INVESTIGATION OF BAMBOO AS REINFORCEMENT IN CONCRETE

by

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ABSTRACT

INVESTIGATION OF BAMBOO AS

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This study investigated the feasibility of using bamboo as a reinforcement alternative to steel in concrete structural members. The specifications studied were the bamboo's tensile strength and its pullout characteristics in concrete.

Two types of bamboo, Solid and Moso, were used for tensile testing. The tensile test specimens were prepared with different lengths, 6 in (152 mm) and 12 in (304 mm), and different physical characteristics (with and without nodes). Tensile test specimens were tested to failure and their load deformation characteristics are reported. The failures of the test specimens were identified as: (1) node failure; (2) splitting failure; and (3) failure of the end-taps. The test results show a high degree of variability between the samples. Test samples without nodes exhibited both a higher strength and stiffness compared to those with nodes.

The pullout samples were prepared by embedding bamboo reinforcement into a concrete cylinder and subjecting it to monotonically increasing load. Two embedment lengths, 6 in (152 mm) and 12 in (304 mm), were used. For each bamboo type, reinforcement of the test samples was placed either at the center or with an eccentricity of 1.5 in (38 mm) in the concrete. The test results indicated that the bond strength for bamboo was lower than those for steel and FRP (Fiber Reinforcement Plastic) as reported in the literature. In general, the variation of test parameters did not yield a conclusive pattern of behavior for the pullout test.

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CHAPTER 1

INTRODUCTION

1.1 Background

In today's society, most buildings are built using such materials as steel reinforced concrete and structural steel. Specifically, concrete is a high quality and economical material with its ability to support fire and earthquake defense in buildings constructed in developed and developing countries. One of the significant faults of concrete is its low tensile strength. Steel reinforcing bars are typically used for reinforcement. Steel is one of the best materials for complementing the low tensile strength of concrete because of its high tensile strength, over 115 ksi (792 N/mm^2).

Unfortunately, structural steel is not easy to find in many countries due to limited natural resources and lack of skilled labor. For the same reasons, use of steel reinforcement in concrete is not widespread. Some buildings in the world have been built of just plain concrete or bricks without steel reinforcement. These buildings typically can not withstand the effects of natural disasters such as earthquakes, hurricanes, and storms. In a few countries, buildings which did not use enough steel have been crumbled by natural disasters such as earthquakes as evident in Figure 1.1.

Figure 1.1 Failure of Concrete Building by Earthquake

Even though steel reinforcement is a very suitable material for complementing concrete's low tensile strength, there are many difficulties such as economics, technique, and efficiency that need to be addressed. To overcome these problems, many scientists and engineers have been trying to seek out new materials for increasing the tensile capacity of concrete. Specifically, bamboo is one of the most suitable materials to substitute for reinforcing bar in concrete.

Bamboo is a kind of giant grass and an orthotropic material. Bamboo culms are cylindrical shells as shown in Figure 1.2, and are divided by nodes as solid transversal diaphragms. Non-uniformly distributed fibers in a parallel direction at culms, which consists of up to 70% longitudinal length, have high strength. Meanwhile, the fibers with perpendicular direction at culms have low strength. Also, Ghavami (2005) researched inter-nodal lengths, diameters, and thicknesses of bamboo relation as shown in Figure 1.3. The strength distribution at the bottom of bamboo is more uniform than at the top or at the middle of it (Ghavami 1995).

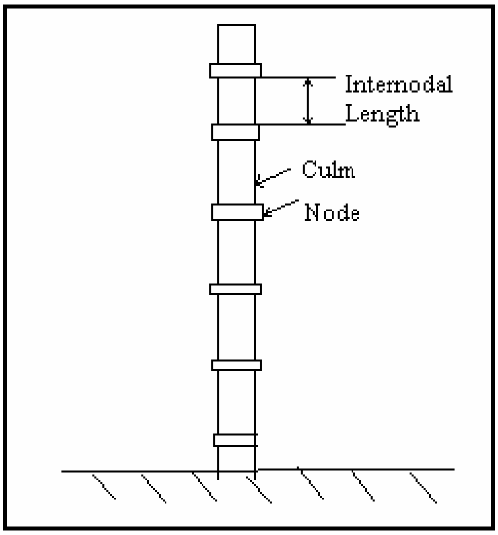


Figure 1.2 Whole Bamboo Culms (Leena 2005)

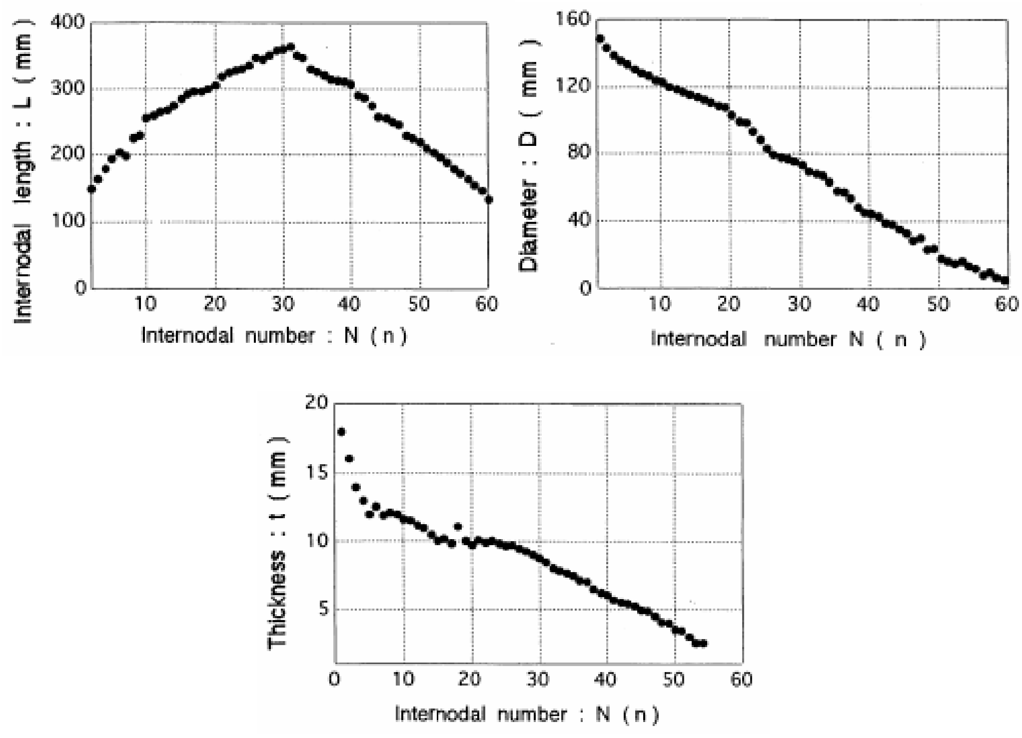


Figure 1.3 Variation of inter-nodal length, diameter and thickness along the whole bamboo culms (Ghavami 1995)

Bamboo is a composite material with long and parallel cellulose fibers in its structure. Also, it exhibits good flexibility and toughness characteristics. The most surprising thing is its growing speed as most growth occurs during the first year and almost all growth ceases by the fifth year (Amada and Untao 2001).

The strength of bamboo does increase with its age, but the maximum strength occurs at 3-4 years and then begins to decrease in strength (Amanda and Unta 2001). Bamboo nodes are spread along the giant grass, and their function is to prevent buckling. In fact, bamboo can bend as much as touching the ground without breaking.

Use of bamboo raises several issues. It fosters fungi and bugs attack. Also, bamboo contains high nutrients so bugs are more likely to attack it than other grasses or plants. On the environment side, the bamboo is a harmless plant at pollution because it assimilates a lot of nitrogen and other function is to decrease the carbon dioxide in the air (Steinfield 2001). Also, some bamboo even sequester up to 12 tons of carbon dioxide from the air per hectare.

Also, bamboo needs to be protected from several conditions including temperature, moisture, and pests. Proven effective protection methods are smoking, heating, immersion, and impregnating coating. The rind of smoked bamboo is unpalatable to insects. When bamboo is cooked, the starch and nutrient content will be reduced. The immersion can remove nourishments which may attract insects.

For several centuries, bamboo has been used in construction, instruments, medicine, and paper. In China, ingredients from the roots of the black bamboo are used to help cure kidney disease. Tradition in Indonesia records that the water within the culm of the bamboo is to be used to treat effectively broken bones.

In construction, bamboo is a high-yield renewable material such as “ply boos” which is a kind of bamboo in the world used for wall paneling and floor tiles. A tower at the “Phanomena” in Zurich is an enormous bamboo structure. On the building, the bamboo canes used were 6 to 11cm (0.2 to 0.36 ft) in diameter. In Hong Kong, double layered bamboo scaffoldings are a typical application on construction. The scaffoldings are used as a working platform for erecting brickwork and curtain walls.

One of the most popular applications of bamboo is in the manufacture of umbrellas which have a simple design with 38 bars. Specifically, umbrellas in European are curved extremely with a textile covering in individual triangular sections. The culm has the ability of maintaining considerable tensile forces transverse to the bars so enabling the bars to be bent considerably when the umbrella is open.

In Asia long ago, bamboo was utilized as musical instruments such as flutes and saxophones as shown in Figure 1.4. Bamboo has also been used for fishing rods.

(a) (b)

Figure 1.4 (a) Bamboo Flutes (b) Bamboo Saxophone

Normally, East Asian, China, India, and other countries use bamboo as construction scaffolding because of its price, weight, flexibility, and toughness. Even though the scaffolding gets a heavy load, it bends but does not break.

Bamboo is grown in many areas of world and is divided into one thousand-two hundred-fifty kinds of bamboo. Most bamboo can be found in East Asia because of its tropical and subtropical regions. Bamboo use in construction is common in Asian due to factors including economical aspects, lightweight, flexibility, and toughness. When compared to steel's tensile strength, bamboo's value of 54 ksi (370 MPa) is very respectable (Amanda et al. 2001).The middle diagram in Figure 1.5 shows where bamboo is commercially grown.

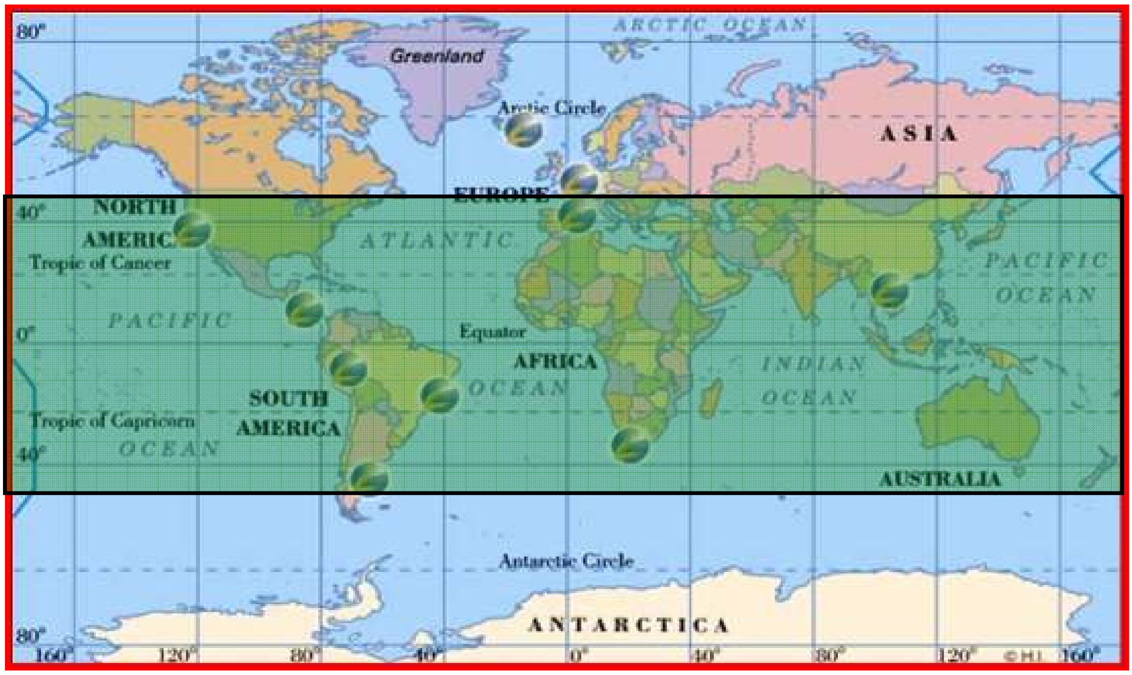


Figure 1.5 Bamboo Distribution around the world

Bamboo is a good replacement material for timber in construction due to its lightweight, good flexibility, low cost, and tough character. Specifically, the tensile strength of bamboo is stronger than conventional grasses. In addition, bamboo reaches its mature growth within five years (Amada et al. 2001). On the negative side bamboo shows weakened bond with concrete, lower modulus of elasticity, strong water absorption, and low durability and low resistance to fire compared to steel reinforcement.

1.2 Goal of Pullout Test

During earthquakes, buildings move up and down, right and left, or forward and backward while losing weight balance. The pullout value varies depending on load processing, binding reinforcement, diameter, strength of concrete and degree of pullout. The pullout value can help evaluate structural stability of buildings.

Normally, bond strength is affected by several conditions such as bar size, bar skin situation, moist condition and concrete thickness and quality, and bar spacing and ties. The casting bamboo specimens are cured 7days in a curing room while maintaining a regular moist state.

Al-Negheimish and Al-Zadi have studied and have performed a pullout test. Their specimens are maintained at a regular temperature range of 17~25°C (62.6~77°F). In 28 days they measured an average compressive strength of 26.5 MPa (3057 psi) at a slump range of 135~150 mm (5.3~5.9 in).

This study investigates the pullout strength between concrete and bamboo reinforcing rods for two kinds of bamboo; Solid and Moso bamboo. Generally, Solid and Moso bamboos have big diameters, and are long. Solid bamboo has 5 in (126.5 mm) diameter and is 9 feet (2745 mm) long. Moso bamboo has 3 in (76 mm) diameter and is 9 feet (2745 mm) long. For experiment purposes, test specimens were to cut from the two bamboos. The bamboos are cut by length of 2 ft (610 mm), width of 1 in and thickness of 0.75 in (19 mm) without treatment. The pullout strength is measured with several equipments; 60 kip (267 KN) tensile or compressive machine, dial gauge, and extensometer. The value can be evaluated economically for application to structural materials.

1.3 Literature Review

During the past few years, several researchers have found new materials for structural purposes in civil engineering. This section is to review two kinds of tests: the tensile test and the pull-out test as related to bamboo.

The investigation reported in International Network for Bamboo and Rattan (INBAR) (2002) suggested bamboo's advantages and disadvantages as a constructive material. The advantages of bamboo are ecological value, good mechanical properties, social and economic value, and energy consumption. The other sides, the disadvantages of bamboo are preservation, fire risk, and natural growth.

Amada and Untao (2001) mention that bamboo is the most effective material in construction by the superior character of bamboo such as being physically powerful, tough, and a low-cost material. Normally, the culm of bamboo with outer surface layer withstand strongly to any loading with stronger fracture resistance than the node. It suggests that the fibers in the node do not contribute any fracture resistance.

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 node do not contribute any fracture resistance.

Abbasi and Hogg (2005) considered bonding test with a composite reinforcing bar instead of steel reinforcing bar. The purpose of the test is to estimate the interfacial strength between concrete and the rebar. In tensile test, the specimens require a certain minimum temperature, 25 (77), 80 (176), and 120°C (248°F). After that, the specimens need 12 minute to cool down to the surface temperature of the rebar.

In the bond tests, the value of stress is not consistent because the pullout strength and modulus of the rebar is changed by the concrete. However, bond strength is related to the lengths and diameter of the rebar. So, for these experiments the l/d ratio does not change. In addition, the bond strength is inversely proportional to the test temperature. Also, the test discovered two kinds of failure such as pull-out of the bar and splitting of the concrete. Although the splitting failure appears in the bond test, that is not bond failure. It is matrix failure.

Galati et al (2005) discussed thermal working between FRP rebar and concrete during bond tests. This study studied several conditions such as the GFRP bar with different bond lengths such as 3 in (76mm) and 6 in (152mm), thermal treatment, concrete cover, and bar placement with identical conditions such as 3/8in thickness and the compression strength of concrete being 4000 psi (28 Mpa). Sometime, FRP broke without any slipping, and the pull-out force of other FRP can be increased to the maximum point, 9 kip (40 KN), with the following breaking force, 12kip (53 KN).

In the test results, this test show different characters between thermal treatment and no thermal treatment. With an untreated sample, little slip is observed while the load is brought to its maximum value, but treated samples have mostly similar values with high slips.

Kawai et al (2000) discussed bonding tests with bamboo reinforced soil-cement concrete. Bamboo reinforced soil-cement concrete has higher yield capacity than brick structures and also shows unlimited possibility in developing countries. The pullout strength is changed by the notch length. In the result, the high strength which was 1.4 N/mm^2 (0.203 ksi) is observed at 30 mm (1.18 in) notch length. The opposite side, low strength which was 0.9 N/mm^2 (0.131 ksi) showed at 40 mm (1.57 in) notch length by decreased number of notch and soil cement concrete was broken at 10 and 20 mm (0.39 and 0.79 in) notch length. Figure 1.6 shows the notch length which was cut regular size on bamboo edge.

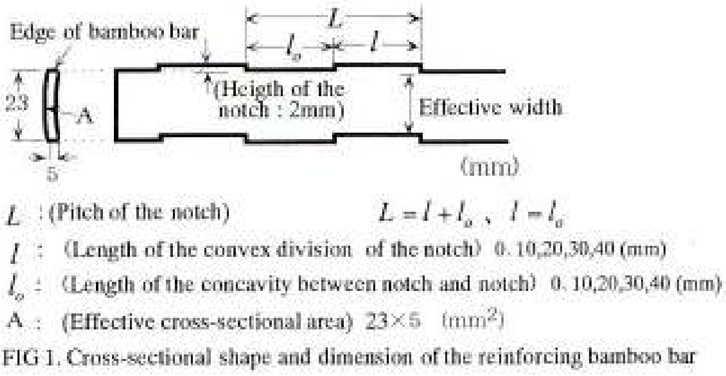


Figure 1.6 Cross-Sectional shape and dimension of the bamboo (Kawai et al 2000)

For example, in Japan Society of Civil Engineering, bond strength between steel reinforcement and the concrete is shown to be about 7 to 8% of the design compressive strength of the concrete. On the bamboo side, the bond strength was approximately 15 to 20% of the design compressive strength of the concrete (Kawai et al 2000).

Ghavami (1995) studied bonding and bending with bamboo in lightweight concrete. Most developing countries have several problems, and one of the main problems is housing. The housing problem has been related to the low skill of the scientists, engineers, and designers who need education for finding inexpensive construction and efficient plans. In additional, specialist systems for education, various information, and vitality of economy are needed.

The values of the test of compression and shear are dependent on the type of bamboo. The tensile strength is higher than the compression strength with the compressive range 12 to 53MPa (1.7 ~ 7.7 ksi). In several tests, Bambusa vulgaris schard and Dendrocalamus were researched the highest value, 141 and 124 MPa (20.5 ~ 18 ksi). The compression strength was observed as 40~62 MPa (6 ~ 9 ksi) for specimens12 cm (0.4 ft) length and 1 cm (0.03 ft) width.

The bond test considered two types of bamboo, treatment and untreated. The treated specimens were wrapped with 1.5mm (0.06 in) steel wire on embedded 4cm (0.13 ft) spacing and cared Negrolin-sand. In this test, treated bamboo, 0.97 N/mm2 (0.141 ksi), was more effective than untreated bamboo, 0.52 N/mm2 (0.075 ksi), with up to 90% improved bond stress.

Ghavami (2005) coordinated reinforcement properties of bamboo in concrete. Due to growing problems in the environment, many countries recognize the importance of environmental specifications. A lot of materials used in industry are turned to non-polluting materials such as natural sources, bamboo, water, recycled materials, and agriculture for engineering applications.

To improve the bond strength between bamboo and concrete, three factor of impermeability treatments were used to the bamboo. First was the adhesion properties of the substance applied to bamboo and concrete, second was the water repellent property of the chosen substance, and last one was the topography of bamboo and concrete interface. The effective treatment of the three types was water repellent treatment with a thin layer of epoxy.

Galati et al (2005) investigated the influence of bond with the flexural behavior based on several parameters such as the service temperature with fiber reinforcement plastics (FRP). In this experimental program, concrete cubes were cast 6 in (152 mm) based on ACI 440. Specimens were then divided into three classifications, bonded length, concrete cover, and exposure to high temperature to characterize the mechanical properties of the FRP. The results of pullout tests can be predicted in terms of applied pullout force and consequent slip at the loaded end and at the free end. The pull-out tests reached a failure of FRP. The investigator applied the pullout tests results to another experimental data and concluded that no thermal FRP is more effective than thermal FRP.

CHAPTER 2

EXPERIMENTAL PROGRAM

2.1 Introduction

The experimental program of this research is designed for two kinds of tests; tensile testing of bamboo and pull-out testing of bamboo in concrete. The tensile tests were conducted to determine the strain stress characteristics of bamboo under load. This test was performed to establish the bamboo's ultimate strength and fracture strain.

For the mechanical testing of a material, a tensile test (tension test) is the most basic type of mechanical test. It is known that tensile tests (tension test) are easy to perform, relatively inexpensive compared to other tests, and fully standardized..

The pullout strength between the bamboo reinforcement and the concrete was controlled by several conditions such as the modulus of elasticity of the concrete, the strength of the concrete, the diameter of the bamboo, concrete spacing, and interface properties. The purpose of this test was to determine the pullout strength based on tension cracking of the bamboo in concrete.

2.2 Tensile Test

2.2.1 Specimen

The tensile test was completed using the guidelines listed by ASTM A 390. To make each specimen, it was required to cut suitable sizes for the tensile test due to big diameter (3~5 inch) and long length (9 feet) of bamboo. Basically, the tensile specimen of steel or FRP is fabricated for a length of approximately 10 in (254 mm), so the bamboo is cut into 6 in (152 mm) and 12 in (304 mm) lengths to compare with and without node. Normally, the bamboo rod is typically 10ft (457 cm) in lengths. Thus a saw was required for making the tensile specimen and is shown in Figure 2.1.

Figure 2.1 A Dewalt Saw

Bamboo contains some of the weaker fiber types in plants. During the tensile test, bamboo requires a strong strength grip from the test equipment, without this, the bamboo tends to shift. To achieve the grip strength needed, a MTS QTEST/150 is used.

Also, normal bamboo consists of a round surface, so an aluminum tab is required to make a flat surface for attaching the bamboo. Bamboo was cut to the desired length by saw, and it was put onto a planer for making 1/8 in (3.2 mm) thickness of bamboo. The planer can reach the desired thickness and also help to obtain a flat surface. When both sides of a sample are uneven, a surface planer first defines the initial flats surfaces as well as the reverse sides as shown in Figure 2.2.

Figure 2.2 Portable Planer

The bamboo was equipped with aluminum tabs which were 1 in (25.4 mm) by 1.5 in (38 mm) for protecting the ends of the bamboo from being harmed by the grip of the tensile testing machine and this is shown in Figure 2.3. Figure 2.4 shows the size representation of the aluminum tab.

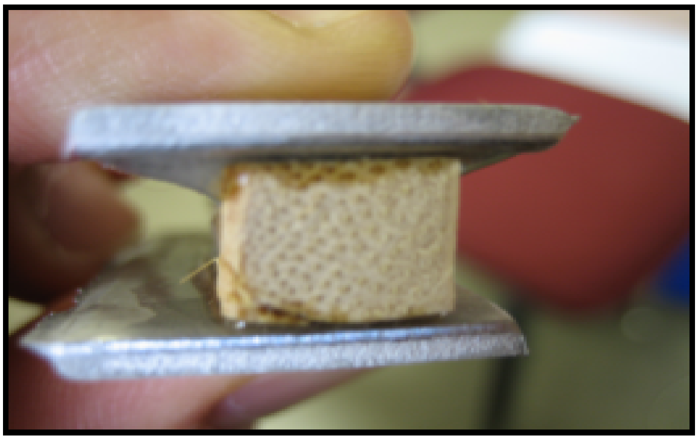


Figure 2.3 Both Aluminum Tabs on Bamboo

Figure 2.4 Photograph of the Aluminum Tab

The epoxy adhesive, TDR 1100-11 and HARDENER 1100-11, were used to attach the aluminum tabs to the bamboo. Normally, the tensile strength of glue is over 10,000 kgf (98.07 KN), so most glues could not withstand the strength of the tensile machine. Also, most glues lose their bond between aluminum tabs and bamboo, often causing the grips to be tightened down so strongly that the bamboo could not withstand it. Figure 2.5 shows the epoxy adhesive.

Figure 2.5 Epoxy Adhesive (TDR 1100-11 & HARDENER 1100-11)

The tensile sample was measured in width and thickness at three points which included the two sides of the ends and the midpoint. Each specimen's data is recorded and saved for calculating the average stress and strain of each one. Dimensions for the tensile samples are shown in Figure 2.6.

To compare the tensile tests between samples, the testing is completed using two types of bamboo, identified as Moso and Solid, for the tensile test specimens in the program. Their characteristic properties are shown in Table 2.1.

Table 2.1 Test Matrix

Variable \ Bamboo	Moso	Solid
Thickness	1/8 in (3.2 mm)	
Node	Yes or No	
Length	6 in (152 mm) or 12 in (305 mm)	

Figure 2.6 Diagram of Tensile Sample

2.2.2 Test Setup

The tensile tests were performed on a MTS QTEST/150 machine testing system with the following components: (1) 100 kip load cell; (2) Grip of MTS QTEST/150; and (3) Extensometer of Epsilon. The MTS QTEST/150 machine is shown in Figure 2.7.

Figure 2.7 MTS QTEST/150

The most important equipment for any weighing conversion into measurable output data is a load cell. It is rated 10 KN (2.3 kips). The picture of the load cell is shown in Figure 2.8.

Figure 2.8 Load Cell

Figure 2.9 shows an enlarged picture of the MTS QTEST/150 grips. It is controlled by hand to tie the specimen, so the bamboo is equipped with aluminum tabs for protecting it from the grip’s strength.

Figure 2.9 Grip of MTS QTEST/150

The extensometer was used to measure the scale elongations from 0.5 to 1 inch (0.12mm to 25mm), with a gauge lengths beginning at 2 inches (50 mm) which is shown in Figure 2.10.

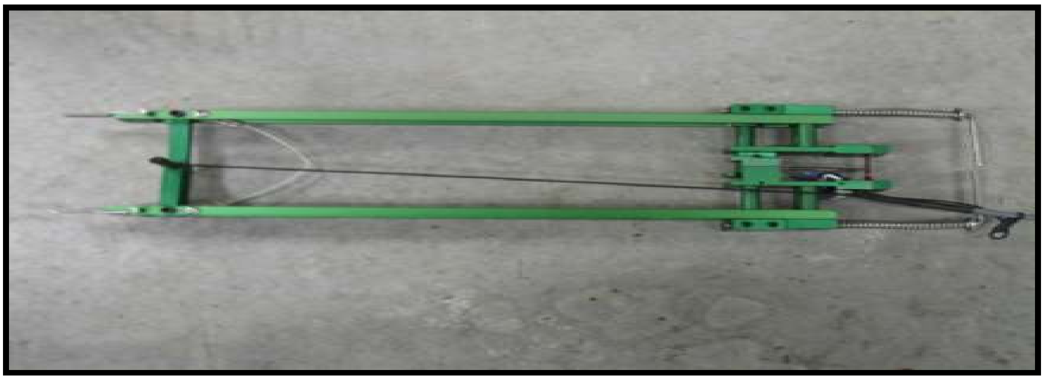


Figure 2.10 Extensometer of Epsilon

2.3 Pullout Test

2.3.1 Specimen

The experimental purpose of this test was to measure the interfacial strength between the bamboo and a concrete block. Also, it was compared to reinforced steel and FRP according to the ACI and ASTM standards and requirements.

The tests were conducted on two types of bamboos; Solid and Moso which were cut into 35.4 in (900 mm) lengths and 1 in (25 mm) widths. These are shown in Figure. 2.11.

The bamboos were embedded at two locations, the center and 1.5 in from the edge of a concrete cylinder of 6 in (152 mm) diameter and 12 in (304 mm) height. The bond lengths were divided into two kinds of 6 in (152 mm) and 12 in (304 mm) height. The bamboo reinforcements were placed in a concrete cast for the pull-out tests at the two points of the 339 in^3 cylinder, as shown in Figure 2.12.

The pull-out tests were performed using an MTS (Material Testing System) machine in which the load cell capacity is 60 kips (273 KN). The testing followed the guidelines of ACI 408 for direct pull-out specimens. As mentioned before, the specimens were designed as concrete cylinders with the rod embedded in the concrete cylinder. As shown in Table 2.2, a total of 16 cylindrical pull-out specimens were tested within the study. As show in Table 2.2, the bonded length of the rods is either shorter 6 in (152 mm), short end, or longer 12 in (304 mm), long end.

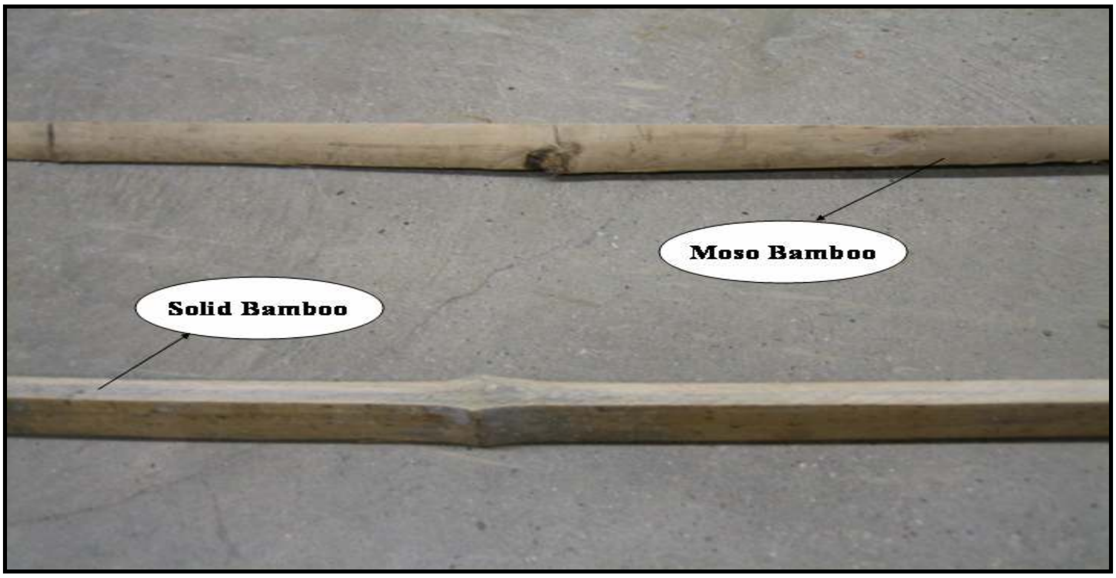
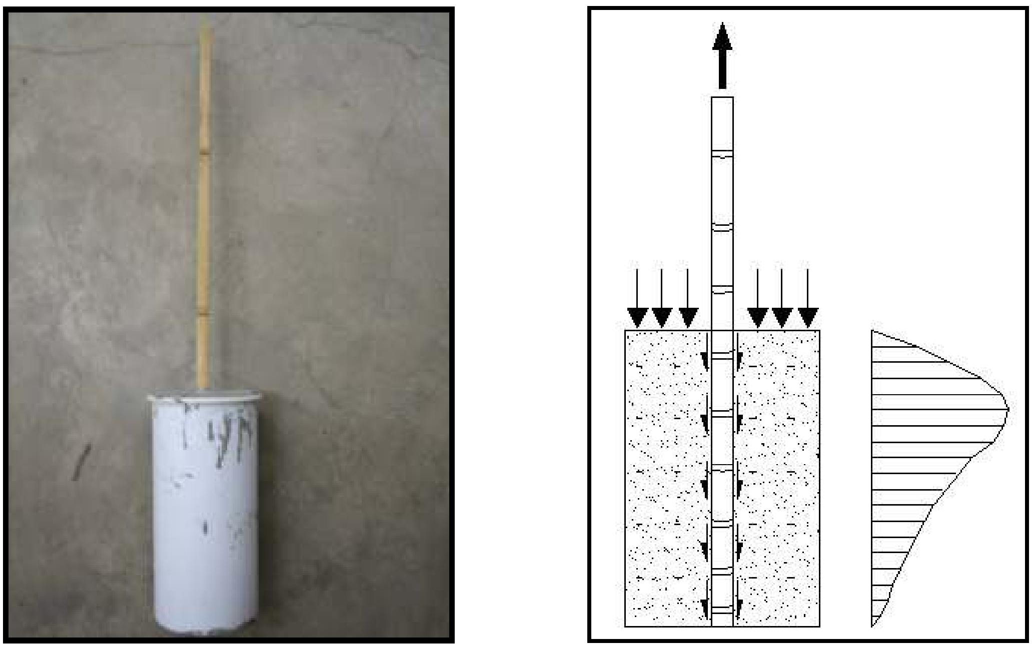


Figure 2.11 Types of Specimens



(a) (b)

Figure 2.12 (a) Photograph of Specimen (b) Schematic of Specimen

Table 2.2 Pullout Test Specimens

	Bonded Length mm(in.)	Point of bamboo	Node	Number
Solid	152 (6)	Center	Yes	2
		1.5in from edge	Yes	2
	304 (12)	Center	Yes	2
		1.5in from edge	Yes	2
Moso	152 (6)	Center	Yes	2
		1.5in from edge	Yes	2
	304 (12)	Center	Yes	2
		1.5in from edge	Yes	2

2.3.2 Concrete Mix Design

Leena (2005) used the following mix design: the concrete was made for the pullout test by mixing Portland Cement Type I / II, limestone fine aggregate, and limestone coarse aggregate with a maximum size of 1 in (25.4 mm). Also, the concrete mix proportion (cement: coarse aggregate: fine aggregate) was 1 : 3 : 2.2 with a 1 : 0.45 water-cement ratio. The mix was designed for seven day strength of 4000 psi (27.56 N/mm^2), and a slump value of approximately 4 in (102 mm) to insure consistency concrete. Table 2.3 shows the ingredients and amounts used.

Table 2.3 Ingredients for Concrete Mixture (Leena 2006)

Water		Cement		Coarse Aggregate		Fine Aggregate	
lb/yd^3	kg/m^3	lb/yd^3	kg/m^3	lb/yd^3	kg/m^3	lb/yd^3	kg/m^3
280	166	610	362	1850	1096	1280.4	759

The basis of the pullout test was going to be sample runs on two kinds of bamboo samples, Solid and Moso bamboo. The concrete mix was going to be identical for all the samples and was going to be poured simultaneously. The concrete was placed in a 12 x 6 in (152 x 304 mm) cylinder mold and the concrete was allowed to set for a period of 28 days (concrete at 28 days strength). Other compression tests of concrete were going to be sample runs for six specimens. The concrete was placed in a 12 x 6 in (152 x 304mm) mold and the concrete was also set for a period 28 days. The calculation of the concrete is as follows:

Volume of the Cylinder = $\pi \times 3 \times 3 \times 12 = 339.428$

Total number of Samples = 22

Total volume of Mix Require = $339.428 \times 22 = 7467.416 / (12^3) = 4.321\ ft^3$

A total mix of $4.321\ ft^3$ =>$4.4\ ft^3$ is required

A total mix of $4.4\ ft^3$ was made in accordance with Table 2.4.

Table 2.4 shown the concrete mixture design

Table 2.4 Ingredients for Concrete Mixture (for 22 cylinders)

Water		Cement		Coarse Aggregate		Fine Aggregate	
lb	kg	Lb	kg	lb	Kg	lb	kg
35	15.8	99.6	45.3	301.5	136.8	219	99.5

The mixed concrete was set for 28 days based on ASTM with an approximate slump value being measured as 1.5 in (38mm).

2.3.3 Step for Mixing the Concrete

All constituents for the 6 in x 12 in (152 x 304 mm) cylinders were placed in a 17280 in^3 concrete mixer. This is used to mix approximately one thirds of a batch for a total volume of 6048 in^3. Concrete mixing is performed according to ASTM. The procedure was as follows;

1. Place all coarse aggregate in the mixer
2. Rotate the mixer
3. add some of the mixing water (25 lb)
4. After a few revolutions, add the fine aggregate
5. Over a few minutes, air-entraining admixture (5 minutes)
6. As the mixer is rotating, add the cement
7. Add the remaining water (10 lb)

8. Operate mixer for rotation three to five minutes; a rolling, folding, and kneading action of the mixer will ensure an end-end admixing of materials.
9. Stop the mixer to allow the concrete mix to set during a rest time
10. After that, rotate the mixer about three minutes to complete the process

After the mixing procedure, the concrete is placed into sixteen cylinders (6 x12); 8 Solid specimens and 8 Moso specimens, and six concrete specimens for compressive tests which is approximately 6000 psi (41.4 Mpa) which is shown Table 2.5.

All the concrete constituents, cement, coarse aggregate, fine aggregate, and water, were weighed to the nearest 0.01 lb by an A & D Engineering FG-150KX Digital Scale

2.3.4 Slump Test of Hydraulic Cement Concrete

Slump testing was studied to measure the stability of plastic concrete in a laboratory. The test was used to check the stability of the concrete in relationship to the amount of water in the mixed concrete with all the other constituents. Stability of slump was defined as the inclination of concrete to flow as a fluid. Mostly, the slump of the concrete was used as a measure of workability. On the other hand, the value of slump was not an accurate application due mostly to particularly aggregate gradation.

Equipment to perform this test included a slump cone, a plate with a coating surface, a tamping rod, and a wood ruler. The slump cone had top and bottom openings of 4 in (102 mm) and 8 in (203 mm) in a frustum of 12 in (304 mm) diameter. The procedure consisted of moistening the cone and the non-absorptive plate. The tamping rod was 20 in (508 mm) long and 5/8 in (16 mm) in diameter with a hemispherical end. The concrete was poured in the cone in three successive layers each equal to 1/3 the volume of the cone. Each layer was consolidated by 25 actions of the tamping rod. The rod action penetrated each layer completely and is shown in Figure 2.13.

After tamping the three layers successively, the excess concrete was knocked off with the rod and the waste concrete was cleaned away from the perimeter. The cone was removed directly upward in a period of 3 to 7 seconds. Figure 2.14 shows a result from a slump test result. The slump was the difference in height of the mold, so the displacement of the cone was measured to the highest point.

This test suggested a uniform comparison of the batch to batch consistency of the concrete before using the same materials for some tests. Normally, the slump test shows the effective concrete values only for concrete samples having a slump between 1/2 in (13 mm) and 9 in (229 mm) from top of cone (Watkins 2003).

Figure 2.13 Tamping of Slump Test with Rod

Figure 2.14 Slump Test Result

After mixing the concrete in one batch, it was taken to the cylinder. While the concrete was placed into the cylinder, the rod was active and a rubber mallet was acting as a vibration tool hitting the outside of the cylinder to vibrate the concrete into empty spaces because the rod could not adequately pack the concrete into all the spaces present. Figure 2.15 shows the motion of the rod and rubber mallet. Finally, the top of the cylinders were finished off smoothly, and all the bamboo rods were marked two kinds of length, 6 in (152 mm) and 12 in (304 mm), and the concrete cylinders were marked the two points, Center and 1.5 in (38mm) form center. After marking, the bamboo rods were put exact lengths and points on the concrete cylinders.

Figure 2.15 Motion of the rod and rubber mallet and pouring concrete

2.3.5 Compressive Strength Testing

For compression tests, 6 in x 12 in (152 x 304 mm) cylinder specimens were prepared, and filled full of the same concrete used in the pull out tests. Compressive strength tests were conducted for 28 days, the pullout test period. Six specimens were made, and the average compressive strengths of the test specimens were recorded for reporting as compressive strength for each day of the curing process.

The following procedures were followed for all the compressive test specimens;

1. The concrete was removed from the cylinder and equipped with steel caps. These were placed in a hydraulic compression machine with neoprene inserts. The steel

caps were centered on the ends of the specimen and the specimen and the samples were placed under the compressive load of the machine.

2. A specimens were centered on the lower plate in relation to the upper block. The machine was turned on, load setting was set at zero, and the upper spherical block was adjusted until the top of the specimen contacted the upper plate.

3. The axial compressive load was applied onto the concrete cylinder at a rate of 20 to 50 psi/sec until failure was reached. When the concrete cylinders reached the maximum load at failure, type of fracture and any notable defects were reported and the pull out test could begin for the respective pull out specimen.

A photograph of a concrete cylinder being loaded in the testing machine is shown in Figure 2.16 and a compression test apparatus with loading value, transmission gear, gauge buster, and output device are shown in Figure 2.17.

Figure 2.16 Compressive Testing

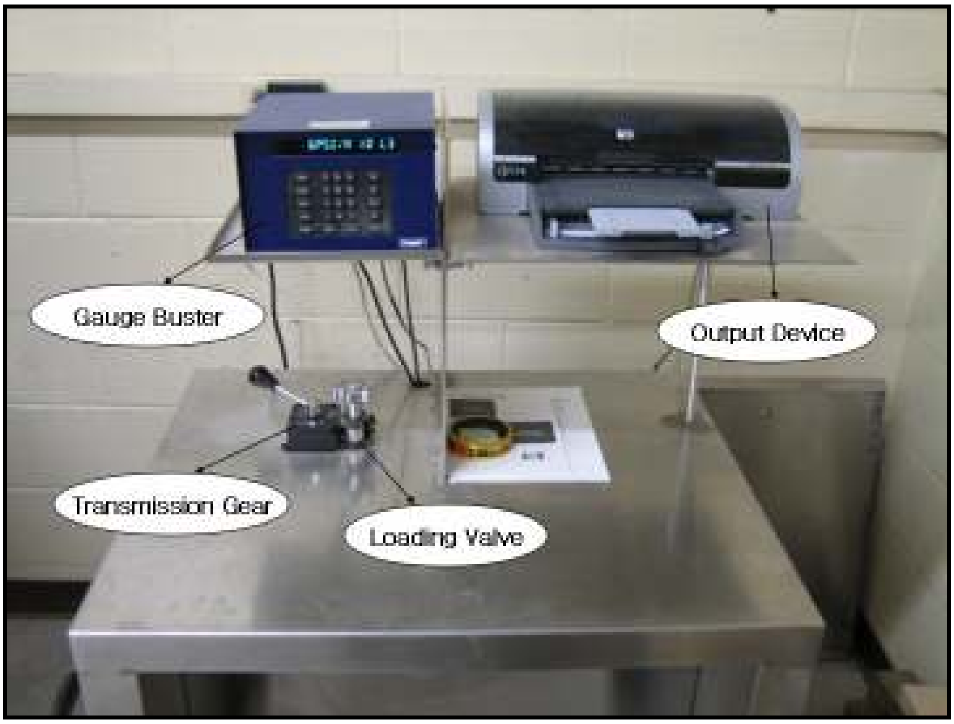


Figure 2.17 Compression Test Apparatus

Table 2.5 shows the results of concrete compressive tests. The compressive strength of test on concrete cylinders with 6 x 12 in (152 x304 mm) observed approximately 6000 psi (41.4 Mpa).

Table 2.5 Results of Concrete Compressive Tests

Specimen	#1	#2	3	4	5	6	average
Concrete Compressive (psi)	5980	6010	5670	5880	6170	6250	5993

Using Table 2.5, the standard deviation is calculated to be 189, and the coefficient of variation is calculated to be 3.16 %.

2.3.6 Test Setup and Instrumentation

A machine capable of producing 60 kips (267 KN) of tensile or compressive force was used for pull-out testing. The specimen was placed on the upper grip of the testing machine. The surface of the concrete cylinder was flat, so an upper plate provided a flat surface for protecting the movement of the concrete cylinder. Also, the upper grip was fixed, and the lower grip was connected to the load plate by two columns.

A 1 in (25.4 mm) hole was required in all of the above apparatus to accommodate the bamboo pole. During pull-out testing, the bamboo is held in three places; the grips of the upper and lower plate and the loading end by C-clip for holding bamboo. Specifically, a load is applied to the end of the bar by the grip of the lower plate, and the C-clip is applied at the end of the bamboo for restricting the bamboo's movement and is shown in Figure 2.21. The length of bamboo needed for the grips to make the connection was around 2ft (61 cm).

For conveying testing data, a desktop computer with MTESTW software was used to read and store the data and is shown in Figure 2.18. All values were calibrated to zero prior to testing. A calibration factor was computed and a linear slope resulted from a plot of loading data.

Figure 2.18 Data Collection with an Automatic Data Acquisition system

Displacement transducers (DT) were used to measure slip at corresponding displacement throughout the pull-out testing. Two kinds of DT were used. One DT, a dial gauge, was placed above the specimen to measure slippage of the unloaded bamboo through the top of the concrete cylinder as shown in Figure 2.19.

Figure 2.19 Dial Gage

Another DT, an extensometer, was attached to the tensile test machine. It was attached directly to the load plate as shown in Figure 2.20, and measured the elongation.

Figure 2.20 Extensometer

The two kinds of displacement transducers were calibrated before each test. Values obtained from the DTs were saved onto the computer program in the acquisition system. When corresponding data was shown on the computer screen by each DT shaft, this was repeated for several different displacements. These values were calculated and a slope of the plot between load and displacement was shown and compared to each bamboo. In each test, the trend line described a linear relationship with an almost 90% accuracy.

The loaded end of the bamboo rod was set into the grips. The slacked bamboo in the system was tightened into place before the load was applied. At this point, the dial gauge was attached to the bottom of concrete cylinder. If the dial gauge had been set before the slack in the system was removed, it could have shifted during the first applied load. Clearly, accurate results would be generated by the transducers due to the correct alignment of the bamboo. Inaccurate results would be obtained if the instruments were not set perpendicular to the bottom surface of the concrete cylinder. The distance from the bottom surface of the concrete cylinder to the point of the zero mounted DT determined the slip of the bamboo and was calculated to compensate for the elongation of the bamboo. All of the components are shown in Figure 2.21.

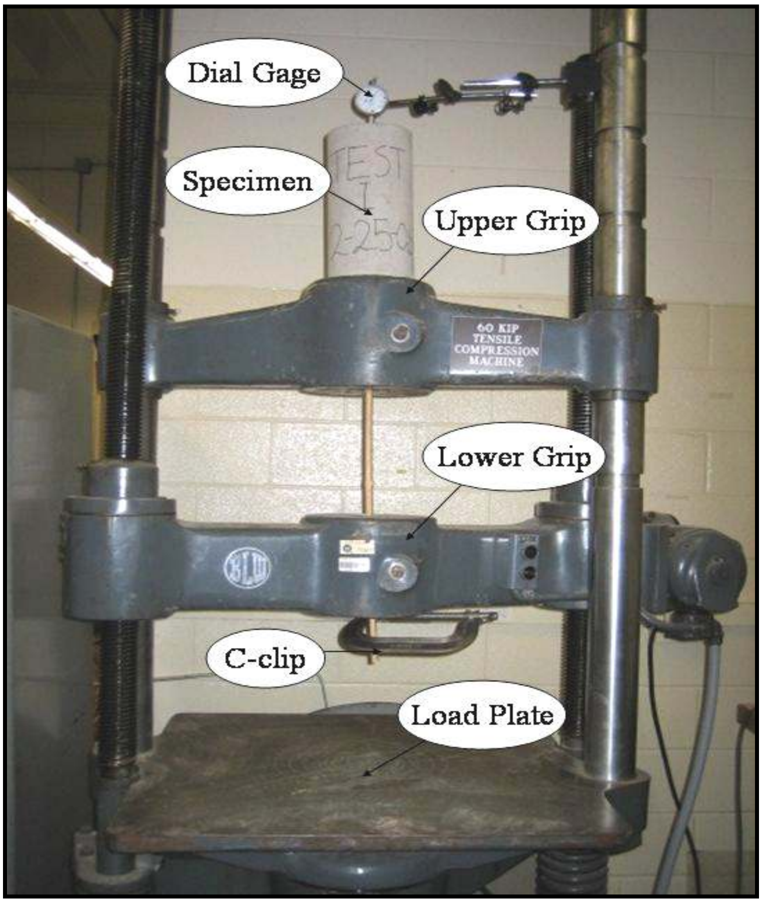


Figure 2.21 Test Set-Up

All data was collected by a unique file name for classifying the results from different tests with a particular character; also, each specimen was given a specific sign based on its special feature. For example, the first specimen of solid bamboo with both 6in bond and center position was marked S6C on the side surface of the concrete cylinder. Each signal in the specimen designations represented a particular specimen in the group containing a particular type of bamboo. After testing, a specimen was rechecked for a possible abnormality in the test results. The specimen could be distinguished from the other data files and physical examples. Data was collected by a computer. The machine was stopped by the computer by failure of any specimen. Sometimes, the data showed a sudden drop in the applied load and a simultaneous increase in the displacements of the specimens. These appear to be irregular failures. The final maximum load was read off the results by the program of the system, and the data was compared later in each data file. Each test finished within 5 to 10 minutes.

All testing processes followed the same step and classified the characteristics of each specimen. Also; at the same time, the compression cylinder was tested to obtain the concrete’s compressive strength. When possible, all tests were finished within one to two days.

CHAPTER 3

EXPERIMENTAL TEST RESULTS

3.1 Introduction

This chapter presents the results of the tensile tests and the pullout test for two different kinds of bamboo, Solid and Moso bamboo. Tensile test specimens depend on node frequency, differing thickness, and lengths of the two kinds of bamboo. The tensile test specimens were used to investigate the effects on bamboo strength. Pullout tests varied based on bond's length and on the points where the rod was placed. The bond's length was 6in (152 mm) or 12 in (304 mm) from the top of the cylinder. It had either 6 in (152mm) embedment lengths, 6 times of the bamboo diameter, or 12 in (304 mm) embedment length, 12 times of the bamboo diameter.

The load in the pull out test was applied at a stable rate of approximately 75 lbs/sec (333 N/sec) with a regular pause of few minutes for reading of deflection in the dial gauge and working with the data acquisition system. The failures load and mode of failure were recorded. Test designations were based on Bamboo type, position of bamboo, and embedded length. For example, the specimen Solid, Center, and 6 in represents a test specimen with Solid bamboo, Center position, and 6 in (152 mm) embedment length.

3.2 Tensile Test Result

The purpose of tensile tests was to determine the tensile capacity of the selected bamboo type. Eighty tests were performed on tensile specimens, 1/8 in (3.2 mm) thickness, 1 in (25 mm) width, and 6 in (152 mm) or 12 in (304 mm) length either with or without. Three types of failure patterns were observed; (1) Typical splitting failure, (2) Typical Failure of the end-tap, (3) Typical failure of node.

According to a tensile test research of bamboo nodes after, the first result typically observed a splitting failure of bamboo. However, if a node is present, bamboo cracks along the node and then splits, are shown in Figure 3.1 to Figure 3.4. Therefore, the sample with nodes often held a larger load before reaching failure in contrast to those without node.

The second failure pattern was at the site of the front aluminum tab. The failure mode suggested that the stress distribution across the cross-section of the bamboo was not uniform. The process of failure occurred firstly in the outer fibers and then the moved towards the core. These suggest that the stresses which were higher in the peripheral district of the cross-section as compared to the core. Figure 3.5 to Figure 3.8 shows failure around the aluminum tabs. The fibers of the Moso bamboo (left side picture) appear to be torn as if shredded, whereas the fiber of the solid bamboo (right side picture) shows a clear failure as if cut by a knife.

The third observed failure pattern was that failure occurred that if a node was present, the failure would occur there. This is shown in Figure 3.9 to 3.10 which show the third type of failure pattern. The fibers in the nodes may be very brittle and stiff because the fibers are much denser than those of the internodes regions and the fibers are chaotic in the node except for internodes regions which are straight. The specimen failures occurred at the node for these reasons.

It seems that the constitutional relationship of the nodes differs from those of the internodal regions with nodes having a brittle behavior while internodal regions exhibit a more ductile behavior. However, the ultimate strength of the node was anticipated to be higher than that of other regions.

In the tensile tests on Moso bamboo with 1/8 in (3.2 mm) thickness, the specimens followed the failure pattern previously discussed. Some of these samples failed at node and others failed at the front of the aluminum tabs.

The experimental test results for tensile stress-strain curves are presented Figure 3.11 to 3.22. Figure 3.11 to 3.13 shows the tensile of stress-strain curves for 6 in (152 mm) Solid bamboo with and without node; Figure 3.14 to 3.16 shows the tensile stress-strain curves for 12 in (304 mm) Solid bamboo with and without node; Figure 3.17 to 3.19 shows the tensile stress-strain curves for 6 in (152 mm) Moso bamboo with and without node, Figure 3.20 to 3.22 shows the tensile stress-strain curves for 12 in (304 mm) Moso bamboo with and without node.

Figure 3.1 Typical Splitting Failure in Tensile Test – 6 in (152 mm) no node

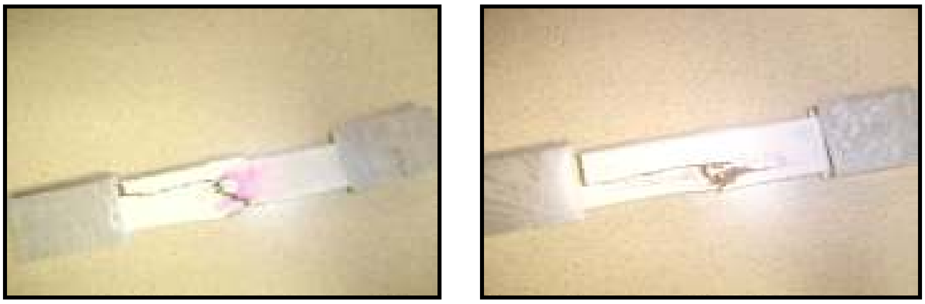


Figure 3.2 Typical Splitting Failure in Tensile Test – 6 in (152 mm) with node

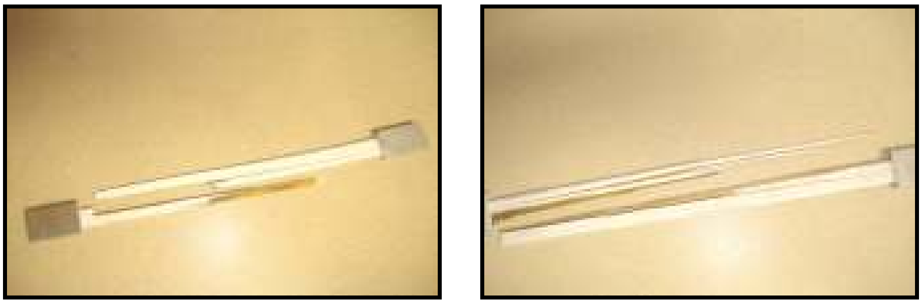


Figure 3.3 Typical Splitting Failure in Tensile Test – 12 in (304 mm) no node

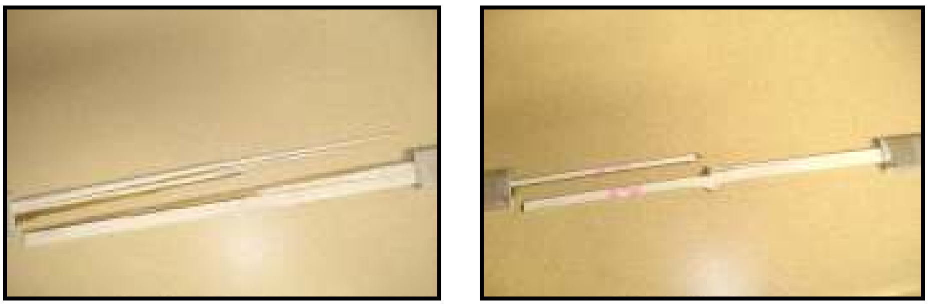


Figure 3.4 Typical Splitting Failure in Tensile Test – 12 in (304 mm) with node

Figure 3.5 Typical Failure of the End-Tap in Tensile Test – 6 in (152 mm) no node

Figure 3.6 Typical Failure of the End-Tap in Tensile Test – 6 in (152 mm) with node

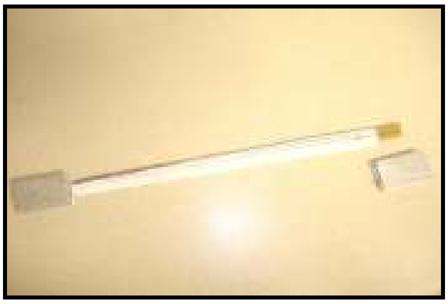


Figure 3.7 Typical Failure of the End-Tap in Tensile Test – 12 in (304 mm) no node

Figure 3.8 Typical Failure of the End-Tap in Tensile Test – 12 in (304 mm) with node

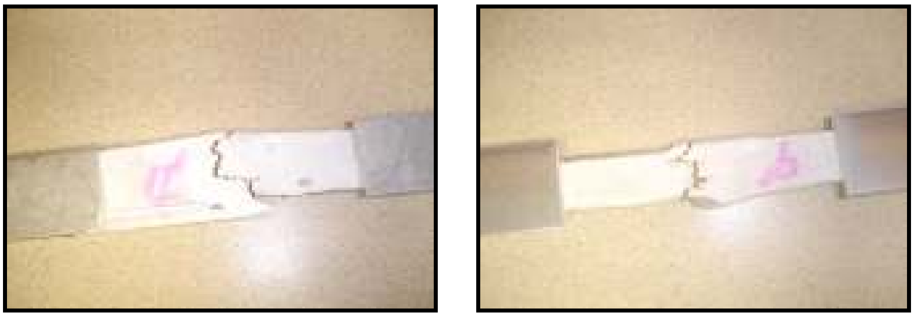


Figure 3.9 Typical Failure of Node in Tensile Test – 6 in (152 mm) with node

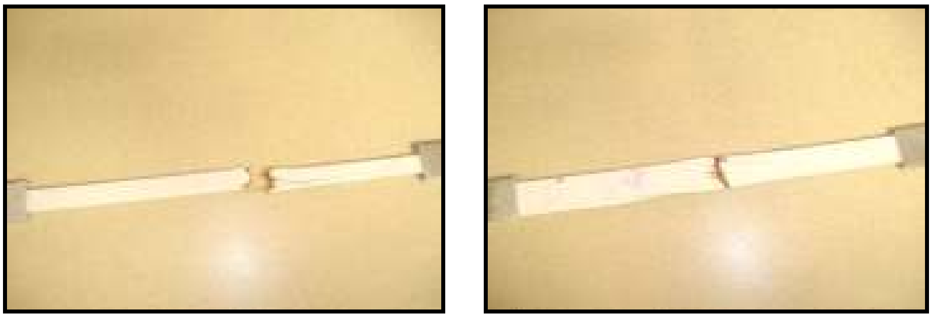


Figure 3.10 Typical Failure of Node in Tensile Test – 12 in (304 mm) with node

3.2.1 Test Solid – 1/8in – 6in

The first tensile test was done with Solid bamboo, approximately 1/8 in (3.2 mm) in thickness, 6 in (152 mm) in length and with or without node. The load of MTS was applied 0.1 mm per minute. The curve was shown generally the non-linear. Table 3.1 shows those test results. In the Table 3.1, the maximum stress was 30 ksi (208 Mpa) which was broken near the grip without crack, and the minimum stress was 20 ksi (138 Mpa) which happened near a parallel crack on the culm and broke secondly at the grip. Generally, most of the specimens are broken between parallel cracks and at the grip. This condition persisted for 10 specimens. After finished the test, one data entry could not be retrieved save from the lab computer. Figure 3.11 shows the equation (3.1) which is

$$\sigma = -5897435\varepsilon^2 + 843054\varepsilon + 638 \tag{3.1}$$

for no node.

In the other case; node present, the maximum stress was 37 ksi (256 Mpa) which was occurred several parallel cracks and broken at the node, and the minimum stress was 18 ksi (127 Mpa) which was cut clearly at the node. Table 3.2 shows those test results and Figure 3.12 shows the equation (3.2) which is

$$\sigma = -3986390\varepsilon^2 + 742861\varepsilon + 32 \tag{3.2}$$

for node present.

Figure 3.13 shows the equation (3.3) which is

$$\sigma = -4915821\varepsilon^2 + 802527\varepsilon + 545 \tag{3.3}$$

for with and without node of Solid bamboo.

Table 3.1 and 3.2 shows the collected data of the 6 in (152 mm) Solid bamboos with and without nodes. According to the results of the test, the specimen with node has failure which occurred with high stress, 37 ksi (256 Mpa) and high strain value, 0.06in/in (mm/mm). Also, two data could not be retrieved due to computer problems in the all Solid bamboo with 1/ 8 in (3.2 mm) in thickness and 6 in (152 mm) in length.

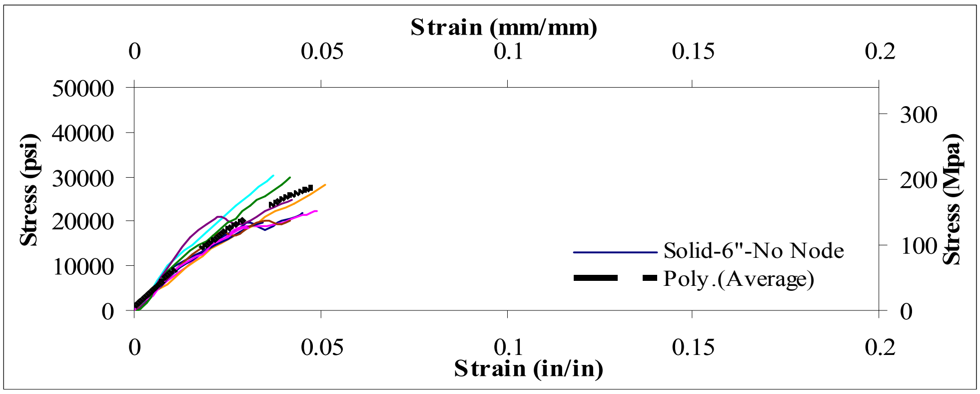


Figure 3.11 Stress-Strain Curve for samples no node
Solid Bamboo 1/8 in (3.2 mm) Thickness, 6 in (152 mm) Length

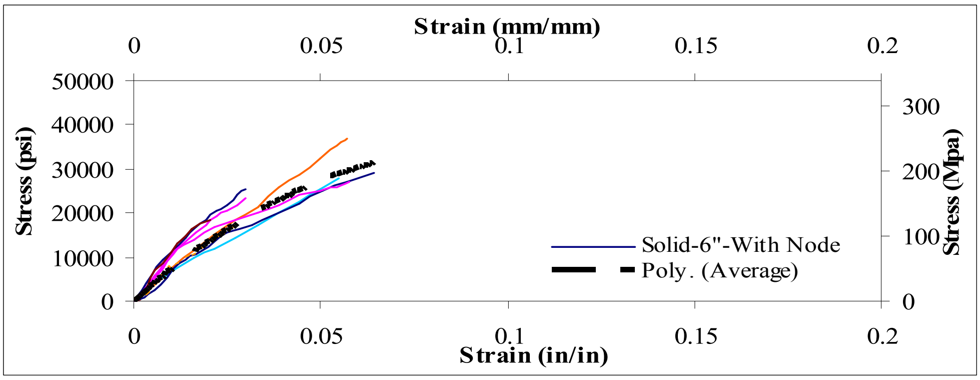


Figure 3.12 Stress-Strain Curve for samples with node
Solid Bamboo 1/8 in (3.2 mm) Thickness, 6 (152 mm) Length

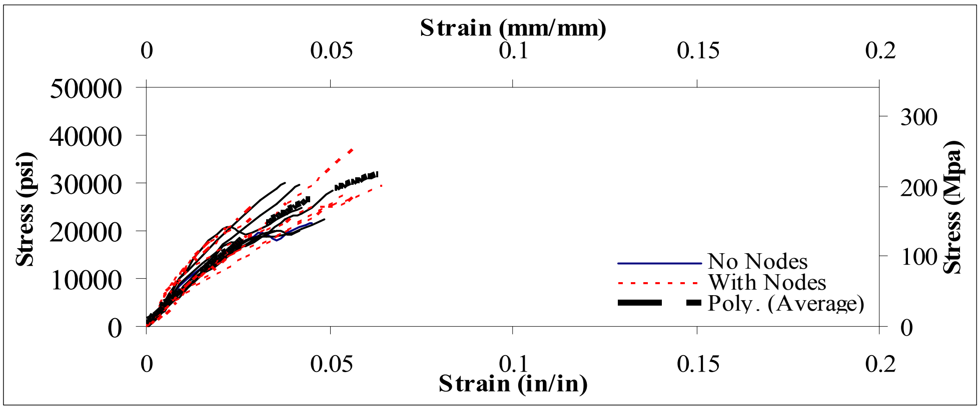


Figure 3.13 Stress-Strain Curve of Solid 6 in sample no node & with node

Table 3.1 Results of Tensile Test – 6 in (152 mm) Solid Bamboo No Node

	Failure Location	Failure Stress		Strain
		(psi)	(Mpa)	(in/in)
Specimen (1)	Parallel crack & Broken at the grip	21790	150	0.045
Specimen (2)	Parallel crack	23073	159	0.049
Specimen (3)	At the grip	28895	199	0.05
Specimen (4)	Parallel crack & Broken at the grip	30130	208	0.038
Specimen (5)	Parallel crack & Broken at the grip	24815	171	0.042
Specimen (6)	Parallel crack & Broken at the grip	20032	138	0.035
Specimen (7)	Parallel crack & Broken at the grip	20314	140	0.042
Specimen (8)	At the grip	19029	131	0.031
Specimen (9)	At the near grip	29838	206	0.042
Average		24213	167	0.042
Standard Deviation		4159	29	0.0059
Coefficient Of Variation (%)		17.2	17.2	13.9

Table 3.2 Results of Tensile Test – 6 in (152 mm) Solid Bamboo With Node

	Failure Location	Failure Stress		Strain
		(psi)	(Mpa)	(in/in)
Specimen (1)	Parallel crack & Broken at the node	25539	176	0.03
Specimen (2)	Parallel crack & Broken at the node and grip	23414	161	0.03
Specimen (3)	At the grip	37073	256	0.057
Specimen (4)	At the grip	27850	192	0.055
Specimen (5)	At the node	19010	131	0.02
Specimen (6)	At the node	28507	197	0.064
Specimen (7)	Parallel crack & At the near grip	27281	188	0.057
Specimen (8)	At the near grip	18442	127	0.027
Average		25890	179	0.043
Standard Deviation		5554	38	0.0162
Coefficient Of Variation (%)		21.5	21.5	37.7

3.2.2 Test Solid – 1/8in – 12in

For the Solid bamboos without node, 1/8 in (3.2 mm) in thickness and 12 in (304 mm) in length, the test results are presented in Figure 3.14 which shows a different behavior in both stress and strain zone. The curve was shown generally to be linear. Table 3.3 shows those test results. In the Table 3.3, the maximum modified tensile strength was 35 ksi (244 Mpa) with a strain approximately 0.01 in/in (mm/mm) which occurred at parallel cracks and at the grip. The minimum stress 6 ksi (39 Mpa) with strain approximately 0.0029 in/in (mm/mm) had failure accruing at the aluminum tab. Figure 3.14 shows the equation (3.4) which is

$$\sigma = -43093309\varepsilon^2 + 3285806\varepsilon + 927 \tag{3.4}$$

for the specimens without node.

The behavior of the Solid bamboos with no node, 1/8 in (3.2 mm) in thickness and 12 in (304 mm) in length is shown and the test results are presented in Figure 3.15 which shows a different behavior in both stress and strain zone. The curve was shown generally to be linear. Table 3.4 shows those test results. In the Table 3.4, the maximum modified tensile strength was 32 ksi (222 Mpa) with a strain approximately 0.01 in/in (mm/mm) which occurred at parallel cracks and at the grip. The minimum stress 23 ksi (157 Mpa) with strain approximately .0067 in/in (mm/mm) occurred at the aluminum tab. Figure 3.15 was shown the equation (3.5) is

$$\sigma = -193798255\varepsilon^2 + 4858791\varepsilon + 581 \tag{3.5}$$

for the specimens with node.

Figure 3.16 shows the equation (3.6) which is

$$\sigma = -99082758\varepsilon^{2} + 3898031\varepsilon + 967 \quad (3.6)$$

for with and without node of Solid bamboo.

According to the results of the test, the specimens with nodes can have failure occurring with high stress, 32 ksi (223 Mpa), and high strain value, approximate 0.01in/in (mm/mm) in the all Solid bamboo with 1/ 8 in (3.2 mm) in thickness and 12 in (304 mm) in length.

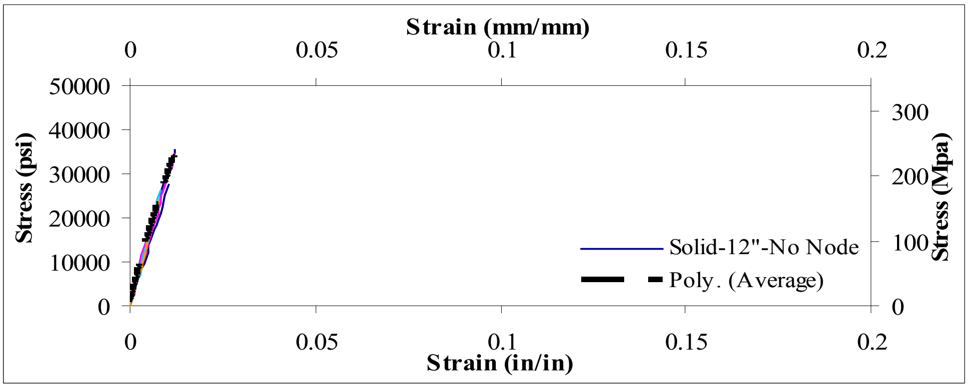


Figure 3.14 Stress-Strain Curve for samples no node
Solid Bamboo 1/8 in (3.2 mm) Thickness, 12 in (304 mm) Length

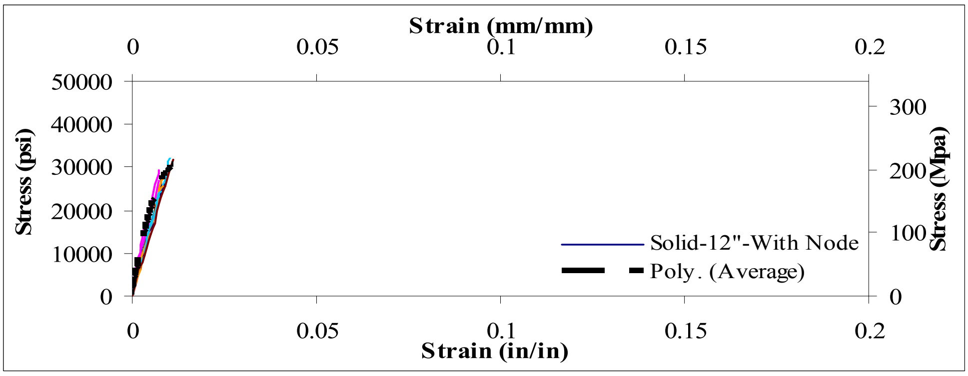


Figure 3.15 Stress-Strain Curve for samples with node
Solid Bamboo 1/8 (3.2 mm) in Thickness, 12 in (304 mm) Length

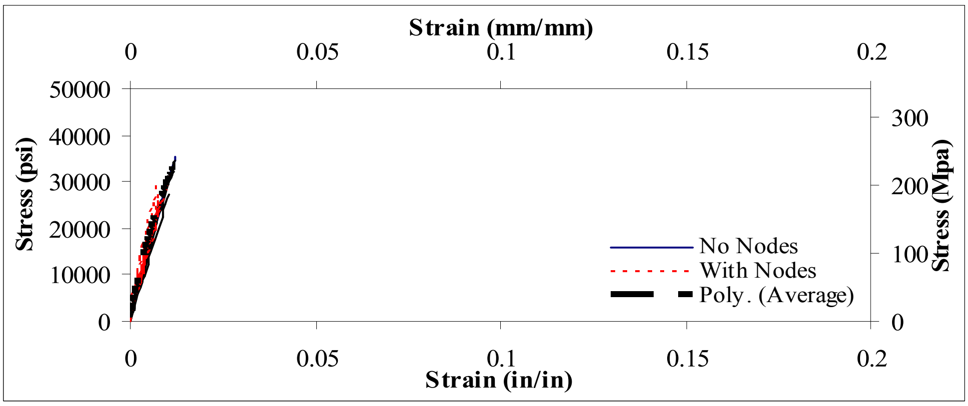


Figure 3.16 Stress–Strain Curve of Solid 12 in sample with no node & with node

Table 3.3 Results of Tensile Test – 12 in (304 mm) Solid Bamboo No Node

	Failure Location	Failure Stress		Strain
		(psi)	(Mpa)	(in/in)
Specimen (1)	Parallel cracks & At the grip	35399	244	0.008
Specimen (2)	Parallel cracks & At the grip	23444	162	0.007
Specimen (3)	Parallel cracks & At the grip	25276	174	0.008
Specimen (4)	Sliding the Aluminum Tab	*11411	79	0.01
Specimen (5)	Sliding the Aluminum Tab	*5585	39	0.007
Specimen (6)	Parallel cracks & At the grip	28892	199	0.008
Specimen (8)	Sliding the Aluminum Tab	34505	238	0.008
Specimen (9)	Parallel cracks & At the grip	26330	182	0.008
Specimen (10)	Parallel cracks & At the grip	21102	146	0.01
Average		27850	192	0.008
Standard Deviation		5017	34.6	0.0085
Coefficient Of Variation (%)		18	18	10.6

* This data should be questionable; therefore, it is not included in the calculation for average failure stress.

Table 3.4 Results of Tensile Test - 12 in (304 mm) Solid Bamboo With Node

	Failure Location	Failure Stress		Strain
		(psi)	(Mpa)	(in/in)
Specimen (1)	Parallel crack & At the node	27841	192	0.008
Specimen (2)	Parallel cracks & At the node	29341	202	0.007
Specimen (3)	Parallel crack & At the node	27164	187	0.008
Specimen (4)	Parallel cracks & At the node	32145	221	0.01
Specimen (5)	At the grip	22794	157	0.007
Specimen (6)	Parallel cracks & At the grip	25997	179	0.009
Specimen (7)	Parallel cracks & At the grip	28217	195	0.007
Specimen (8)	Parallel cracks & At the grip	25769	178	0.008
Specimen (9)	Parallel cracks & At the node	24553	169	0.008
Specimen (10)	Parallel cracks & At the grip	31655	218	0.011
Average		27548	190	0.0083
Standard Deviation		2811	19	0.0013
Coefficient Of Variation (%)		10.2	10.2	15

3.2.3 Test Moso – 1/8in – 6in

The first tensile test was done with the Moso bamboo, approximately 1/8 in (3.2 mm) in thickness, 6 in (152 mm) in length and with or without node. Also, the loading was applied 0.1 mm per minute. The curve was shown to be a general tensile curve. Table 3.5 shows those test results. In the Table 3.5, the maximum stress was 33 ksi (229 Mpa) which was broken at parallel cracks without parallel crack, and the minimum stress was 19 ksi (133 Mpa) which was broken at a parallel crack on the culm and also broken at the grip. Generally, most of the specimens are broken at the parallel cracks and one bamboo pole did not show any crack, but the bamboo measured a 24 ksi (165 MPa) tensile strength. These results come from specimens. Figure 3.17 shows the equation (3.7) which is

$$\sigma = -1003422\varepsilon^2 + 333602\varepsilon + 1407 \qquad (3.7)$$

for the specimen containing a no node.

For the other case with a node, the maximum stress was 33 ksi (229 Mpa) which broke at several parallel cracks and also broke at the node, and the minimum stress was 13 ksi (89 Mpa) which was cut clearly at the node. Table 3.6 shows those test results and Figure 3.18 shows the equation (3.8) which is

$$\sigma = -2291006\varepsilon^2 + 468544\varepsilon - 377 \qquad (3.8)$$

for the specimen containing a node.

Figure 3.19 shows the equation (3.9) which is

$$\sigma = -1331060\varepsilon^2 + 381533\varepsilon + 649 \qquad (3.9)$$

for with and without node of Moso bamboo.

According to the result of the tests, the specimen with no nodes can be broken at points of high stress 33 ksi (229 Mpa) and high strain value, approximate 0.14 in/in (mm/mm). Also, the specimen with node can be broken at points of high stress 33 ksi (229 Mpa) and high strain value, approximate 0.086 in/in (mm/mm) in the all Moso bamboo with 1/ 8 in (3.2 mm) in thickness and 6 in (152 mm) in length.

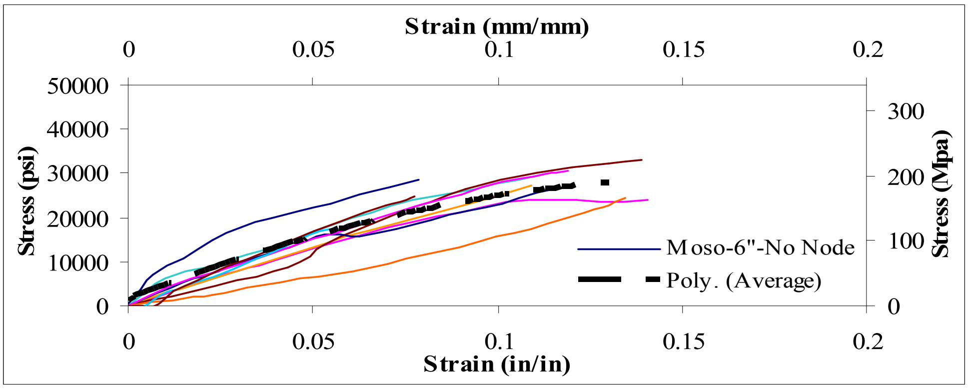


Figure 3.17 Stress-Strain Curve for samples no node
Moso Bamboo 1/8 in (3.2 mm) Thickness, 6 in (152 mm) Length

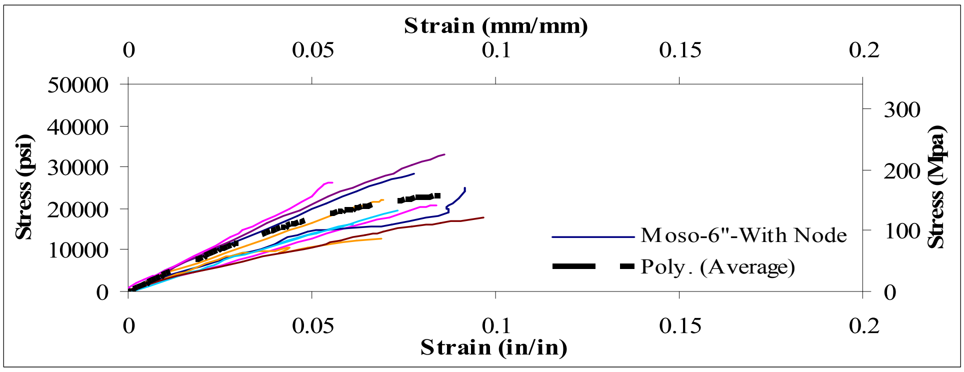


Figure 3.18 Stress-Strain Curve for samples with node
Moso Bamboo 1/8 in (3.2 mm) Thickness, 6 in (152 mm) Length

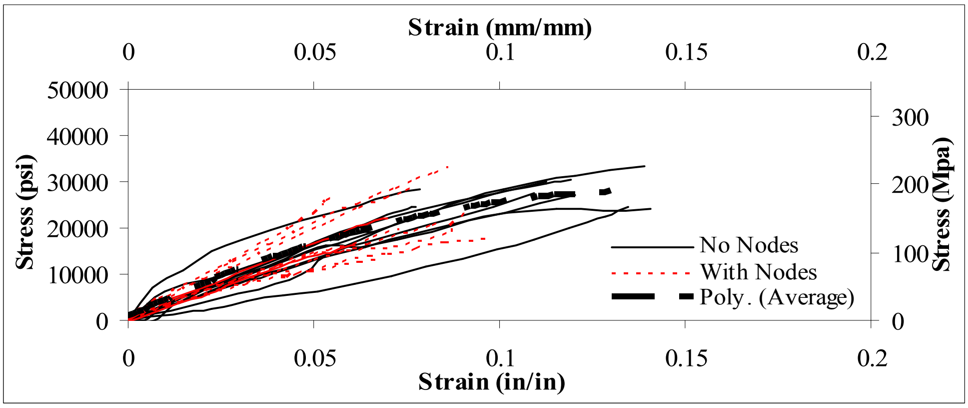


Figure 3.19 Stress-Strain Curve of Moso 6 in sample with no node & with node

Table 3.5 Results of Tensile Test - 6 in (152 mm) Moso Bamboo No Node

	Failure Location	Failure Stress		Strain
		(psi)	(Mpa)	(in/in)
Specimen (1)	Parallel cracks	28561	197	0.08
Specimen (2)	Parallel cracks	24923	172	0.14
Specimen (3)	Parallel cracks	30011	207	0.11
Specimen (4)	Parallel crack & At the grip	29995	207	0.11
Specimen (5)	Parallel cracks	33182	229	0.14
Specimen (6)	Parallel crack	27373	189	0.12
Specimen (7)	Parallel cracks	30589	211	0.12
Specimen (8)	No crack	24464	169	0.134
Specimen (9)	Parallel crack & At the grip	19262	133	0.07
Specimen (10)	Parallel cracks & At the grip	24789	171	0.077
Average		27315	189	0.11
Standard Deviation		3824	26	0.0248
Coefficient Of Variation (%)		14	14	22.6

Table 3.6 Results of Tensile Test - 6 in (152 mm) Moso Bamboo With Node

	Failure Location	Failure Stress		Strain
		(psi)	(Mpa)	(in/in)
Specimen (1)	Parallel crack & At the grip	28536	197	0.077
Specimen (2)	Parallel crack & At the node	20987	145	0.083
Specimen (3)	At the node	22244	153	0.07
Specimen (4)	At the node	19445	134	0.073
Specimen (5)	Parallel crack & At the node	33233	229	0.086
Specimen (6)	Parallel crack & At the node	24835	171	0.092
Specimen (7)	At the node	26448	182	0.055
Specimen (8)	At the node	12898	89	0.069
Specimen (9)	At the node	16342	113	0.061
Specimen (10)	Parallel crack & At the node	17609	121	0.097
Average		22258	153	0.076
Standard Deviation		5812	40	0.0127
Coefficient Of Variation (%)		26	26	16.7

3.2.4 Test Moso – 1/8in – 12in

For the Moso bamboo without node, 1/8 in (3.2 mm) in thickness and 12 in (304 mm) in length, the test results are presented in Figure 3.20 which shows a different behavior in both stress and strain zone. The curves are shown general tensile curves. Table 3.7 shows those test results. In the Table 3.7, the maximum modified tensile strength was 45 ksi (311 Mpa) with a strain approximately 0.165 in/in (mm/mm) which occurred along the parallel cracks and at the grip. The minimum stress was 16 ksi (114 Mpa) with a strain of approximately 0.1 in/in (mm/mm) which occurred along the aluminum tab. Figure 3.20 shows the equation (3.10) which is

$$\sigma = -199993\varepsilon^2 + 271670\varepsilon + 2043 \tag{3.10}$$

for the Moso bamboo no node.

For the behavior of the Moso bamboo with node 1/8 in (3.2 mm) in thickness and 12 in (304 mm) in length, the test results are presented in Figure 3.21 which shows a different behavior in both stress and strain zones. The curves are shown general tensile curves. Table 3.8 shows those test results. In the Table 3.8, the maximum modified tensile strength was 32 ksi (221 Mpa) with a strain approximately 0.14 in/in (mm/mm) which occurred along the parallel cracks and at the grip. The minimum stress was 15 ksi (103 Mpa) with a strain of approximately 0.11in/in (mm/mm) which occurred along the aluminum tab. Figure 3.21 shows the equation (3.11) which is

$$\sigma = -770156\varepsilon^2 + 302216\varepsilon + 925 \tag{3.11}$$

for the Moso bamboo with node.

Figure 3.22 shows the equation (3.12) which is

$$\sigma = 129736\varepsilon^2 + 227396\varepsilon + 3209 \tag{3.12}$$

for with and without node of Moso bamboo.

Depending on the results of the tests, the specimen with no nodes can have failure occur with high stress, 45 ksi (311 Mpa) and high strain value, approximate 0.165 in/in (mm/mm) in the all Moso bamboo with 1/ 8 in (3.2 mm) in thickness and 12 in (304 mm) in length.

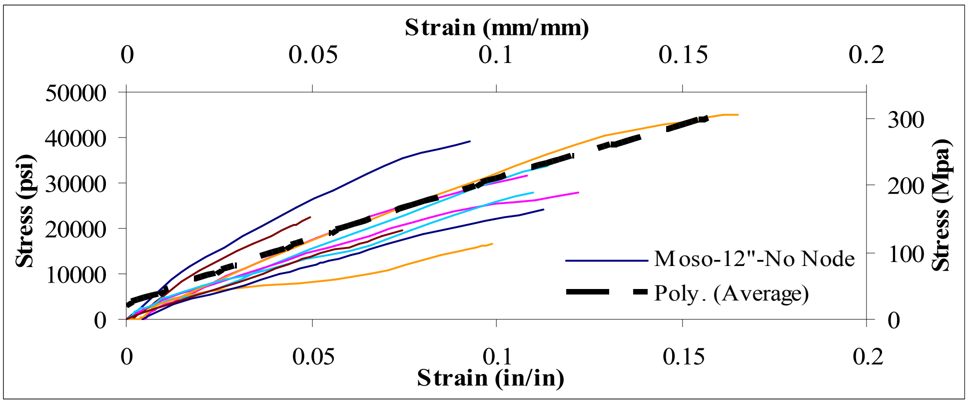


Figure 3.20 Stress-Strain Curve for samples no node
Moso Bamboo 1/8 in (3.2 mm) Thickness, 12 in (304 mm) Length

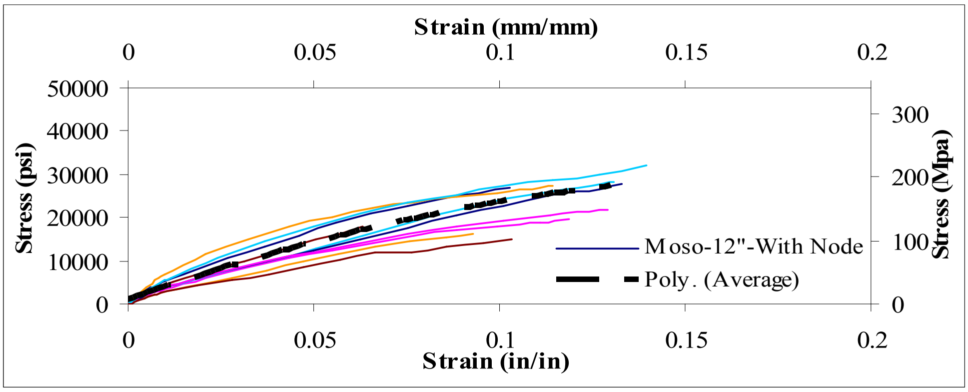


Figure 3.21 Stress-Strain Curve for samples with node
Moso Bamboo 1/8 in (3.2 mm) Thickness, 12 in (304 mm) Length

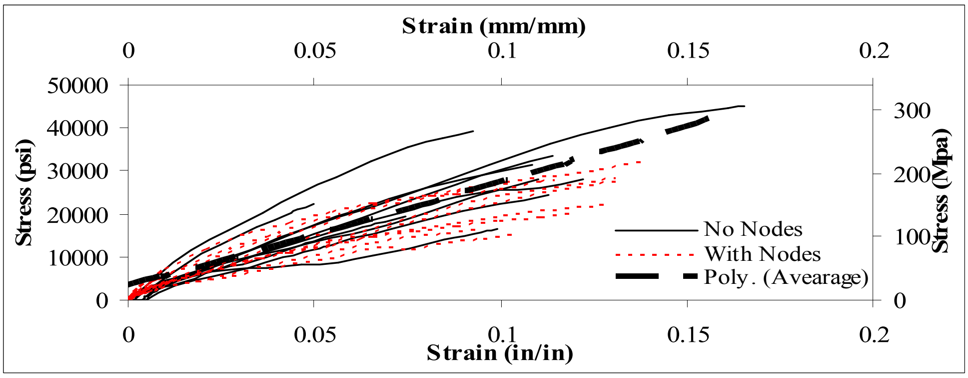


Figure 3.22 Stress-Strain Curve of Moso 12 in sample with no node & with node

Table 3.7 Results of Tensile Test – 12 (304 mm) in Moso Bamboo No Node

	Failure Location	Failure Stress		Strain
		(psi)	(Mpa)	(in/in)
Specimen (1)	Parallel cracks & At the grip	39235	271	0.093
Specimen (2)	Parallel cracks & At the grip	31495	217	0.108
Specimen (3)	At the grip	16469	114	0.1
Specimen (4)	Parallel cracks & At the grip	35871	247	0.11
Specimen (5)	Parallel cracks & At the grip	22426	155	0.05
Specimen (6)	Parallel cracks & At the grip	24325	167	0.11
Specimen (7)	Parallel cracks & At the grip	27934	193	0.122
Specimen (8)	Parallel cracks & At the grip	45128	311	0.165
Specimen (9)	Parallel cracks & At the grip	28018	193	0.11
Specimen (10)	Parallel cracks & At the grip	19538	135	0.074
Average		29044	200	0.104
Standard Deviation		8556	59	0.0285
Coefficient Of Variation (%)		29.5	29.5	27.3

Table 3.8 Results of Tensile Test - 12 in (304 mm) Moso Bamboo With Node

	Failure Location	Failure Stress		Strain
		(psi)	(Mpa)	(in/in)
Specimen (1)	Parallel cracks & At the grip	27050	186	0.103
Specimen (2)	Parallel cracks & At the grip and the node	19961	138	0.119
Specimen (3)	Parallel cracks & At the grip and the node	16115	111	0.093
Specimen (4)	Parallel cracks & At the node	28381	196	0.131
Specimen (5)	At the node	18024	124	0.063
Specimen (6)	Parallel crack &At the node	27610	190	0.133
Specimen (7)	Parallel crack &At the node	21962	151	0.129
Specimen (8)	At the node	27729	191	0.114
Specimen (9)	Parallel crack &At the node	32066	221	0.14
Specimen (10)	Parallel cracks &At the grip	14915	103	0.103
Average		23381	161	0.113
Standard Deviation		5635	39	0.022
Coefficient Of Variation (%)		24.1	24.1	19.5

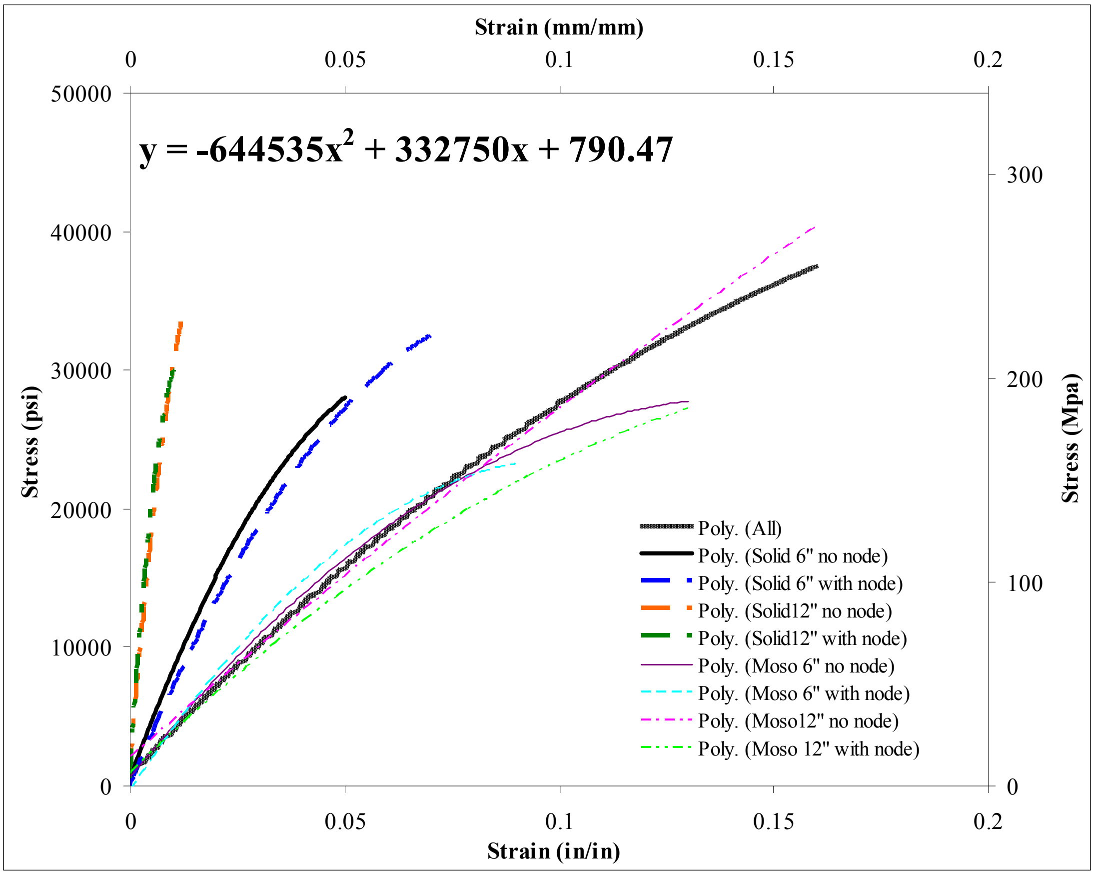


Figure 3.23 Stress-Strain Curve with All Averages

Table 3.9 shows tangent modulus, secant modulus, and average modulus in all tensile tests. In the Table 3.9, Solid bamboo shows high value at all data. Specially, 12 in (304 mm) Solid bamboo exhibited the best results both in terms of tangent modulus and secant modulus. The values of 12 in (304 mm) Solid bamboo were 3 to 9 times higher than that of other bamboos.

Table 3.9 Modulus of Elasticity of Solid and Moso Bamboo

Test Specimen		Tangent Modulus		Secant Modulus		Average Modulus	
		(ksi)	(Mpa)	(ksi)	(Mpa)	(ksi)	(Mpa)
Solid Bamboo	6 in (152 mm) No Node	837	5770	560	3858	699	4814
	6 in (152 mm) With Node	645	4444	466	3211	556	3831
	6 in (152 mm) With & No Node	860	5925	466	3211	663	4560
	12 in (304 mm) No Node	2679	18458	2679	18458	2679	18458
	12 in (304 mm) With Node	2727	18789	2727	18789	2727	18789
	12 in (304 mm) With & No Node	2709	18665	2709	18665	2709	18665
Moso Bamboo	6 in (152 mm) No Node	320	2206	221	1526	271	1866
	6 in (152 mm) With Node	406	2799	261	1797	334	2298
	6 in (152 mm) With & No Node	316	2175	214	1473	265	1824
	12 in (304 mm) No Node	313	2159	281	1938	297	2049
	12 in (304 mm) With Node	285	1966	218	1500	252	1733
	12 in (304 mm) With & No Node	255	1757	255	1757	255	1757

3.3 Pullout Test Result

In the test results, the failures of most bamboo occurred at the interface between the reinforcing bamboo and the surrounding concrete which is shown in Figure 3.24. While the bamboo slipped out of the concrete, the bamboo was broken at the grip which is shown in Figure 3.25. The final bond strength was dictated by the shear strength of the concrete and the geometrical properties of the bamboo.

Figure 3.24 Pullout Failure Specimen

Figure 3.25 The Grip Failure of Pullout Test

Figure 3.26 shows the cross-sections of failure specimens. Pullout failure occurred due to the shear strength between the bamboo and the concrete. During the first several seconds, bamboo does not show any movement. After that, the bamboo came out smoothly and without any resistance.

The average bond stress at each load, P, was calculated using the following equation (3.13):

$$\mu = \frac{P}{\pi d l} \tag{3.13}$$

where μ is the average bond stress (psi); d is the diameter of the bamboo (Solid= 2.2 in and Moso= 2.5 in); and l is the embedment length (6 in or 12 in).

In some specimens, the bamboo broke during slip. From the tensile tests on the two bamboos, the breaking stress was 35 ksi (241 Mpa) for Solid bamboo, and 45 ksi (310 Mpa) for Moso bamboo. The maximum bond stress was approximately 161 psi

(1.11 Mpa) as shown in Table 3.10, Moso bamboo as 1.5 in (38 mm) from edge and 6 in (152 mm). For example, the testing machine might not be in perfect alignment with the eccentricity of the load.

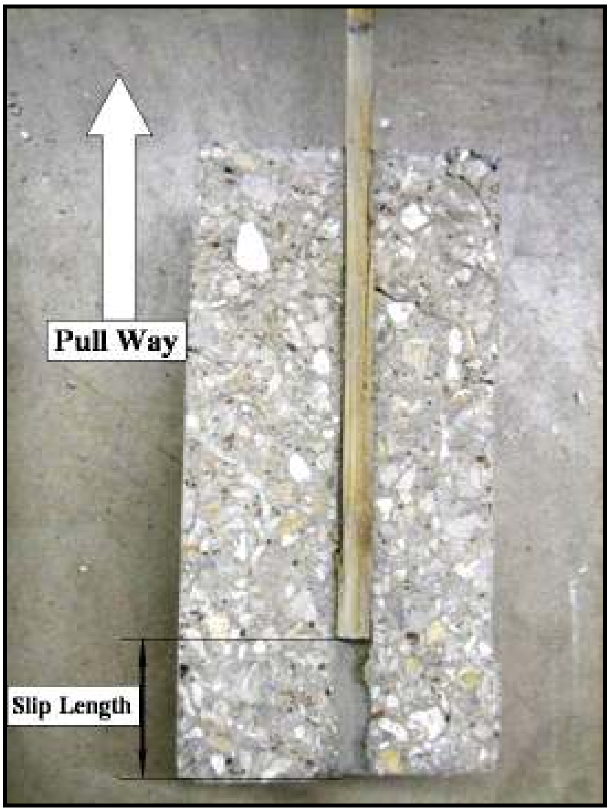


Figure 3.26 Internal Side of Pull-Out Specimen

Experimental results for the pullout testing with the two kinds of bamboo, Solid and Moso bamboo, are shown in the bond stress-slip curves in Figures 3.27 to 3.32. At the tensile test, 12 in (304 mm) Solid bamboo has lower strain values (0.008 in/in) than 6 in (152 mm) Solid bamboo (0.05 in/in). Also Figure 3.23 shows that Moso bamboo has a regular strain value of 0.1 in/in. Table 3.10 shows the different rate of fluctuation. A high rate of fluctuation occurs at the bond strength of Solid bamboo. Meanwhile, a low rate of fluctuation occurs at the bond strength of Moso bamboo. These results prove that the tensile stress-strain behavior of bamboo is directly related to the bond strength.

The bond strength depends on the embedment lengths, 6in (152 mm) and 12in (304 mm) and position, Center and 1.5 in (38 mm) from edge, with the different kinds of bamboo, Solid and Moso. Test results in terms of failure location and stress are summarized in Table 3.10.

For the Solid bamboo, plots are found to be non-linear. When the bamboo is positioned close to the edge of the concrete cover, bond strength of the 6 in (152 mm) embedment length specimen is weaker. When Solid bamboo is located near the center of the concrete block, the 6 in (304 mm) embedment length displayed high strength, 134 ksi (0.93 Mpa), and low slip, 0.1 in (2.5 mm), but 6 in (152 mm) embedment lengths and located the center showed non-linear plots with high slips values.

Also, Moso bamboo shows only non-linear plots, and higher values can be observed for the bamboo embedded near the edge. With the Moso bamboo located near the center, the 12 in (304 mm) embedment lengths reached an ultimate stress value, 116 psi (0.8 Mpa), with slip values of 1.3 in (32.9 mm). For the 6 in (152 mm) embedded lengths and located center, high slip values 1.4 in (35.9 mm), occurred. Moso bamboo with 6 in (152 mm) embedment lengths at the center position show typical bond stress versus displacement curves at the loaded end.

These curves show the difference between the behavior of the specimens for both length and position. The maximum stress, 161 psi (1.11 Mpa), can be found in the 6 in (152 mm) embedment lengths Moso bamboo, 1.5 in (38 mm) from edge. The bond strength was low at 48 ksi (0.33 Mpa) when the Solid was located 1.5 in (38 mm) from the edge with 6 in (152 mm) embedment.

From Table 3.10, Solid bamboo with 6 in (152 mm) embedment lengths and the rod placed at the center of the cylinder shows twice as much bond stress as Solid bamboo with 12 in (304 mm) embedment lengths and the rod placed at the center of the cylinder. On the other hand, Moso bamboo with 12 in (304 mm) embedment lengths and the rod placed at the center of the cylinder shows two times as much bond stress as Moso bamboo with 6 in (152 mm) embedment lengths and the rod placed at the center of the cylinder. On the other hand, a point placed 1.5 in (38mm) from the center of Solid and Moso bamboos shows the opposite of the center point results. Therefore, the bond strength depends on the bamboo point and embedment length.

Normally, the concrete cracking can be observed in pullout testing of reinforce steel bars and FRP (Fiber Reinforcement Plastic), but bamboos show smooth slipping without any cracking of concrete. Also, no damage was observed to the bamboo after the pullout tests.

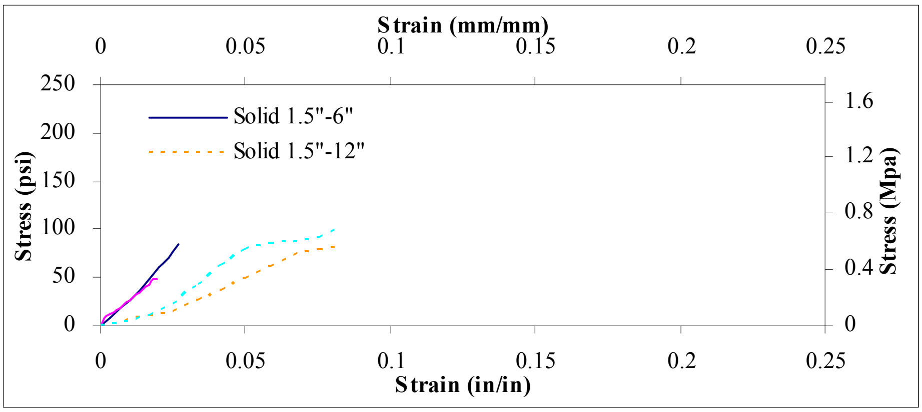


Figure 3.27 Bond Stress-Slip Behavior for Solid Bamboo - 1.5 in (152 mm) from Edge

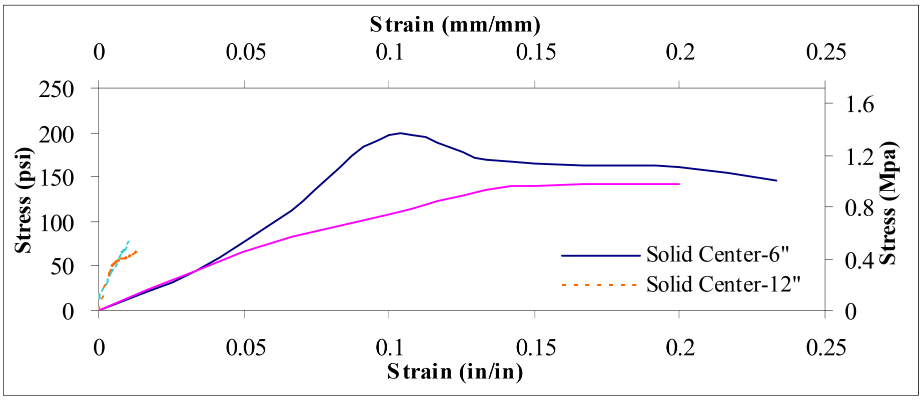


Figure 3.28 Bond Stress-Slip Behavior for Solid Bamboo - Center

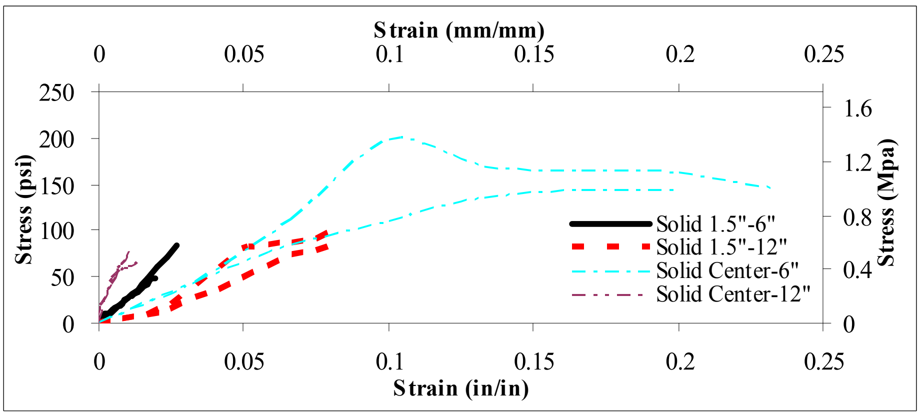


Figure 3.29 Bond Stress-Slip Behavior for combined Solid Bamboo test geometry

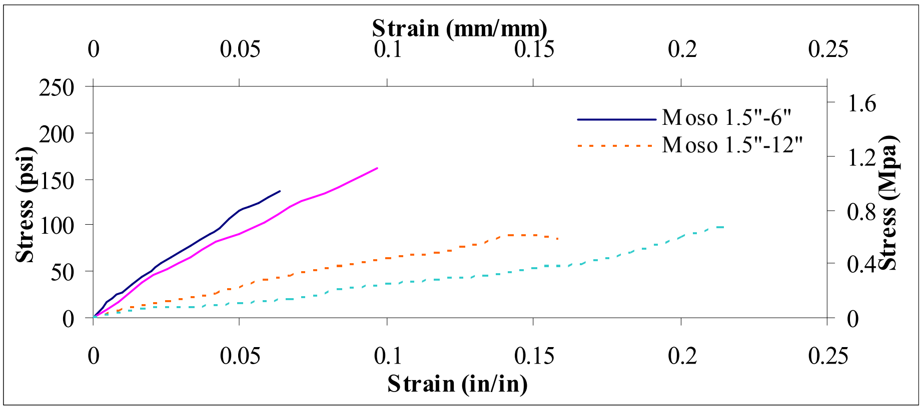


Figure 3.30 Bond Stress-Slip Behavior for Moso Bamboo - 1.5 in (38 mm) from Edge

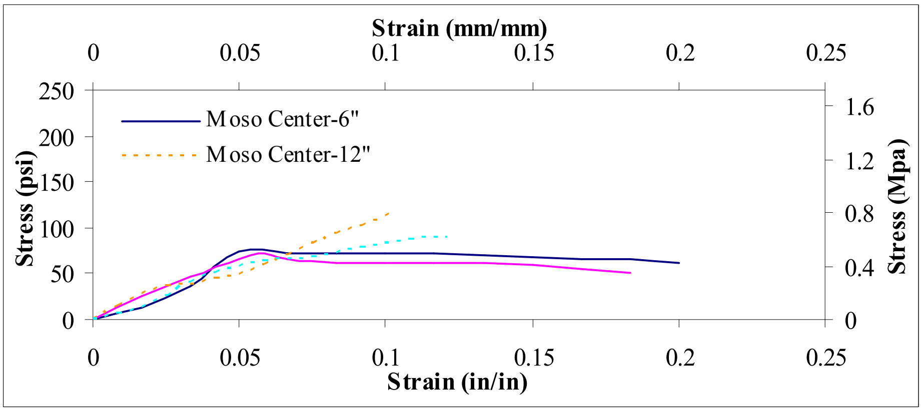


Figure 3.31 Bond Stress-Slip Behavior for Moso Bamboo - Center

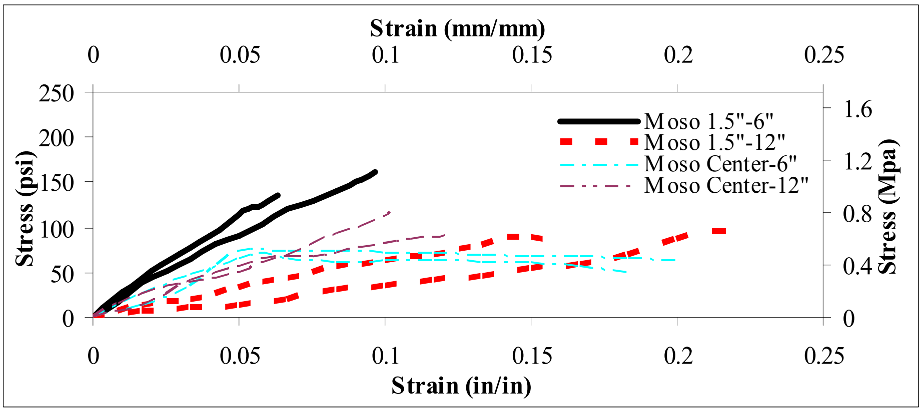


Figure 3.32 Bond Stress-Slip Behavior for combined Moso Bamboo test geometry

Table 3.10 Results of Bond Test (Solid & Moso Bamboo)

	Specimen	Failure Location	Bond Stress (psi)	Bond Stress (Mpa)
Solid (1.5" from edge & 6" deeper)	Specimen (1)	Regular Sliding	84	0.58
	Specimen (2)	Broken at the grip	48	0.33
Moso (1.5" from edge & 6" deeper)	Specimen (1)	Regular Sliding	136	0.94
	Specimen (2)	Broken at the grip	161	1.11
Solid (1.5" from edge & 12" deeper)	Specimen (1)	Broken at the grip	89	0.61
	Specimen (2)	Broken at the grip	103	0.71
Moso (1.5" from edge & 12" deeper)	Specimen (1)	Broken at the grip	84	0.58
	Specimen (2)	Broken at the grip	95	0.65
Solid (Center & 6" deeper)	Specimen (1)	Regular Sliding	134	0.93
	Specimen (2)	Regular Sliding	134	0.92
Moso (Center & 6" deeper)	Specimen (1)	Regular Sliding	63	0.43
	Specimen (2)	Broken at the grip	50	0.34
Solid (Center & 12" deeper)	Specimen (1)	Regular Sliding	78	0.54
	Specimen (2)	Regular Sliding	66	0.45
Moso (Center & 12" deeper)	Specimen (1)	Regular Sliding	116	0.80
	Specimen (2)	Regular Sliding	90	0.62

CHAPTER 4

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

4.1 Summary and Conclusion

In this research program, the feasibility of the use of bamboo as a reinforcement agent in concrete is evaluated through tensile and pull-out tests. The several tensile tests with two types of bamboo and the bond strength of bamboo reinforcing bars in concrete were studied. Also the compressive strength of test on concrete cylinders with 6 x 12 in (152 x303 mm) observed approximately 6000 psi (41.4 Mpa). The main purpose of those experiments, tensile and pullout tests with Solid and Moso bamboo, is to evaluate the possibility of using bamboo as reinforcement instead of steel and other materials as FRP.

Two types of bamboo were used; Solid and Moso. To adjust the tensile specimens, bamboo was tested with several conditions: 6 in (152 mm) and 12 in (304 mm) embedment lengths, and with or without nodes. To make as identical specimens as possible, a planer was used. Aluminum tabs were attached with epoxy glue to prevent crushing of the bamboo samples when the specimens were placed in the grips of the MTS machine. The MTS machine was loaded at a rate of 0.1 in/min (3 mm/min) until failure.

The tests were processed through an extensive, systematic experimental method, in which 16 pullout specimens were manufactured and tested until failure by a monotonically increasing load. It was found that the tensile stress-strain behavior and compressive strength of concrete are directly related to the bond strength. Hence, peak cracking stress and corresponding strain, composite elastic modulus, and matrix compressive strength experimentally determined the bond strength by tensile response.

The following conclusions are shown from the research study:

(1) Tension Tests

(a) In general sample failure was caused by; (1) node failure, (2) splitting failure, and (3) failure at the vicinity of the aluminum tab.

(b) Moso tensile samples exhibited more strength and ductility.

(c) Almost all the 12 in (304 mm) samples of Solid and Moso without node failed earlier than 6 in (152 mm) samples mostly at the grip.

(d) The samples with nodes for Solid bamboo failed at slightly higher load and with nodes for Moso bamboo failed at slightly lower loads.

(e) Almost all the Solid bamboo samples failed at the grip, but the Moso and Solid specimens with node failed at the node.

(f) In general, node was the week point of the sample with the exception of some Solid test specimen.

(2) Pullout Tests

(a) According to the assumption that the bond strength is the highest and slip is smallest when the length of bamboo is 12 in (304 mm) and bamboo is put 1.5 in (38 mm) from center.

(b) Load-bond slip relationship for different test specimens behaved differently.

(c) High slop values at low loads were observed.

(d) According to the average data for the bamboo pull-out test compared to steel tests reported in the literatures, the bond strength of bamboos was lower than that of steel reinforcing bar, approximately 8 Mpa (1160 psi). Also, the bond strength of bamboos was lower when compared to that of the FRP reinforcing bar, approximately 2.5 Mpa (363 psi), reported in the literatures.

4.2 Recommendations

(a) Additional test data is required to conduct a comprehensive statistical analysis to obtain tensile load-deformation equation.

(b) 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 pull-out test.

(c) More various tensile tests are needed to investigate the relationship between the tensile strength of bamboo and its performance as reinforcements in concrete such as composite bamboo and waterproofed bamboo etc.

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

(e) Two kinds of bamboo were used in the pull-out tests. It is recommended that research be performed on specimens utilizing additional sizes of bars.

(f) Thermal treatment of bamboo is suggested before conducting pull-out tests to provide greater bamboo strength.

(g) In this study two different types of bonded length were used. If available, pull-out test should be conducted with different accommodating bonding applications to investigate the necessary conditions for better bonding between the concrete and bamboo.

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BIOGRAPHICAL INFORMATION

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