ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Abolmaali and my committee members for their guidance and support throughout the duration of this research project. This project was funded by a grant from the National Science Foundation. I would like to recognize the following people for their hard work and dedication to this project: Young-Si as my research partner; Roshan Shakya for helping me in Mix Design; Olivia Corey, Kerri Parmer, and Jeremy Spray who were involved in the Research Undergraduates Experience Program sponsored by National Science Foundation and assisted in many phases of the research; Jimmy Lanhart and Tom Leeds for their machining expertise, suggestions and guidance; and Barbara Wallace who helped with all administrative matters. I would also like to give special recognition to my parents Mr. Dattetray and Mrs. Deepashri Khare and my brother Bhushan Khare without them none of this would have been possible. Lastly, I would like to express my gratitude to my fiancée, Abhijeet Patankar, for believing in me and encouraging me to pursue my dreams.

August 11, 2005
ABSTRACT

PERFORMANCE EVALUATION OF BAMBOO REINFORCED CONCRETE BEAM

Publication No ______

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This study presents the evaluation of the feasibility of the use of bamboo as a potential reinforcement in concrete structural members. To achieve this objective, a series of tensile tests on three types of bamboo—Solid, Moso, and Tonkin—were conducted to obtain their constitutive relation. Also, four-point bending tests on concrete beams reinforced with bamboo were performed to identify their behavior compared to steel reinforced concrete members.

Tensile tests specimens were prepared by cutting the bamboo typically in $\frac{1}{2}$ in (13 mm) wide strips of 9 to 12 in (228 mm to 305 mm) in length. In order to prevent
crushing of the bamboo samples when placed in grips of the MTS machines end-tabs were epoxy glued to the bamboo samples. The results for the tensile tests which we performed indicated that the presence of nodes in Solid Bamboo samples did not affect the behavior. There was an indication that the fracture points of the tensile samples containing nodes occurred at the nodes, which was also verified in the beam tests. In general, samples failed in one or more of the following ways: (1) node failure; (2) end-tap failure; and (3) failure at the vicinity of the end-tap. Tensile tests of the three aforementioned bamboo types showed that the specimens with nodes behaved in a less ductile manner with higher strength than those without nodes.

Six four-point bending tests were conducted on 8 in x 20 in x 96 in (203 mm x 508 mm x 2429 mm) reinforced bamboo concrete beams. The variables used with test beams were two a/d ratios (1.5 and 2), four percentages of reinforcement (1%, 2%, 3% and 4%), and bamboo types (Moso and Solid). Tonkin bamboo was used for stirrups due to their highly ductile behavior observed during the tensile testing. Strain gages were applied at L/2 and L/4 of the beam and one on the stirrup at a distance ‘d’ from the support for each beam. Coating was applied over strain gages to protect them from damage during casting. The test set-up consisted of placing the test beam under the Baldwin universal testing machine. A 200 k (890 kN) load cell was placed on the top of a rigid-beam, which was used to transfer the load from the hydraulic cylinder to the concrete beam through the two roller supports. Instrumentation consisted of a laser
sensing device capable of measuring up to 4 in (102 mm) displacement with the accuracy of $1 \times 10^{-4}$ in (0.00254 mm). White washing material was applied to the beam for crack detection during testing. The initiation and widening of cracks and their respective loads were recorded. The test results were compared with plain concrete and steel reinforced concrete beams behavior. In general, the test results indicated that bamboo reinforcement enhanced the load carrying capacity by approximately 250% as compared to the initial crack load in the concrete beam. This study also showed that the ultimate load carrying capacity of bamboo reinforced concrete tested, on averaging all percent reinforcement, was about 35% of the equivalent reinforced steel concrete beams. The load carrying capacity of the Moso Bamboo reinforced beam was higher than that of Solid Bamboo reinforced beam. Also, the Solid bamboo reinforced beam in general deflected less than the Moso bamboo reinforced beam indicating that Moso bamboo behaved in a more ductile manner. Stirrups design provided small resistance to shear forces. Also, it was noticed that a direct relationship existed between the percentage of reinforcement and the load carrying capacity of the beams tested.
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CHAPTER 1
INTRODUCTION

1.1 Background

In most countries, concrete is widely used as the foundation for the infrastructure. Concrete is used largely because it is economical, readily available and has suitable building properties such as its ability to support large compressive loads. However, the use of concrete is limited because it has low tensile strength. For this reason, it is reinforced, and one of the more popular reinforcing bars (rebar) is steel. Steel has a relatively high tensile strength, as high as 115 ksi (792 N/mm$^2$), complementing the low tensile strength of concrete. It is available and affordable in most developed countries but unfortunately not all parts of the world. In many countries, none or very little steel reinforcement is used in construction, which is evident from the crumbling of buildings as in Figure 1.1

![Figure 1.1 Failure of Concrete Building](image-url)
Steel reinforcement at some point may no longer be available. Even today there exists a need for more economical and readily available substitute reinforcements for concrete.

In some parts of the world many buildings are constructed only with concrete or mud-bricks. This is dangerous in case of seismic activity. These buildings have little hope of standing in the case of an earthquake. Steel reinforcement would be an ideal solution, but cost is a considerable problem. Scientists and engineers are constantly seeking for new materials for structural systems; the idea of using bamboo as possible reinforcement has gained popularity.

1.2 Bamboo Characteristics

Bamboo is giant grass, not a tree. Bamboo culms (Figure 1.2) are a cylindrical shell divided by solid transversal diaphragms at nodes and have some intriguing properties such as high strength in the direction parallel to the fibers, which run longitudinally along the length of the culm, and low strength in a direction perpendicular to the fibers. The density of fibers in cross-section of a bamboo shell varies with thickness as well as height. Fiber distribution is more uniform at the base than at the top or the middle. This is because bamboo is subjected to maximum bending stress due to wind at the top portion of the culm (Ghavami 2004)

Bamboo is a natural Functionally Graded Material (FGM). It is a composite with hierarchical structure. The strength of bamboo is greater than most of the timber products.
Figure 1.2 Whole Bamboo Culms

Figure 1.3 Variation of inter-nodal length, diameter and thickness along the whole bamboo culms (Ghavami 1995)
The mechanical properties vary with height and age of the bamboo culm. Research findings indicate that the strength of bamboo increases with age. The optimum strength value occurs between 2.5 and 4 years. The strength decreases at a later age (Amanda and Untao 2001). The function of the nodes is to prevent buckling and they play a role of axial crack arresters.

One major problem with bamboo is that it is a living organism which is subject to fungi and insect attacks. Bamboo is more prone to insect attack than other trees and grasses because of its high content of nutrients. In order to combat this problem, it becomes necessary to treat the bamboo to protect it from the environment. One of the amazing aspects of bamboo is the way it interacts with the environment. It has been discovered that bamboo can prevent pollution by absorbing large amounts of nitrogen from waste water and reducing the amount of carbon dioxide in the air (Steinfield 2001).

1.3 Bamboo as a Construction Material

Bamboo reaches its full growth in just a few months and reaches its maximum mechanical strength in just few years. Its abundance in tropical and subtropical regions makes it an economically advantageous material. Some of the positive aspects such as a lightweight design, better flexibility, and toughness due to its thin walls with discretely distributed nodes and its great strength make it a good construction material. Bamboo is used as structural material for scaffolding at construction sites in India, China and other countries as it is a tough, flexible, light weight and low cost material. In nature when bamboo is covered with heavy snow, it will bend until it touches the ground without breaking. This implies that bamboo has greater flexibility than wood.
“The energy necessary to produce 1 m$^3$ per unit stress projected in practice for materials commonly used in civil construction, such as steel or concrete, has been compared with bamboo. It was found that for steel it is necessary to spend 50 times more energy than for bamboo”. The tensile strength of bamboo is very high and can reach 54 ksi (370 N/mm$^2$). This makes bamboo an alternative to steel in tensile loading applications. This is due to the fact that the ratio of tensile strength to specific weight of bamboo is six times greater than that of steel (Amanda et al. 1997)

1.4 Applications of Bamboo

Bamboo has been and is being used in a wide variety of applications such as recreation, defense, housing and construction. In regards to recreation bamboo has been used to construct a variety of musical instruments. In addition to the fact that bamboo can be used in the arts, it can also be eaten. The market for bamboo shoots has grown rapidly in the last years. In fact Taiwan exports $50 million dollars worth of shoots that are eaten worldwide. One of the major applications of bamboo is for construction and housing. It is estimated that one billion people live in bamboo houses. It can also be used to make furniture. Over a period of nine year the exports of bamboo furniture almost doubled in Philippines. In India and China bamboo is used in construction of temporary suspension bridges. In Tokyo and Hong Kong it is used as scaffolding in high rise buildings.

There is a company that currently manufactures surfboards out of bamboo (www.bamboosurfboards.com.au). Bamboo can also be used in the arts. It can be fashioned into many shapes leading to artistic freedom as bamboo has been crafted into
furniture, decorative items such as home decoration, dishware, dolls, toys, jewelry and more. The imagination goes on forever and so does the artist as shown in figures 1.4 (a) and (b).

Figures 1.4 (a) Bamboo Bicycle and (b) Bamboo Street Sweeper

Bamboo is also a popular tool for acquiring food: as bamboo fishing rods have been used to catch fish for long time. In earlier times, bamboo could be used as a blunt
weapon, or it could be sharpened to provide food or defense. It would also make a decent shaft for a spear.

Even in the US, bamboo is beginning to gain exposure as flooring and paneling. There are companies that make plywood out of bamboo called ply-boo.

1.5 Comparison of Bamboo and Steel

One of the properties that would make bamboo a good substitute to steel in reinforced concrete is its strength. The strength of bamboo is greater than most timber products which are advantageous, but it is approximately half the tensile strength of steel. Bamboo is easily accessible as it grows in almost every tropical and subtropical region, this lowers the cost of construction and increases the strength of the buildings that would otherwise be unreinforced. One major problem with bamboo is that it attracts living organism such as fungi and insects. Bamboo is more prone to insects than other trees and grasses because it has a high content of nutrients. In order to combat this problem, it becomes necessary to treat bamboo to protect it from the environment. Steel does not have this problem but it also needs to be coated in order to protect it from rusting. Bamboo is very light in weight compared to steel. Due to its low modulus of elasticity, bamboo can crack and deflect more than steel reinforcement under the same conditions. These aspects put bamboo on the list of viable construction materials. These properties, when combined, suggest that bamboo will make a fine addition to the current selection of materials, but it is necessary that people in general be made more familiar with its strengths and weaknesses.
1.6 Goals and Objectives

The goal of this research is to determine the feasibility of bamboo reinforcement for concrete beams. Whereas the mechanical properties and behavior of steel reinforced concrete have been thoroughly studied and well documented, there exists no comprehensive data describing Bamboo reinforced concrete. Therefore, the aim of this study is to provide a preliminary contribution toward the collection of the mechanical properties and behaviors of Bamboo reinforced beams.

In concrete, reinforcement is put in place to provide tensile strength, a property that concrete lacks. Therefore, if Bamboo is to be used as concrete reinforcement, it is necessary to understand how Bamboo behaves in tension. This study will consider three species of Bamboo—Moso, Solid and Tonkin. All types will be seasoned, cut into thin strips, and tested without waterproofing agents. Once all the data is collected, a series of stress vs. strain graphs will be constructed and analyzed to determine the tensile properties of Bamboo.

To examine the behavior of Bamboo in concrete, four-point bending tests of Bamboo reinforced concrete beams will be conducted. Only two types of Bamboo will be considered in these tests—Moso and Solid. These will be dried, cut into ¾ in (19 mm) wide 7 ft 9 in (2.36 m) long strips, and treated with a waterproofing agent. The beams will be 8 ft (2.44 m) long, 8 in. (203 mm) wide and 20 in (508 mm) deep. The following parameters will be varied: (1) four different percentage reinforcement (1%, 2%, 3% and 4%); (2) two different a/d ratios; and (3) two types of bamboo will be used.
When the tests will be completed, the results will be compared with steel reinforced balanced section and plain concrete beams to compare their performances.

1.7 Literature Review

This section presents a literature review spanning the range of the complex biology of Bamboo for understanding to prior research conducted on mechanical behavior and different applications of the Bamboo.

Ghavami (1995) discussed the mechanical properties of Bamboo, specifically pertaining to Bamboo in concrete. This study showed that the ultimate load of a concrete beam reinforced with Bamboo increased 400% as compared to un-reinforced concrete. It was found that, compared to steel, there was lower bonding between the Bamboo and concrete, and the Bamboo had an Modulus of elasticity 1/15 of steel. Bamboo’s compressive strength was much lower than its tensile strength, and there was high strength along the fibers, but a low strength transverse to the fibers. Stated is the need for the development of a simple design code for the application of Bamboo as a construction material.

Ghavami (2004) studied the mechanical properties of six different types of Bamboo, proper treatments that should be applied to Bamboo, and the methods that should be employed when utilizing Bamboo as concrete reinforcement. The positive attributes of Bamboo are listed, supporting its environment-friendly nature. Some negative attributes of Bamboo were also given, focusing on its tendency to absorb water. The properties of Bamboo were found to be based upon a functionally graded construction, with its most important property being that its ratio of strength to specific
weight is six times greater than steel. Test results showed the ideal value for the percentage of Bamboo in concrete to be 3% of the cross-sectional area of concrete beam, allowing for the highest applied load, and the necessity for drying and water repellent treatments. This study concluded that Bamboo can substitute steel satisfactorily, and that there is a need to establish the characteristic strength of Bamboo for design purposes.

The United States Naval Civil Engineering Laboratory (1966, 2000) reported a study providing a set of instructions on how to properly construct a variety of structures and structural elements using Bamboo. This study suggested not to use green, unseasoned Bamboo for general construction, nor to use un-waterproofed Bamboo in concrete. Concerning Bamboo reinforced concrete, it was found that the concrete mix designs may be the same as that used with steel, with a slump as low as workability will allow. It was recommended that the amount of Bamboo reinforcement in concrete be 3-4% of the concrete’s cross-sectional area as the optimum amount. It concludes that Bamboo reinforced concrete is a potential alternative light construction method at a low cost.

Lo et al. (2004) gave a detailed description of the mechanical properties of Bamboo in their study. They found that the physical, as well as mechanical attributes vary with respect to diameter, length, age, type, position along culm, and moisture content of Bamboo.

Amada et al. (1997) investigated the mechanical and physical properties of Bamboo. They conducted a thorough investigation into the structure and purposes of
the nodes, which they found to strengthen the Bamboo culm. They also commented on the advantage Bamboo has over other natural building materials with its fast growth rate.

Masani (1977) conducted an in-depth study outlining the proper ways to utilize Bamboo in construction. A listing of the positive aspects of Bamboo is given, citing examples pertaining to its economical, mechanical, and environmental properties. When used as reinforcement in concrete, directions are given to insure a better performance, including discussions on waterproofing, pressure-treating, concrete design, and beam design. This study found that the Bamboo reinforcement area should be 5 times the typical steel reinforcement area, and that even when fine cracks develop on the surface of Bamboo, the load carrying capacity of the member is not reduced. The only negative properties of Bamboo given are its susceptibility to attack by insects, fungi and dried bamboo is prone to catch fire.

Amada and Untao (2001) studied the fracture properties of Bamboo. In contradiction to other studies, this study states that the tensile strength of Bamboo fibers almost corresponds to that of steel. The main discovery is that the fracture properties of Bamboo depend upon the origin of fracture. In the nodes, it is found that the average fracture toughness is lower than the minimum value of the entire culm, suggesting that the fibers in the nodes do not contribute any fracture resistance.

Power (2004) tells of a study conducted by the U.K. Department of International Development in response to a devastating earthquake that killed 40,000 people in Iran. The engineers were looking for cheap earthquake-proof housing to take the place of
mud brick. They constructed a prototype Bamboo reinforced concrete house and used an earthquake simulator to find that the house stood sound during a 7.8 (on the Richter scale) earthquake. They found no cracking in the concrete, the Bamboo to be extremely resilient to earthquakes, and the cost to be split in half compared to mud-and-brick construction.

A study reported in International Network for Bamboo and Rattan (INBAR) (2005) compared Bamboo to other plants such as trees by looking at how fast it grows the basics of the plant, its habitat, its history and its modern uses. For instance, we see that the same height tree takes just as many years to replace as Bamboo takes days. A single Bamboo clump can spread 15 km in its lifetime. Bamboo is the most diverse group of plant in the grass family and has tropical and subtropical distribution spreading from 46N to 47S latitude, giving many cultural uses for Bamboo.

Steinfeld (2001) researched the remarkable current uses of Bamboo around the world. In the United States, it is almost completely used as decoration. A discussion is presented on the astonishing feature Bamboo brings to the table as mentioned in other articles. Another special feature about Bamboo is that harvesting Bamboo does not harm the plant, producing more of its timbers. Bamboo buildings are definitely a prospect of the future in the US; however in Asia, the Pacific islands, and South & Central America, they are quite traditional. The main prevention of Bamboo structures in America are building codes. There are not standardized codes for buildings of Bamboo though there are attempts towards them. Bamboo is also still being looked at as
a way to clean environmental pollution. It is a consumer of Nitrogen, which could soon be part of a huge effort to prevent air pollution.

The American Bamboo Society (2005) provided a very intricate collection of specialized terms followed by their definitions relating to Bamboo. It also has a glossary of questions and answers common to someone new to the topic. These questions ranged from identifying Bamboo, preserving Bamboo, finding help with your Bamboo, to other topics not as closely connected to the research of this project.

A study reported in International Network for Bamboo and Rattan (INBAR) (2002) considered the advantages and disadvantages of Bamboo used as a structural material. The advantages found in their study concluded to be areas of: ecological value, good mechanical properties, social and economic value, and energy consumption. They found disadvantages to be: preservation, fire risk, and natural growth.

Mardjono (1998) provided research with the effort to give some sort of organization of a system to building with Bamboo between cultures, species, and countries having varying designs. The objective of their research was to improve the functions of Bamboo buildings by this organization to provide privacy, safety, comfort, durability, and accessibility. Overall Bamboo used as a structural material suffers from an incredible disadvantage due to inadequate applied scientific research. They do feel that Bamboo products should be brought to the level of acknowledged and received building materials. The results of their research will be published as a thesis and guide for designing Bamboo structures to be dispersed to people in developing countries.
A study reported in International Network for Bamboo and Rattan (INBAR) (2002) coordinated research and a project located in Costa Rica with the Technical University of Eindhoven as the supervisor, with the aim as Bamboo to be used as a building and engineering material. They found that their project in Costa Rica has become a success story due to the fact that it was “a local initiative and the staff was fully national.” In 1999, 3 drafts were submitted to National Standard Institutes of 20 growing nations seeking support, which lead to having the drafts accepted as draft International Standard Organization texts in 2001.

A Study reported in International Standard Organization (ISO) (1999) provides the first draft for International Standard that applies to Bamboo structures based on their performance and on limit state design. The limit states are defined as states beyond which the structure no longer satisfies the design performance stipulations. The two limit states are split into ultimate limit states and serviceability limit states. Ultimate limit states are those related with structural failure which may jeopardize the safety of people. Serviceability limit states match up to states beyond specified criteria. This International Standard is only worried about the necessities for serviceability, mechanical resistance, and durability of structures. Bamboo used as composite makeup may require additional considerations beyond this Standard. This article is a compliment of Determination of Physical and Mechanical Properties of Bamboo (1999) and Laboratory Manual on Testing Methods for Determination of Physical and Mechanical Properties of Bamboo (1999).
A study reported in International Standard Organization (ISO) (1999) composed a second standard that covers a group of tests on specimens of Bamboo that are carried out to find data, which can be used to institute characteristic strength functions and to land at the allowable stresses. The figures can also be used to establish the connection between mechanical properties and factors such as density, moisture content, and growth site, incidence of node and internodes, and arrangement along the culms. The article supplies methods of testing Bamboo for evaluating the characteristic physical and strength properties to follow: density, moisture content, shrinkage, compression, shear, bending, and tension. The purpose of the article overall is to provide clear essentials for standard tests that need to be carried out in order to determine the properties of Bamboo as a building or engineering material. This article is a complement to Bamboo Structural Design (1999) and Laboratory Manual on Testing Methods for Determination of Physical and Mechanical Properties of Bamboo (1999).

A study reported in International Standard Organization (ISO) (1999) fashioned a lab manual for determining the physical and mechanical properties of Bamboo. The purpose for publishing this manual is first of all so that these methods are available all over the world. Research is done in so many places, very precise, yet is stuck in the laboratories. With this document, the methods are made available. Secondly, this document gives a practical step by step explanation of how to perform each test specifically following the International Standard Complement Document “Determination of Physical and Mechanical Properties of Bamboo.” Another complement document is Bamboo Structural Design (1999).
Janseen (2000) conducted her study on building with Bamboo. This book covered a wide variety of aspects of Bamboo going back to the structure of the plant and its natural habitat. It gives calculations to show why it’s economically competitive, mechanical properties, its many uses, its natural durability, and the preservation of the Bamboo. In much more detail, it discusses the joints and building with pure Bamboo. In relation to this project, her book does touch on Bamboo used as reinforcement in concrete. Listed in her book are several things that are more of a hassle than steel reinforcement. Of those, the bonding between the Bamboo and concrete is considered the biggest problem due to absorption of water and smooth wall of the Bamboo culm.
Chapter 2 presents the experimental program of this research consisting of tensile testing of bamboo materials and four-point bending tests of bamboo reinforced concrete beams. Tensile tests involve specimen preparation, application of epoxy to the specimens to apply end-taps, test set-up and instrumentation. Beam testing includes beam design, concrete mix design, bamboo preparation, reinforcement preparation, form preparation, concrete casting, and the conduction of the tests. The beam test set-up and instrumentation are described in detail. Finally, the loading history and testing procedure are presented.

2.2 Tensile Tests

2.2.1 Specimen Preparation

In order to conduct the tensile tests, it was necessary to prepare the bamboo samples. First, the samples were cut to the proper size and shape. The length of the samples was largely determined by the distance between the nodes. Most of the samples tested were between 9 and 12 in (229 and 305 mm) long. The widths of the samples were reduced since some of the original samples were too strong to be broken. The thickness, along with the width, differed between the samples because Bamboo is a natural material whose physical properties vary. For this reason a careful dimensioning of the sample was done before testing the bamboo.
The dimensions were measured at five points along the length of the sample. To calculate average dimensions of the test specimen. The five points included the midpoint, the ends, and two points approximately halfway between the middle and the ends. The distance between these points was measured and recorded, along with the width and thickness. These dimensions are pictured below in Figure 2.1. Measuring the dimensions of the specimens made it possible to determine the average stresses and strains in each sample.

Since the information given in literature is limited with regards to the effect of the node on bamboo’s strength, it was desired to investigate this effect. Thus, some samples with nodes were selected to compare their behavior to un-noded samples. The samples with nodes were prepared so that a node was at the center of the gauge length.

To protect the bamboo from being crushed by the grips of the testing machine, aluminum tabs were fabricated and applied to the bamboo samples as shown in Figure 2.2. Figure 2.3 also shows a size representation of the aluminum tabs.
Figure 2.2 Photograph of the Aluminum Tabs

Figure 2.3 Size Representation of Aluminum Tab

Figure 2.4 Tensile Specimens with Aluminum Tabs
Figures 2.4 and 2.5 represent finished test specimen for tensile test. For some of the first samples, the tabs were bent into a gentle curve in order for better contact to be made with the bamboo. However, after several trials it was determined that this was not necessary. When the bamboo and tabs were curved, the grips of the machine were only contacted the bamboo at three places. For this reason, the grips had to be tightened down with more force than the bamboo could withstand, often causing the aluminum tabs to lose their bond with the bamboo. This behavior was also related to the bonding agent that was being used: an epoxy with a tensile strength of 1000 psi (6895 kN/m²). At approximately 1000 pounds (4.4 kN) of load, the grip would fail due to a spike in the strain (elongation). Thus new epoxy was used called “JB Weld” brand weld; it has a tensile strength of 4000 psi (27580 kN/m²)

Since this study aims at using bamboo as reinforcement for concrete beams, the bamboo samples were waterproofed in order to be consistent with the reinforcement preparation.
2.2.2 Test Setup

For tensile strength testing a *MTS QTEST/150* machine was used. This machine is able to apply tensile loads of up to 34 kips (151 kN) which is shown in Figure 2.6.

![Tensile Test Setup](image1)

Figure 2.6 Tensile Test Setup

![Grips of the Tensile Machine](image2)

Figure 2.7 Grips of the Tensile Machine
An enlarged picture of the grips shows end tabs protecting the Bamboo at the grips, shown in Figure 2.7.

2.2.3 Load History

The machine that was used was setup to have a constant movement of the grips. This produced a loading history pictured in Figure 2.8.

![Figure 2.8 Loading History](image)

2.3 Beam Test

2.3.1 Beam Design

Since it is the purpose of this research to determine the feasibility of the use of Bamboo as reinforcement in concrete, it is necessary to compare its behaviors to steel, the traditional reinforcement. Therefore beam designs were in accordance with ACI and ASTM standards and specifications.

In the beginning of the beam design, the width-to-depth ratio of 0.4 was assumed, along with a width of the bamboo bars of ¾ in (19 mm), as suggested by
reference (U.S. Naval Civil Engineering Laboratory 1966, 2000) concerning bamboo reinforced concrete. Per ACI 318-02, the clear cover (the distance from the outside of the beam to the reinforcement, shown in Figure 2.9) is between 1.5 to 2 in (38 and 51 mm) for steel reinforced concrete, and the clear spacing between reinforcement be the greater of 1 in (25 mm) or 1.33 times the maximum aggregate size, with a minimum of 1 in (25 mm). Both the clear cover and the spacing were chosen to be 1.5 in (38 mm). Considering these dimensions and those that would allow for practicality of testing and construction, a width of 8 in (203 mm) and a depth of 20 in (508 mm) was chosen for the test beam as shown in Figure 2.10.

![Figure 2.9 Beam Cross Section](image)

Due to unknowns associated with the behavior of bamboo reinforced concrete, the percentage of reinforcement area was varied from 1% to 4%, as suggested by literature concerning Bamboo reinforced concrete (Mardjono 1998). This introduced a
variable depth, d, measurement for test beams. Figure 2.10 shows the typical arrangement of reinforcement, and distance d for 4% reinforcement, where \( d = 14 \) in (355 mm).

![Figure 2.10 Cross-Section Dimensions](image)

The next step was to determine the length of the beam. Evaluating the lab conditions and desired testing set-up, a beam length of 8 ft (2.43 m) was chosen. Figure 2.11 shows the final dimensions of the test beam.

![Figure 2.11 Beam Dimensions](image)
The reactions were placed 6 in (152 mm) from each edge of the beam, thus providing a span length of 7 ft (2.13 m). With the length of the beam known, it was possible to determine the maximum feasible a/d ratio that could be tested.

![Figure 2.12 Definition of a/d Ratio](image)

For the a/d ratio, the ‘a’ is defined as the distance from the load to the support, and the ‘d’ is defined as the distance from the top of the beam to the center of gravity of reinforcement, as shown in Figure 2.12. Varying a/d ratio controls the extent of the region of constant moment, and thus the stress conditions in the beam.

Figure 2.13 shows that for smaller values of the a/d ratio, a comparatively smaller region of shear and larger region of constant moment exists, with a smaller magnitude of maximum moment causing final failure in shear or bonding. A larger a/d ratio has a larger region of shear, providing a larger region in combined shear and moment, and a bending moment with greater magnitude, causing final failure to more likely occur in flexure.
Since the behavior of bamboo reinforced concrete is not known, it was important for this research to observe how bamboo reinforced concrete responded to the variance of the a/d ratio, and to compare with the expected behavior of steel reinforced concrete.
The maximum feasible a/d ratio that can be tested on a beam with span length 7 ft (2.13 m) is approximately 2. Thus, two values of a/d were employed in designing the beam test matrix: a/d = 2.0; and a/d = 1.5.

2.3.2 Test Variables

The test variables used are: (1) Bamboo type; (2) a/d ratio; and (3) percent of reinforcement. The types of Bamboo used were Moso and Solid. The percentages of reinforcement tested were 1%, 2%, 3% and 4%. The a/d ratios were selected to be 1.5 and 2. All of the Bamboo received a waterproofing coating. Table 2.1 presents the test matrix:

<table>
<thead>
<tr>
<th>Test</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bamboo Type</td>
<td>Solid</td>
<td>Moso</td>
<td>Solid</td>
<td>Moso</td>
<td>Moso</td>
<td>Solid</td>
</tr>
<tr>
<td>% Area</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>a/d ratio</td>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>2</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>d (in)</td>
<td>14</td>
<td>16.81</td>
<td>16.81</td>
<td>16.81</td>
<td>17.375</td>
<td>14</td>
</tr>
</tbody>
</table>

2.3.3 Reinforcement Preparation

There is very limited information in literature regarding bamboo reinforced concrete concerning the design and construction of the actual reinforcement. Therefore it was the aim of this research to design the process of fabricating the reinforcement for the beams.
Since it was desired to reuse the formwork in which the concrete was poured, it was necessary to construct a free-standing reinforcement. Many methods were attempted before developing an efficient and successful method of creating the reinforcing structure.

It was known from literature that the finest width of the Bamboo strips was $\frac{3}{4}$ in (19 mm) (Mardjono 1998), providing the maximum area with the least amount of curvature. Since the beam was 8 ft (2.43 m) long, it was determined that the Bamboo culms needed to be cut 8 ft (2.43 m) long and $\frac{3}{4}$ in (19mm) wide without adjusting their thickness, as this could reduce the strength of the strips.

After the Bamboo was cut, it was waterproofed. Thompson’s brand deck water sealer was applied in a thin coat using a paintbrush to all of the strips. A thin coat is necessary to reduce the negative bonding effects that the waterproofing may have on the Bamboo. Next the Bamboo was cured for 24 hours before it could be handled. Benefiting from this project’s location in Texas during summer, the Bamboo was left outside to cure.

Choosing the best method to attach the Bamboo strips together required careful consideration. Different ideas consisted of using thin string or fishing line to tie the strips together. String or fishing line would not support bamboo bars well enough for the reinforcement to stay in the desired shape. The method eventually preferred for tying the Bamboo bars together was twisting ties.

After much deliberation, it was decided to tie each layer separately, and then tie the layers together. For the design of 4% reinforcement, five layers of reinforcement
were provided. This was determined by measuring the cross-sectional area of each strip of Bamboo, calculating the average area, then calculating how many strips at that given cross-sectional area would provide 4% cross-sectional area of the entire beam (For the remaining tests this method was changed to calculating the exact cross-sectional area of each strip, adding the total, and then calculating the required number of strips. This allowed for a more accurate calculation.)

![Figure 2.14 Hook Length of Beam](image)

Before tying the strips together, they were cut to the exact length needed. Generally with steel reinforced concrete beams, a hook length, as shown in Figure 2.14, is employed at the ends of the beam to enhance the bond between the reinforcement and the concrete. Due to the nature of Bamboo, it is impossible to provide this hook length. Therefore, the Bamboo strips of about 8 ft (2.4 m) long, were cut to 7 ft 9 in (2.667 m), to providing 1.5 in (38 mm) cover on either side of reinforcement as shown in Figure 2.15.
Another component of the reinforcement is the stirrup, which provides shear reinforcement. Figure 2.16 shows the two most common methods of providing stirrups.
Figure 2.17 Bamboo Stirrups Developed

Typical steel stirrups constructed were either open loop or closed loop stirrups, as shown in Figure 2.16. Bamboo, stirrups made of Tonkein was constructed as shown in Figure 2.17 and 2.18. Tonkin Bamboo was chosen because of its flexible nature. Tonkin Bamboo culms were split vertically with a knife, waterproofed, then bent into shape and secured with steel wire. This proved to be very difficult to manufacture. The closed loop type shown in Figure 2.16 was impossible to construct for the same reasons that providing the development length was impossible. Therefore, it was decided to make the U-shape without curving the ends, as shown in Figure 2.18.
For the first beam, each layer of reinforcement was made by securing each bar at each end and in the middle with small bamboo splints and steel wire. Considering the cross section dimensions and the width of the Bamboo strips, the spacing from the outsides of the outer two strips needed to be 5 in (127 mm). When the middle strip was placed in the center between them, a distance of 1.33 in (34 mm) between each strip was provided. Once all the layers were made, they were stood on one side and attached together a distance of 1.5 in (3.81 cm) center to center per ACI 318-02, again using Bamboo splints and steel wire. This is shown in Figure 2.20.

Next, thin strips of waterproofed Tonkein were attached at 6 in (152 mm) spacing along the longitudinal of the reinforcement with steel wire, as shown in Figures 2.18 and 2.19. The compression reinforcement was then attached to the stirrups with steel wire at a distance of 17 in (431 mm) from the bottom of the reinforcement, as determined from the beam dimensions. With the trimming of any excess Bamboo, the first reinforcement was completed.
The method used to construct the first reinforcement was tedious and slow. A more efficient method was needed for the following reinforcements. Instead of steel wire, steel rebar ties were employed to attach the Bamboo to the splints, as shown in Figure 2.21. Using the special rebar tie tool shown in Figure 2.20, this method proved to be more efficient.
Figure 2.21 Rebar Tie Tool and Ties

Figure 2.22 Tying Layers Directly to Stirrups
Also, instead of attaching the separate layers together with bamboo splints, the new technique involved tying the layers directly to the stirrups as shown in Figure 2.22. This also proved to be much faster, and more structurally sound, as the use of splints in the first reinforcement caused the Bamboo to shift. Thus, a more efficient and successful method was developed to construct the reinforcement. A final view of the reinforcement is shown in Figure 2.23, and in the formwork in Figure 2.24.

Figure 2.23 Finished Reinforcement

Figure 2.24 Finished Reinforcement in Form
2.3.4 Formwork Preparation

Formwork was constructed to support the freshly placed concrete and the Bamboo reinforcement of the beam, as shown in Figure 2.24. Basic concerns were accuracy of the design, pertaining to length and shape, as well as the finish of the beam. Elements used in the construction of the formwork were ¾ in (19 mm) BC plywood. The BC plywood ensured a clean smooth finish to the concrete, and the supports would help keep the measurements shaped after the concrete was placed inside the formwork. Lifts were attached beneath the form to enable easy movement by a forklift after the curing had taken place and the beam was ready for testing.

![Figure 2.25 Formwork](image)

2.3.5 Concrete Mix Design, Pouring, and Compression Tests

The concrete used for the beams was made using the Portland Cement Type I/II, limestone sand as the fine aggregate, and limestone coarse aggregate with a maximum
size of $\frac{3}{4}$ in (19 mm). The concrete mix proportions were 1:3:2.2 (cement: coarse aggregate: fine aggregate) and a water-cement ratio was 0.45. The mix was designed for seven day strength of 4000 psi (27560 kN/m$^2$), and a slump value of approximately 4 in (102 mm) to insure consistency concrete. The mix design’s ingredients and amounts are given in Table 2.2.

Table 2.2 Ingredients for Concrete Mixture

<table>
<thead>
<tr>
<th>Water</th>
<th>Cement</th>
<th>Coarse Aggregate</th>
<th>Fine Aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>lb/yd$^3$</td>
<td>kg/m$^3$</td>
<td>lb/yd$^3$</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>280</td>
<td>166</td>
<td>611</td>
<td>362</td>
</tr>
</tbody>
</table>

A typical beam had the dimensions of 8 ft x 20 in x 8 in (2.43 m x 508 mm x 203 mm) and the volume of 8.89 ft$^3$ (0.252 m$^3$). A single beam’s concrete mix was then reduced from the original mix design and designed for a rounded 10 ft$^3$ (0.283 m$^3$) mix. A water reducing agent was also added to the mix with a 3/100 cement weight. The mix for a 10 ft$^3$ (0.283 m$^3$) beam is shown in Table 2.3.

Table 2.3 Ingredients for Concrete Mixture (One Beam)

<table>
<thead>
<tr>
<th>Water</th>
<th>Cement</th>
<th>Coarse Aggregate</th>
<th>Fine Aggregate</th>
<th>Water Reducing Agent</th>
</tr>
</thead>
<tbody>
<tr>
<td>lb</td>
<td>kg</td>
<td>lb</td>
<td>kg</td>
<td>lb</td>
</tr>
<tr>
<td>80</td>
<td>36</td>
<td>226.3</td>
<td>103</td>
<td>685.2</td>
</tr>
</tbody>
</table>
After mixing the concrete in two batches, it was taken to the formwork. A 1.5 in (38 mm) clear cover was first placed in the bottom of the form and then the reinforcement was placed on top of that. Concrete was then placed into the form and around the Bamboo reinforcement. Using steels rods, the concrete was pushed down in between the reinforcement as well as in the more open areas to help ease out air pockets. Rubber mallets, acting as vibration tools, were then hit along the outside wall of the formwork to vibrate the concrete into spots that the steel rods might not have reached, and to settle the concrete in all the space provided. When all the concrete was added to the formwork, the top was finished off smoothly and the curing process began.

Cylinders were also prepared (as per ASTM standards) for compression tests. This was done by pouring them full of the same concrete used in the beam. The cylinders cured so that they could be tested in compression to tell the strength of the concrete at that point in the curing process. If several cylinders were made, tests could be performed each day of the curing process.

To find the strength of the concrete, the concrete would be removed from the cylinder and placed under a compressive load using a hydraulic compression machine. The machine would increase the load onto the concrete cylinder until failure was reached. When the concrete cylinders reached the desired values, the test could begin for the respective beam. Figure 2.26 shows a concrete cylinder, and Figure 2.27 shows a concrete cylinder loaded to failure in the compression machine.
2.3.6 Test Set-Up, Instrumentation, and Data Acquisition System

The test set-up began with picking up the beam with the forklift. The beam was then placed under the testing machine as shown in Figure 2.28. The beam was carefully placed to provide the supports at the measured placement of 6 in (153 mm) from each
end. With the forklift and the research team, the concrete beam and steel support beam were pushed sideways into place above the cylinder and between the bar frame of the hydraulic compression machine being used for the four point bending test.

Figure 2.28 Test Set-up

Instrumentation consisted of a dial gauge and a laser displacement device, both which were placed at the center of the beam to measure maximum deflection. Strain gauges were also attached to the Bamboo reinforcement, being placed in the critical areas of the beam to follow and record the strain behavior. One strain gauge was placed on a stirrup a distance ‘d’ from the support. A second strain gauge was placed in the center of the bottom layer of reinforcement, in the area of maximum bending moment (L/2). The third strain gauge was place a quarter of the way from one end of the reinforcement (L/4). A schematic of the strain gauge placement is shown in Figure 2.29.
Strain gages are very delicate devices, and they could not be applied on top of the waterproofing agent due to a chemical reaction between those and the adhesive. Therefore, to safely apply the strain gauges, the desired sections were taped over before waterproofing. Then the adhesive was applied to those sections. It then had to cure for 24 hours, providing a smooth, guarded surface for the strain gauges. After the curing, the strain gauges were applied, after which they also had to be pressed to cure for 24 hours so that they could be soldered. A photograph of strain gaged reinforcement is shown in Figure 2.30. A CEA-06-250 UW-350 strain gages supplied by Vishay micro measurements were used.
Following that, wiring was soldered to the strain gages and soldering terminals so that readings would be outputted during the test. A photograph of a wired strain gauge and soldering terminal is shown in Figure 2.31.

A multi-stage protective coating was applied over the wired strain gauge to prevent damage. A photograph of a protected strain gauge is shown in Figure 2.32.
The data acquisition system consisted of instrumentation to collect, digitize, and process sensor and signal inputs for the purpose of monitoring and analyzing the failure process. All of the components are shown in Figures 2.33 and 2.34.
The equipment used for measurements from the beam was the laser deflection sensor, the load cell, and the strain gages. The laser, manufactured by Micro-epsilon, measured the deflection at the center of the beam and transmitted these measurements as electronic signals to the InstruNet system. The load cell measured the load transferred through it and transmitted it to the precise digital controller. This digital controller, manufactured by Admet, was calibrated to match the load cell, and thus sent these calibrated readings to the InstruNet system. The strain gauges on the reinforcement were connected to wires attached outside of the beam. These wires were then connected to the instrumentation board set-up, which joined them to a Wheatstone bridge, reducing the voltage coming from the strain gauges so the InstruNet could accept it. The reduced voltage was then transmitted to the InstruNet system. The
InstruNet system converted all of the voltage readings obtained from the measurement equipment to digital signals on the computer. These signals were then converted to readable data through a PC card inserted into the computer.
CHAPTER 3
EXPERIMENTAL TEST RESULTS

3.1 Introduction

This chapter presents the results of the tensile tests and the four point bending beam tests conducted with Bamboo reinforced concrete using specified a/d ratios and percentage reinforcement. Tensile samples varied the presence of nodes to investigate their effect on Bamboo strength. Beam tests varied the a/d ratio where “a” is the distance from the support to the load and “d” is distance from the top fiber of cross-section to the center of reinforcement. The four point bending test used a load that was applied at a steady rate of approximately 75 lbs/sec (333 N/sec) with a flow of pauses for reading of deflection in the dial gauges and working with the data acquisition system. Crack propagation and failures were also recorded and dissected at the same time. Test designations were based on “Bamboo type – a/d ratio – percentage of reinforcement”. For example, beam Moso-R1.5-PR2 represents a test specimen with Moso Bamboo, an a/d ratio of 1.5, and 2% Bamboo reinforcement.

3.2 Tensile Test Results

The first set of tensile tests was conducted on different species of Bamboo to find a pattern of behavior based on the structure of Bamboo as a plant. These tests were performed on several specimens with and without nodes. The results suggested two vague patterns. The first pattern observed was that if a node was present, the failure
often occurred at the node as shown in Figures 3.1 and 3.2, which shows four different test specimens after failure at the nodes.

![Figure 3.1 Tensile Test Specimens](image)

The second pattern observed was that specimens with nodes often held a larger load before reaching failure in contrast to those without a node.

Examination of the node structure shows that the fibers in the nodes are much denser than those of the internodal regions. Also, the fibers which are straight elsewhere become chaotic in the node. Tests and study of Bamboo nodes indicate that the node may be very brittle and stiff, suggesting the reason why the specimen fails at the nodes. Test sample suggested the internodal regions of the Bamboo elongated until it reached a limiting value and then the load was transferred to the node.
It seems that constitutive relationship of the nodes differs from those of internodal regions with nodes having a brittle behavior while internodal regions exhibit a more ductile behavior. However, the ultimate strength of the node is anticipated to be higher than other regions.

Tensile tests were conducted on Tonkein Bamboo, which was used as the stirrup reinforcement in the concrete beams. The Tonkein specimens followed the pattern previously discussed. Figure 3.3 shows that the samples with nodes carried a higher load than those without a node. Specimens failed quickly and straight across the nodes.

![Figure 3.3 Stress-Strain Curve Tonkein Bamboo](image)

Moso and Solid Bamboo were used in the beam tests, so the remainders of the tensile tests were conducted on these two types. Some of these samples failed at their
nodes while others failed near the grips. More research is needed to better understand the fracture properties of the Moso and Solid Bamboos.

Figure 3.4 displays a stress-strain curve of Solid Bamboo samples consisting of both noded and un-noded samples. This graph shows that the Solid sample with no node had the highest strength and stiffness. Stiffness is varied amongst the samples shown, implying that the presence of nodes in Solid Bamboo samples does not affect the behavior. This may be because Solid Bamboo is very thick and dense and thus, the nodes provide negligible improvement in their performance.

Figure 3.5 shows stress-strain curves of Moso Bamboo samples with and without nodes.
This plot is very similar to the plot of Solid Bamboo in that it did not seem to show a specific pattern with regard to the presence of nodes. A comparison of the tensile tests for the Moso and Solid Bamboos are presented in Figures 3.4, 3.5 and 3.6. There is a significant amount of variation amongst the behavior of the two Bamboo type’s renders this data inconclusive. Also, due to failure in different locations, such as near the tabs, a thorough analysis of the tensile specimens is difficult to complete without further study.
3.3 Beam Tests Results

3.3.1 Test Solid-R2-PR 4

The first beam test was done with waterproofed Solid Bamboo, a/d = 2, and 4% (4.4 % provided) Bamboo reinforcement. The distance between the loads was 28 inches (711mm) and d was 14 in (356 mm). The loads applied on top of the beam were at a centered 28 inches (711mm) apart. Deflection was recorded from the dial gauge after every 1 kip (4.45 kN) until 10 k (45 kN) was reached. Once 10 k (45 kN) was reached, deflection was recorded after every 2 k (9 kN) until 52 k (231 kN) was reached. After 52 k (231 kN) load was applied, the load was applied with no recordings until ultimate failure at 72 k (125 kN). Crack initiation and propagation were recorded throughout the testing. The first crack initiated in the vertical direction, the front and
center of beam at 20 k (88 kN). This was a flexure crack and was followed by a second
crack extending from it at 22 k (98 kN), as shown in Figure 3.8.

![Figure 3.7 Solid-R 2-PR 4 First and Second Cracks](image)

The third crack occurred on the right side of the beam at 24 k (107 kN) followed
by the 4th crack mirrored on the left side of the beam at 27 k (120 kN), both still in the
vertical direction as shown in Figure 3.8.

![Figure 3.8 Solid-R 2-PR 4 Third and Fourth Cracks](image)

Development of the cracks extended toward the supports, and shear cracks
formed to the right and left of the concentrated loads as shown in Figure 3.9.

![Figure 3.9 Solid-R 2-PR 4 Crack Patterns at Failure](image)
Failure for this test occurred in crushing underneath the left load atop the beam at approximately 68 k (303 kN). This indicated the case of over-reinforcement. At the ultimate load of 72 k (321 kN), failure shear crack on the left side of the beam was formed. A photograph of the failed beam sample is presented in Figure 3.10.

Figure 3.10 Failure in Solid-R2-PR 4

Investigation of the failed beam indicated that a piece of concrete fell out (Figure 3.11) from the lower section of the beam, which had a nearly perfect imprint of the Bamboo reinforcement and stirrups in it.
Figure 3.11 Imprints of Bamboo Reinforcement

This suggested a poor bonding between the concrete and Bamboo, leading to bond failure. Pieces of the waterproofing agent were also found in the aforementioned piece, indicating that the waterproofing agent may bond better to concrete than to the Bamboo. In other pieces however, the failure did not occur in bonding, as shown in Figure 3.12.

Figure 3.12 Bonding of Bamboo and Concrete

Upon examining the beam at the region of failure crack (Figure 3.13) the Bamboo in tension seemed to be still in tact, leading to the assumption that the beam failed in shear.
The first beam test was conducted measuring deflections with dial gages rather than more accurate laser method. Figure 3.14 shows the load-deflection graph obtained from the data recorded during the test.

![Figure 3.13 Bamboo Reinforcement In-Tact at Failure Crack](image)

![Figure 3.14 Solid-R2-PR 4 Load-Deflection Plot](image)
A slight change in slope occurs at about 20 k, as shown in Figure 3.14, which was approximately the load at the first crack.

### 3.3.2 Test Moso -R1.5-PR 2

The second beam test was conducted with waterproofed Moso Bamboo a/d ratio of 1.5, and 2% Bamboo reinforcement with d= 16.81 in (427 mm). The distance between the loads was 33.625 in (844 mm). The first crack developed due to bending, appeared at 12 k (53 kN), and was 1 in (25mm) from the center of the beam (Figure 3.15).

![Figure 3.15 Moso-R1.5-PR 2 First Crack](image)

This crack continued widening and exceeded 0.01 in (0.254 mm) at 16 k (71 kN). The second crack as shown in Figure 3.17 was formed at 19 k (85 kN) and was greater than 0.01 in (0.254 mm) upon initiating. This crack formed 11.25 in (286 mm) to the left of the beam’s center.

![Figure 3.16 Moso-R 1.5-PR 2 Second Crack](image)
The third crack initiated on the surface at 22 k (98 kN) at a distance of 15.75 in (400 mm) to the right of the beam’s center (Figure 3.17). This crack exceeded 0.01 in (0.254 mm) at 25 k (111 kN). At 30 k (133 kN), the fourth crack appeared which was greater than 0.01 in (0.254 mm), and was 22.5 in (571 mm) to the left of the beam’s center (Figure 3.18).

![Figure 3.17 Moso-R1.5-PR 2 Third Crack](image)

Figure 3.17 Moso-R1.5-PR 2 Third Crack

![Figure 3.18 Moso-R1.5-PR 2 Fourth Crack](image)

Figure 3.18 Moso-R1.5-PR 2 Fourth Crack

The sound of Bamboo cracking was heard at 60 k (267 kN), and the beam failed at the load of 63 k (280 kN) in bending. Figure 3.19 shows the plots of the load-strain curves at L/2 and L/4, as obtained from the strain gauge readings, for Moso-R1.5-PR 2 test.
From this graph, it can be seen that there was little strain present in the reinforcement until after the concrete cracked. The first crack appeared at 12 k (53 kN), which corresponds to the first change in slope at L/2. This graph also shows that more strain was experienced at L/2 compared with L/4. This is consistent with the fact that the value of bending moment is greater at L/2 than L/4.

3.3.3 Test Solid-R1.5-PR 2

The third beam test was conducted with waterproofed Solid Bamboo, a/d ratio of 1.5 and d= 16.8 in (427 mm), a distance between the load of 33.625 in (844 mm), and 2% Bamboo of the cross-sectional area. For the third beam test, the first crack was
due to bending and appeared at 12 k (53 kN), which was 10.5 in (266 mm) from the center of the beam. Figure 3.20 shows the location of the first crack.

![First Crack](image1.png)

**Figure 3.20 Solid - R 1.5 - PR 2 First Crack**

The crack continued widening, but did not exceed 0.01 in (0.254 cm) until the load was 20 k (89 kN). The second crack is pictured in Figure 3.22 and occurred 11 in (279 mm) to the right of center. It was seen at 20 k (89 kN) and exceeded 0.01 in (0.254 mm) at 24 k (107 kN).

![Second Crack](image2.png)

**Figure 3.21 Solid - R1.5 -PR2 Second crack**

The third and fourth cracks, pictured in Figure 3.23, were shear cracks present at 32 k (142 kN). They were 0.01 in (25 mm) wide upon initial cracking. The third crack occurred 27 in (685 mm) to the left of center, and the fourth crack occurred 25.5 in (647 mm) to the right of center.
After the load of 38 k (169 kN) was reached, the displacement began increasing constantly at a noticeable rate until failure in shear occurred at 41 k (180 kN). The beam finally failed at the location of 3rd crack. Photograph of the failed beam specimen is shown in Figure 3.23.
Figure 3.25 shows the strain gauge readings at L/2 and L/4. This graph provides a clear representation of the stress conditions at different parts of the beam. The value of strain at L/2, within the region of maximum bending, was higher than that of L/4. However, the values of strain were very small, suggesting that Solid Bamboo reinforced concrete behave stiffer than Moso Bamboo reinforced concrete, which is consistent with the crack propagation (Figures 3.18 and 3.22) and failure conditions of both beam types tested. Figure 3.25 shows the load-strain measured in the stirrup a distance ‘d’ from the support.
Figure 3.25 Solid-R1.5-PR 2 Load-Strains at Stirrup

The change in slope corresponds to the initial cracking of the concrete. The strain experienced in the stirrup was in shear. Figure 3.26 shows the load-displacement for tests 2 and 3 together.
The initial slopes of the graphs of Figure 3.26 differ, most likely due to differences in concrete compressive strength. At 12 k (53 kN) the Moso beam had a stiffness change due to cracking, and at 19 k (85 kN) the Solid beam had a stiffness change due to cracking. It can be seen from the slopes of both tests that the Solid beam was stiffer than the Moso beam, and the Moso beam exhibited more ductile behavior.
3.3.4 Test Moso-R2-PR2

The fourth test was conducted with waterproofed Moso Bamboo, 2% reinforcement, a/d ratio of 2 and the distance between the loads was 17 in (711 mm). The first crack surfaced due to flexure and appeared at 11 k (49 kN) which was 0.01 in (0.254 mm) wide.

Figure 3.27 Solid -R2 -PR2 First and Second cracks near the center of the beam followed by a second crack at 16 k (71 kN) which was 13 in (330 mm) to the left of the center of beam as shown in Figure 3.27. A series of cracks occurred at 17 k (75 kN), 19 k (85 kN) and 25 k (111 kN) which were also flexure cracks similar to those on the left side of the beam at 26 k (115 kN) these cracks widened at 34 k (151 kN) at a distance-of 14 in (355 mm) from left support as shown Figure 3.29.

Figure 3.28 Moso -R2 -PR2 Crack Propagation
Final failure occurred at 46.4 k (206 kN) at a distance of 20 in (355 mm) from the right support which was a flexure failure.

![Failure at 46.4 k (206 kN)](image)

**Figure 3.29 Moso-R2-PR2 Final Failure**

Figure 3.30 shows a Photograph of failed beam in bending under the point of application of load.

![Point of Application](image)

**Figure 3.30 Moso-R2-PR2 Failed Test Specimen**

Figure 3.31 shows the load-deflection curve for the center of beam. At 11k the first crack appeared. This crack did not cause degradation in beams stiffness. The beams stiffness reduced at verge of the second crack load (Figure 3.31). The slope of the load-deflection plot changed significantly due to reduction in the beams stiffness. The ultimate load for this beam was of 46.4 k (206 kN)
Figure 3.32 shows the load versus percentage strain plot with strain gauges installed at L/2 and L/4 location. From this figure it is inferred that the strain gauge at the middle was not functional. The strain gage at L/4 showed no strain until 7 k (31 kN) which moved linearly until 25 k (111 kN). At approximately 26 k (115 kN), the strain increased without a significant increase in load from approximately 28 k (125 kN) the strain started to increase in a linear fashion, until failure.
Figure 3.33 is the plot of load versus percentage strain measured on the stirrup. Strain reading was observed at approximately 7 k (31 kN). The rate of straining increased at about 10 k (44 kN) load, and the bamboo was strained until failure. The failure strain was 0.007 %
The fifth test was conducted with waterproofed Moso Bamboo a/d ratio of 1.5, 1% Bamboo reinforcement, and distance between the loads was 32 in (812 mm). The first crack was observed at 12 k (53 kN), which was a flexure crack, followed by second crack at 14 k (62 kN) which was 0.01 in (0.254 mm) wide as shown in Figure 3.34.
Cracks continued occurring at 18 k (80 kN) and widened out more than 0.01 in (0.254 mm) at 20 k (88 kN), and at 36 k (160 kN) there was a quick snap of Bamboo resulting in the final failure in bending. Figure 3.36 shows a Photograph of the failed beam in bending.

Figure 3.35 Moso-R1.5-PR1 Final Failure

Figure 3.36 Moso-R1.5-PR1 Photograph of Final Failure

Due to laser deflection sensor device malfunction during the test, the load-deflection plot for this test is not available. Figure 3.37 is a load versus percentage strain plot. Strain at middle section of Moso Bamboo (L/2) is significantly higher than strain at (L/4). In Moso Bamboo reinforced beams strain felt on the beam is much earlier than the occurrence of the first crack in comparison to Solid Bamboo reinforced
concrete beams. Figure 3.38 shows Load versus percentage strain graph for stirrup type reinforcement. The strain gage seems to be dysfunctional.

![Graph showing Load versus percentage strain](image)

Figure 3.37 Moso- R1.5-PR1 Load-Strains at L/4 and L/2

3.3.6 Test Solid-R2-PR3

The sixth test was performed with waterproofed Solid Bamboo with a/d ratio of 2, the distance between the loads of 28 inches (711 mm), and 3% Bamboo reinforcement. The first crack occurred at 14 k (62 kN) which was nearly at the center of beam followed by another crack at 18 k (80 kN). At 20 k (88 kN) first crack widened to be more than 0.01 in (0.254 mm) and at 24 k (106 kN) second crack widened to be more than 0.01 in (0.254 mm) at a distance of 36 in (914 mm) from left support as
shown in Figure 3.38. First shear crack was observed at 31 k (138 kN) at a distance of 19 in (482 mm) from left support.

![Figure 3.38 Solid-R2-PR3 Series of Cracks](image)

Crushing under the right load and shear failure from right load to right support was observed simultaneously at 56.65 k (252 kN) which was the final failure; it was a perfectly inclined crack pattern. Figure 3.40 shows the failed test specimen, performance of which under loading was similar to that of Solid Bamboo with 4% reinforcement as both failed in shear and crushing.

![Figure 3.39 Solid-R2-PR3 Final Failure](image)
In Figure 3.41 the load-deflection plot shows that at approximately 20 k (89 kN) the stiffness of the beam reduced, at which the first crack widened. The first, second and third cracks are noted by changes in slope as well. The beam used for the first test (Solid R-2-PR-4) failed at about 16 k (71 kN) more than this test. This beam with 3% reinforcement failed at a higher load level compared to the other beam tested with Solid Bamboo with less reinforcement. This clearly indicates a direct relationship between the percentage of reinforcement and ultimate failure load.
Figure 3.41 Solid-R2-PR3 Load-Deflections

Figure 3.42 Solid-R2-PR3 Load-Strains at L/2
Measurements of strain at L/4 showed no results suggesting that the strain gauge in that location was dysfunctional. Figure 3.42 display the load versus strain curve at L/2. There was a high strain at the location of maximum bending moment as expected. However, Figure 3.37 of Moso-R1.5 PR1 test shows that Moso Bamboo at the L/2 location experienced a much larger strain, differing at approximately 0.2%. This indicates that Moso Bamboo behaves in a more ductile manner than Solid Bamboo.

Table 3.1 Comparison of Four-Point Bending Beam Test

<table>
<thead>
<tr>
<th>Test Designation</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solid-R2-PR4</td>
</tr>
<tr>
<td>Failure Mode</td>
<td>Shear</td>
</tr>
<tr>
<td>Failure Load</td>
<td>kip</td>
</tr>
<tr>
<td></td>
<td>kN</td>
</tr>
<tr>
<td>Failure Moment</td>
<td>kip-in</td>
</tr>
<tr>
<td></td>
<td>kN-m</td>
</tr>
<tr>
<td>First Crack</td>
<td>kip</td>
</tr>
<tr>
<td></td>
<td>kN</td>
</tr>
</tbody>
</table>

The test results of the entire four point bending test are summarized below in Table 3.1 which shows that beams with 3% and 4% Bamboo reinforcement failed in Shear. In addition, Solid Bamboo with 2% reinforcement and a/d=1.5 also failed in Shear at 41 k (182 kN) as expected because of the a/d ratio. The failure load for Moso-
R1.5-PR2 was of 63 k (280 kN) which is higher than that for Solid-R2-PR3 which was 41 k. Moreover, comparing Moso-R1.5-PR2 and Solid-R1.5-PR2 tests with identical a/d ratio and reinforcement percentages confirms that Moso Bamboo beams are capable of carrying more loads. For the aforementioned tests Moso beam carried 53% more load than the corresponding beam with Solid bamboo reinforcement before failure. Also comparing Moso-R1.5-PR2 and Moso-R2-PR2, it is observed that both failed in flexure, but Moso with a/d of 1.5 carried more load than that of Moso with a/d of 2. This behavior can be explained (Figure 2.11) with the fact that smaller a/d ratio will develop smaller region of combined shear and bending near the support and magnitude of maximum moment will also be smaller, while in larger a/d ratio larger region of combined shear and bending will be developed and magnitude of maximum moment will be higher for the same load.

3.3 Comparison of Ultimate Loads for Bamboo Reinforced and Steel Reinforced Concrete

By using the compressive strength obtained from the cylinder tests of each beam, the capacity of each beam was calculated per ACI by replacing bamboo with Grade 60 steel. Table 3.2 shows the comparison between the experimentally obtained failure loads for the reinforced bamboo concrete beams tested with those calculated for the equivalent reinforced steel beams per ACI.
Table 3.2 Comparison of Experimentally Obtained Ultimate Load for Reinforced Bamboo Beams and Calculated Load Capacity for Reinforced Steel Beams

<table>
<thead>
<tr>
<th>Test Designation</th>
<th>$f_{c'}$</th>
<th>Reinforced Concrete Bamboo</th>
<th>Equivalent Reinforced Concrete Steel</th>
<th>Ratio of Bamboo /Steel Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kip</td>
<td>kN</td>
<td>kip</td>
<td>kN</td>
</tr>
<tr>
<td>Moso-R1.5-PR2</td>
<td>5000</td>
<td>63</td>
<td>280</td>
<td>275</td>
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<tr>
<td>Moso-R2-PR2</td>
<td>4800</td>
<td>46.4</td>
<td>206</td>
<td>205</td>
</tr>
<tr>
<td>Moso-R1.5-PR1</td>
<td>4800</td>
<td>36</td>
<td>160</td>
<td>296</td>
</tr>
<tr>
<td>Solid-R1.5-PR2</td>
<td>5000</td>
<td>41</td>
<td>182</td>
<td>275</td>
</tr>
<tr>
<td>Solid-R2-PR3</td>
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<td>57</td>
<td>254</td>
<td>79</td>
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<tr>
<td>Solid-R2-PR4</td>
<td>6000</td>
<td>72</td>
<td>320</td>
<td>109</td>
</tr>
</tbody>
</table>

This table shows that the ultimate load capacity of bamboo reinforced concrete was on average about 35% when compared with ultimate load of steel reinforced concrete beam section. It is interesting to note that a beam with 1% bamboo reinforced
would enhance the load carrying capacity of the plain concrete based on first crack load by 250%.
CHAPTER 4
SUMMARY, CONCLUSION, AND RECOMMENDATION

4.1 Summary

This study evaluated the feasibility of the use of bamboo as a potential reinforcement in concrete structural members. To achieve this objective a series of tensile tests were conducted on three types of bamboo followed by four point bending tests of concrete beams reinforced with bamboo. The test results were compared with plain and steel reinforced concrete beams behavior.

Three types of bamboo used were: Moso (China); Solid (South America; and Tonkin (China). Tensile tests specimens were prepared by cutting the bamboo typically in $\frac{1}{2}$ inch (13 mm) strips of 9 to 12 in (228 mm to 305 mm). Two types of tensile samples were manufactured with nodes. In order to prevent crushing of the bamboo samples when placed in grips of the MTS machines end-tabs were epoxy glued to the bamboo samples. The specimens were then loaded at a rate of 0.1 in/sec (3 mm/sec) until failure. In general, tensile tests of the three aforementioned bamboo types showed that the specimens with nodes behaved in a less ductile manner with higher strength than those without nodes, which were more ductile and carried lesser loads before failure.

Six four-point bending tests were conducted on 8 in x 20 in x 96 in (203 mm x 508 mm x 2429 mm) reinforced bamboo concrete beams. The variables used with test
beams were a/d ratios, percentage of reinforcement, and bamboo types (Moso and Solid). The reinforcement for beams tests were cut in ¾ in (19 mm) strips from the bamboo culms of Solid and Moso that were held in place by ½ in (13 mm) Tonkin stirrups. Tonkin bamboo was used for stirrups due to their highly ductile behavior observed during the tensile testing. Strain gages were applied at L/2 and L/4 of the beam and one on stirrup which was at a distance ‘d’ from the support. Coating was applied over strain gages to protect them from any damage during casting. The test beams were casted in Hanson Products in order to obtain consistent mix design and vibrating process. White washing material was applied to the beam for crack detection during testing.

The test set-up consisted of placing the test beam under the Baldwin universal testing machine. A 200 k (890 kN) load cell was placed on the top of a rigid-beam, which was used to transfer the load from the hydraulic cylinder to the concrete beam through the two roller supports. Instrumentation consisted of a laser sensing device capable of measuring up to 4 in (102 mm) displacement with the accuracy of 1x10⁻⁴ in (0.00254 mm). The test beams was loaded incrementally in order to capture any non linear behavior without overshooting the load that cause it. During testing, initiation and widening of cracks and their respective loads were recorded.

In general, the test results indicated that bamboo reinforcement enhanced the load carrying capacity in average by 250 % as compared to the initial crack in the concrete beam. Also, it was noticed that a direct relationship existed between the percentage of reinforcement and the load carrying capacity of the beams tested.
4.2 Conclusion

Based upon the tests conducted, the following conclusions are at the forefronts:

1. The failure loads varied with the compression strength of the concrete, providing a lower failure load for lower compression strengths.

2. The beam with 4% Bamboo reinforcement produced an over-reinforced failure mode.

3. The load carrying capacity of the Moso Bamboo was higher than that of Solid Bamboo. Also Solid bamboo deflected less than Moso indicating that Moso behaved in more ductile manner.

4. Tensile tests indicated that presence of nodes in Solid Bamboo samples did not affect the behavior.

5. The constitutive relationship of the nodes differs from those of internodal regions with nodes having a brittle behavior while internodal regions exhibit a more ductile behavior.

6. The waterproofing agent chosen provided poor bonding. Bond-enhancing applications should be required to strengthen the bonding between the concrete and the Bamboo.

7. The stirrups were developed using flexible Tonkein Bamboo. The size selected for stirrups was ½ in (13 mm) to obtain flexibility. This stirrups design provided small resistance to shear forces.
8. Based on the limited number of testing conducted, it was concluded that Bamboo can potentially be used as substitute steel reinforcement. However, for regions of the world that availability of steel is limited and plain concrete members are commonly being used, the use of reinforced bamboo concrete is highly recommended.

9. The breaking patterns of the tensile tests were overall inconclusive. However, there was an indication that the fracture points of the tensile samples containing nodes occurred at the nodes, which was also verified in the beam tests.

10. In general, samples failed by: (1) node failure; (2) end-tap failure; and (3) failure at the vicinity of the end-tap.

11. The failure load patterns of the tensile samples were overall inconclusive. However, the samples with nodes generally failed at higher loads than those samples without nodes.

4.3 Recommendations

This project suggests many recommendations for future research.

1. Different clear cover dimensions are suggested to be used. The cover used is based on protecting steel from corrosion. Since Bamboo does not corrode in concrete, the cover could potentially be less.

2. More a/d ratios with different beam lengths should be tested. Increasing in beam length would allow for testing of larger a/d ratios.

3. Beam tests with different percentage of Bamboo reinforcement should be investigated.
4. The same test matrix used in this project using steel stirrups could be used, creating a hybrid beam.

5. The stirrups were designed per ACI requirements. Smaller distances between the stirrups are suggested to provide better shear resistance capability since the section of stirrup sizes is limited to the capability of bamboo to bend.

6. An extensive study to evaluate the behavior of different types of bamboo is recommended as the bamboo type and behavior is different at different regions of the world.

7. The development of finite element models for each type of Bamboo is suggested. This would assist identification of bamboo behavior with different geometric variables.

8. Low frequency fully cyclic experimental tests could be conducted to identify the behavior of Bamboo reinforced concrete in earthquake induced ground acceleration.

9. In this study two different types of epoxy were used. However, if available, a stronger epoxy is suggested while testing tensile samples to eliminate the variable of grip failure.

10. Pull-out tests should be conducted with different waterproofing agents and accommodating bonding applications to investigate the necessary conditions for better bonding between the concrete and Bamboo.

11. Pressure treatment of Bamboo is suggested before conducting four-point bending tests to provide a greater Bamboo strength.
12. Long-term studies investigating the durability of Bamboo reinforced concrete should be conducted.

13. Further experimental coupled with numerical studies are recommended to better understand the effects of nodes on tensile strength of bamboo.

14. The effect of thickness on the strength of bamboo tensile samples is suggested to be investigated by conducting tensile tests on samples with the same dimensions as those used in concrete.

15. Variation of Bamboo tensile specimen length is suggested to determine if this is a factor for tensile strength.

16. More tensile tests is suggested to investigate the relationship between the tensile strength of bamboo and its performance as reinforcement in concrete.

17. To investigate the behavior of bamboo in flexure, it is suggested to conduct four-point bending tests with bamboo itself.
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BIOGRAPHICAL INFORMATION

Leena Dattatray Khare was born in Nagpur, India in November of 1980. She earned her Bachelor of Engineering in Civil Engineering from Nagpur University, India in August 2003. After she decided to pursue a Master's degree in Civil Engineering (Major in Structural Engineering) at University of Texas at Arlington. She finished her research in Performance Evaluation of Bamboo Reinforced Concrete under Supervising Professor Dr. Ali Abolmaali. She was awarded with Civil Engineering scholarship from University of Texas at Arlington; she worked as a Graduate Research Assistant for Dr. Abolmaali and Graduate Teaching Assistant for Dr. Ramirez.