UTILIZATION OF SULPHUR-TREATED BAMBOO FOR LOW-VOLUME ROAD CONSTRUCTION

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This paper presents the current research findings on the utilization of sulphur treated bamboo for road construction. Basic engineering properties of bamboo culm (stem) including modulus of elasticity, compressive and tensile strength, as well as bamboo-water interaction are summarized and discussed. Two major applications, namely: bamboo rod used as a substitute for steel bar in structural concrete and bamboo reinforced earth are presented. Performance and durability of bamboo structures for engineering uses are examined. Finally, a field application procedure for bamboo used as reinforced earth for protecting low-volume roads against landslide is proposed.

For road construction, large quantities of materials are generally required. Since economic consideration is one of the major decision factors, it is necessary to examine alternate or low-cost materials for future road construction. In some regions the conventional construction materials, such as steel, not only are costs high but also hard to get. In such regions, the utilization of indigenous and replenishable material is ideal for road material, and it is believed that bamboo is one of such an ideal material (6).

Bamboo is classified as Bambusoideae or as Bambusaceae. It can be found in many parts of the world and has been used as a low-cost construction material for many years. However, bamboo has a major weakness due to high water absorption potential which leads to swelling-skrinking and decay and perhaps these factors are the main reason why bamboo is not widely used in today's modern construction. Recently, a low-cost simple treatment technique using a sulphur-sand method to overcome the above mentioned problems has been developed (7,10). The purpose of this paper is to present the additional research findings on bamboo rod used as substitute for steel bar in structural concrete and to reinforce earth with a bamboo mat and/or bamboo-lime column for new or existing highway embankments. Basic engineering properties of bamboo and durability of bamboo structures together with the field application for low-volume road construction are also presented.

Engineering Properties of Bamboo Culm

In using bamboo for engineering application, it is necessary to examine the basic characteristics of bamboo culm (stem). Bamboo consists of two distinctive layers of fibers. The inner portion is soft and spongy-like with a white color containing 15% to 30% of the fibers. The outer portion is stiffer with a light green or yellowish color and contains 40% to 60% of the fibers. As indicated by Fang and Fay (9), the fiber content and its behavior are mainly related to the bamboo age, type of bamboo and its sampling location within the culm. Figure 1 shows the variations of fiber contents versus sampling location (11,17,22). It indicates that the bottom portion has more fiber content than the top portion. The aged bamboo (3 to 6 years old) has more fiber than young green bamboo. The general strength characteristics of bamboo fiber and culm include tensile strength and compressive strength, modulus of elasticity, modulus of rupture, specific gravity, and others as summarized in Table 1. Based on previous and present research findings, it can be concluded that the aged bamboo gives higher strength of all kinds than green (young) bamboo. The bottom portion of the bamboo has higher strength, higher specific gravity than the top portion of the bamboo culm. To consider bamboo for comparison with other materials, Table 2 lists the strength-weight ratio of various materials among which the strength-ratio of bamboo shows an excellent condition. Since bamboo is a fiber material, the longitudinal and transverse directions are different. To examine this point, a Pennsylvania bamboo has been used for study. Two strain-rosettes were installed on the surface of bamboo culm, one on the knob (joint) and the other one between the knob. The typical stress-strain curves of the bamboo culm are shown in Figure 2. Both with and without knobs, the longitudinal directions have higher strain.

Using bamboo rod for reinforcement of concrete, the bamboo-water interaction should be examined. Bamboo will swell or shrink during a wet-dry cycle, and consequently, causes a loosening at the bamboo matrix interface and cracking. Fore reinforced concrete, the bamboo absorbs the moisture from fresh concrete and swelling occurs. If the swelling pressure of the fibers is large enough, it pushes the wet concrete aside. At the end of the curing period when the concrete becomes hard, the bamboo having lost the water shrinks, leaving voids between the bamboo rod and the concrete. The mechanisms of bamboo-concrete interaction during the curing process are discussed in references (8) and (9). Figure 3 shows the water absorption potential of various bamboo culms, and how the sulphur treatment techniques can reduce the absorption potentials.

Substitute for Steel Bar in Structural Concrete

Using bamboo for reinforced concrete was started early in 1914 by H. K. Chu at Massachusetts Institute of Technology (2). Since then, similar studies have been made in China, Germany, France, Japan, the Philippines, India, Egypt, Colombia, and more recently at the Waterways Experiment Station (3). Based on their general conclusions, bamboo has three major weaknesses of low modulus, low bond stress and high water absorption potential which leads to swelling, shrinking and decay. Therefore, using bamboo for a substitute steel bar in structural concrete or other engineering applications creates certain problems. As mentioned previously, a low-cost simple technique using the sulphur-sand treatment of bamboo rod will give better results (10). The procedure can be briefly described as follows: all bamboo specimens were sand blasted and thin wire wrapped around the bamboo culm. Then the specimens were impregnated with molten sulphur at 280° to 300°F for approximately one hour and then air dried. Before the sulphur-impregnated bamboo is completely dry, a coating of sand is applied. The main reasons for treating bamboo with molten sulphur are: to increase the confined pressure and to reduce the cracks during loading conditions, to waterproof the bamboo to minimize its swelling-skrinking potential as shown in Figure 3, and to aid the uniform coating of sand adhere to the bamboo surface making a rough surface in order to increase the bond strength between the bamboo and concrete. A series of experiments using 6"x6"x30" (15.2cm x 15.2cm x 76.2cm) and 6"x6"x72" (15.2cm x 15.2cm x 182.9cm) bamboo-concrete beams for examining the load-deflection characteristics of the beam were conducted. Various water-cement ratio, size of bamboo culm, and position of bamboo culm in the concrete beam were studied. The curing periods were all reached in 28-days. A typical load-deflection curve is shown in Figure 4 and the failure mode of the bamboo-concrete beam is shown in Figure 5. In all cases, the concrete portion reached failure first (see points A,B,C, and D in Figure 4) and the bamboo fiber in the concrete held together showing the ductility characteristics of concrete structures.

It is understandable, that for bamboo reinforcing concrete there is much less strength than in steel reinforced concrete in compression, bending, and rupture, however, bamboo shows high strength-weight ratio and a unique behavior of ductility which is very useful in earthquake regions or in developing countries (15,19) especially for low-volume road construction.

Reinforced Earth with Bamboo

The purpose of reinforced earth is mainly to increase the bearing capacity of weak subgrade soils, or to increase the resistance for retaining structures. The original concept developed by Vidal (21) was used with thin metal strips placed horizontally in layers held together by internal friction between the reinforcing strips and the material. This technique has been used frequently in various highway projects around the nation for protecting dams, embankments, etc. against landslide potential. Recently, the concept has been extended to the use of other materials to form tensile reinforcement elements of various configurations and sizes, such as: plastic membranes, fabrics, timber or corduroy mat, bamboo mat or strips and paper grid cells (4,5,11, 13,16).

As previously mentioned, road construction requires large quantities of materials. Since the economic factor plays an important role for road construction, using inexpensive bamboo mat or strips is one of the most attractive materials for reinforced earth construction.

Seismic responses of bamboo-reinforced earth also show good results in comparison with non-bamboo reinforced embankments, earth dams, and adobe walls (8,11,14). Figure 6 shows the proposed field installation layout for bamboo used for reinforced earth. For the existing earth embankment or dams, the vertical-type bamboo-pile is recommended, as shown in Figure 6(a). The length of bamboo culm should be larger than the depth of the theoretical failure plane. This theoretical failure plane can be determined by conventional slope stability analysis which is available in any standard soil mechanics and foundation engineering textbook. Since bamboo culm cannot take large impact loading, it is suggested to first excavate a boring hole and then install the bamboo culm. The boring hole should be slightly larger than the diameter of the bamboo culm to be used. The voids between the bamboo and soil wall in the boring hole are then filled with bentonite or quicklime as shown in Figure 6(b). The small diameter type of bamboo (varying from 1cm to 5cm) with lengths varying from 3m to 5m is preferred. The bamboo culm should be placed with the top part first as shown in Figure 6(c). The reason for this is to utilize the bamboo's natural branches in order to increase the skin friction of the bamboo culm. For long-term use, the bamboo culm should be treated with molten sulphur as described in a previous section. Using quicklime as a filler between bamboo culm and soil wall in the boring hole has shown many advantages due to the natural characteristics of water absorption and volume expansion of quicklime (1,12). It also indicates that bamboo-lime composite pile not only increases the bearing capacity, but also has high earthquake resistance. This type of material is useful for reinforced earth in earthquake regions where the conventional construction materials are hard to get. It is also useful in low-volume roads, such as forest roads and many roads in developing countries (6,15,19).

For reinforcing new embankments or dams, the horizontal type of bamboo mat or strip is suitable, as shown in Figure 6(d), 6(e), and 6(f). Standard AASHTO compaction criteria should be applied on each layer, in order to minimize the voids between bamboo mat and soil layers. The bamboo strip or mat also should be sulphur treated. A suggested bamboo mat is shown in Figure 7.

Durability of Bamboo Structures

The durability of bamboo is one of the major objects for our concern. A review of the literature on bamboo durability indicates that there is very little factual information available. However, a survey was made on the performance of existing bamboo structures throughout the world indicating that bamboo structures could stand for a long period of time. Figure 8 shows one of the many case studies carried out by the Geotechnical Engineering Division at Lehigh University. It shows a non-treated bamboo culm used in reinforced concrete wall built in 1940 and found in the vicinity of Taichung Harbor, Taiwan in 1976. Based on observation, the bamboo culm inside the concrete block still is in excellent condition despite the ocean environment and long period of exposure. Laboratory study carried out comparisons between sulphur treated and non-treated bamboo culm used in concrete beams (6,7). Of course, more research should be done on the long term performance study of bamboo structures.

Summary and Conclusions

1. Bamboo is a fast growing replenishable biological material and can be found in many places around the world. It can be grown in temperatures between 7°C below zero to 50°C provided it has water.

2. All bamboo used for engineering purposes should be seasoned (3 to 6 years old).

3. Sulphur treatment of bamboo is low cost and easy to apply. This procedure can reduce the water absorption potential significantly during the concrete curing process. It also will increase the modulus of elasticity and bond stress.

4. Using bamboo mat or strip for reinforced earth is a low cost ideal construction material, especially useful in low-volume road construction, forest roads, and some developing countries where the conventional construction material is hard to obtain.

5. Using bamboo-lime composite pile for reinforcement of existing earth embankment or dams shows many advantages in earthquake regions because the bamboo culm will take lateral seismic loading effectively.

6. Bamboo-reinforced structural concrete also shows good ductility characteristics and useful in earthquake regions.

7. The strength-weight ratio of bamboo shows excellent potentials in comparison with any other construction material currently used.

8. Utilization of modern geotechnical engineering techniques, such as field moisture control, compaction methods or combination with other soil stabilization, such as bentonite or lime improves the stability of the bamboo reinforced earth systems.

9. Further study is needed in long-term performance of bamboo structures, improvement in the durability of bamboo with other additives, and engineering identification, classification and standard test procedures.

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Table 1. Summary of strength characteristics of bamboo culm (stem).

		Range	References
1	Tensile Strength		
	U.S.A.	485 to 1,760 kg/cm^2	(3) (9)
	Japan	390 to 3,789 "	(25)
	Philippines	Ave. 1,674 (with knob) Ave. 2,371 (no knob)	(3)
	India	Ave. 1,547 (inner layer) Ave. 3,199 (outer layer)	(18)
	Egypt	Ave. 1,920 (with knob) Ave. 2,600 (no knob)	(24)
	China (Taiwan) Ma-bamboo Makino-bamboo	 2,546 to 2,751 3,061 to 3,452	(17) (22)
2	Compressive Strength, kg/cm^2		
	U.S.A. and others	460 to 610	(3) (20)
	Taiwan	404 to 929	(6) (17) (22)
3	Modulus of Elasticity, kg/cm^2		
	U.S.A. and others	54,300 - 149,100	(3) (6)
	Taiwan	45,313 - 176,988	
4	Modulus of Rupture, kg/cm^2		
	Taiwan	649 - 2,180	(17) (22)
5	Specific Gravity	0.30 to 0.80	(3) (22) (17) (25)
6	Poisson's Ratio	0.25 to 0.409	(3)
7	Coefficient of Thermal Expansion		
	Across Fiber ^oF Parallel to Fiber ^oF	Ave. 23.70 x 10^{-6} Ave. 1.42 x 10^{-6}	(3)
8	Creep - Stress-strain-time relationships	see Ref. (11)	

Table 2. Average strength-weight ratio of various construction materials

Material Types	Compressive Strength q, kg/cm^2	Specific Gravity G	Strength/Weigth Ratio q/G	Strength/Weight Index with respect to Steel
Bamboo	742.0	0.72	1030.06	1.26
Steel,hot rolled	6,400.0	7.80	820.51	1.00
Zelkova wood	558.5	0.700	797.86	0.97
Cast Iron	5,637.0	7.20	782.92	0.95
Quartz	2,000.0	2.65	754.72	0.92
Wrought Iron	4,227.0	7.70	548.96	0.67
Dolomite rock	1,500.0	2.80	535.71	0.65
Bronze	3,946.0	8.17	482.99	0.59
Copper	3,170.0	8.92	355.38	0.43
Sandstone	750.0	2.30	326.09	0.40

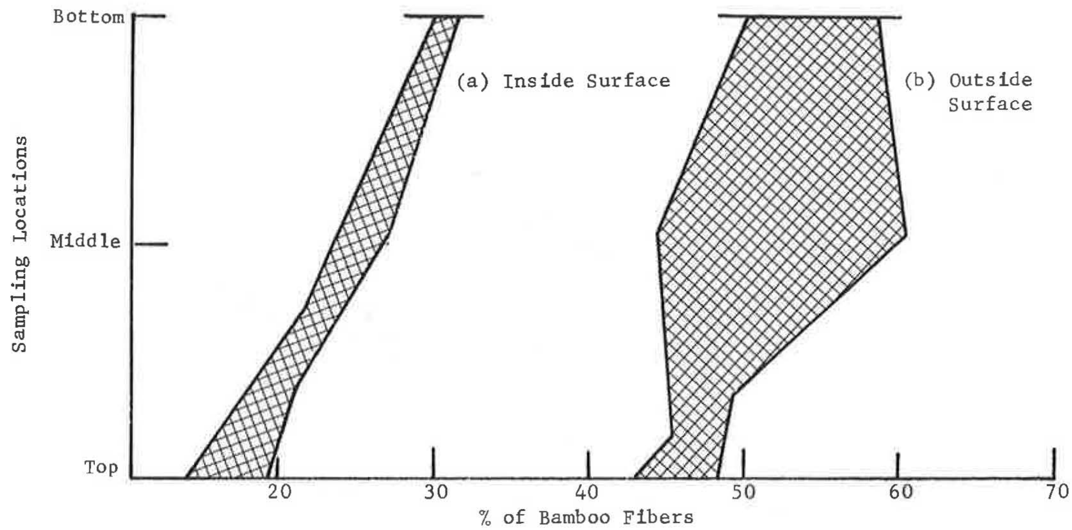

Figure 1 Variations of Bamboo Fiber Content at Various Parts of Bamboo Culm

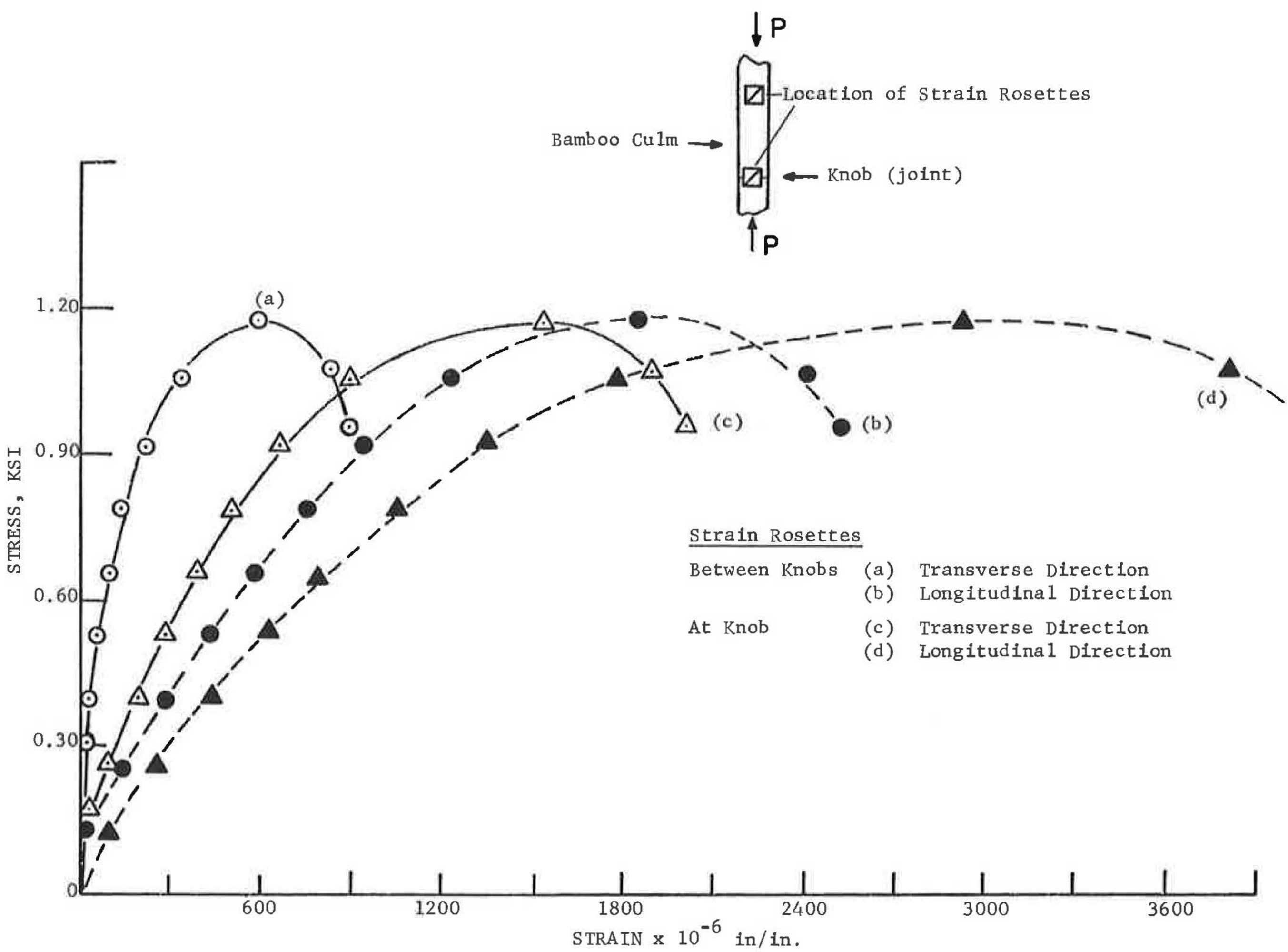

Figure 2 Stress-Strain Curves of a Pennsylvania Bamboo Culm

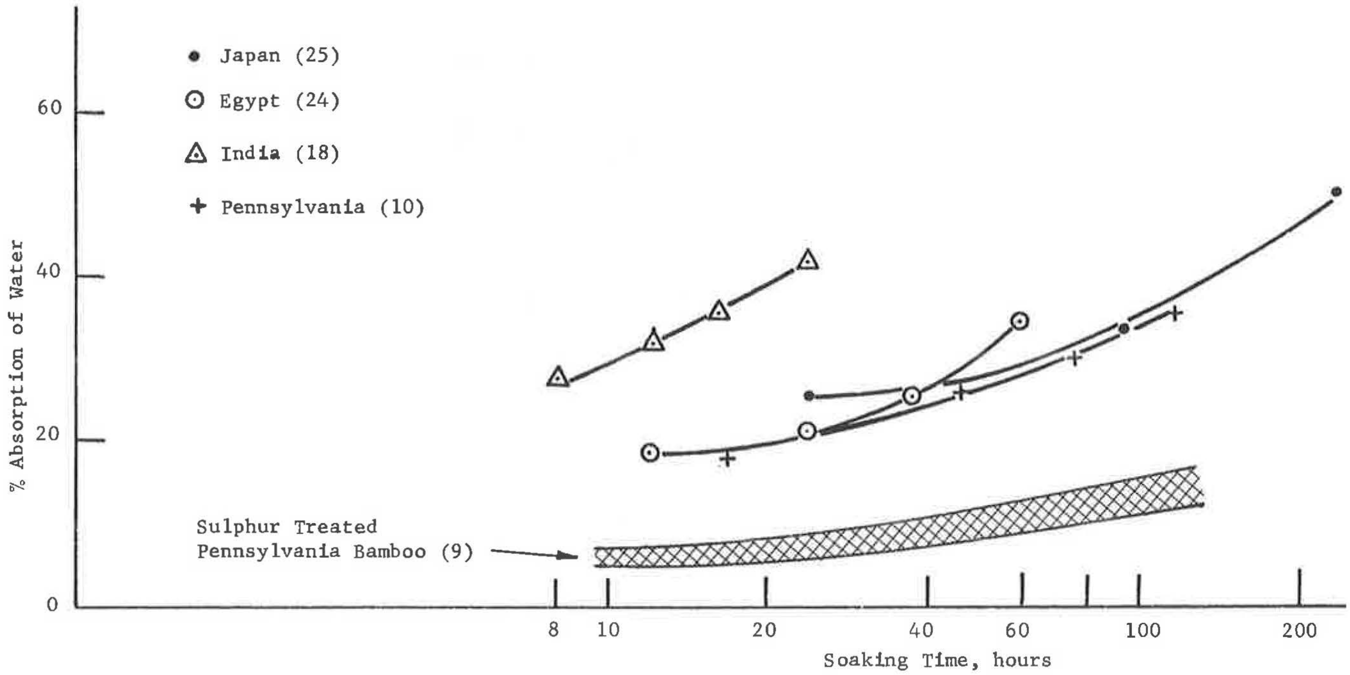

Figure 3 Absorption Characteristics of Various Bamboo Culms

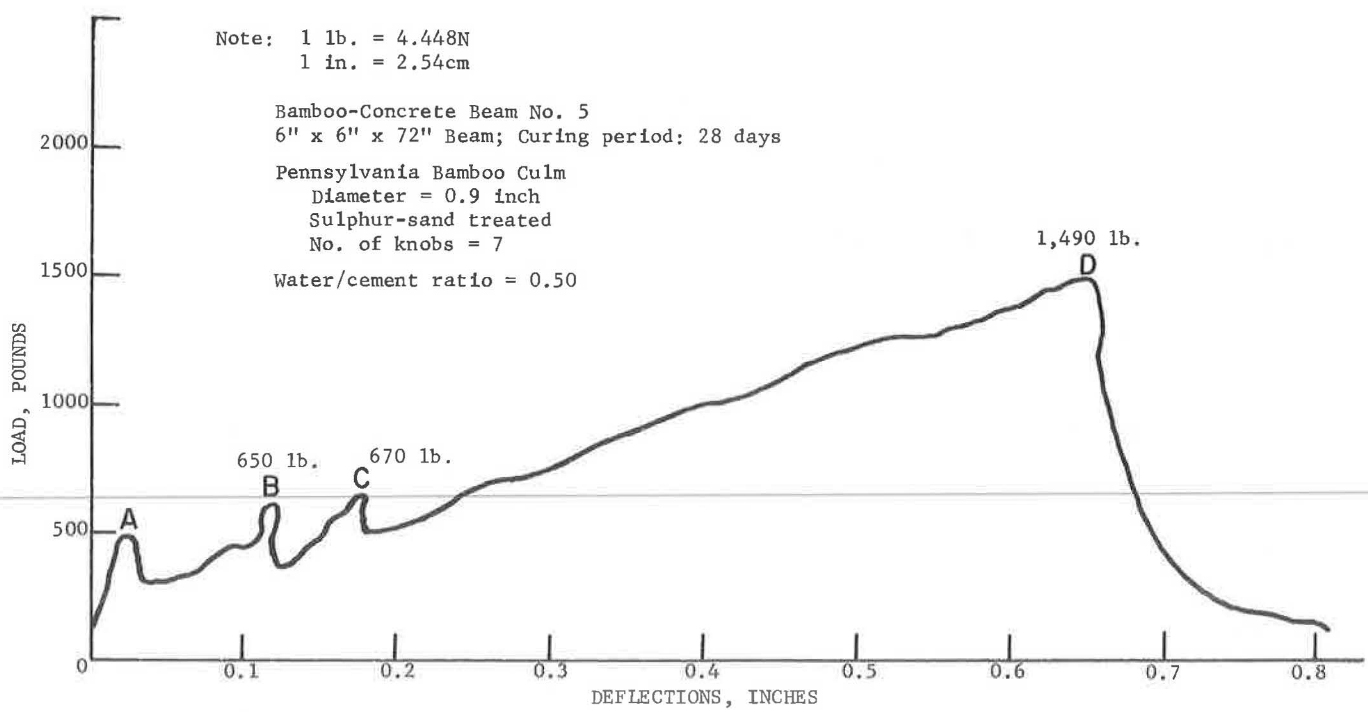

Figure 4 Load-Deflection Curve of Bamboo Reinforced Concrete Beam

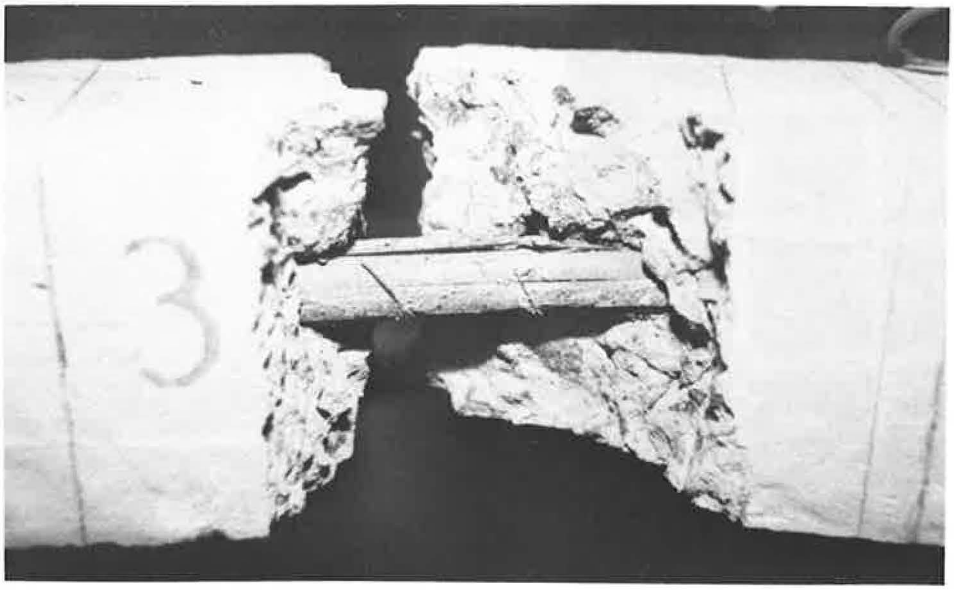

Figure 5 Failure Mode of Bamboo Reinforced Concrete Beam

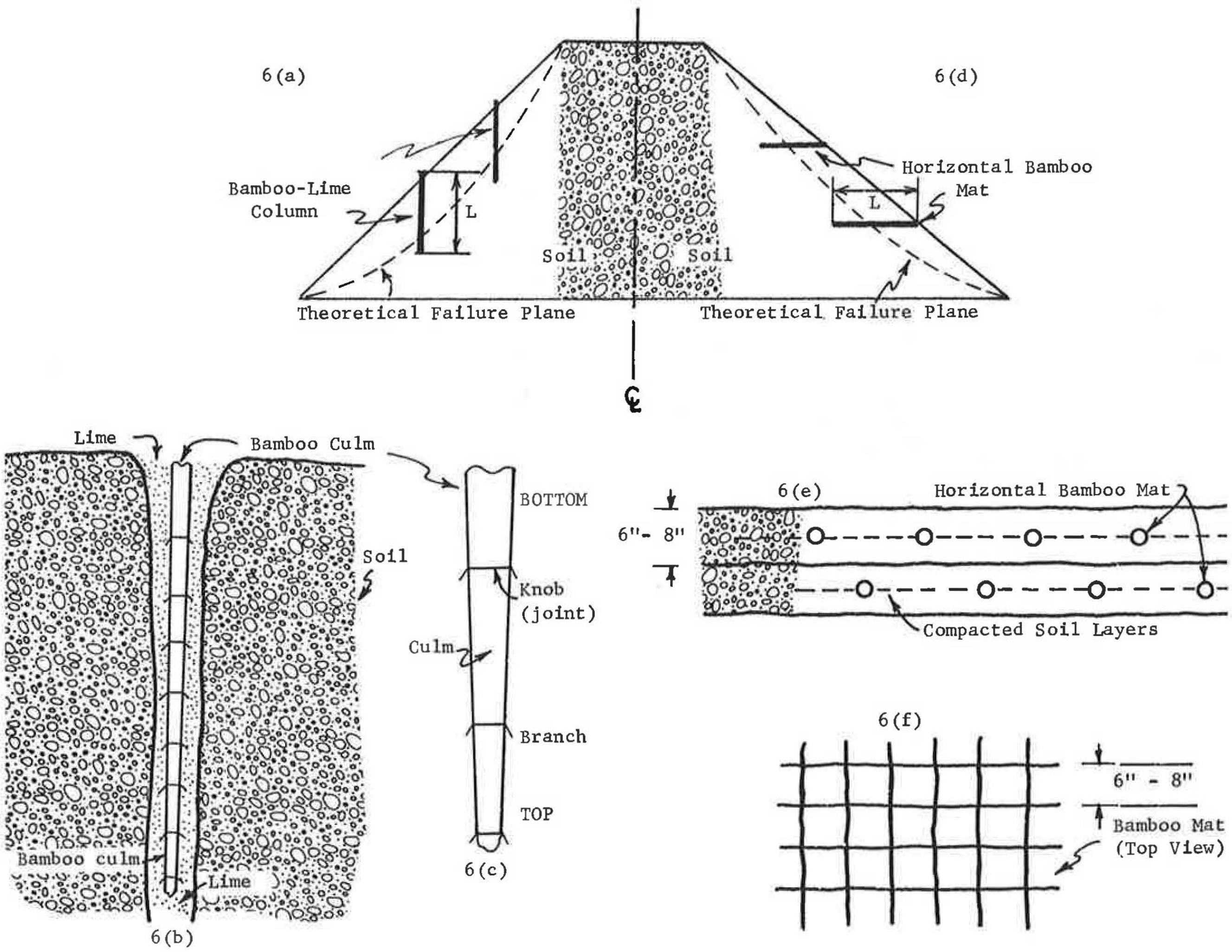

Figure 6 Proposed Field Installation Procedures for Bamboo Used as Reinforced Earth

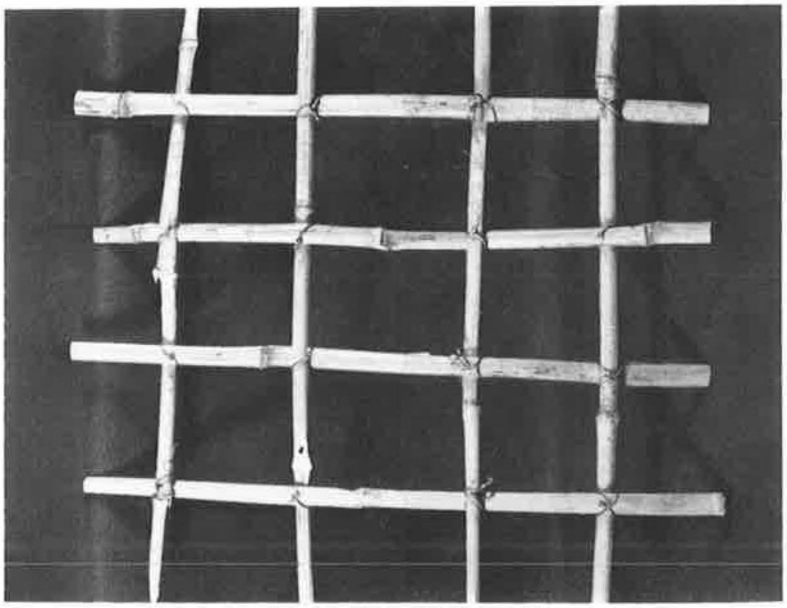

Figure 7 Bamboo Mat Used for Reinforced Earth.

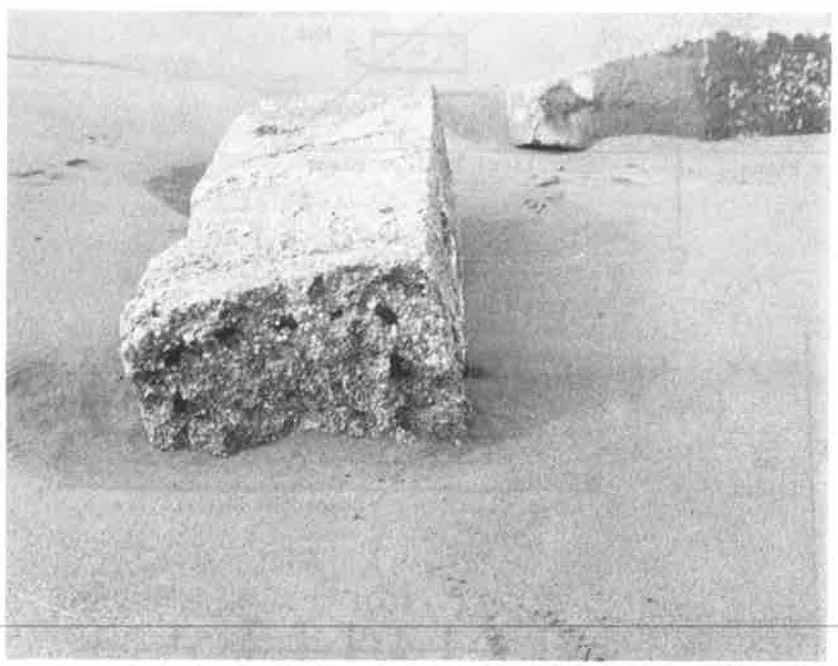

Figure 8 Bamboo Reinforced Concrete Wall Built in 1940 Found in Vicinity of Taichung Harbor, Taiwan, in 1976. Shows Bamboo Culm Inside the Concrete Wall Still in Excellent Condition. (Courtesy of H. C. Chiu, Taichung Harbor Construction Bureau)