	6,000	69.1	36,000	414.8	7,850	550	8,050	565	9,510	670	2270	160	1.00	2.540	Bond	
	14	90	3190	225	11	Split, green culms presoaked in water	2.96	20,000	230.4	54,000	622.1	8,300	585	8,390	590	10,480	735	3050	215	1.25	3.175	Bond and crushing of concrete	
	15	90	3190	225	11	Split, green culms presoaked in water	4.53	27,000	311.1	66,000	760.4	6,750	475	7,440	525	10,460	735	3600	255	1.33	3.378	Bond	

(Continued)

Table 10 (Concluded)

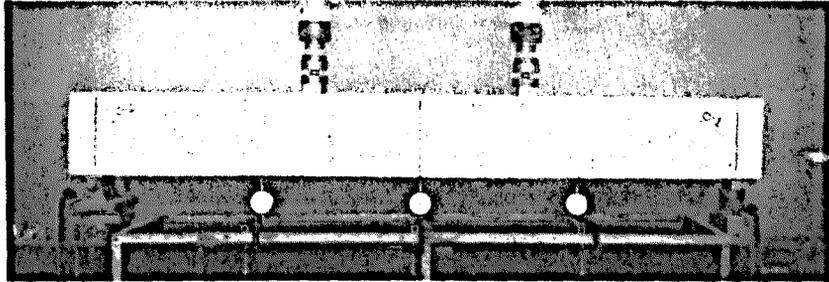
Group No.	Beam No.	Age of Concrete When Tested days	Concrete Cylinder Strength (Average of Three 28-Day Tests on 3- by 6-in. (7.62- by 15.24-cm) Cylinders)		Age of Culm After Cutting When Cast days	Type of Reinforcement	Bamboo Reinforcement (Percent of Total Cross-Sectional Area of Beam)	Beam Cracking Moment		Ultimate Moment		Approximate Average Stress in Bamboo Reinforcement				Approximate Average Stress in Lower Culm of Bamboo at Failure (Elastic Analysis)		Outer Fiber Concrete Stress at Failure (Working Stress Analysis)		Deflection at Maximum Load		Type of Failure	Remarks		
			psi	kg/cm ²				in.-lb	m-kg	in.-lb	m-kg	Ultimate Strength Analysis		Elastic Analysis		psi	kg/cm ²	psi	kg/cm ²	psi	kg/cm ²			in.	cm
												psi	kg/cm ²	psi	kg/cm ²										
6	16	28	2960	210	108	Split, seasoned culms coated with polyester and sand	3.50	18,000	207.4	66,000	760.4	8,800	620	9,140	645	12,070	850	3670	260	0.88	2.235	Bond and crushing of concrete	Initial beam cracking due to culms absorbing part of concrete mixing water		
	17	28	2960	210	108	Split, seasoned culms coated with epoxy and sand	3.50	18,000	207.4	72,000	829.5	9,690	680	9,970	700	13,170	925	4010	280	1.00	2.540	Bond, crushing of concrete and some culms in tension			
7	18	28	3180	225	155	Split, seasoned culms presoaked in water, coated with epoxy and sand	3.50	24,000	276.5	72,000	829.5	9,610	675	10,020	705	13,210	930	4080	285	1.10	2.794	Bond and some culms in tension	No initial cracking		
	19	28	3180	225	155	Split, seasoned culms presoaked in water, coated with polyester and sand	3.50	24,000	276.5	78,000	898.6	10,350	730	10,850	765	14,310	1005	4410	310	0.77	1.956	Bond and some culms in tension	No initial cracking		
8	20	28	3980	275	55	Split, seasoned culms with ends consisting of whole culms	3.50	18,000	207.4	78,000	898.6	10,290	725	10,750	755	14,120	995	4600	325	0.60	1.524	Culms in tension	No initial cracking		

Table 11

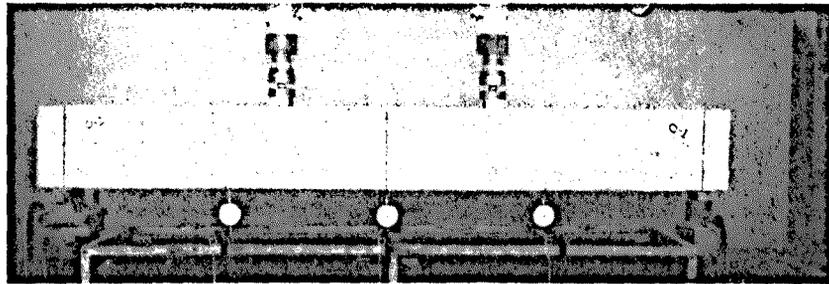
Results of Tests of Concrete Slabs Reinforced with Presoaked Split Bamboo

Group No.	Slab No.	Dimensions	Age of Culms After Cutting When Cast days	Age of Concrete When Tested days	28-Day Concrete Cylinder Strength		Approximate Bamboo Reinforcement (Percent of Total Cross-Sectional Area of Slab), %	Midspan Deflection at Ultimate Load		Maximum Crack Width at Ultimate Load		Ultimate Load		Maximum Moment		Approximate Average Stress in Bamboo (Elastic Analysis)		Type of Failure	Remarks
					psi	kg/cm ²		in.	cm	in.	cm	lb/ft. ²	kg/m ²	in.-lb/ft	m-kg/m	psi	kg/cm ²		
1	1	6 ft by 4 ft by 4 in. (1.83 m by 1.22 m by 10.16 cm)	154	28	3830	270	1.125*	1.20	3.048	0.40	1.016	1512	7382.2	18,817	711.3	12,180	855	Bond and culm in tension and kinking	Reinforcement was split presoaked culms 2-1/3 in. (5.93 cm) on center in each direction
	2		154	28	3830	270	1.125*	1.32	3.353	0.30	0.762	1584	7733.8	19,713	745.1	12,750	895		Reinforcement was split presoaked culms 2-1/3 in. (5.93 cm) on center in each direction
2	3	5 ft 10 in. by 5 ft 10 in. by 3 in. (177.8 by 177.8 by 7.62 cm)	55	28	3980	280	1.210*	2.00	5.080	1.00	2.540	576	2812.3	9,238	349.2	11,170	785	Same as No. 1 except 3 in. (7.62 cm) on center	Same as No. 1 except 3 in. (7.62 cm) on center
	4		55	28	3980	280	2.420*	2.50	6.350	0.75	1.905	835	4076.8	13,394	506.3	8,260	580		Same as No. 1 except 1-1/2 in. (3.81 cm) on center
3	5	5 ft 10 in. by 5 ft 10 in. by 4 in. (177.8 by 177.8 by 10.16 cm)	77	27	4200	295	1.500*	1.70	4.138	1.13	2.870	1332	6503.4	21,362	807.5	10,400	730	Same as No. 1 except 1-1/2 in. (3.81 cm) on center	Same as No. 1 except 3 in. (7.62 cm) on center
	6			28	4200	295	0.750*	1 to 6	2.540 to 15.240	2.00	5.080	1080	5273.0	17,320	654.7	16,620	1170		Same as No. 1 except 3 in. (7.62 cm) on center

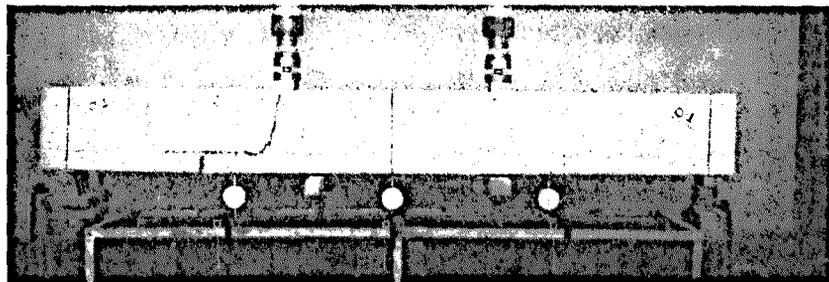
* In both directions.



a. No load

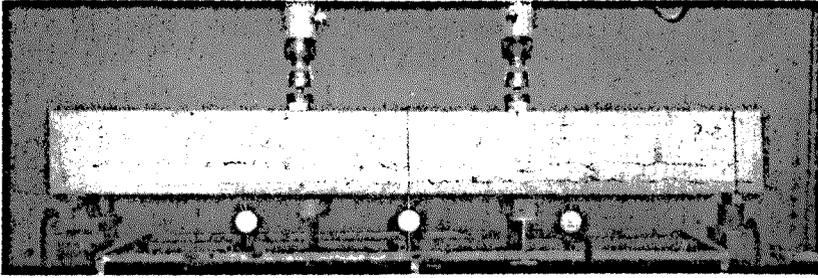


b. Total load = 500 lb (226.8 kg)

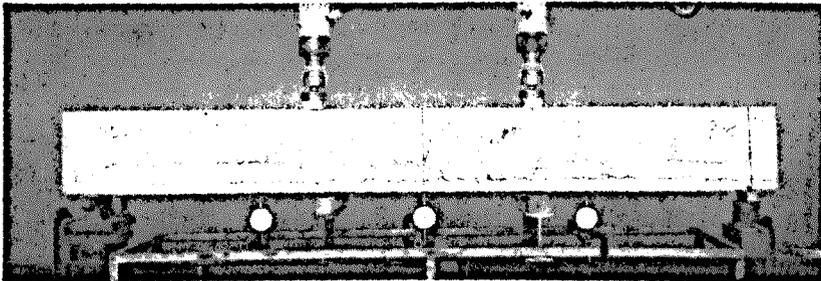


c. Total load = 1160 lb (526.2 kg), failure

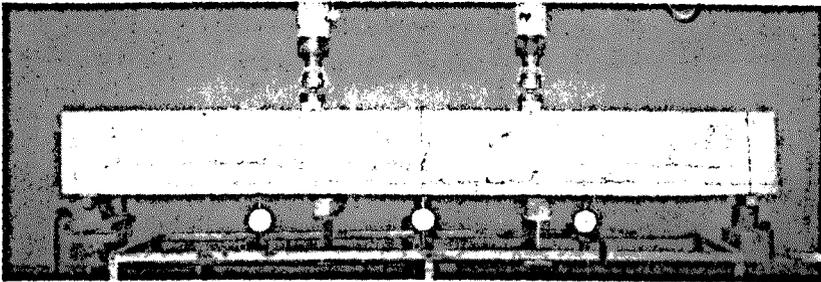
Photograph 1. Crack pattern, beam 1



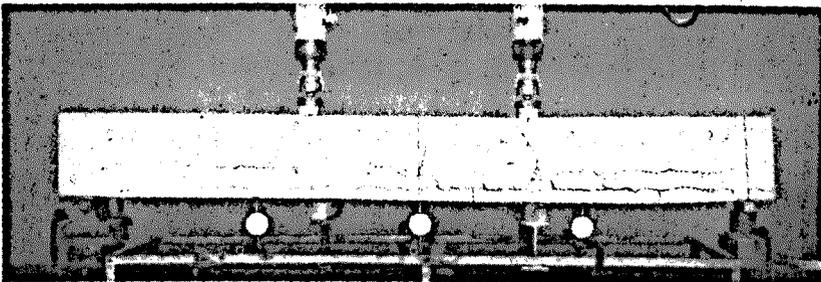
a. No load



b. Total load = 1500 lb (680.4 kg)

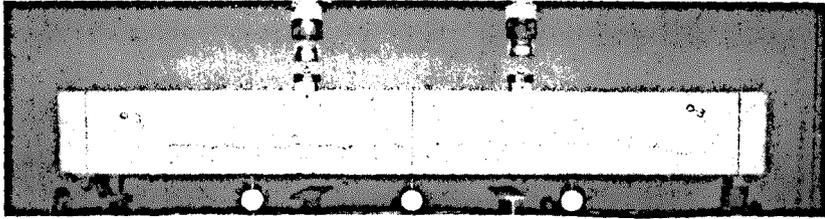


c. Total load = 2000 lb (907.2 kg)

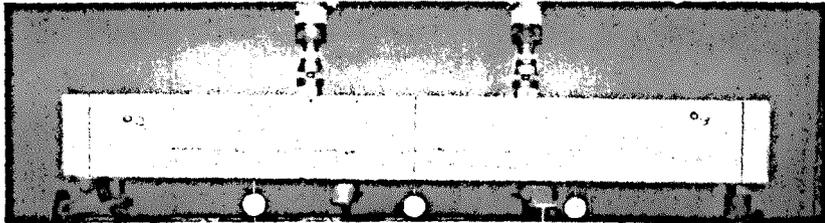


d. Total load = 2500 lb (1134.0 kg), failure

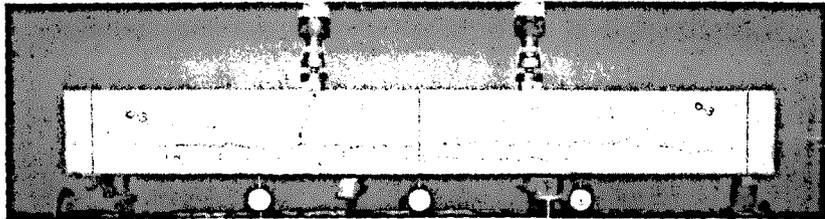
Photograph 2. Crack pattern, beam 2



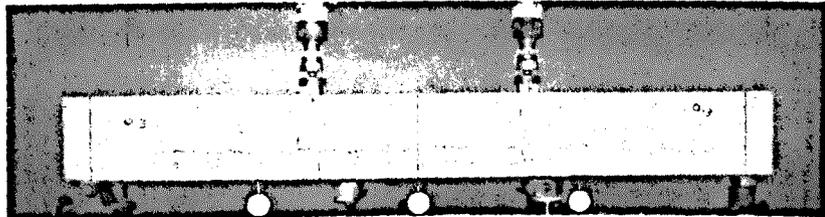
a. No load



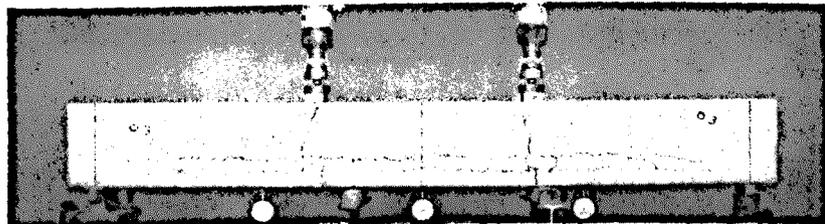
b. Total load = 1000 lb (453.6 kg)



c. Total load = 1600 lb (725.8 kg)

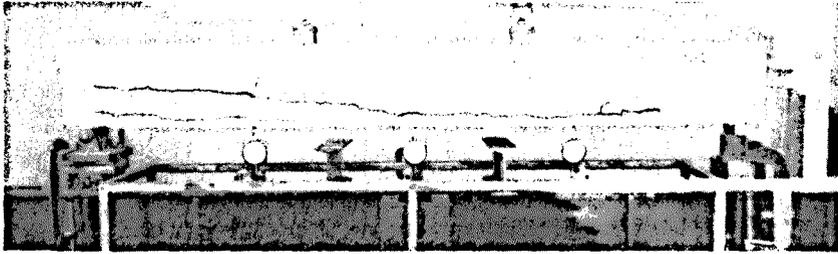


d. Total load = 2000 lb (907.2 kg)

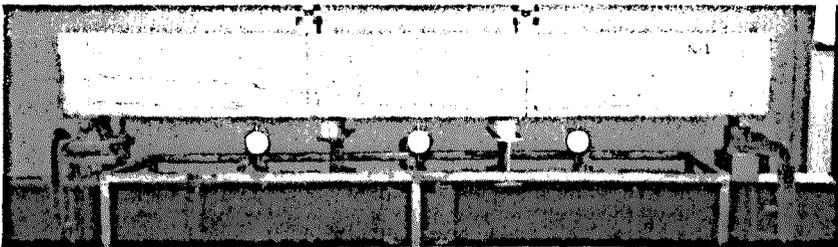


e. Total load = 2750 lb (1247.4 kg), failure

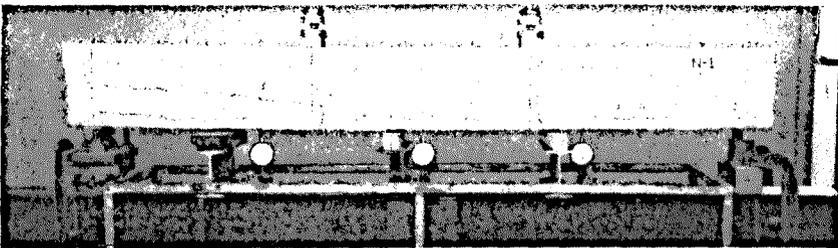
Photograph 3. Crack pattern, beam 3



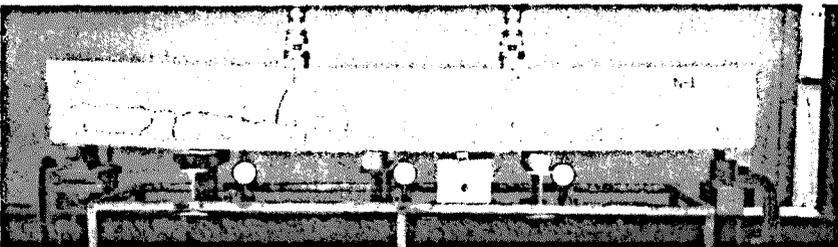
a. No load



b. Total load = 1500 lb (680.4 kg)

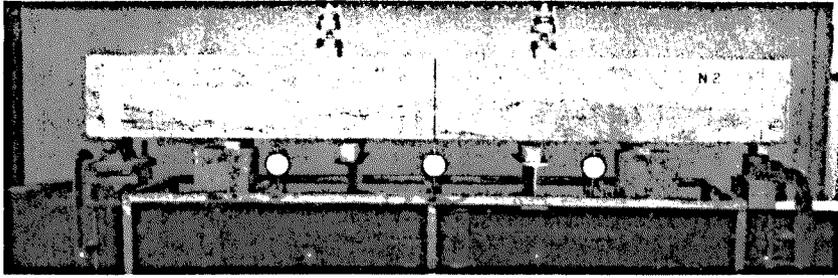


c. Total load = 2000 lb (907.2 kg)

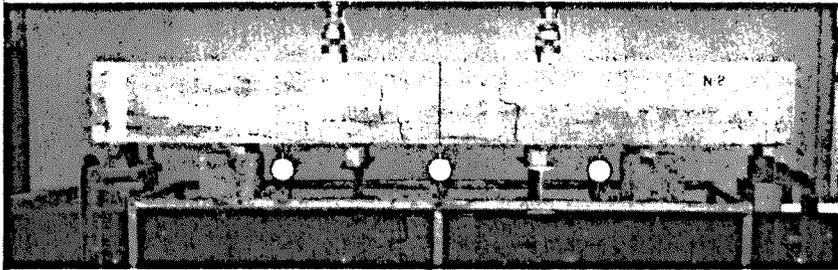


d. Total load = 2460 lb (1115.8 kg), failure

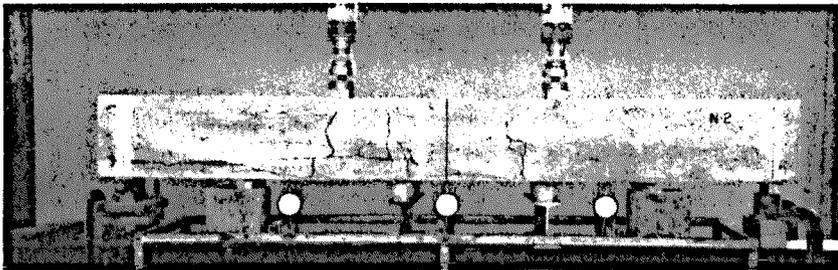
Photograph 4. Crack pattern, beam 4 .



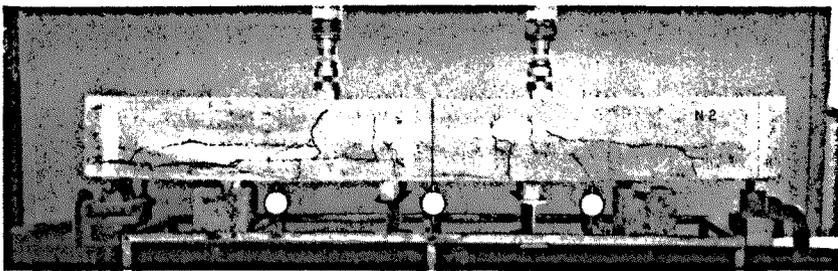
a. No load



b. Total load = 1500 lb (680.4 kg)

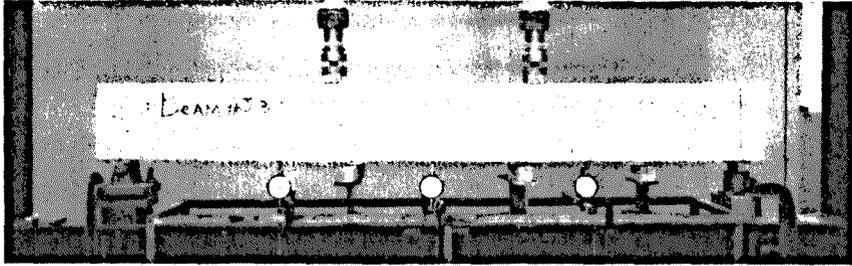


c. Total load = 2500 lb (1134.0 kg)

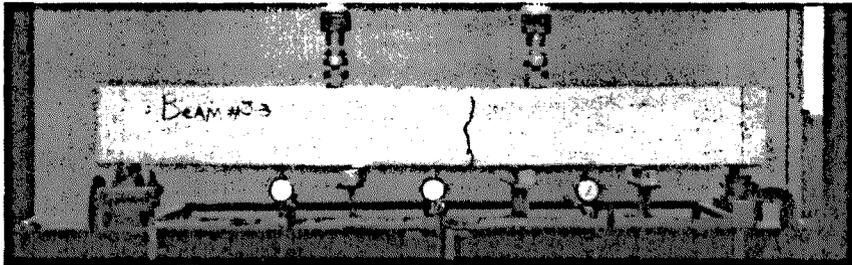


d. Total load = 3000 lb (1360.8 kg), failure

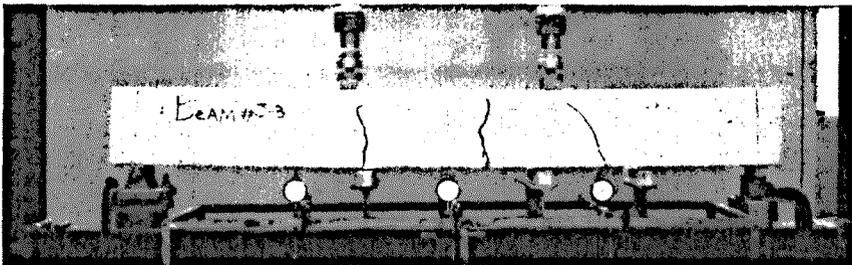
Photograph 5. Crack pattern, beam 5



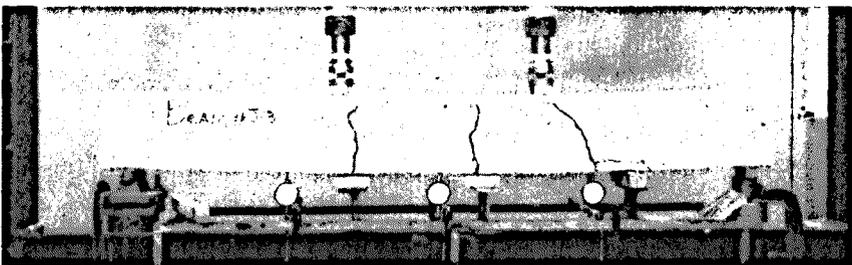
a. No load



b. Total load = 1500 lb (680.4 kg)

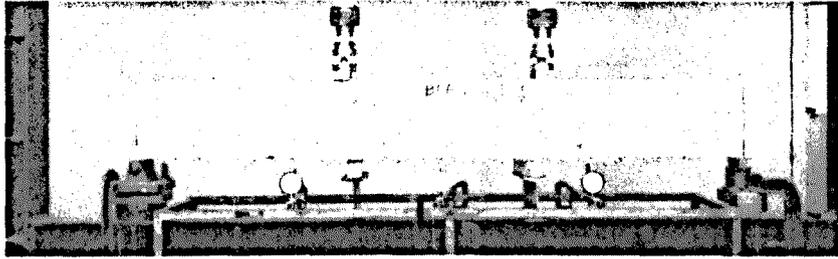


c. Total load = 2500 lb (1134.0 kg)

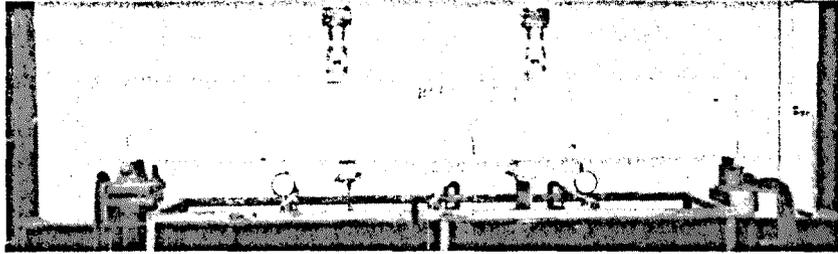


d. Total load = 4500 lb (2041.2 kg), failure

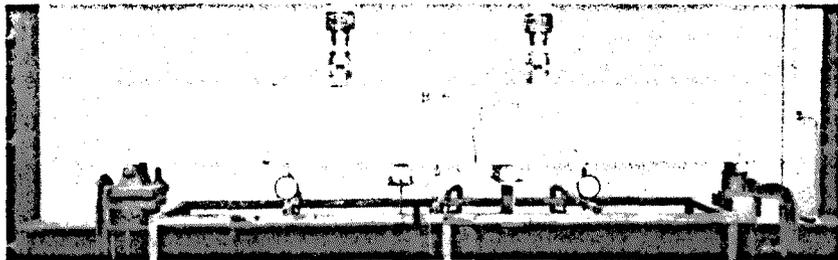
Photograph 6. Crack pattern, beam 6



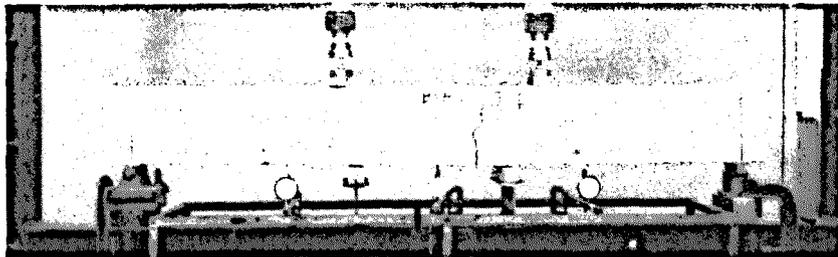
a. No load



b. Total load = 1500 lb (680.4 kg)

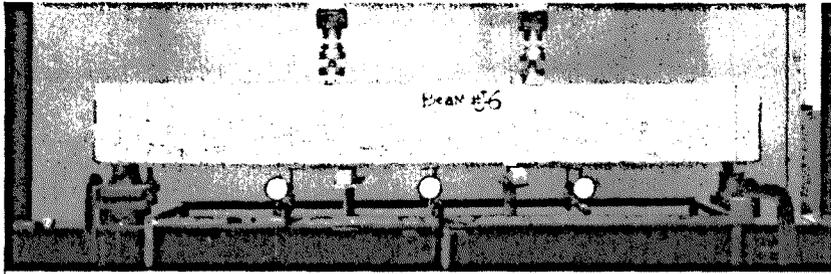


c. Total load = 2000 lb (907.2 kg)

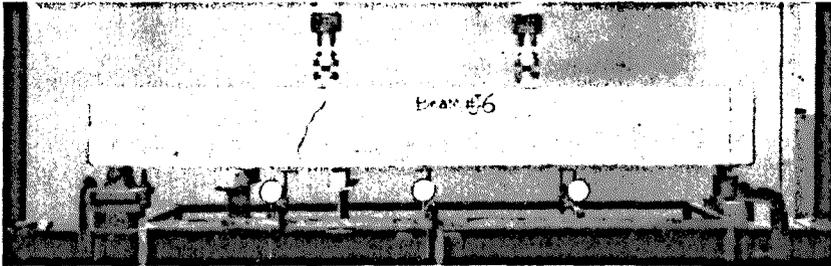


d. Total load = 2800 lb (1270.0 kg), failure

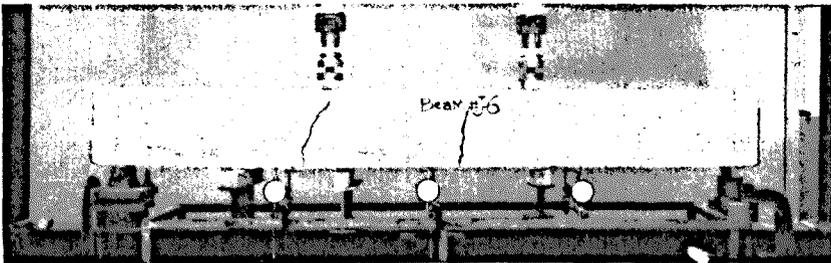
Photograph 7. Crack pattern, beam 7



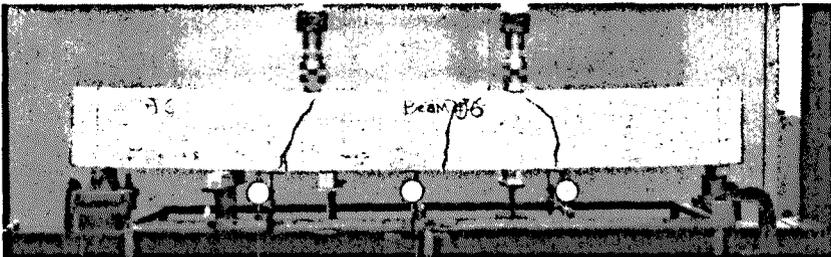
a. No load



b. Total load = 1500 lb (680.4 kg)

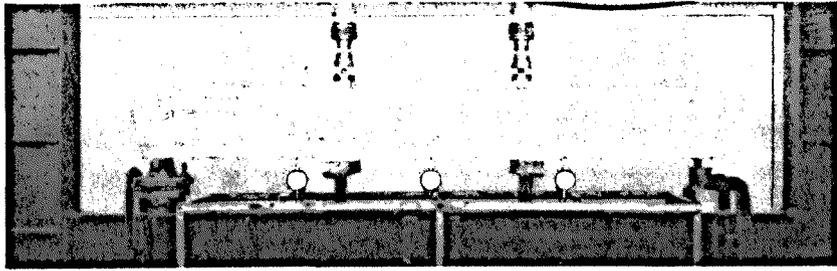


c. Total load = 2500 lb (1134.0 kg)

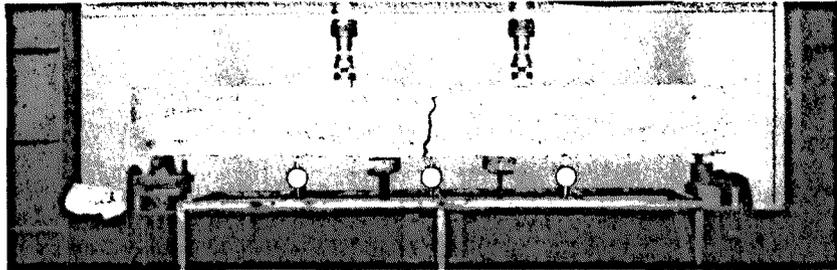


d. Total load = 3800 lb (1723.6 kg), failure

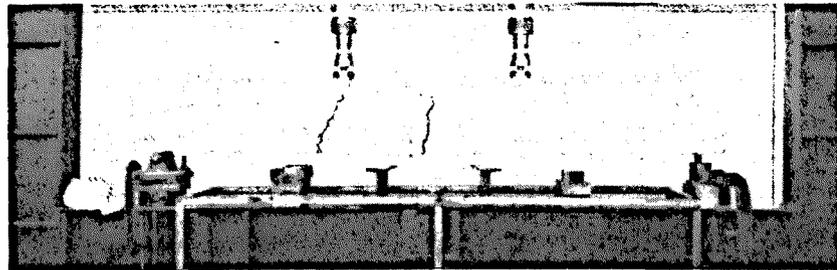
Photograph 8. Crack pattern, beam 8



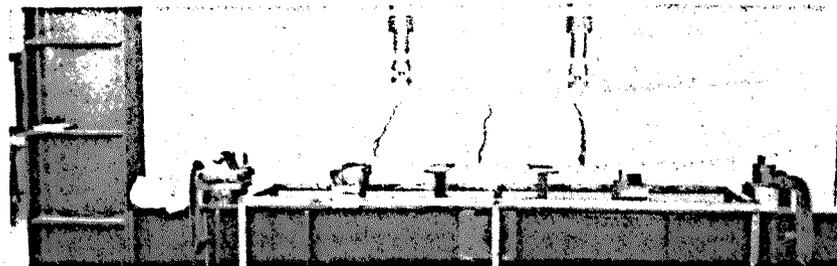
a. No load



b. Total load = 1500 lb (680.4 kg)

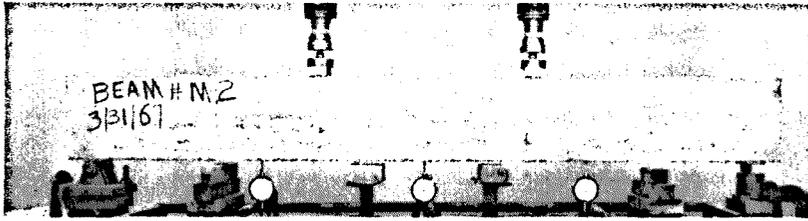


c. Total load = 2000 lb (907.2 kg)

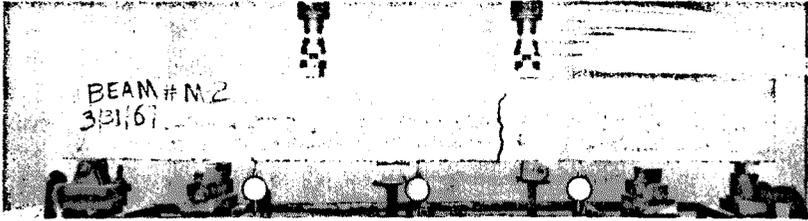


d. Total load = 2500 lb (1134.0 kg), failure

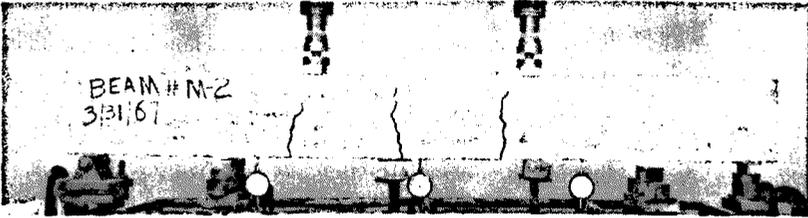
Photograph 9. Crack pattern, beam 9



a. No load



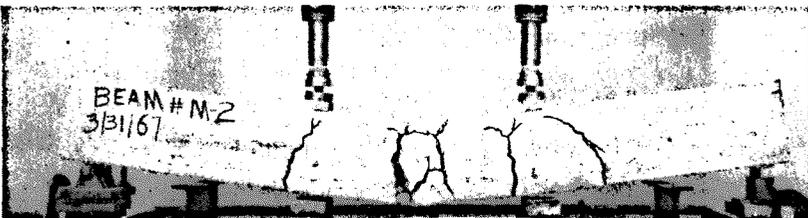
b. Total load = 1000 lb (453.6 kg)



c. Total load = 1500 lb (680.4 kg)

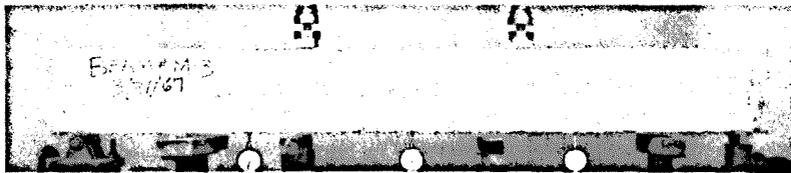


d. Total load = 4000 lb (1814.4 kg)

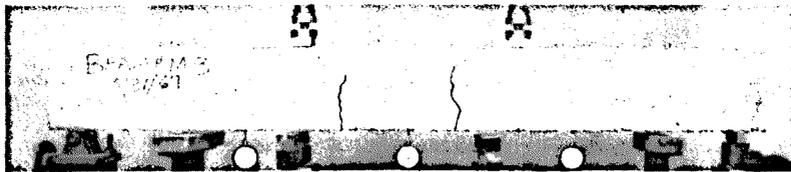


e. Total load = 4000 lb (1814.4 kg), failure

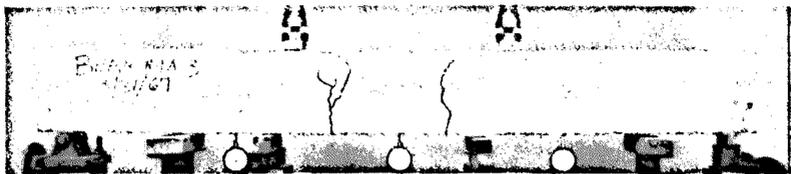
Photograph 10. Crack pattern, beam 10



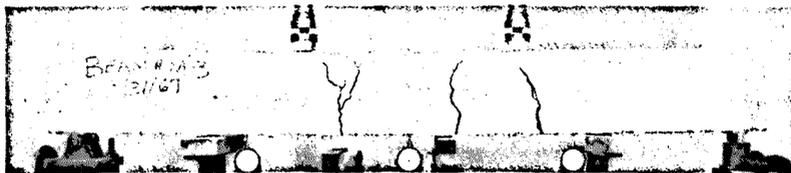
a. No load



b. Total load = 1000 lb (453.6 kg)



c. Total load = 2500 lb (1134.0 kg)



d. Total load = 3000 lb (1360.8 kg)



e. Total load = 3500 lb (1587.6 kg)

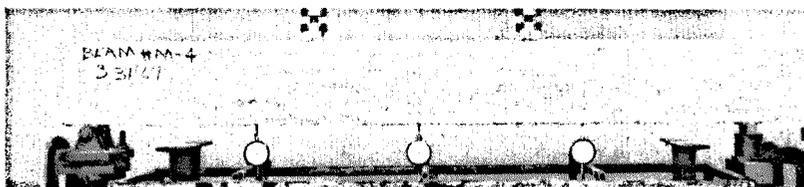


f. Total load = 4500 lb (2041.2 kg)

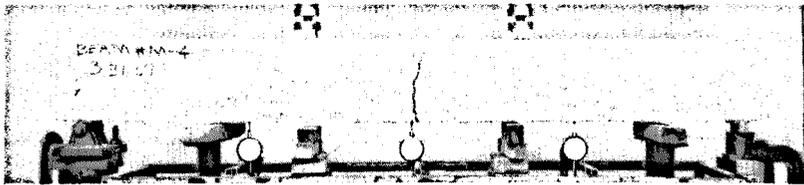


g. Total load = 5000 lb (2268.0 kg), failure

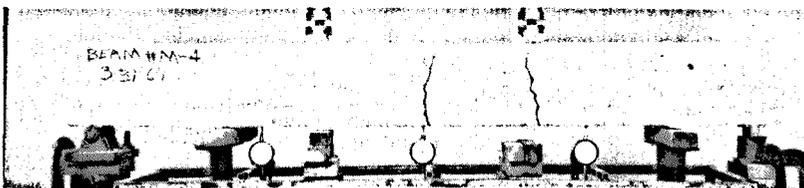
Photograph 11. Crack pattern, beam 11



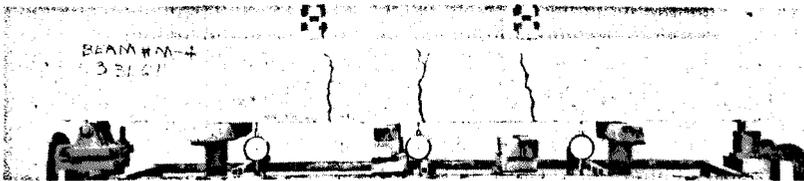
a. No load



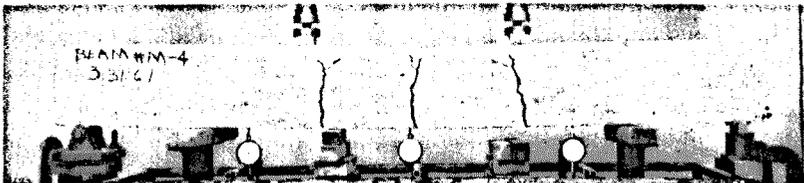
b. Total load = 1500 lb (680.4 kg)



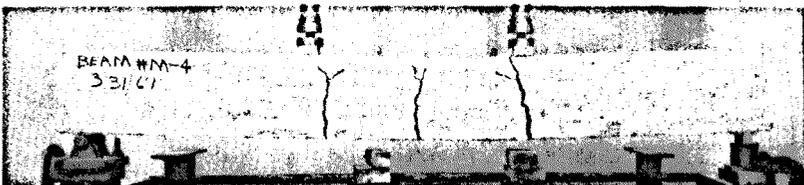
c. Total load = 2000 lb (907.2 kg)



d. Total load = 2500 lb (1134.0 kg)

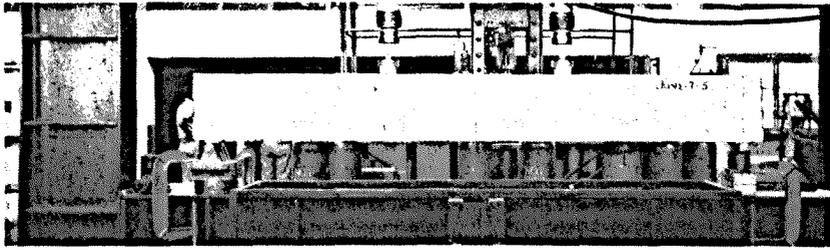


e. Total load = 3500 lb (1587.6 kg)

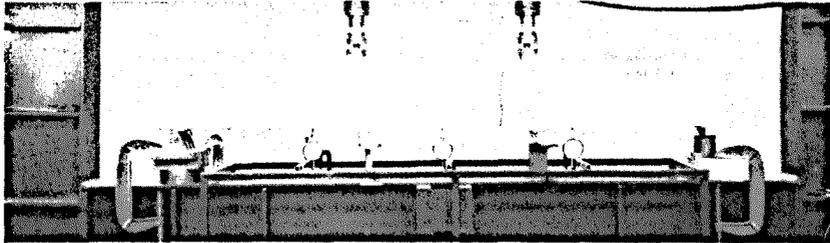


f. Total load = 4000 lb (1814.4 kg), failure

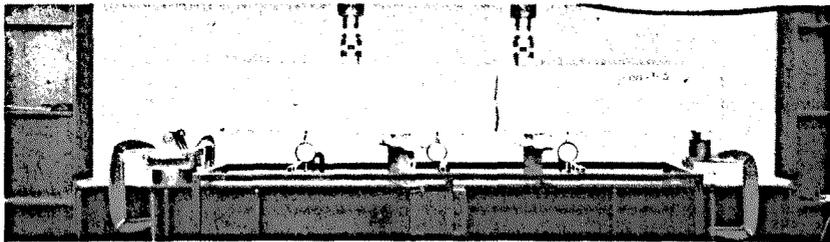
Photograph 12. Crack pattern, beam 12



a. No load



b. Total load = 500 lb (226.8 kg)

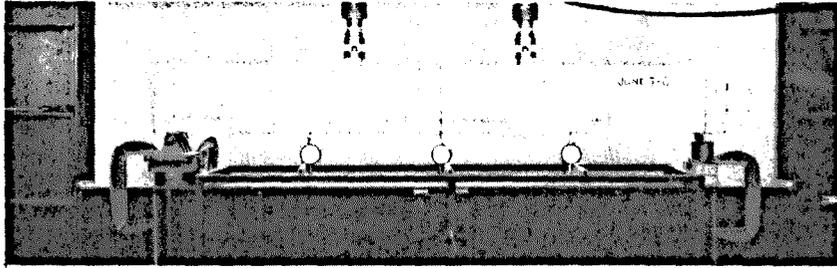


c. Total load = 1500 lb (680.4 kg)

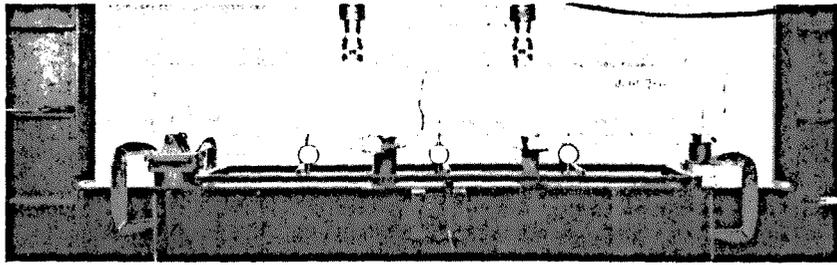


d. Total load = 3500 lb (1587.6 kg), failure

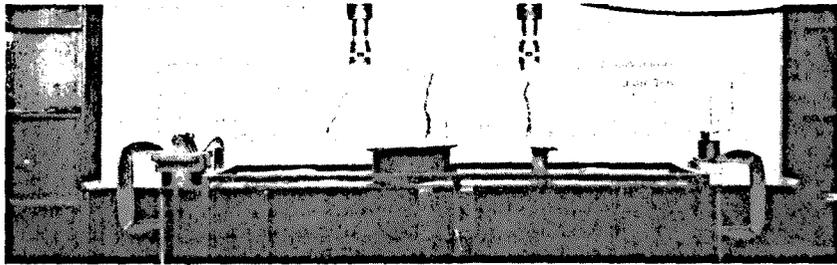
Photograph 13. Crack pattern, beam 13



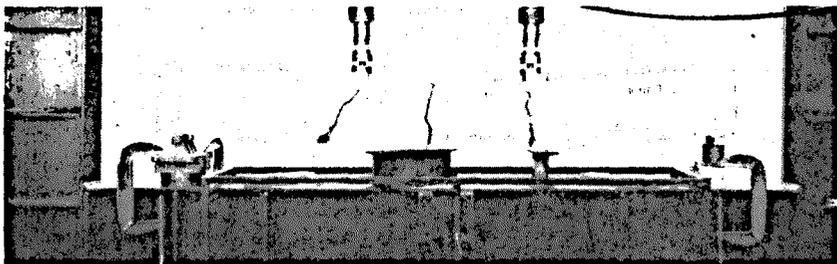
a. No load



b. Total load = 2000 lb (907.2 kg)

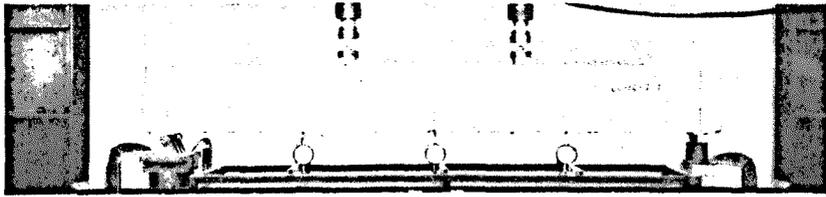


c. Total load = 4000 lb (1814.4 kg)

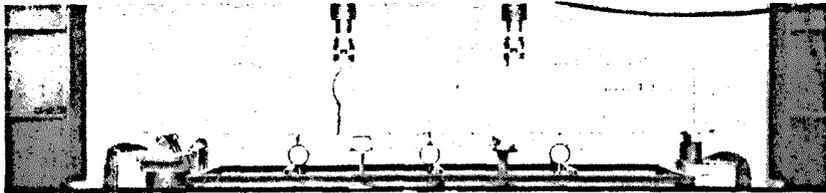


d. Total load = 4500 lb (2041.2 kg), failure

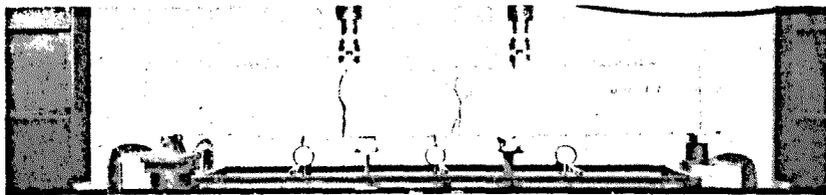
Photograph 14. Crack pattern, beam 14



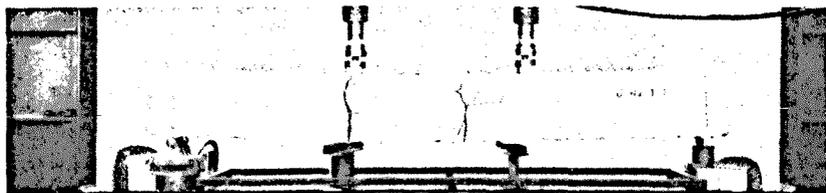
a. No load



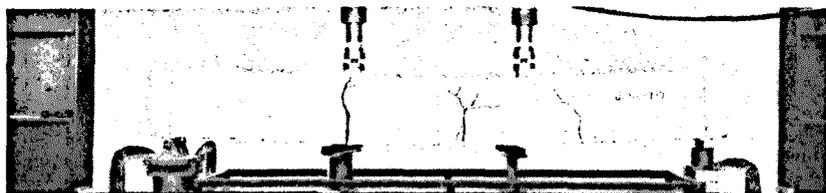
b. Total load = 2500 lb (1134.0 kg)



c. Total load = 3000 lb (1360.8 kg)

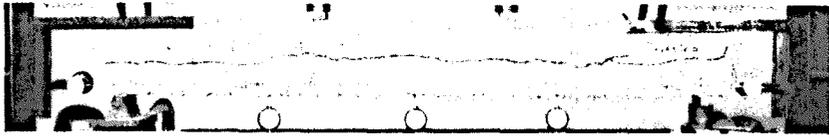


d. Total load = 5000 lb (2268.0 kg)

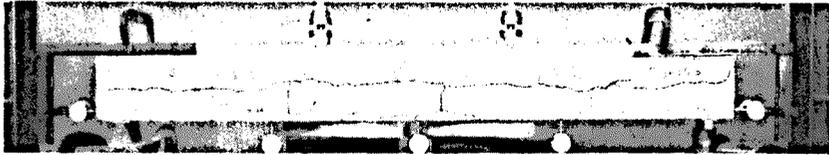


e. Total load = 5500 lb (2494.8 kg), failure

Photograph 15. Crack pattern, beam 15



a. No load



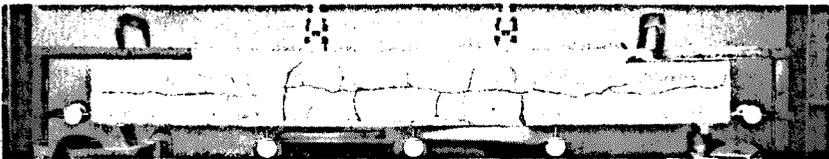
b. Total load = 1500 lb (680.4 kg)



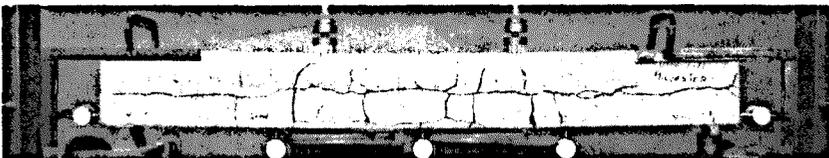
c. Total load = 2000 lb (907.2 kg)



d. Total load = 3000 lb (1360.8 kg)



e. Total load = 4000 lb (1814.4 kg)



f. Total load = 4500 lb (2041.2 kg)



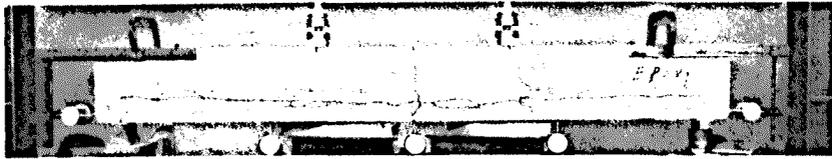
g. Total load = 5500 lb (2494.8 kg), failure
Photograph 16. Crack pattern, beam 16



a. No load



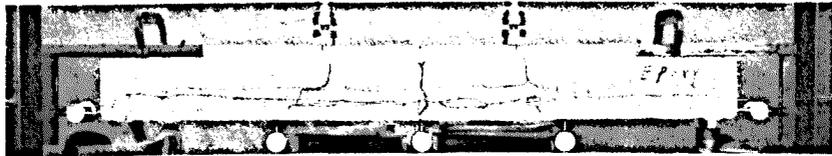
b. Total load = 1500 lb (680.4 kg)



c. Total load = 2000 lb (907.2 kg)



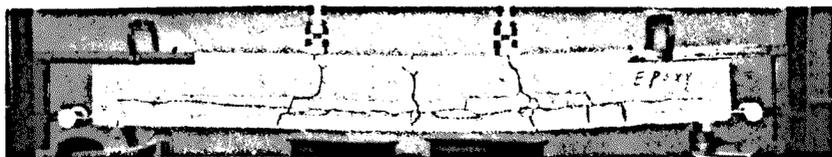
d. Total load = 2500 lb (1134.0 kg)



e. Total load = 3500 lb (1587.6 kg)

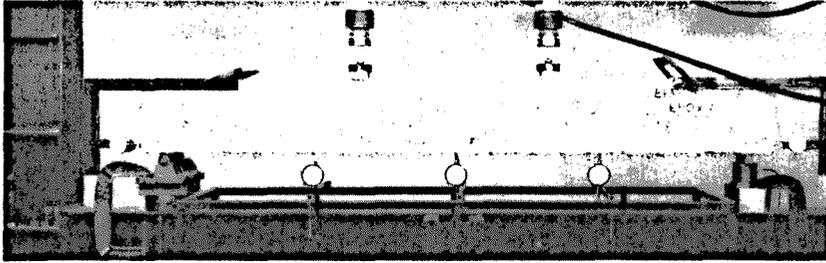


f. Total load = 5500 lb (2494.8 kg)

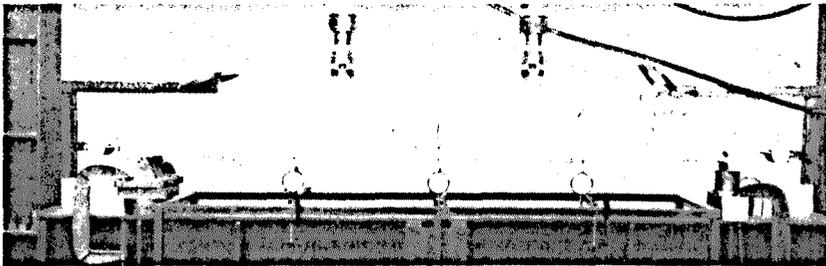


g. Total load = 6000 lb (2721.6 kg), failure

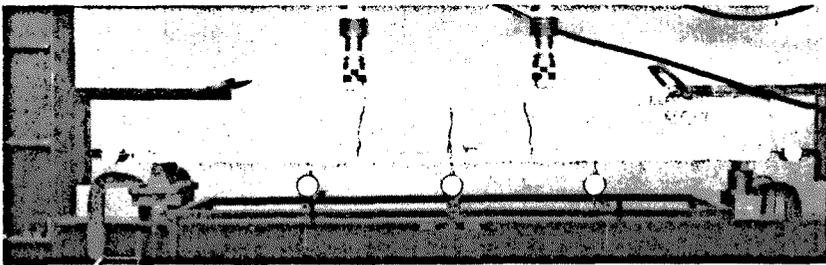
Photograph 17. Crack pattern, beam 17



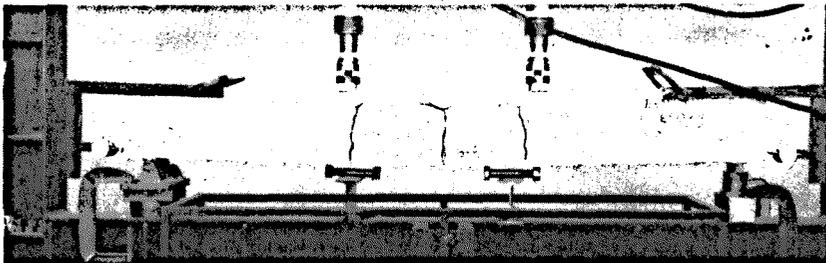
a. No load



b. Total load = 2000 lb (907.2 kg)



c. Total load = 3000 lb (1360.8 kg)



d. Total load = 6200 lb (2812.2 kg), failure

Photograph 18. Crack pattern, beam 18



a. No load



b. Total load = 2000 lb (907.2 kg)



c. Total load = 2500 lb (1134.0 kg)



d. Total load = 3500 lb (1587.6 kg)



e. Total load = 5000 lb (2268.0 kg)



f. Total load = 5500 lb (2494.8 kg)

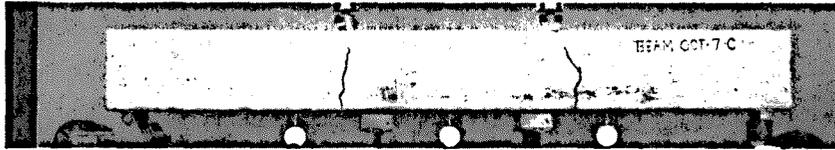


g. Total load = 6500 lb (2948.4 kg), failure

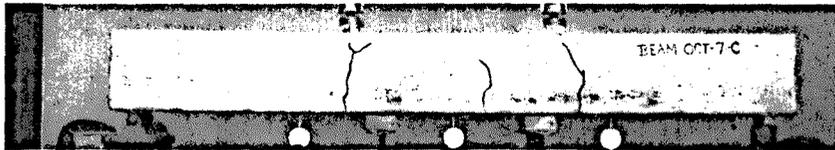
Photograph 19. Crack pattern, beam 19



a. No load



b. Total load = 1500 lb (680.4 kg)



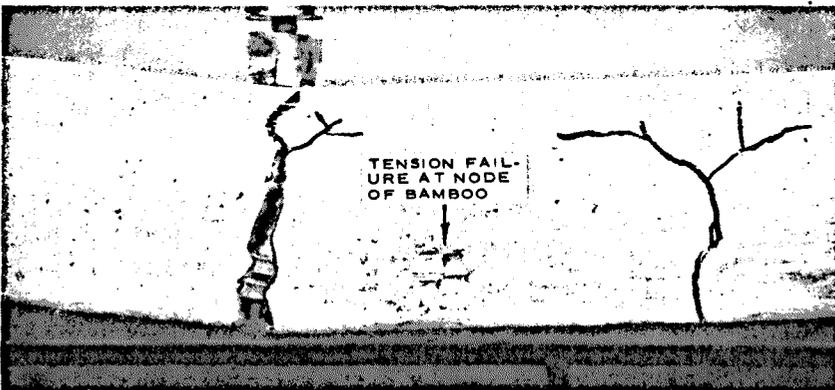
c. Total load = 3500 lb (1587.6 kg)



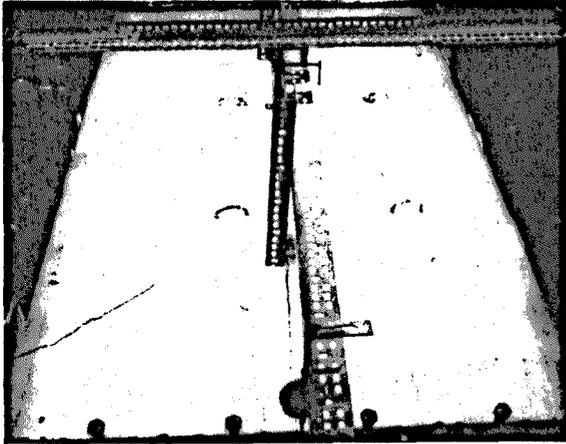
d. Total load = 4500 lb (2041.2 kg)



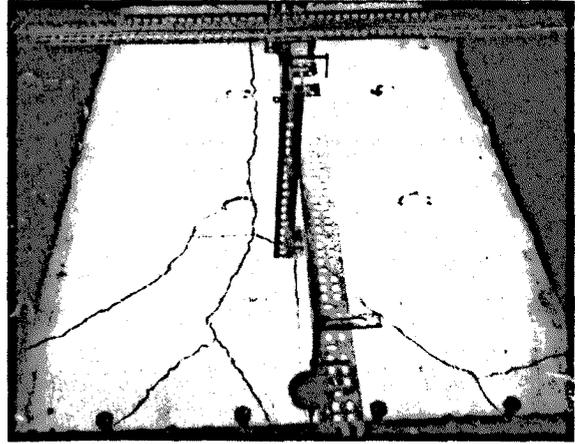
e. Total load = 6500 lb (2948.4 kg), failure



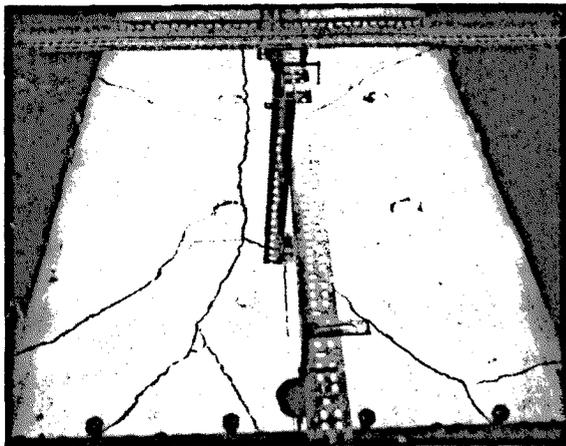
f. Close-up at failure



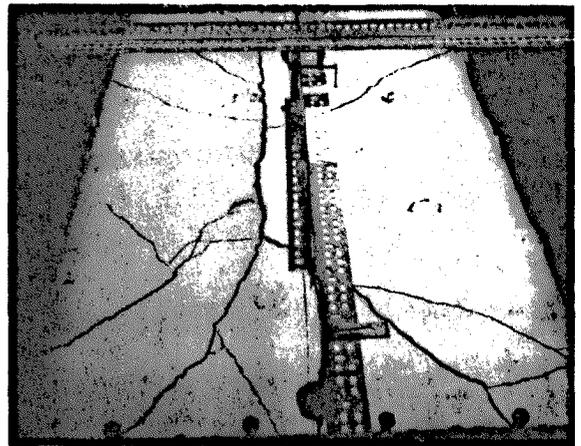
a. 576 psf (2812.3 kg/m²)



b. 936 psf (4570.0 kg/m²)



c. 1080 psf (5273.0 kg/m²)



d. 1368 psf (6679.2 kg/m²)

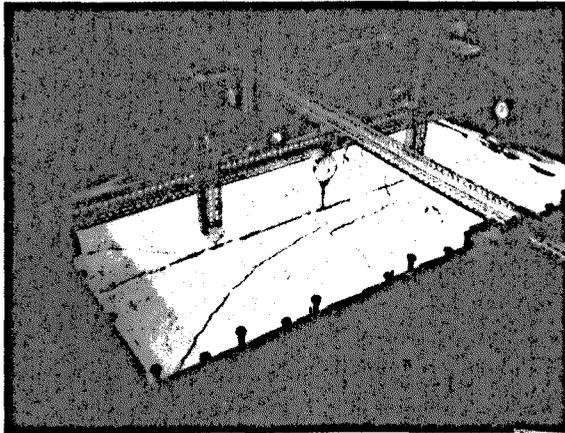


e. 1512 psf (7382.2 kg/m²), failure

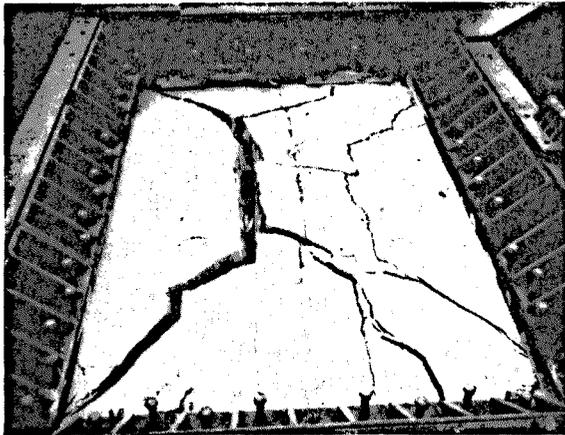
Photograph 21. Crack pattern, slab 1



a.. 691 psf (3373.8 kg/m^2)

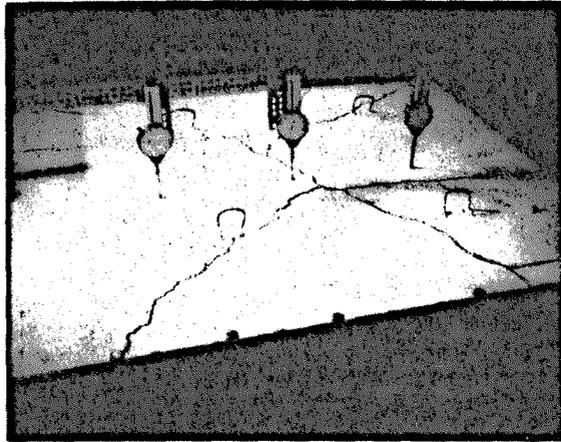


b. 1296 psf (6327.6 kg/m^2)

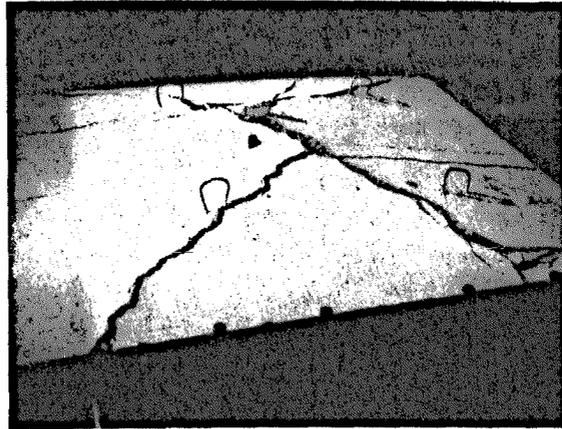


c. 1584 psf (7733.8 kg/m^2), failure

Photograph 22. Crack pattern, slab 2

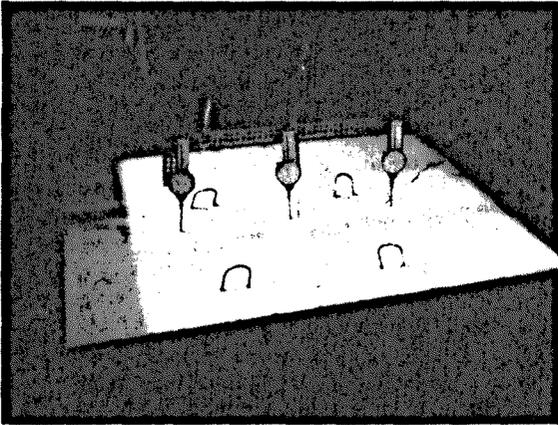


a. 576 psf (2812.3 kg/m^2), failure

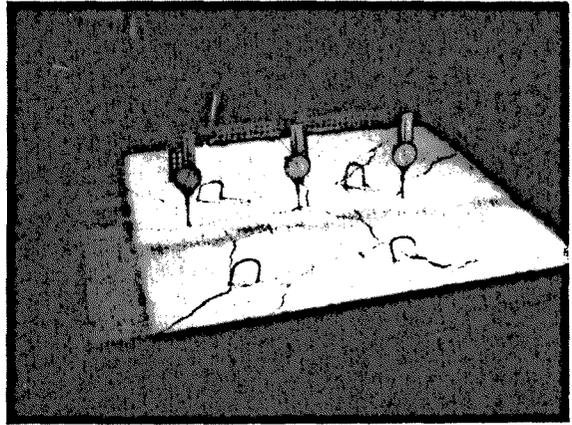


b. 360 psf (1757.7 kg/m^2), after failure

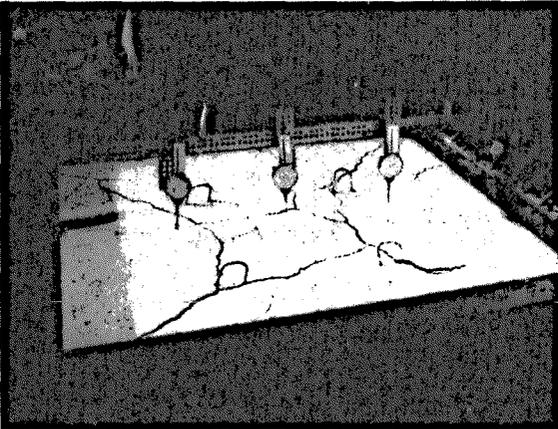
Photograph 23. Crack pattern, slab 3



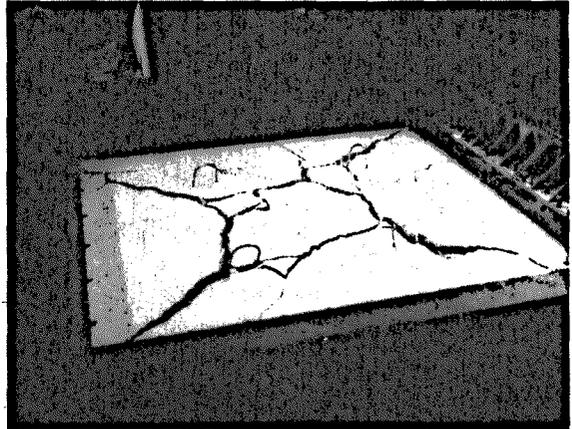
a. 432 psf (2109.2 kg/m²)



b. 504 psf (2460.7 kg/m²)

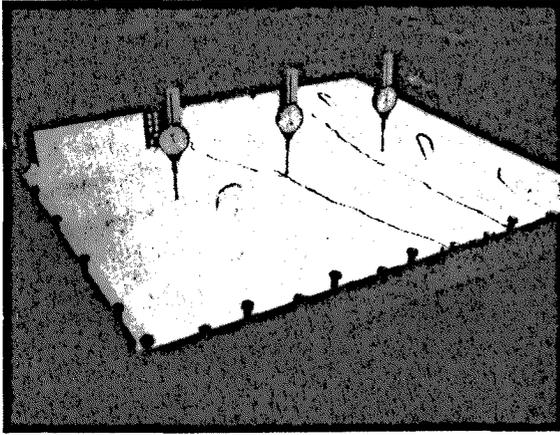


c. 792 psf (3866.9 kg/m²)

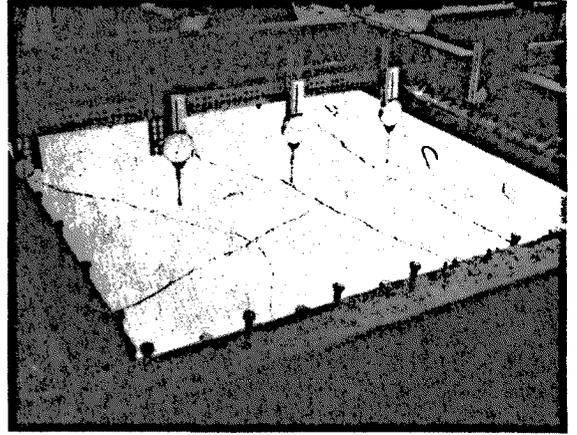


d. 612 psf (2988.0 kg/m²), after failure

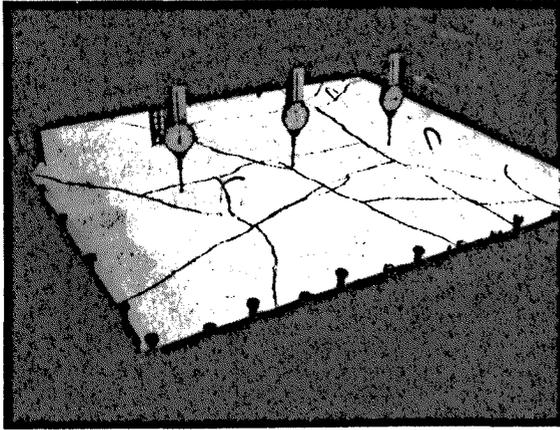
Photograph 24. Crack pattern, slab 4



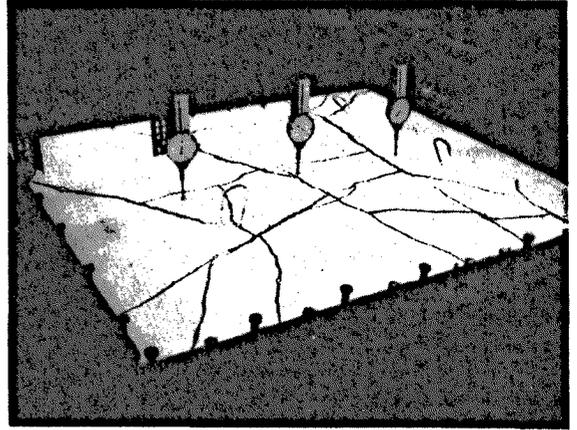
a. 648 psf (3163.8 kg/m²)



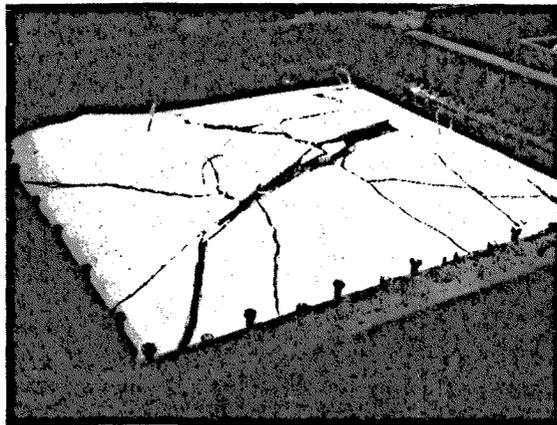
b. 792 psf (3866.9 kg/m²)



c. 1008 psf (4921.5 kg/m²)

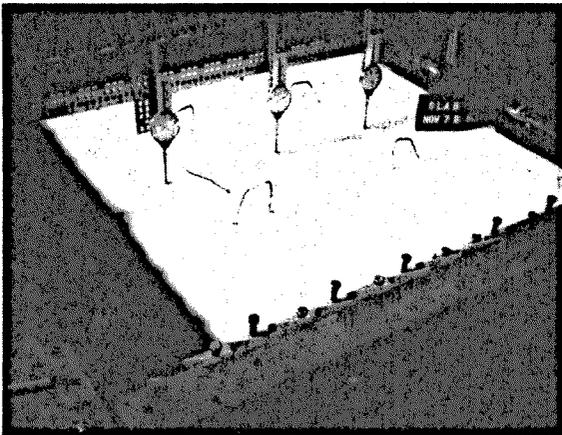


d. 1296 psf (6327.6 kg/m²)

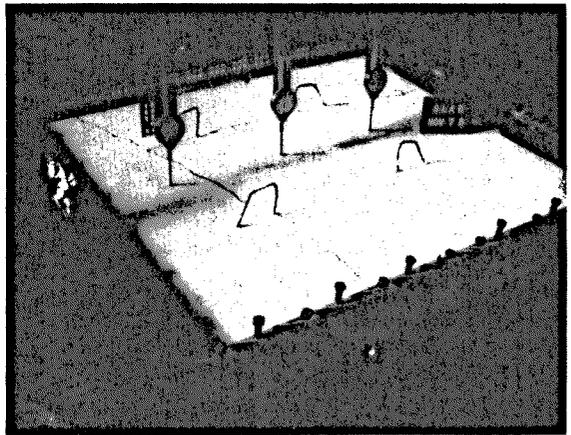


e. 576 psf (2812.3 kg/m²), after failure

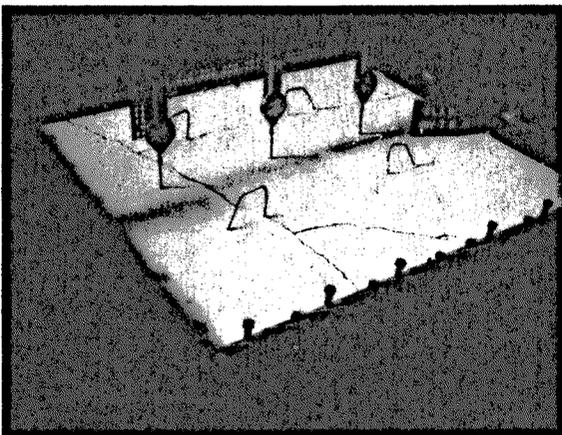
Photograph 25. Crack pattern, slab 5



a. 576 psf (2812.3 kg/m²)



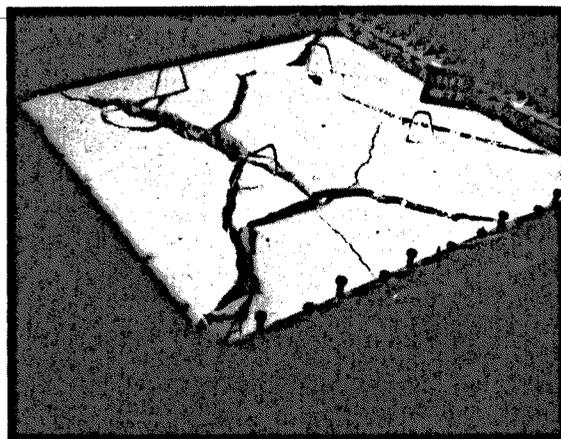
b. 792 psf (3866.9 kg/m²)



c. 864 psf (4218.4 kg/m²)

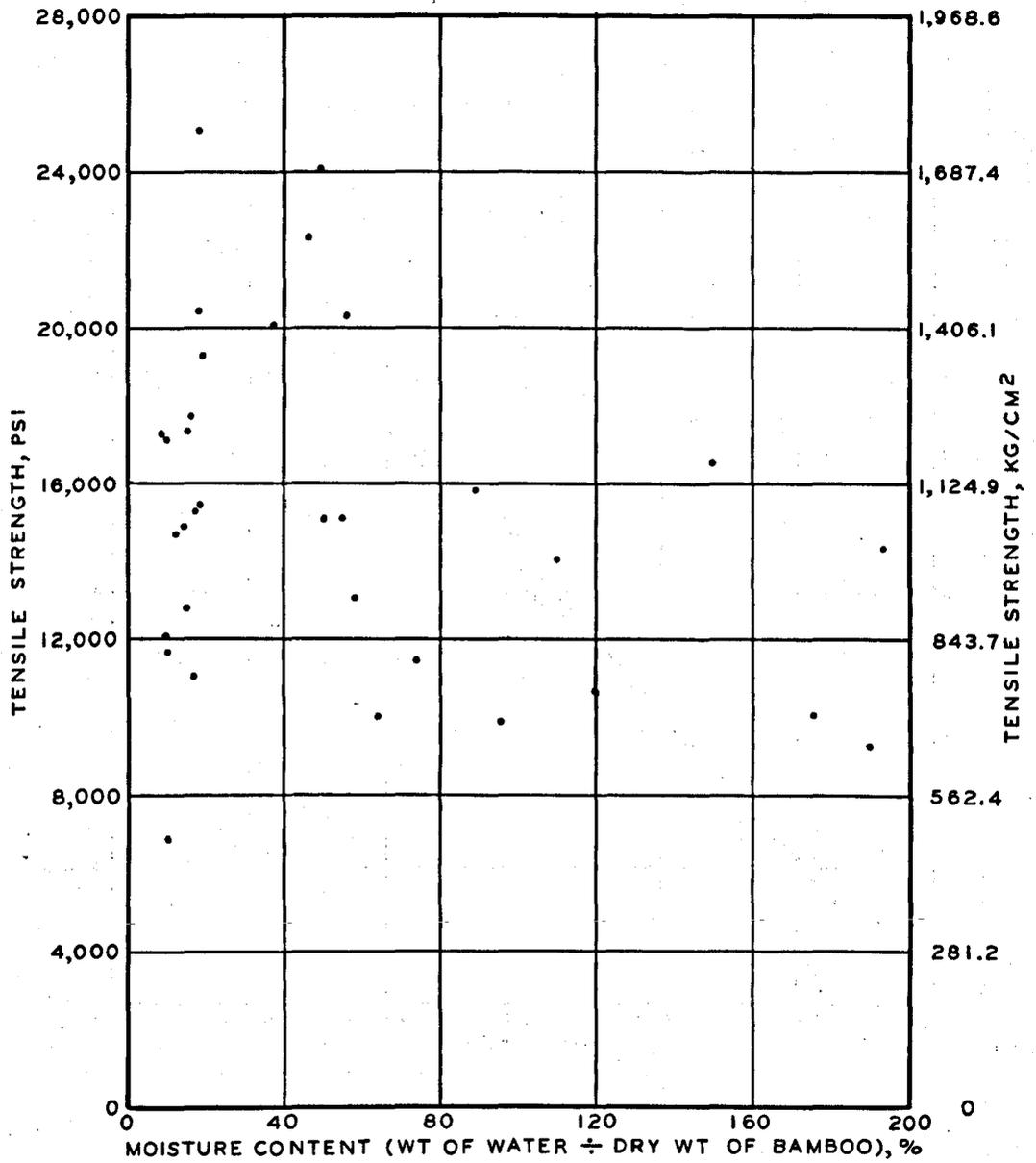


d. 936 psf (4570.0 kg/m²)

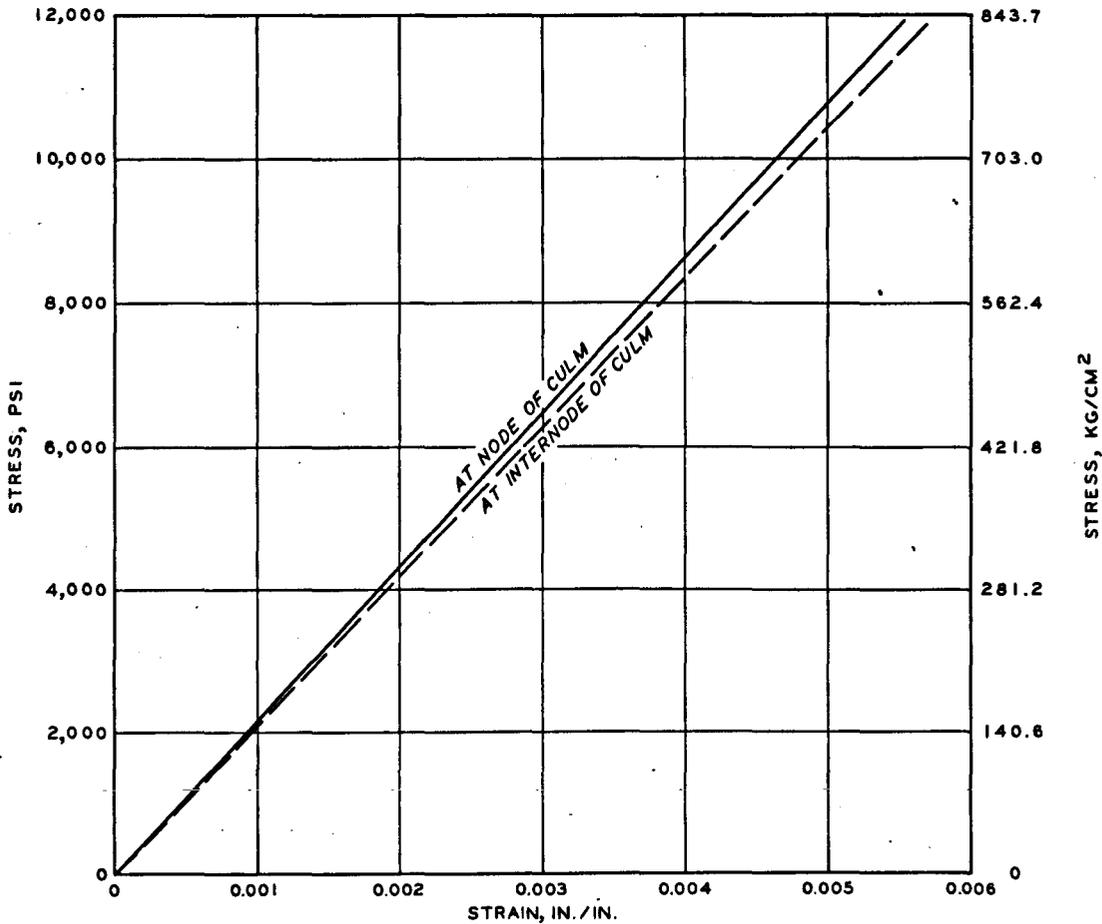


e. 1080 psf (5273.0 kg/m²), failure

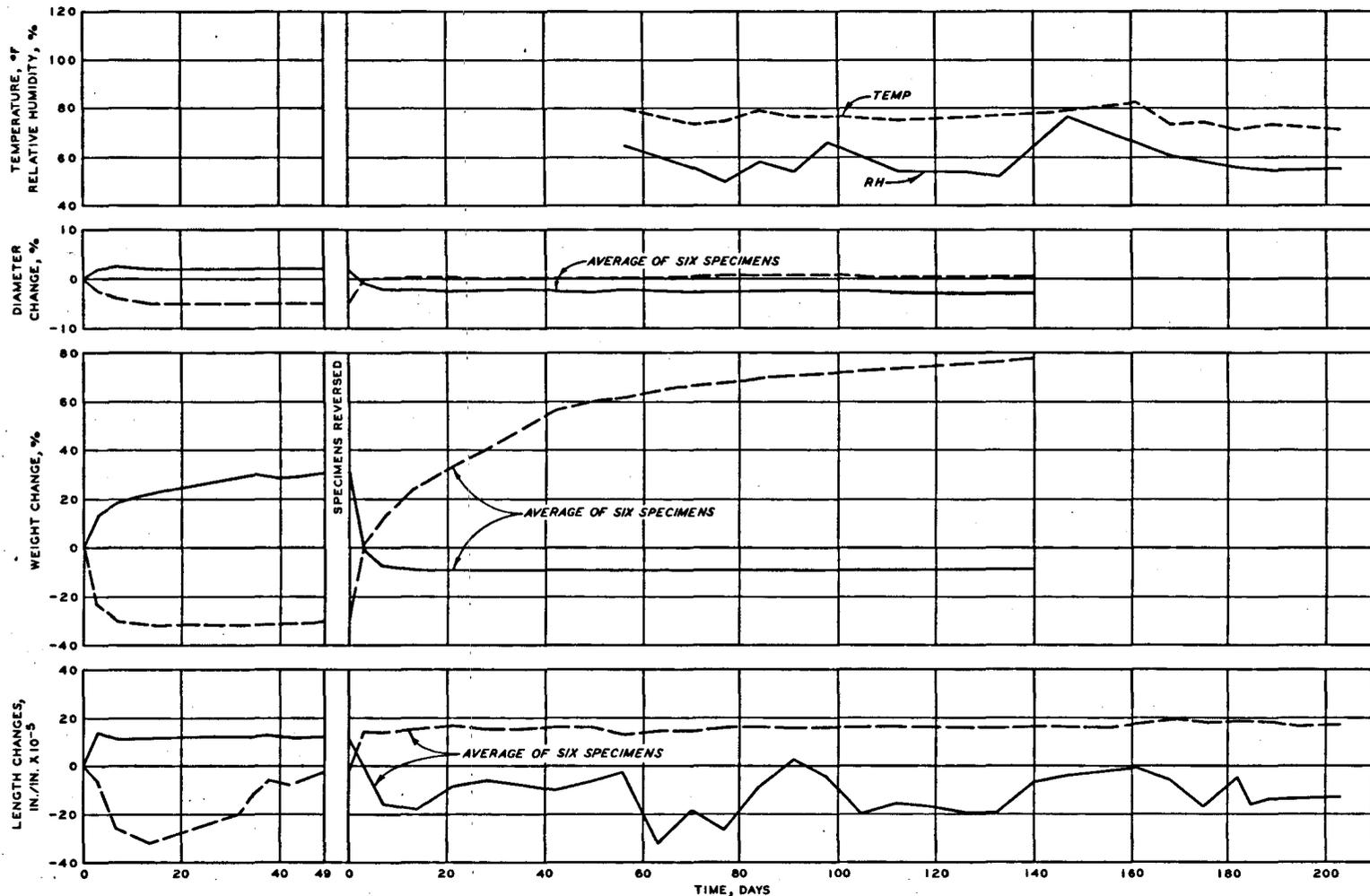
Photograph 26. Crack pattern, slab 6



RELATION OF MOISTURE
CONTENT OF BAMBOO
TO ITS TENSILE STRENGTH



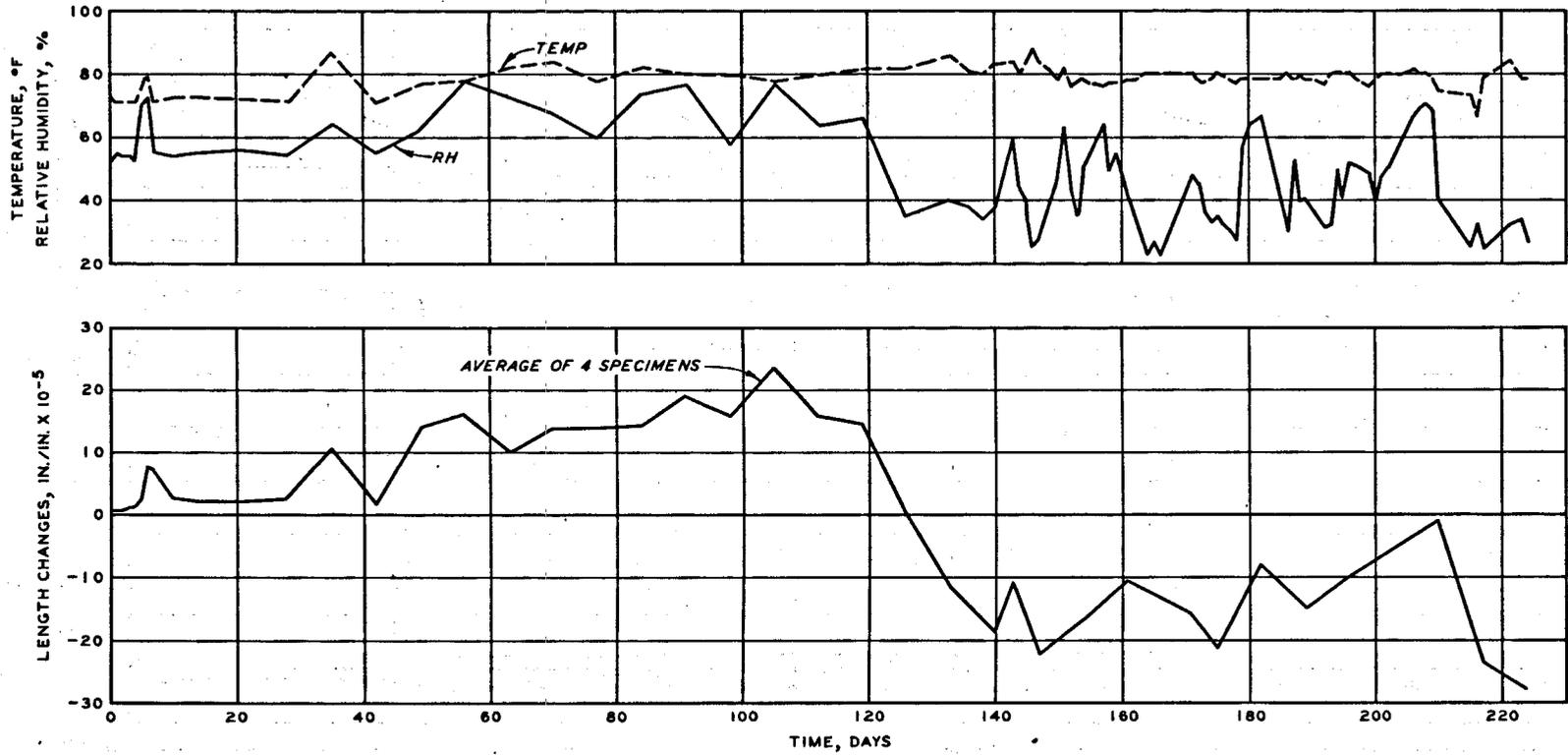
TYPICAL
STRESS-STRAIN CURVE
FOR WHOLE BAMBOO CULM



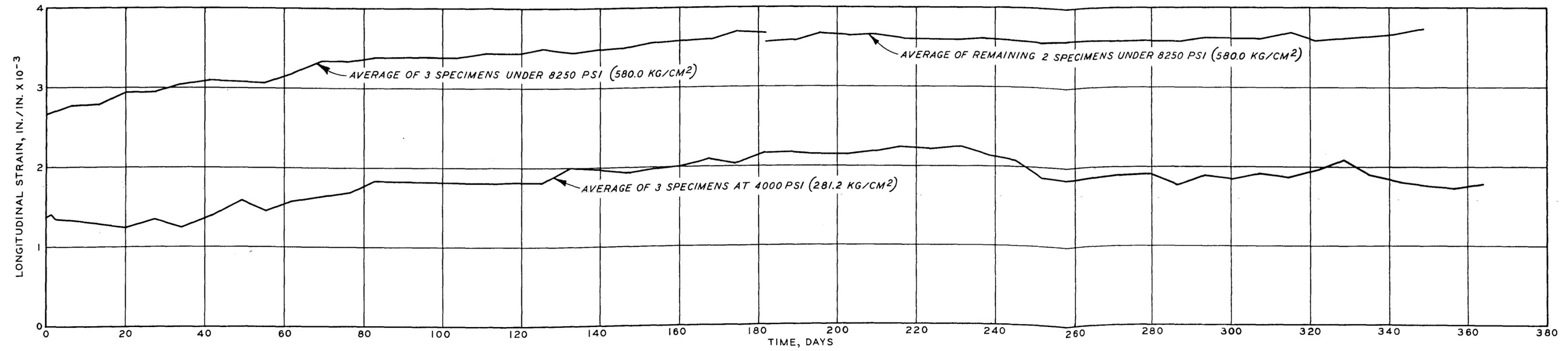
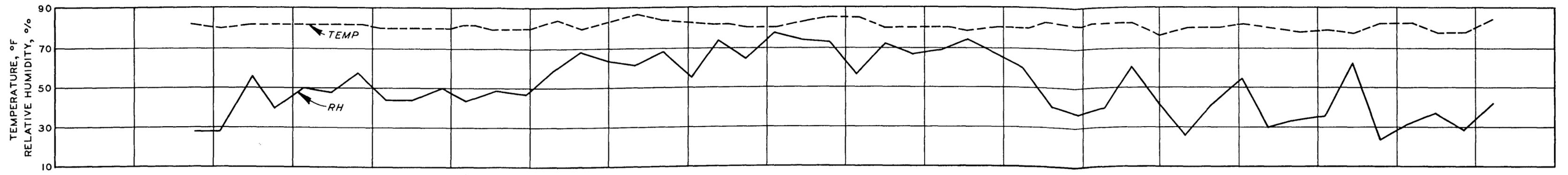
LEGEND

- SUBMERGED IN WATER FOR 49 DAYS, THEN ROOM-DRIED
- - - ROOM-DRIED FOR 49 DAYS, THEN SUBMERGED IN WATER

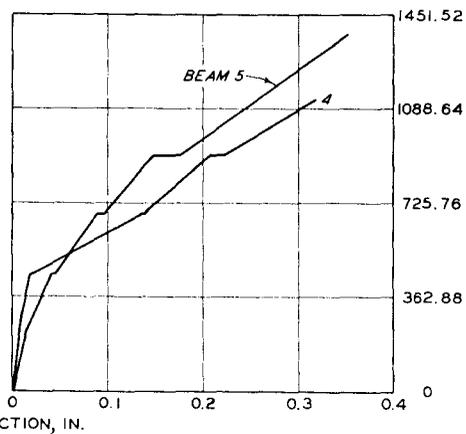
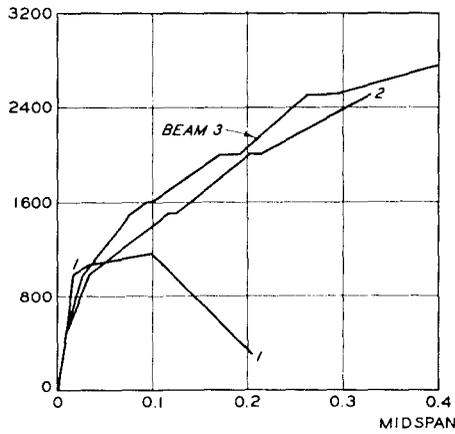
**DIMENSIONAL
CHANGES OF BAMBOO
DUE TO MOISTURE VARIATIONS**



SUPPLEMENTAL TEST
 OF DIMENSIONAL CHANGES
 OF BAMBOO DUE TO CHANGING
 RELATIVE HUMIDITIES, WARPING ELIMINATED

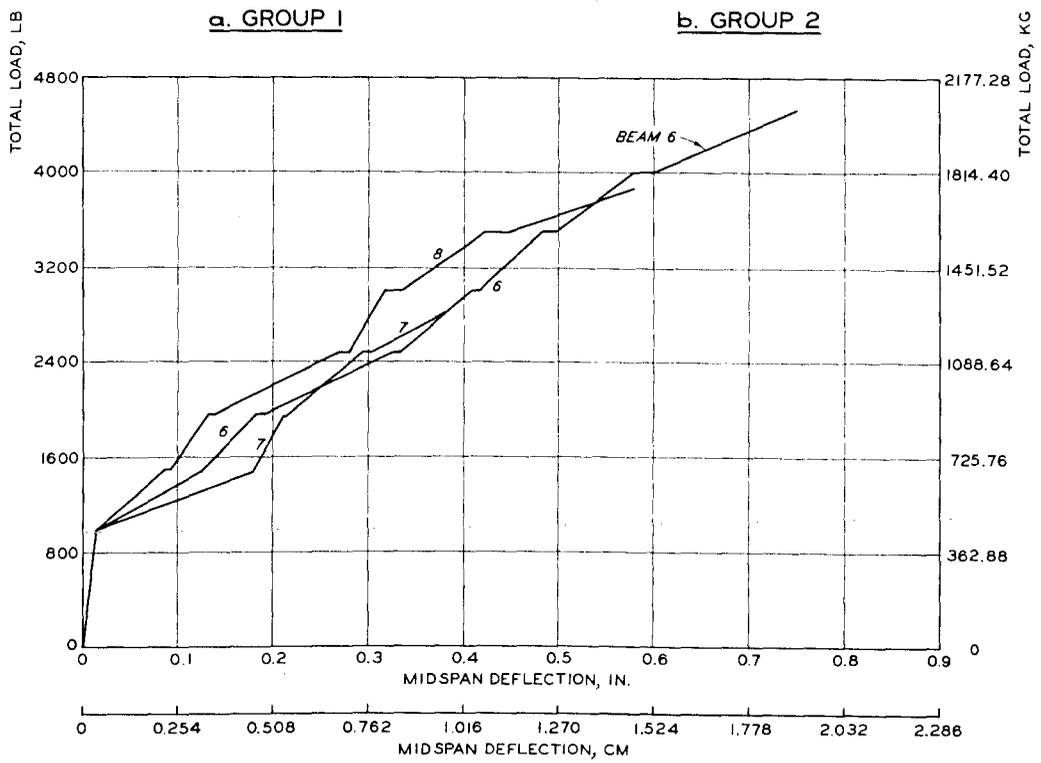


CREEP OF BAMBOO CULMS
UNDER SUSTAINED LOADS



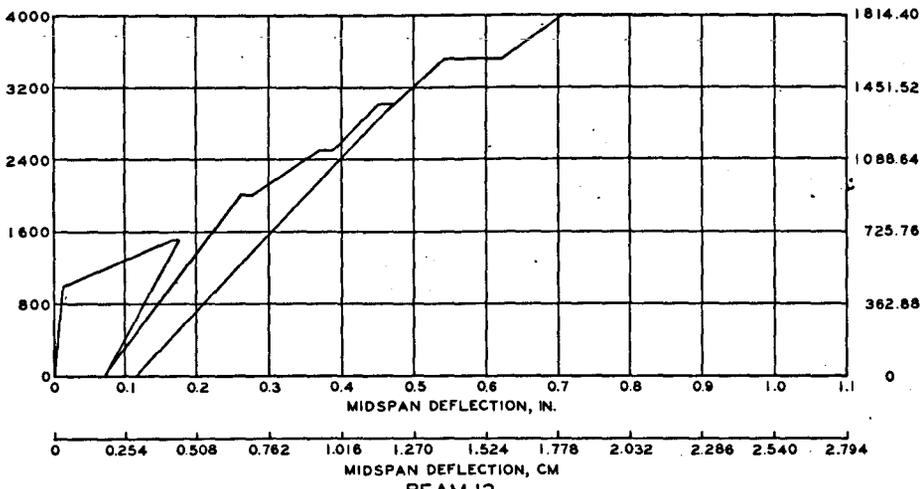
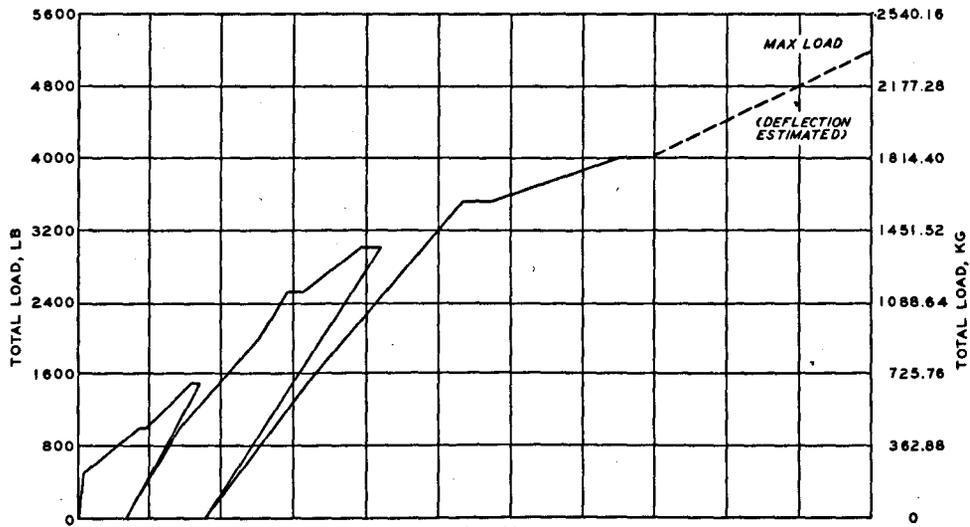
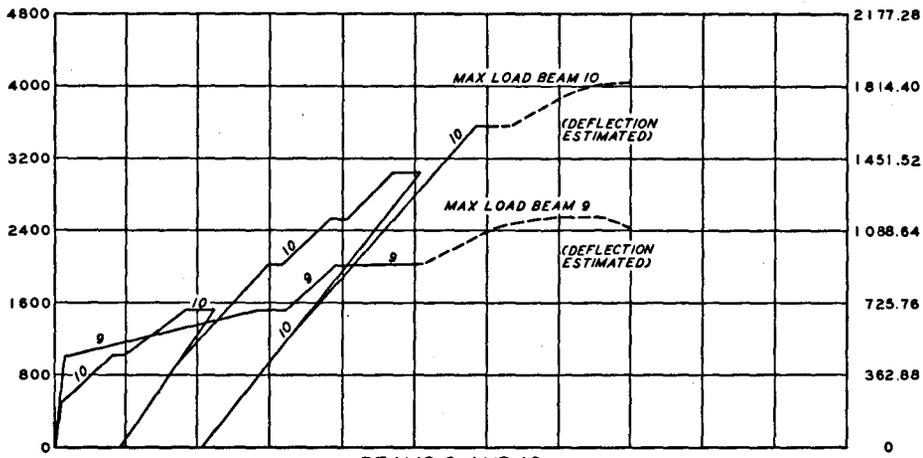
a. GROUP 1

b. GROUP 2

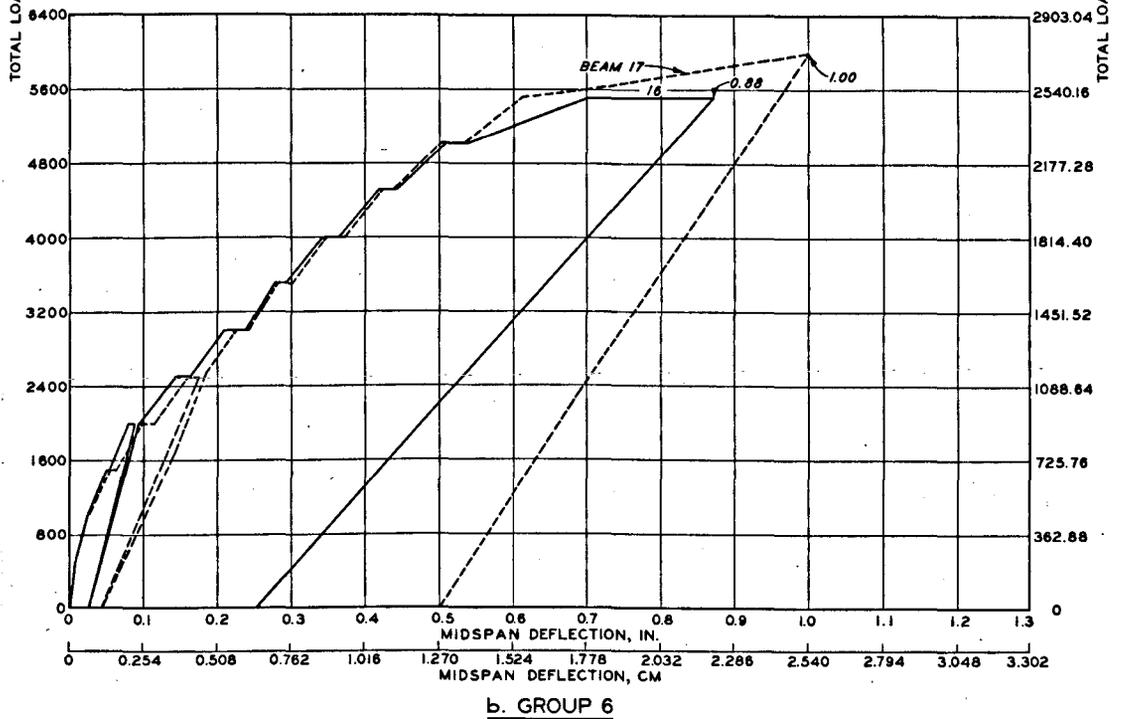
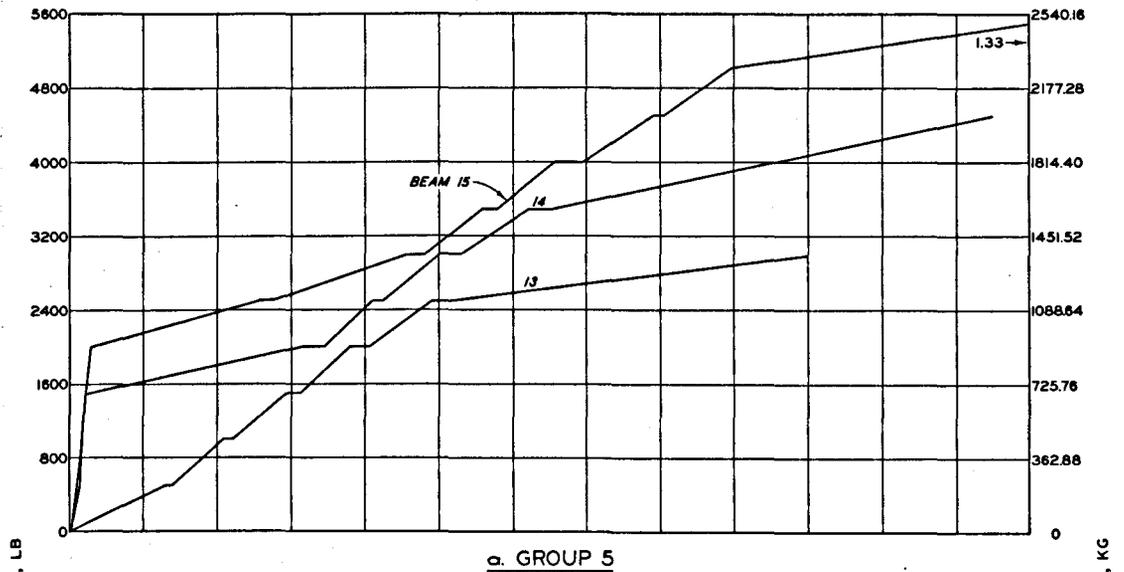


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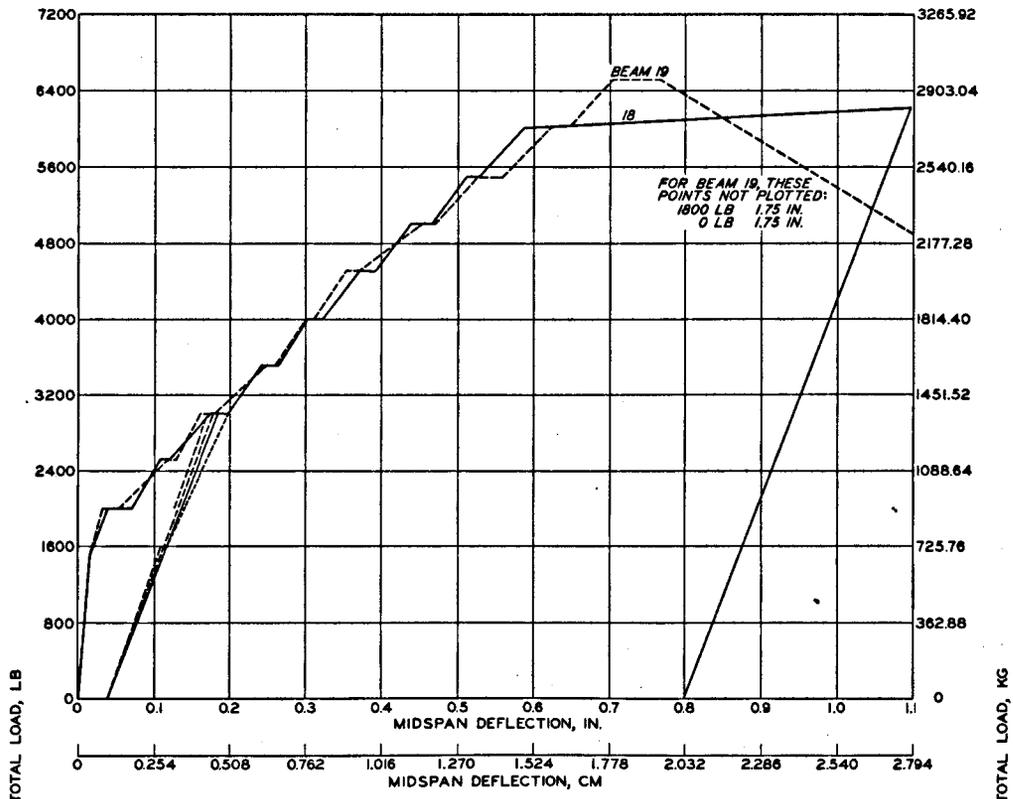
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GROUPS 1-3, BEAMS 1-8



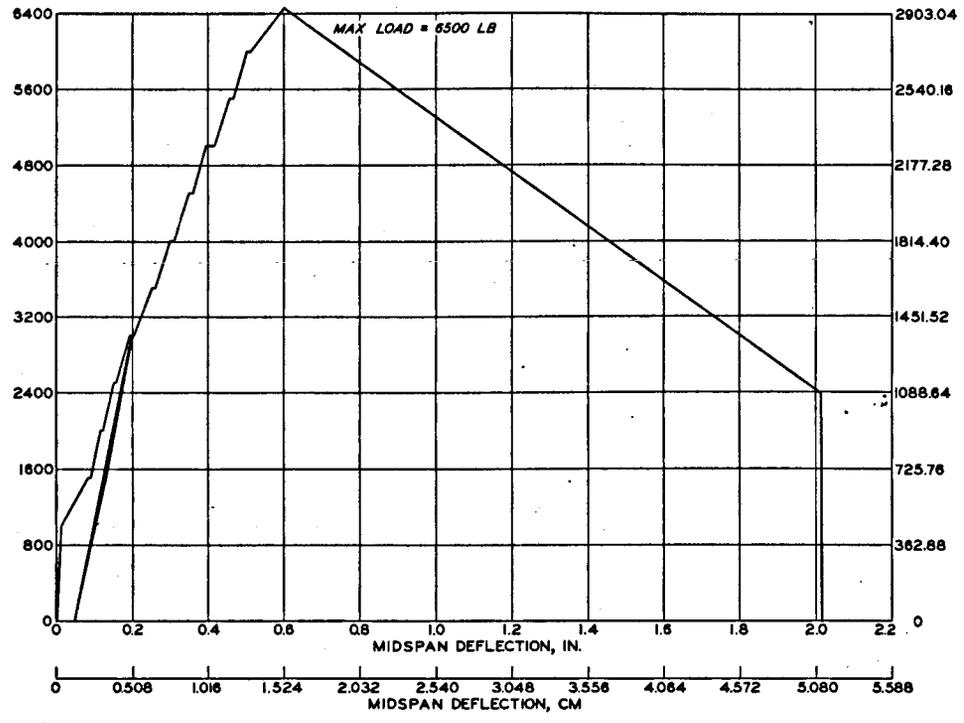
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GROUP 4, BEAMS 9 - 12**



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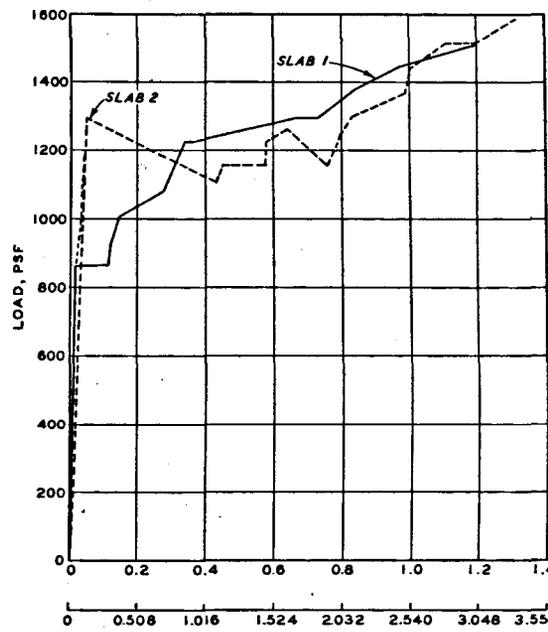


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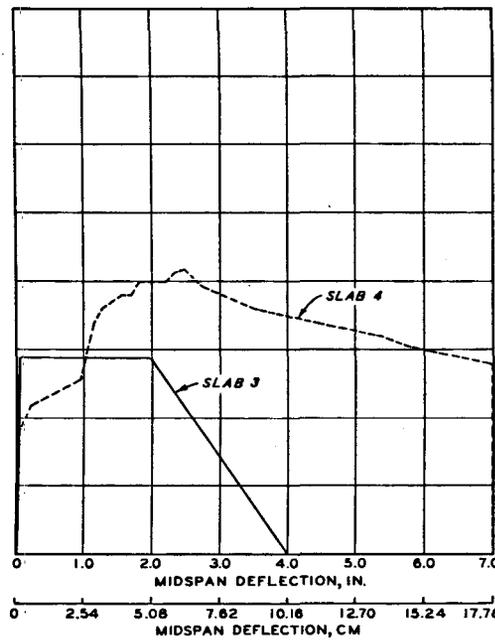


b. GROUP 8

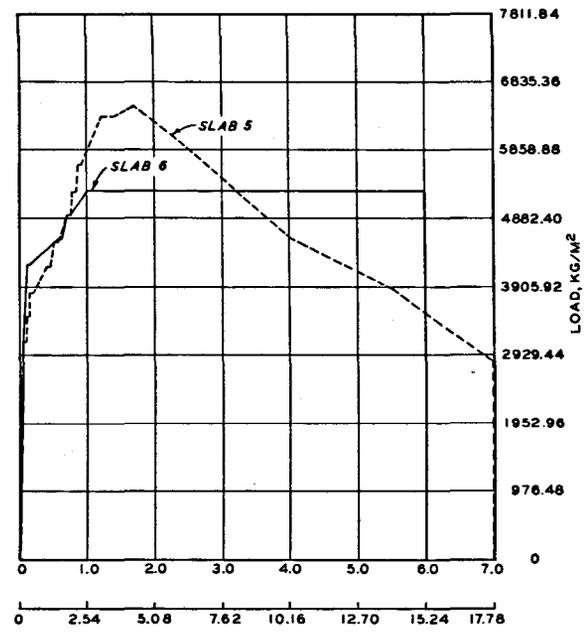
LOAD VS MIDSPAN DEFLECTION
GROUPS 7 AND 8, BEAMS 18-20



a. SLABS 1 AND 2



b. SLABS 3 AND 4



c. SLABS 5 AND 6

LOAD VS MIDSPAN DEFLECTION
GROUPS 1-3, SLABS 1-6

APPENDIX A: ELASTIC ANALYSIS

1. The following is a typical example (beam 4) illustrating the elastic analysis used to determine stresses for beams and slabs shown in tables 10 and 11.

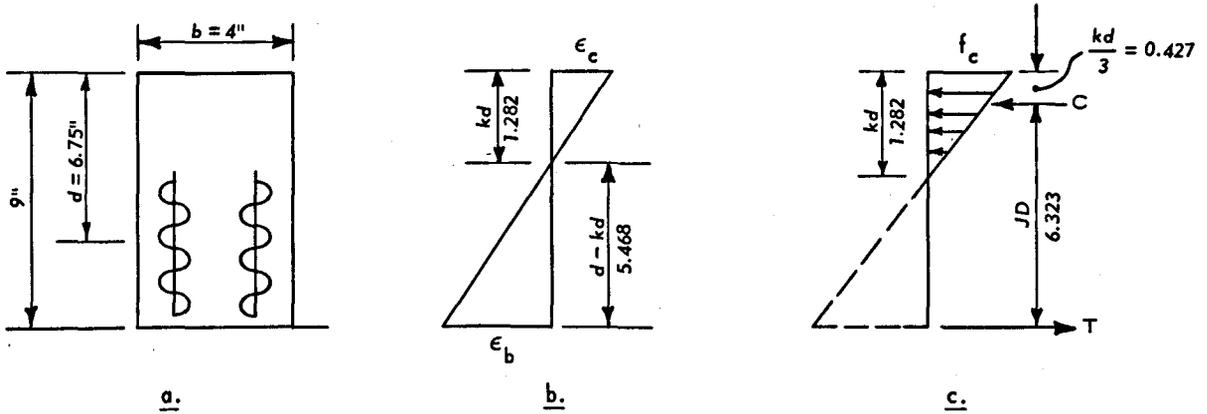


Fig. A1

2. The subsequent computations are based on the following assumptions.

$$f'_c = 2843 \text{ psi}$$

$$d = 6.75 \text{ in.}$$

$$A_b = 0.706 \text{ sq in.}$$

$$\text{Weight of concrete} = 145 \text{ pcf}$$

$$E_c = W^{1.5} 33 \sqrt{f'_c} \text{ (from ACI Code No. 318-63)}$$

$$E_c = (145)^{1.5} 33 \sqrt{2843} = 3.06 \times 10^6 \text{ psi}$$

$$E_b = 2.62 \times 10^6 \text{ psi (average for bamboo tested during this investigation)}$$

Straight-line strain and stress distribution

Perfect bond between bamboo and concrete until failure

From fig. Alc:

$$C = 1/2 f_c b k d = T = A_b f_b$$

$$C = 1/2 E_c \epsilon_c bkd = T = A_b E_b \epsilon_b$$

From fig. Alb:

$$\frac{\epsilon_c}{kd} = \frac{\epsilon_b}{d - kd}$$

$$\epsilon_c = \frac{\epsilon_b (kd)}{d - kd}$$

$$\frac{1}{2} \frac{(3.06)(10^6)(\epsilon_b)(kd)(4)(kd)}{d - kd} = 0.706(2.62)(10^6)(\epsilon_b)$$

$$6.12 \overline{kd}^2 = 0.706(2.62)(6.75 - kd)$$

$$6.12 \overline{kd}^2 + 1.85 kd - 12.49 = 0$$

$$kd = 1.282 \text{ in.}$$

From fig. Alc:

$$M = T(JD) = A_b E_b \epsilon_b JD$$

$$29,520 \text{ (from beam test)} = 0.706(2.62)(10^6)(\epsilon_b)(6.323)$$

$$\epsilon_b = \frac{29,520}{(0.706)(2.62)(10^6)(6.323)} = 2523.99 \times 10^{-6}$$

$$f_b = (2523.99 \times 10^{-6})(2.62 \times 10^6) = \underline{6610 \text{ psi}}$$

From fig. Alb

$$\frac{2523.99 \times 10^{-6}}{5.468} = \frac{\epsilon_c}{1.282}$$

$$\epsilon_c = 591.76 \times 10^{-6}$$

$$f_c = (591.76 \times 10^{-6})(3.06 \times 10^6) = \underline{1810 \text{ psi}}$$

For approximate average stress in lower culm of bamboo.

$$\epsilon_c = 591.76 \times 10^{-6}$$

$$\frac{591.76 \times 10^{-6}}{1.282} = \frac{\epsilon_b}{6.468}$$

$$\epsilon_b = 2985.57 \times 10^{-6}$$

$$f_b = (2985.57 \times 10^{-6})(2.62 \times 10^6) = \underline{7820 \text{ psi}}$$

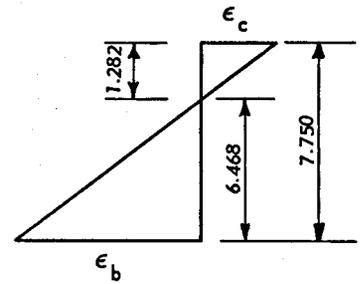


Fig. A2

APPENDIX B: ULTIMATE STRENGTH ANALYSIS

1. The following is a typical example (beam 4) illustrating the ultimate strength analysis used to determine stresses for beams shown in table 10.

2. The following computations are valid providing these assumptions are made.

- a. $f'_c = 2843$ psi.
- b. $d = 6.75$ in.
- c. $A_b = 0.706$ sq in.
- d. Straight-line distribution of stresses until the effective bond strength of the bamboo is reached and continuous slippage of culms at a constant tensile strength result in a bilinear resistance function equivalent to the bilinear stress-strain curve assumed in ACI Code 318-63 (fig. B1b).
- e. Validity of standard assumptions for ultimate strength design, e.g. straight-line strain distribution, Whitney stress block, ultimate concrete strain of 0.003.
- f. Due to assumptions d and e, equation 16-1 of the ACI Building Code 318-63 may be used, letting $\phi = 1$. (Note: Bamboo-reinforced members will always be underreinforced.)

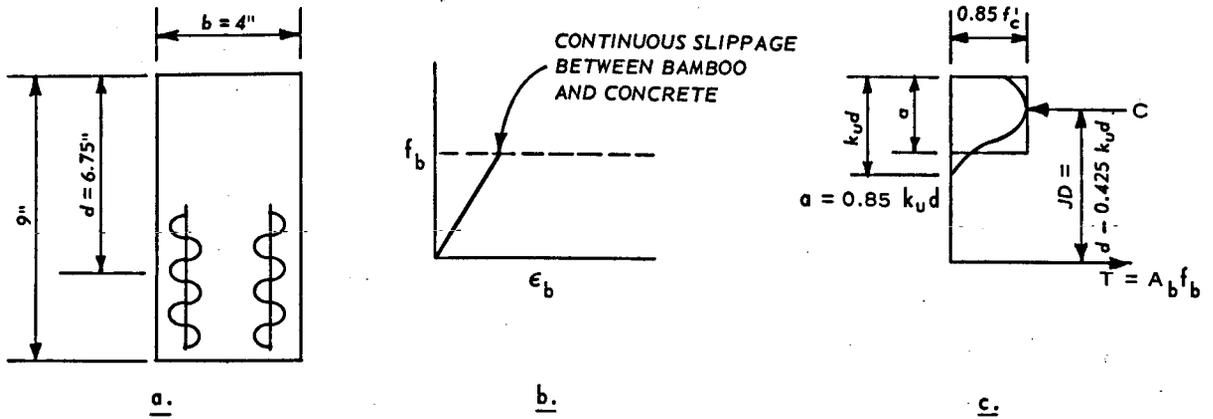


Fig. B1

$$M = C(JD)$$

$$\begin{aligned}
 &29,520 \text{ (from test data, see table 10)} \\
 &= (0.85)(2843)(0.85)(k_u d)(4)(6.75 - 0.425 k_u d)
 \end{aligned}$$

$$3491.91 \overline{k_u d^2} - 55,459.82 k_u d = -29,520$$

$$\overline{k_u d^2} - 15.88 k_u d + 8.45 = 0$$

$$k_u d = 0.555 \text{ in.}$$

$$M = T(JD)$$

$$29,520 = [6.75 - (0.425)(0.555)] [(0.706)(f_b)]$$

$$f_b = \frac{29,520}{(6.514)(0.706)} = \underline{6418 \text{ psi}}$$

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13. ABSTRACT This report summarizes the preliminary results of a current U. S. Army Engineer Waterways Experiment Station (WES) study of the feasibility of using bamboo as an expedient reinforcement for temporary, reinforced concrete structures. The report contains an extensive review of the literature, a description of the test procedures, results of an investigation of the most important engineering properties of bamboo, descriptions of tests of 26 bamboo-reinforced structural elements (20 simply-supported beams with 6-ft (1.83-m) spans, and 6 simply supported two-way slabs of varying length, width, and depth), and conclusions and tentative recommendations for the design of bamboo-reinforced structures. The recommended procedures are based on results obtained from tests of local (Mississippi) small cane (<i>Arundinaria tecta</i>), and are believed to be conservative when other species of bamboo are used because most of the properties of the small cane were generally somewhat lower than the properties reported by others for other species. Some of the principal conclusions are: a. Although bamboo has a fairly high tensile strength (values as high as 53,894 psi or 3,789 kg/cm ² have been reported), its tensile modulus of elasticity is relatively low (usually less than 1/10 of that of conventional steel reinforcement). This low tensile modulus leads to large deflections and wide cracks when bamboo-reinforced structures are loaded to capacity. b. The principal problems associated with bamboo reinforcement are volume changes (i.e. swelling and shrinking) due to moisture variations, low bond strength, and possibly decay. However, if special precautions are taken in preparing and placing the culms (such as splitting, presoaking for 72 hr, coating, etc.), these problems can be minimized. c. Bamboo-reinforced members that are designed and constructed according to the tentative recommendations outlined herein can be expected to develop from two to four times the ultimate flexural load-carrying capacity of unreinforced members of equal dimensions.		

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