ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

INVESTIGATION OF THE FLEXURAL AND BOND STRENGTHES OF BAMBOO USING DIFFERENT SPLITS (FORMS) IN COCRETE MEMBERS

BY

FIKREMARIAM MENGISTU ASSAMINEW

MARCH 2010

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INVESTIGATION OF THE FLEXURAL AND BOND STRENGTH OF BAMBOO USING DIFFERENT SPLITS (FORMS) IN COCRETE MEMBERS

A Thesis Submitted to the School of Graduates Studies in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Structures)

BY

FIKREMARIAM MENGISTU

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Fikremariam Mengistu

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ABSTRACT

This study presents the evaluation of the feasibility of the use of bamboo as reinforcement in concrete members. To achieve this objective a series of tensile, compression, pullout and flexural tests are carried on Gumero bamboo species collected from Gurage zone SNNPS. The tests were prepared and performed in accordance with the standard procedure established in ISO-22157, ASTM and other related references. The results for the tensile test indicated that the tensile strength of the bamboo species up to 149.5N/mm^2 has been recorded and failure of the tensile samples occurred at the nodes. Similarly, the compression test indicates that the compression strength of the bamboo species up to 44.17N/mm^2 are obtained and failures of the compression samples were initiated primarily due to splitting and end brooming. The compressive strength was found to be much less than the tensile strength. This confirmed the fact that bamboo fiber grows in the longitudinal direction and it has less resistance in the transverse direction**.**

On the other hand pullout test were conducted for untreated full , half, quarter sections and treated quarter section. From the test result the treated quarter sections have a slightly better bond strength than the untreated quarter section. Moreover, the untreated quarter sections have more bond strength than the untreated half and full sections. Further, the node helps the bamboo in the reinforcement to have a bearing action .

Flexural tests were also made for 2.5%, 3.5%, 4.5% and treated 2.5% as percentage of bamboo to net concrete area. From the experimental result beam specimens with bamboo concrete ratio of 4.5%, sustained greater load than those specimens with 2.5 and 3.5 percentages. Furthermore, beam specimens with 3.5% sustained greater load than beams with 2.5 percentages. With this intention the carrying capacity of bamboo reinforced beam was maximized by increasing the percentage of bamboo reinforcement. Comparison with minimum steel reinforced concrete and equivalent stress steel reinforced concrete was made. It was obtained that the 2.5 % bamboo had ultimate load resistance by more than 20% than the minimum steel reinforcement. It was also shown that the ultimate load capacity of bamboo was about 45% equivalent steel reinforced concrete beam.

1 INTRODUCTION

1.1 Background of the Study

Building materials are commonly selected through functional, technical, financial and requirements in addition to the type of facility used for production or processing. 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 [1, 5].

Problems encountered with the commonly used construction material like steel are rise in cost, degradation of the non-renewable material, the pollution of the environment due to industrial process etc. are common in the globe [1]. However, with sustainability as a key issue in the last decades the environmental load of building materials has also become a more important criterion. The building industry, directly or indirectly causing a considerable part of the annual environmental damage, can take up the responsibility to contribute to sustainable development by finding more environmentally benign ways of construction and building. One of the directions for solutions is to look for new material applications: recycling and reuse, sustainable production of products, or use of renewable resources. Attention has to be given to materials such as vegetable fibers including bamboo, jute, and glass, wastes from industry, mining and agricultural products for engineering applications to control environmental degradation and to minimize cost [1, 2].

Bamboo is one of the ecological material for this purpose having many advantages. Some of these are [1, 2];

- It reaches its full strength in just few months;
- It reaches its maximum strength in few years;
- Is renewable material;
- Have simple production process;
- Have high tensile strength along the fiber;
- Have low weight;
- Is corrosion resistance;
- Low cost etc.

Due to the above advantageous characteristics of bamboo, in the last few years, studies have been made on bamboo as structural material and reinforcement in concrete. The main obstacle for the application of bamboo as a reinforcement is the lack of sufficient information about its interaction with concrete, strength and durability. This thesis presents the results of experimental study carried and a concise summary of the information about the bond strength of different forms of bamboo and flexural strength of bamboo which finally concludes on the potential status of bamboo as reinforcement and its application.

1.2 Objective and Scope of the Study

The main objective of this research was to study the potential use of bamboo as reinforcement by investigating the bond strength for different forms (splits) of bamboo and the flexural behaviors for different percentage of bamboo reinforced concrete beams. Moreover, comparative flexural analysis of bamboo reinforced concrete with theoretical calculated minimum steel reinforcing concrete and equivalent steel reinforced concrete were made with an intension of addressing the feasibility of bamboo reinforcement in concrete.

Generally the following points were the main objectives of this research;

- Determination of the physical and mechanical properties of Gumero bamboo collected from Gurage
- Determination of the bond strength of different forms (splites) of bamboo and assessment of resisting capacity of bamboo reinforced concrete members
- Assessment of bamboo reinforcement percentage ratio in concrete
- Comparative assessment study of steel versus bamboo reinforced concrete, and
- Design applications for bamboo as reinforcement in concrete.

The scope of this study was limited to the investigation of the bond strength of different splits of bamboo and flexural behavior of bamboo for three different percentages (for 2.5%, 3.5% and 4.5%). However, the comparison of bamboo with steel reinforcement was made for theoretical calculated steel reinforcement for the same grade of concrete obtained in the experimental progeramme.

1.3 Source of Data and Methodology

The primary sources of data are reference materials. The referred materials include books, standards and web sites.

To meet the above-mentioned objectives, bamboo samples from Gurage zone were collected for the investigation. Experimental programme were made to find out the mechanical properties of Gumero species bamboo. Then, experimental programme on pull out test for different splits and flexural test for different percentage were performed. Samples tested for the tensile, compression, pull out and flexural tests were prepared in the following manner.

- 15 tensile test specimens with nodes at gauge position at the location of top, middle and bottom parts of the bamboo culms 5 in each case,

- 15 compression test specimens without nodes at the location of top, middle and bottom parts of the bamboo culms 5 in each case and 3 compression test specimens with nodes from three bamboo culms,
- 12 pull out test specimen for half, quarter and full section without treatment and for half section with applying treatment three in each case,
- 12 flexural test specimens with 2.5%, 3,5% and 4.5% without treatment and 2.5% with treatment three in each case.

In preparation and testing ASTM, EBCS and ISO standards and other related materials were used as a guideline.

1.4 Organization of the Thesis

This work is organized in five chapters. The first is devoted to brief description of the thesis background, objectives, scope, and the methodology. The second chapter presents literature review on bamboo characteristics, historical development as reinforcement and bond strength, storage, harvesting and diversity of bamboo in Ethiopia. The third chapter deals with the Experimental program made in the sample preparation and test set up for mechanical properties, pullout and flexural tests. The fourth chapter addresses laboratory test results. The fifth chapter deals with analysis and discussion on mechanical properties pull out and flexural test results. The last chapter devoted to drawn conclusions and recommendations.

2 BRIEF REVIEW OF BAMBOO

2.1 Introduction

Bamboos are giant grasses belonging to the family of the *Bambusoideae*. It is estimated that 60–90 generae of bamboo exist, encompass approximately 1100–1500 species and there are also about 600 different botanical species of bamboo in the world. Bamboo mainly grows in tropical and sub-tropical regions of Asia, Latin America and Africa [1, 2, 6].

It is obvious that ecological materials satisfy fundamental requirements like pollution prevention and cost minimization. The use of agricultural by-products, which are environmentally benign, such as rice husk, coconut fibres, sisal and bamboo minimizing energy consumption, conserving non-renewable natural resources, reducing pollution and maintaining a healthy environment [1, 2]. Bamboo is one of the ecological material that fulfills these advantages. 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 that of bamboo. It was found that for steel it is necessary to spend 50 times more energy than for bamboo [2]. Different researchers conduct tests on the mechanical properties for different species of bamboo as a function of age moisture content and density. Research findings indicate that, the strength of bamboo increases around the initial then decreases on later age. The optimum strength value occurs between 2.5 to 4 years. Moreover, the strength decreases from bottom to top [5, 7]. Many researchers describe that bamboo has a tensile strength greater than 150MPa and reaches up to 300MPa. The ratio of tensile strength to specific weight of bamboo is six times greater than that of steel [2, 7].

The structural advantage, over other engineering materials is studied in terms of modulus of elasticity, E, and density, ρ, using the material selection method developed at

Cambridge University. From this research based on the above criteria it has been shown that bamboo has a better performance, whereas, steel, concrete and aluminum have worse performance [2].

2.2 Characteristics of Bamboo

The bamboo culm, in general, is a cylindrical shell, which is divided by transversal diaphragms at the nodes. Bamboo shells are orthotropic materials with high strength in the direction parallel to the fibres and low strength perpendicular to the fibres. The thickness and strength of bamboo, however, decreases from the base to the top of the bamboo shell [1, 2].

The density of the fibres in the cross-section of a bamboo shell varies along its thickness. On the outer skin of a bamboo shell the fibres are concentrated and more resistant to environmental degradation. This presents a functionally gradient material, grew according to the state of stress distribution in its natural environment [2].

In view of the hollowness and the fibers in longitudinal direction, bamboo has a very efficient natural structural design and less material mass is needed than materials with a massive section, such as timber. In terms of load-bearing mass, as with all tubular elements, bamboo functions as an I-shaped cross-section, in each direction it is loaded, whereas other cross-sections are most efficient in one or two directions [1]. Figure 1.1 shows the parts of a bamboo which are usual to most of the species. First, the part called the trunk or the stem in the case of a tree is called the culm for a bamboo. Usually, a culm is hollow. The hollow space inside a culm is called the cavity “a”. The cavities are separated from each other by diaphragms “b”, which appear at outside of the culms as nodes “c”, where branches “d” leave the culm. A culm between two nodes is an internode “e”; and finally the wall thickness “f” [6, 12].

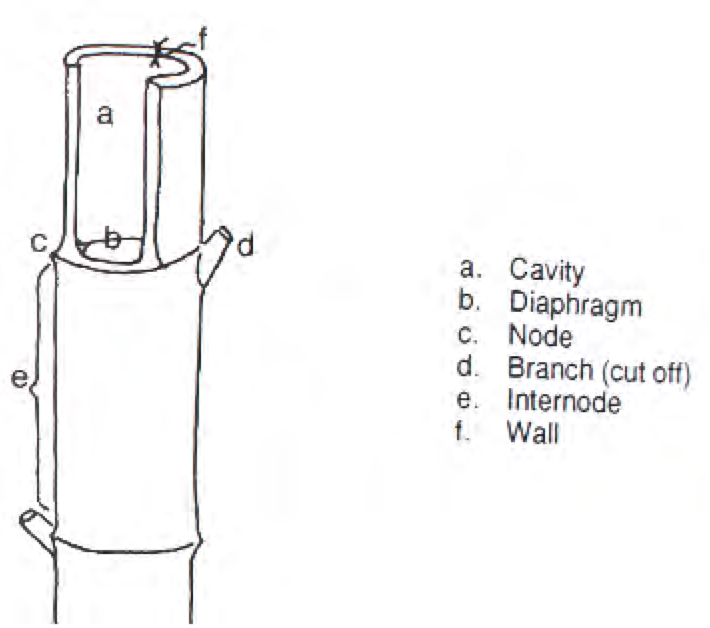


Figure 2.1Parts of bamboo

One major problem with bamboo is that it is a living organism which is subjected to degradation and decay. It is more prone to insect attack because of its high content of nutrients [2, 5]. The other constraint to the application of bamboo species is swelling behavior when it is in contact with water, shrinking behavior when it dries, degradation behavior when in contact with alkaline environment, [6, 3, 9].

2.3 Historical Background of Bamboo as Reinforcement

The advantage and disadvantage of bamboo as reinforcement have been studied for several years among which include the most extensive and organized publication made by US Naval Civil Engineering Laboratory in 1966. In this paper preparation, mix design, placement anchorage and design principle of bamboo reinforced concrete were discussed in detail. This study suggests splits of bamboo approximately ¾ inch (19mm) wide to perform better bond strength. It is recommended, according to the paper, the same concrete mix design as for steel but the concrete slump should be as low as workability will allow minimizing swelling of bamboo due to excess water. It also suggests a splicing in any member should be at least overlapped 25 inches (635mm) [3].

Lu Xiu-xin etal has studied the mechanical properties of bamboo on 54 culms for four different species at different age classes from 1 to 7 years. From this research a tensile strength greater than 200N/mm^2 was obtained. Moreover, an optimum age of 4 years was obtained [7].

Ghavami K. (2004) has studied the behavior of bamboo in the reinforcement of beams. The bamboo strips used for this research were 30cm wide rectangular sections which were coated with thin layer of impermeable product and roughed with sand. By varying the percentage of bamboo from 0.75% to 5% flexural tests were performed. The test result had demonstrated that the ultimate applied load increased by more than 400% as compared with concrete beams without reinforcement, for a 3% bamboo reinforcement adopting as optimum [2].

Khare L. conducted two-point bending test on bamboo reinforced concrete beams for 1%, 2%, 3% and 4%. The test results have showed that bamboo reinforcement enhance the load carrying capacity in average by 250 % as compared to the initial crack in the concrete beam. Moreover, a direct relationship was observed between the percentage of reinforcement and the load carrying capacity of the beams [5].

On bamboo forums Meckes summaries the results obtained from the tests of bamboo reinforced concrete beams by Glenn H. E. It was concluded that load required to cause the failure of concrete beams reinforced with bamboo was from four to five times greater than that required for concrete members having equal dimensions with no reinforcement. Moreover, it was also confirmed that concrete members reinforced with seasoned bamboo treated with a brush coat of asphalt emulsion developed greater load capacities than did equal sections in which the bamboo reinforcement was seasoned untreated or unseasoned bamboo [9].

Janssen (1995) discussed the practicability of bamboo as reinforcement and recommends a design guide line for bamboo reinforced concrete beams. In concrete, the common tensile stress in steel is 160N/mm^2, and in bamboo 20 N/mm^2, a ratio of 8:1 and the mass per unit volume is 7850kg/m^3 and 500 kg/m^3 respectively, a ratio of 16:1. Consequently, bamboo will be cheaper because the price by weight of bamboo will be less than half that of steel. It strongly recommends melted bitumen for both to increase bond and protect bamboo from alkaline attack. With this precaution, a concrete beam with 4% bamboo as a reinforcement and 20N/mm^2 tensile stress in bamboo, can be designed with a formulae $M = 0.75h*0.04*bh*20 = 0.6bh^2$ [where M is bending moment, 0.75h is distance between compression and tensile force in a bean, 0.04 is percentage of reinforcement, b width and h is height of the beam [6].

Saucier K.L and Smith E.F has conducted experimental test on two series of bamboo reinforced pre-cast concrete beams. Series I, designed to study the behavior of optimally reinforced pre-cast concrete beams and series II designed to study the behavior of maximally reinforced pre-cast concrete beams. The test results showed that series II beams sustained approximately twice the load that was sustained by series I beams at a corresponding deflection. From this, it was concluded that the maximum amount of bamboo reinforcement that can be reasonably placed in the beam was used, to obtain a maximum load carrying capacity of bamboo reinforced concrete flexural members.

2.4 Bond Strength of Bamboo

When fresh concrete poured, its water moistens the bamboo. Then during the next month the concrete will harden and loss water so it will again dry out. This drying process can result in shrinkage of bamboo with more than the shrinkage of concrete. The differecial shrinkage breaks down the bond between concrete interface and bamboo. But, in case of steel bar the dimensions will remain constant while the concrete shrinks. Consequently this problem will not happen in steel reinforcement [6, 2]. To minimize the above problem many researches have been made on bond strength with different treatment and suggest techniques that improve the durability as well as the bond strength of bamboo. Here, a few outcomes of the researches are discussed in detail.

Ghavami K. (2004) discussed the factors that affect the bond strength between the bamboo and the concrete. These governing factors are adhesive properties of the cement matrix, the diameter of bamboo, concrete spacing, the compression friction forces appearing on the surface of the reinforcing bar due to shrinkage of the concrete and the shear resistance of concrete due to surface form and roughness of the reinforcing bar [2]**.** The researcher spell out that by applying Sikadur 32-Gel on the surface of reinforcing bamboo segments increases the bond strength by 5.29 times compared to that of untreated segment [2].

Other researcher called Janssen discusses four techniques that minimize shrinkage and increase bond strength of bamboo. The methods are;

1. Melting bitumen and applying it to the bamboo strips uniformly with a brush to form a thin coats while still hot, the bamboo is covered with coarse sand for 24hours. The bitumen has proved an effective moisture barrier and the sand makes rough surface thus improving the bond.
2. Melting bitumen, as above, but 25mm diameter nails are driven into the bamboo strips 75mm apart, so that they protrude on either side of the strips. This nails will maintain the bond.
3. Outer half of the bamboo possesses better tensile strength, better younge's modulus and less shrinkage than the inner part. In order that uses of only the outer half of the bamboo as reinforcement is recommended.
4. Bitumen coat, but the bond is provided by roughly 3mm diameter coconut fibre ropes wound around the strips at a 100mm pitch along their length. The rope is also dipped in hot bitumen before being wound around the bamboo strips [6].

US Patent 4137685 - Sulfur-coated bamboo reinforcement member for concrete articles provides a moisture resistant, non-swelling bamboo reinforcement member for concrete containing a roughened bamboo surface and a substantially continuous coating of crystallized sulfur contacting and adhering to the cortex to prevent moisture absorption and swelling of the bamboo rod. The rod may have a helical wrapping of wire to further prevent swelling [20].

U.S Naval Civil Engineering Laboratory in 1966 reported a study providing a set of instructions on how to design and properly construct using bamboo as a reinforcement in concrete members. This study recommends 3/4inch (19mm) wide bamboo splits to use as reinforcement and apply waterproof coating to reduce swelling when in contact with concrete. The type of coating depends on the materials available. A brush coat or dip coat of asphalt emulsion is preferable. Native latex, coal tar, paint, dilute varnish, and water-glass (sodium silicate) are other suitable coatings. In any case, only a thin coating should be applied; a thick coating will lubricate the surface and weaken the bond with the concrete [3]

2.5 Harvesting, Storage, Preparation, Preservation and Durability of Bamboo

In the harvesting of bamboo culms only adult culms should be cut. A bamboo culm is ripe in three years and the ripened bamboo has a pronounced brown color. The age of the culm can be estimated from the color but this depends on the botanic species [3, 6]. Harvesting should be done in dry season, because the bamboo culms have lower moisture content, making transport easier and reducing the chance of attack by fungi and rut [6]. Usually bamboo culms are cut with a sharp machete, but for heavy culms a pruning saw or an axe can be used. In case falling causes splitting, two people should work together: one cuts the culm, the other holds it [3, 6].

Storage of bamboo requires special care. The ground must be clean, free of refuse of all kinds and free of termites. Bamboo should be stored under cover to protect it from rain, and clear of the ground (20 – 30cm) good ventilation and inspection are necessary. Cracking can occur if drying takes places too quickly [6].

Great care should be taken in the selection and preparation of bamboo for structural purpose. The bamboo shall be sound and free from any defects. Splitting the bamboo can be done by separating the base with a sharp knife and then pulling a dulled blade through the culm. The dull blade will force the stem to split open; this is more desirable than cutting the bamboo since splitting will result in continuous fibers and a nearly straight section [3, 6].

Just like timber, bamboo is vulnerable to environmental degradation and attacks by insects and moulds. There is a strong relation between insect attacks and the levels of starch plus humidity content of bamboo culm. In order to reduce the starch content, bamboo receives a variety of preservatives including curing on the spot, immersion, heating or smokes [2, 6].

The durability of bamboo depends strongly on the preservative treatment methods. Durability analyses were made on five hundred specimens which were extracted from a *Dencrocalamus giganteus* bamboo culms and part of them were set into concrete prisms. A set up was developed to expose the specimens to wetting and drying cycles. Each exposure to wetting and drying lasted 24 hours. The specimens without concrete were submitted to a calcium hydroxide solution and the samples with concrete were immersed in tap water. Tensile strength and Young's Modulus were measured after 7, 15, 30, 45 and 60 cycles. This test results did not show any significant variation on these mechanical properties, attesting the durability of bamboo in these aggressive tests [10].

2.6 Diversity of Bamboo in Ethiopia

Different bamboo species are available here in Ethiopia. Ethiopia has Africa's biggest Bamboo Resources and this wooden grass can be harvested in sustainable cycles on 30%-40% of the mature culms every two years [18]. The total resource base of Ethiopia is confined to two indigenous bamboo species out of more than 1500 species of bamboo in the world and 43 species in Africa. The highland bamboo (*Yushania alpina*), 8cm diameter and 17m height covers 15% and the monotypic genus lowland bamboo (*Oxythenantera abyssinica*), with solid culms at maturing age, 5cm diameter and 7m high covers 85% [18]. The location of the bamboo rich sources in Ethiopia are as shown in Figure 2.2 [18].

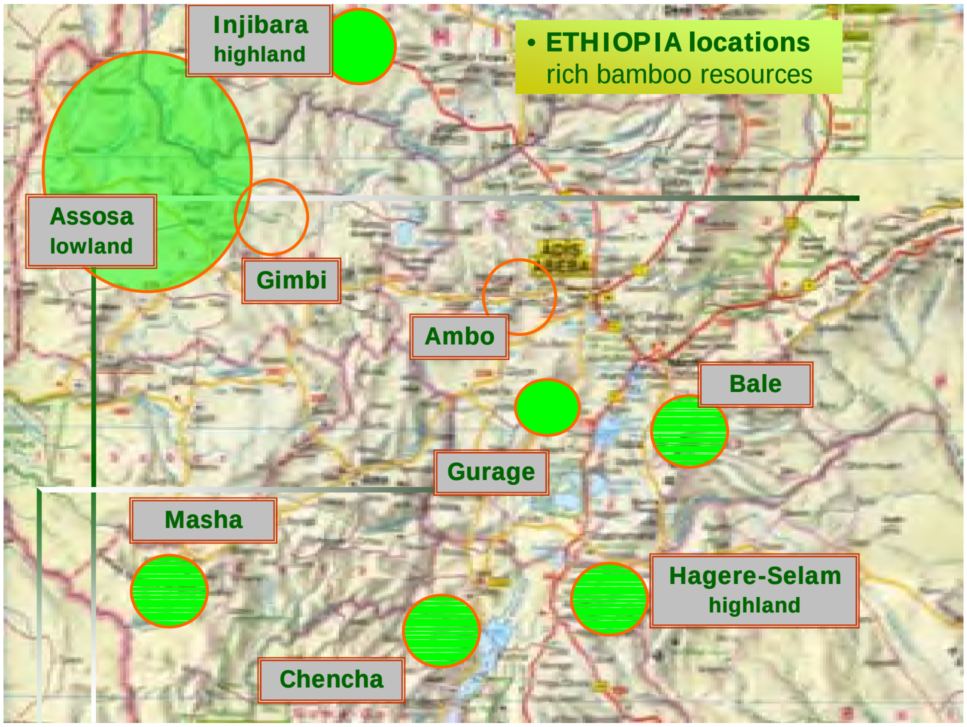


Figure 2.2 Diversity of Bamboo in Ethiopia (From ECBP-Documentation, Workshop Presentation)

From the Figure 2.2 above Assosa, Injibara, Gimbi, Ambo, Gurage, Bale, Masha, Chencha and Hagere-Selam are rich in bamboo sources. Even though, there are large source of bamboo in Assosa it is lowland type of bamboo which has solid culm at maturating age. Due to its solid culm behavior at maturating age it is not preferable to use bamboo splits as a reinforcement. This is because as wall thickness increase the internal soft part thickness will increase. Consequently the durability, compactness and the average tensile strength will be decreased. Therefore, due to its abundance, thin wall thickness nature and accessibility, bamboo species from the highlands of Gurage called Gumero was selected for this investigation.

3 EXPERIMENTAL PROGRAM

3.1 Introduction

The experimental program of this research is designed to obtain physical and mechanical properties, in addition to pull out and flexural tests on bamboo and bamboo reinforced concrete members. The tensile and compressive tests were conducted to determine the ultimate tensile strength, the ultimate compression strength and modulus of elasticity of bamboo, which are the most basic type of mechanical properties.

Pull out tests were conducted for untreated full, half and quarter sections and treated quarter section of bamboo. From these the average bond strength of bamboo for different splits were determined and comparisons between different splits were made. The flexural strength by varying the percentage of bamboo as 2.5%, 3.5% and 4.5% were also conducted. Moreover flexural tests were conducted for 2.5% by applying treatment on bamboo with AC85/100 asphalt for comparison purpose.

In the preparation of samples and conducting tests the guideline in ISO and ASTM standards were followed. In this chapter the general sample preparations and the experimental set up to accomplish the test are discussed.

3.2 Physical and Mechanical Properties of Bamboo

3.2.1 Introduction

The physical and mechanical properties of bamboo were determined according to ISO 22157-1 and 2. Bamboo is an orthotropic material; it has particular mechanical properties in the three mutual directions (longitudinal, radial and tangential). This study was carried out to investigate the tensile and compression strength in the longitudinal direction. In addition to be acquainted with the variations in strength along culm, tests for different locations in the Culms were made. For this research test samples were taken from the forest plantation in Gurage, SSNPS specifically called Gumero.

3.2.2 Mass by Volume

Mass by volume of bamboo was determined according to ISO 22157-1 standard. The specimens were prepared immediately after conducting each mechanical test. According to this standard the size of specimens were having approximately width of 25mm, height of 25mm and as thick as the thickness of the wall. Then, the mass by volume was calculated by dividing the oven dry mass by the volume of the specimens.

The volumes of the specimens were determined by immersion method. First the mass of sample in air was determined in gram and then the mass of the specimen with iron in water was determined. Finally, calculation of volume was made as:

$$V_t = m_a - W_u + W \qquad \text{[Eq. 3.1]}$$

Where: V_t – the green volume of the test pieces, in cm^3

m_a – air-dry mass in gram of the test specimens

W_u – mass of test specimen and iron in water

W – mass of iron in water

Finally, after drying the sample in oven for 24h±4h, the mass by volume of the test specimen is calculated as follow:

$$\rho = \frac{M}{V} \times 10^6 \qquad \text{[Eq. 3.2]}$$

Where;

ρ= density in kg/m^3

M= the oven-dry mass in gm of the test specimens

V= the oven-dry volume of the test specimens in mm^3

The mass by volume is reported at the natural moisture content of a test specimen. Here, the volume is taken at the natural moisture content of the specimen and the mass is taken as the oven-dry because these will not change irrespective of weather condition. The arithmetic mean of the results obtained for the individual test pieces reported as the average value for the mass per volume of the test pieces [12].

3.2.3 Shrinkage

The determinations of shrinkage were made according to ISO 22157-1 standard. Based on this standard, the determination was made by taking the intermodal full bamboo culms section near the test specimens, which has a height of 100mm. To compute the shrinkages, recording of outer diameter D, wall thickness t and height h of the specimen before and after oven-drying were carried out.

Then, the radial and longitudinal shrinkages are calculated as follow.

$$SH(\%) = \frac{(I - F)}{I} \times 100 \qquad \text{[Eq. 3.3]}$$

Where; SH = Shrinkage in %

I = initial reading of average diameter, thickness or height of the sample.

F = Final reading of average diameter, thickness or height of the sample.

3.2.4 Moisture Content

The mechanical property, moulds attack and durability of bamboos are highly related to the moisture content. As the moisture content reduces the strength of the element increase and less prone to moulds attack [2, 12]. The Moisture content of the bamboo was determined according to ISO 22157-1 and 2. The specimen for moisture content was prepared for each mechanical specimen immediately after test near the place of failure. The test pieces have an average width of 25mm, a height of 25mm and as thick as the thickness the wall.

The moisture content of a test piece is calculated as the loss in mass, expressed as a percentage of the oven dry mass, according to the Equation below.

$$MC(\%) = \frac{(m_o - m)}{m} \times 100 \qquad \text{[Eq. 3.4]}$$

Where; MC = moisture content in %

m_0 = the mass of the test specimen before drying.

m= the mass of the test specimen after oven drying.

The arithmetic mean associated with standard deviation of the results obtained from the individual test piece is reported as the mean value for the moisture content of the test specimens [12].

3.2.5 Tensile Test

The tensile tests were made for a strip of bamboo parallel to the fibers for different position of a culm. In the preparation of test samples ISO 22157was used as a guideline.

a) Specimen Preparation

The test specimens were prepared according to ISO 22157-1 and 2. According the report of ISO 22157 the difference in tensile strength between specimens with node and without node is tremendous. The tensile strength of a node region is only 30% of an internode region. As a result of this, ISO recommends the specimens for tensile test to have at least one node at a gauge position.

To avoid grip failure ISO 22157 1 and 2 proposes three different methods in the preparation of test specimen.

i A wedge test pieces: - this is used in many laboratories. The dimension and shape of the test specimen look like as shown Figure 3.1 below. Failure in shear is mostly observed for this kind of specimen [12].

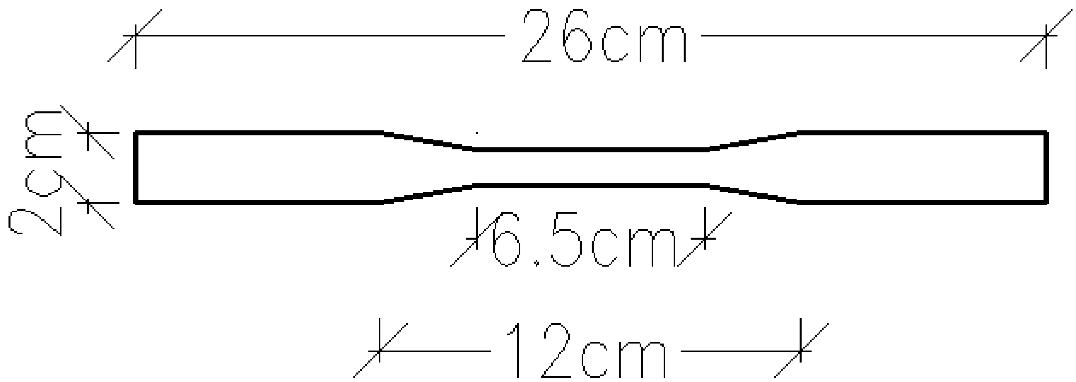


Figure 3.1 Shape and Dimension of Wedge Test Piece

ii Test pieces with glued wooden on both ends: - the test specimen are glued with wood as shown in the Figure 3.2 The length of glue is determined by the allowable shear stress in the glue joint

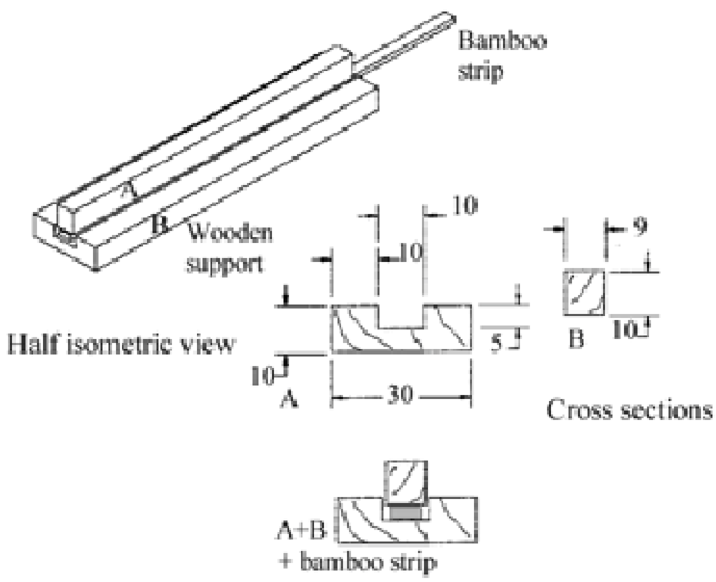


Figure 3.2 Component of Test Piece with Glued Wooden Ends

iii The size and shape of the third type specimen is look like the one shown in Figure 3.3 below. It is a modified type of wedge test piece, which is mostly used in Japan. For this type of specimen mostly failures occur in the gauge length.

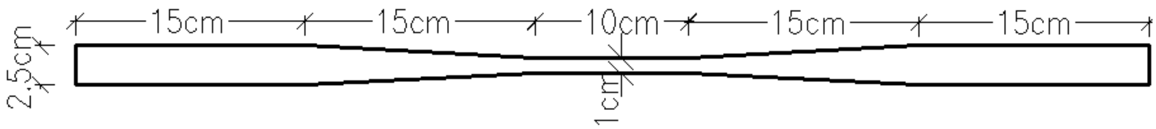


Figure 3.3 Shape and Dimension of a Modified Type of Wedge Test Piece

Due to the availability of testing machine set up and the simplicity in the preparation of test samples the third type of test specimen was selected for this work. A total of fifteen test pieces were taken (5 from bottom, 5 from middle and 5 from top part of culms of bamboos) with node in gauge position. These test specimens were marked as B, M and T, respectively.

Table 3.1 Tensile Test Program

Specimen Code	Specimen Position	Sample Position	Specimen Size			Cross Sectional Area [mm^2]
			L [mm]	W [mm]	T [mm]	
TT1	T	With node	700	9.8	5.2	50.8
TT2	M	With node	700	9.5	5.7	54.4
TT3	B	With node	700	9.2	6.5	59.7
TT4	T	With node	700	10.0	6.5	65.0
TT5	M	With node	700	9.5	6.8	64.9
TT6	B	With node	700	9.5	7.2	68.1
TT7	T	With node	700	10.0	5.8	57.8
TT8	M	With node	700	10.3	6.7	69.3
TT9	B	With node	700	9.5	6.8	65.0
TT10	T	With node	700	9.5	5.7	54.1
TT11	M	With node	700	9.5	7.3	69.2
TT12	B	With node	700	8.7	8.1	70.8
TT13	T	With node	700	10.0	4.9	49.0
TT14	M	With node	700	10.0	5.7	56.7
TT15	B	With node	700	9.6	6.2	59.6

b) Test setup

Tensile tests were conducted on Universal Testing Machine with model 70-C0807/C. According to ISO 22157-1 the load should be applied continuously throughout the test at a rate of motion of the movable cross head of 0.01mm/s. To get this rate assuming 20,000N/mm^2 modulus of elasticity of bamboo the rate of the testing machine was adjusted to 1N/mm^2/s. When clamping made, rubbers were attached from the outside and inside surface of test pieces. This minimizes the failure of grip. After a light clamping of the test pieces, the test machine was made on to start test. Then, during the time of testing, tightening of the test pieces were made. If it would have been fixed totally before the testing started, initial compression force would be applied to the test specimen and causes buckling of the test pieces which make out of use. But this causes a slippage when the axial force acts on the specimen. The Encoder which is fixed on the test frame reads the movement of the mobile cross beam of the frame on which the upper grips holding the sample are mounted. Thus, it should be noted that the measurement is total, which is the elongation plus the slippage of the grip. Whereas, the extensimeter, which is a measurement device, is fitted directly on the test specimen, reads only the actual elongation of the specimen. In this regard, to avoid the reading of slippage, extensimeter was used to measure the elongation. After the test specimen was fixed with the grip of the UTM, the extensimeter would be attached to the gauge portion of the test specimen as shown in Figure 3.4

Generally before test has been started extensimeter was selected for elongation measurement, the sample type was selected, the descriptive data was filled as requested. Then samples were placed in the grips after that the load reading in the CELL window to was made to be zero by clicking on the zero command. Finally, when clicking on the Start Test a window will be appeared which shows the load through the test. After failure the test should be stopped manually by clicking on STOP.

The program allows displaying load in kN, stress in N/mm^2, reading of encoder in mm and reading of extensimeter in mm.

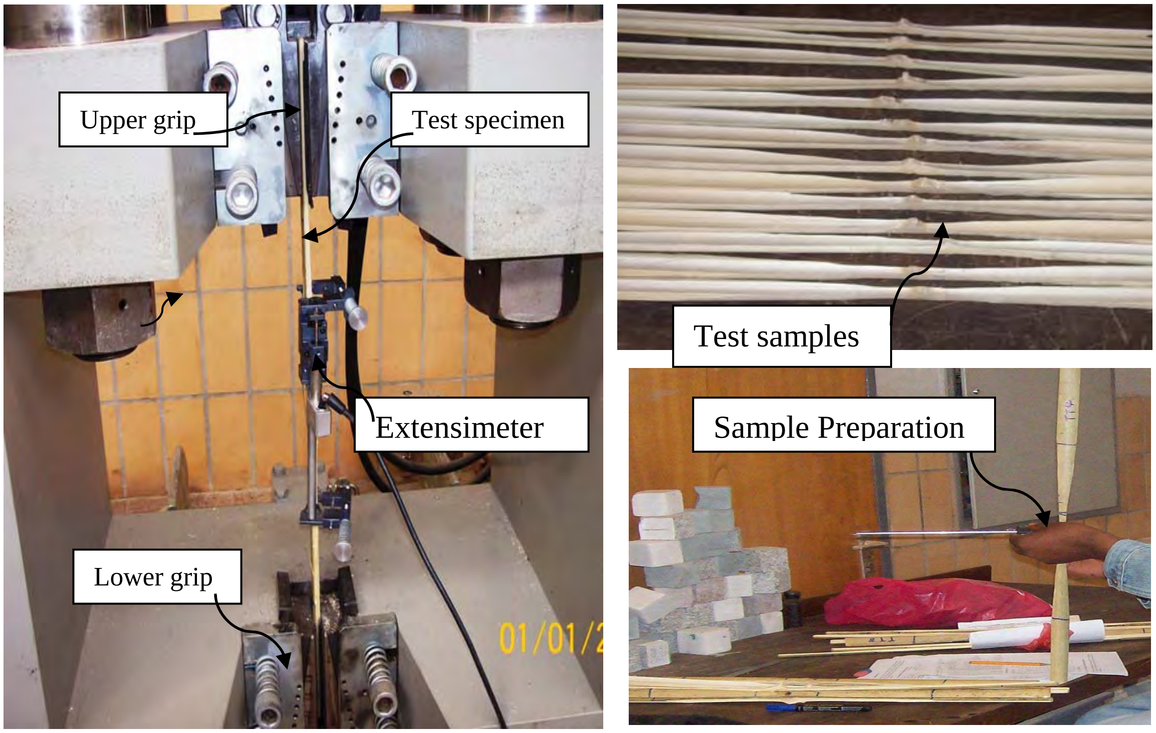


Figure 3.4 Tensile Test Set Up and Specimens Preparation

3.2.6 Compressive Test

The compressive tests were made for a segment of bamboo culm parallel to the fibers for different position of a Culm according to ISO-22157.

a) Specimen Preparation

The test specimen was prepared according to ISO 22157-1 and 2. Because of the internodes test specimen are simpler than with node and there is no significant difference between test results with nodes and without nodes, ISO 22157 suggests to use internodes sample. In doing so a total of fifteen intermodal samples and three with node were made. Distribution of test samples were made as follow; 5 from bottom 5 from middle and 5 from top parts of culms were internodal samples and the other 3 with node from middle part of the culm. According to ISO 22157 recommendation, the height of the test sample was equal to the outer diameter for bamboo which have less than 20mm diameter and twice the outer diameter for bamboo which have greater than 20mm outer diameter.

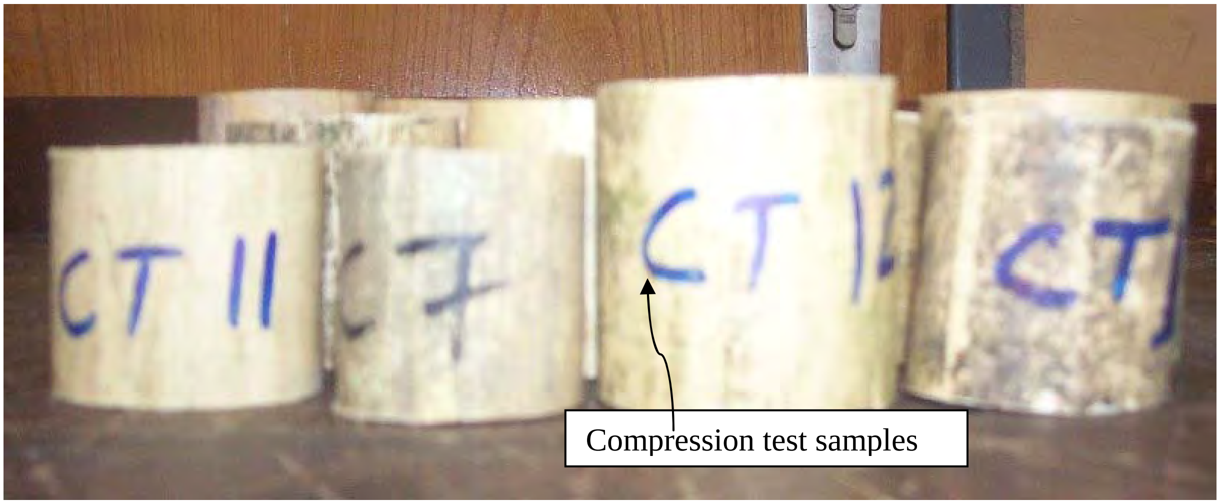
Table 3.2 Compression Test Program

Specimen Code	Specimen position	Gauge Position	Specimen Size			Cross Sectional Area [mm^2]
			D [mm]	T [mm]	H [mm]	
CT1	T	Inter node	39.3	5.3	39.0	565.8
CT2	M	Inter node	46.6	5.9	46.0	754.0
CT3	B	Inter node	49.8	6.8	49.0	918.1
CT4	T	Inter node	43.3	6.4	43.0	741.5
CT5	M	Inter node	45.2	7.3	45.2	868.7
CT6	B	Inter node	50.0	7.8	50.0	1033.5
CT7	T	Inter node	33.2	5.9	33.0	505.8
CT8	M	Inter node	38.4	6.9	38.0	682.5
CT9	B	Inter node	41.0	7.2	41.0	765.0
CT10	T	Inter node	39.6	5.8	39.0	615.6
CT11	M	Inter node	45.7	8.3	45.0	889.9
CT12	B	Inter node	50.5	7.8	52.0	1100.2
CT13	T	Inter node	35.3	4.7	35.0	451.6
CT14	M	Inter node	37.1	5.7	37.0	562.0
CT15	B	Inter node	43.7	6.1	43.0	720.2
CT16	M	With node	37.2	6.5	37.2	626.6
CT17	M	With node	43.1	7.2	43.1	811.6
CT18	M	With node	39.2	6.4	39.2	659.1

b) Test Setup

Compressive tests of bamboo were conducted on Automatic Compression testing machines with model 50-C36V. Procedure outlined on ISO 22157-1 was used in performing testing. The load was applied at an average rate of 0.01mm/sec or (1N/mm^2/s).

The specimen placed so that the centre off the movable head was vertically above the centre of the cross section of the specimen, after closing the door of the test machine, loading was started. After failure of the sample the ultimate load and type of failure were recorded.



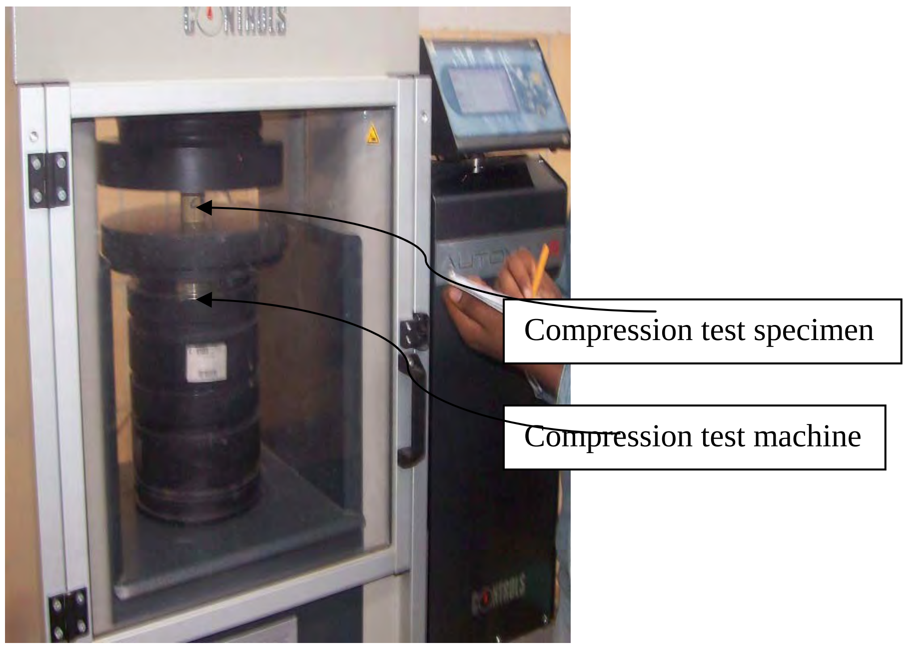


Figure 3.5 Compression Test Specimens and Set Up

3.3 Concrete Mix Design

ACI mix design method used for normal steel reinforced concrete is applied in the preparation of mix design for bamboo reinforced specimens [8]. However, concrete slump was made as low as workability will allow minimizing excess water which causes swelling of the bamboo.

3.3.1 Materials

Water: Water from municipality was used to prepare concrete mix and cure the test specimens.

Cement: Through the investigation, Portland Pozzilana Cement (PPC) from Mugger Cement Factory was used for the concrete mix.

Aggregates: Natural sand and coarse aggregates were used in this test preparation. The sand the aggregate were first washed and dried. Maximum size of 20mm aggregate was used for this test. By sieving the aggregate on 25mm and 4.75mm sieve, the aggregate, that were retained on 25mm and pass 4.75mm sieves were rejected. Similarly the sand was sieved on 9.5mm sieve which were rejected all retained. In the determination of the fineness modulus, gradation, specific gravity, absorption capacity, and compacted unit weight of aggregates procedures outlined in ASTM standard were followed [17]. The results obtained from the laboratory are shown in Table 3.3, below.

Table 3.3 Specific Gravity, Absorption Capacity and Unit Weight of Aggregates

Aggregate	Bulk specific gravity	Bulk specific gravity (SSD)	Apparent specific gravity	Absorption capacity (%)	Unit weight (kg/m^3)
Sand	2.38	2.47	2.62	3.95	1560
Gravel	2.69	2.75	2.84	1.90	1600

From sieve analysis 3.0 fineness modules of sand was obtained.

3.3.2 Mix Proportioning

Using ACI mix design method proportions of materials by weight were made. The properties of material used include those values determined in the laboratory in section 3.3.1 above.

The procedure that was followed in designing a concrete mix was detailed below:

Step-1 **Choice of Slump**: Minimum slump from 25 to 50mm was selected [8].

Step-2 **Choice of Maximum Size of Aggregate**: Based on dimension of beam and clear spacing of bamboo a maximum size of 19mm aggregate was selected

.

Step-3 **Estimation of Mixing Water and Air Content**: Based on the maximum size aggregate 190kg/m^3 was selected [8].

Step-4 **Selection of Water/ Cement Ratio**: For a compressive strength of 20MPa at 28 days, for non-air entrained concrete, a water to cement ratio of 0.69 was selected [8].

Step-5 **Calculation of Cement Content**: The cement content is calculated from the water content and the water/cement ratio required.

Mass of cement = 190/0.69 = 275.36kg/m^3

Step-6 **Estimation of Coarse Aggregate Content**: The coarse aggregate content was estimated based on the maximum size of aggregate and the fineness modulus of sand.

3.0 F.M of sand as determined in section 3.3.1 above the dry rodded coarse aggregate volume will be 0.6 [8]. The dry rodded density of coarse aggregate was 1600Kg/m^3 as determined above in section 3.3.1. Therefore;

Then Mass of coarse aggregate = 0.6 m^3x1600Kg/m^3 = 960Kg

Step-7 **Estimation of Fine Aggregate Content**: The fine aggregate content was determined by subtracting the sum of the mass of coarse aggregate, cement and water from the estimated concrete mass. For 19mm maximum size of aggregate and non-air entrained concrete the mass of the concrete per meter cube is estimated 2345Kg/m^3 [8].

Weight of fine aggregate = 2345 – 190 – 275.36 – 960 = 919.64Kg/m^3

Since in the preparation of mix, surface dried aggregate was used, and hence no adjustment of moisture was made.

Table 3.4 Summary of material proportion per meter cube of aggregate

Water kg/m^3	Cement kg/m^3	Coarse Aggregate kg/m^3	Fine Aggregate kg/m^3
190	275.36	960	919.64

3.3.3 Procedure for Mixing the Concrete

The mixer can mix 0.07m^3 of concrete. To produce 0.07m^3 the proportion of materials by weight required was shown in Table 3.5, below

Table 3.5 Proportion of materials to produce 0.07m^3 of concrete by weight

Material	Cement	Coarse Aggregate	Fine Aggregate	Water
Quantity (kg)	19.0	67.5	64.4	13.3

Concrete mixing operation is performed following to ASTM [17]. Procedure which can be summarized as follows;

1. Coarse aggregate was placed in the mixer,
2. Cement was placed next,
3. Fine aggregate followed and
4. Dry mixing was made for one minute
5. The water was added continuously as the mixer was rotating.

6. The mixer was operated for about two to three minutes and then finally the mixer was stopped and preparation of test specimens was made.

Slump test was used as a measure of workability. Equipment to perform this test were made ready and includes a slump cone, a plate with a coating surface, a tamping rod, and a steel ruler. According to ASTM the slump cone had top and bottom openings of 102 mm and 203 mm in diameter and a frustum height of 304 mm diameter.

The concrete was tamped with 508mm long and 16mm in diameter tamping rod in three equal layers in this frustum. Each layers consolidated 25 actions of the tamping rod. After tamping the three layers successively, the excess concrete was removed with the rod and the waste concrete was cleaned away from the perimeter. Then, the cone was removed directly upward in a period of 3 to 7 seconds. The slump was the difference in height of the mold so that the displacement of the cone was measured to the highest point. From the tests a slump of 26mm was recorded.

The concrete mix was kept identical for all flexural and pullout test samples and the concrete was allowed to set for a period of 28 days to obtain the concrete 28 days strength.

3.3.4 Compressive Strength of Concrete

Compression tests of concrete were made for six specimens with cube size of 150mm. Three of the cubes were prepared at the beginning of test preparation and the other three were casted at the last day to check the mix design strength used.

The compression tests were conducted on cube specimens cured for 28 days. The test cubes were removed from the moist storage 24 hours before testing. According to ASTM standard compression test were performed using UTM test machine model UTM- C-905, 330V AC+GND+N, 50V CY, 2.2kW. UTM-C-40 U-32. The procedures were as follow;

1. A specimen was centered on the lower plate in relation to the upper block.
2. The door of the machine was closed
3. Machine was turned on and adjustment made, then load was set to zero
4. Loading was made at a rate of 0.3MPa/s (ASTM C- recommends a loading rate of 0.15 to 0.35Mpa/s).
5. The maximum load was recorded after the concrete cubes reached the maximum load

Using the above procedure the following test results of the compressive strength were recorded.

Table 3.6 Compression Test Result of concrete

Samples	Section (L,W,D)	Area (mm^2)	Force in (KN)	Compressive Stress at Failure (MPa)
Sample 1	150x150x150	22500	342.0	15.2
Sample 2	150x150x150	22500	339.7	15.1
Sample 3	150x150x150	22500	333.0	14.8
Sample 4	150x150x150	22500	348.7	15.5
Sample 5	150x150x150	22500	328.5	14.6
Sample 6	150x150x150	22500	337.5	15.0
Average compressive strength = 15.03MPa				

3.4 Pullout Test

3.4.1 Specimen Preparation

In the preparations of pull out test specimens ASTM C 234-71 were used as guidelines. Molds of 150mmx150mmx150mm were used as a formwork to embed bamboo in the concrete. According to this standard, the bamboo bar was projected vertically down wards up to a desired distance, and it was projected upwards from the top face up to 110cm to provide adequate length to be gripped for application of load.

In the determination of the projection length of bamboo bar down ward from the top requires a great care to avoid grip failure. The grip strength and the bond strength of bamboo are the governing factors in the determination of embedded height. Based on the average bond strength (which was obtained from the literature and the previous laboratory outcomes) and grip strength of the bamboo (which was determined in the laboratory) the embedment length was estimated for the different splits. Finally, keeping the estimated embedment length, the bamboo bars were casted in 150mm concrete cubes.

For a half and one fourth section bamboo bar the concrete embedded from one side and the other side was free and griped by the testing machine at the time of testing. But the full culms of bamboo bar demand a special arrangement in the preparation test specimen due to the limitation of the grip of test machine. The diameter of full section bamboo was greater than 25mm, whereas the UTM can only grip a diameter up to 25mm only. Because of this the concrete cubes were casted on both sides for full section. In the preparation, from one side the bamboo bar was embedded the whole height of concrete cube, but from the other side only 130mm was embedded in the concrete. This help to control the slippage from one sides of the sample.

For this study pull out test specimens were prepared;

- For full section of bamboo without treatment
- For half section of bamboo without treatment
- For one fourth section of bamboo without treatment and
- For one fourth section of bamboo coated with AC-85/100 asphalt and roughened with coarse sand.

Moreover, in the preparation of pull out specimens all specimens have a node indenting 5cm from the bottom.

3.4.2 Test Setup

The setup of the pull out experiment was made on a Universal Testing Machine with model 70-C0807/C which is mainly modeled for tensile and compressive strength test. As mentioned before, the specimens were molded in concretes with 150mm cubes with the rod embedded in the concrete. To conduct the experimental programme first the bottom jaws of the UTM testing machine were removed. Then, the concrete part was attached from the bottom part by making in contact with the bearing face of the concrete and the horizontal surface testing machine so that the slippage of the bar can be measured. The upper part of bamboo bar was gripped by the upper jaws of the testing machine. Finally, an axial load is applied to pull-out the bamboo reinforcement out of the concrete with a rate of 0.5N/mm^2/s. The rate of load was modified according to ASTM C234-71 which recommends 22kN/min for steel pullout test.

But for full culm bamboo, as explained above, the concrete were casted on both sides of the bamboo bar. This demands a special arrangement of the testing machine. First both the upper and the lower grips of the testing machine were removed. Then, the concrete cubes were attached to the upper and lower part of the testing machine. Appling axial load with upwards the bamboo bar was pulled out from the side which has small embedment length.

Figure 3.6 Pullout Test Set Up and Test Specimens

3.5 Flexural Test

3.5.1 Specimen Preparations

In the preparation of test specimen beams, procedure outlined in ASTM standard and U.S Naval Civil Engineering Laboratory was followed. Considering the laboratory conditions and the sizes of bamboo strips a beam length of 100cm was preferred. According to ASTM standard, which recommend a ratio of length to depth greater than 4, a cross sectional area of 20cmX20cm was used. To be acquainted with the behavior of bamboo in concrete, different percentage of bamboo reinforced concrete beam specimens were prepared. The different types of flexural beam specimen were:

- Specimen consisting of 2.5 percent of quarter section bamboo without treatment
- Specimen consisting of 3.5 percent of quarter section bamboo without treatment
- Specimen consisting of 4.5 percent of quarter section bamboo without treatment
- Lastly, specimen consisting of 2.5 percent of quarter section bamboo coated with AC-85/100 asphalt bamboo and rouged with coarse sand for comparison purpose.

Subsequently a total of 12 flexural test specimens beams (three for each case) were prepared.

For this research one fourth splits of bamboo were used as a reinforcement bar. Generally with steel reinforced concrete beams, a hook length is employed at the end of the beam to enhance the bond between the reinforcement bar and concrete. But due to difficulty to bend bamboo in the desired shape, it is impossible to provide this hook length and was not applied in the preparation.

First bamboo culms were cut into a length of 95cm, then the culm spliced into four parts approximately. After a number of bamboo splice prepared, the average cross sectional area of each strips were calculated by measuring the top and bottom thickness (t_b and t_t) and the internal and external cords at the top and bottom parts (c_{it},c_{et}, c_{ib} and c_{eb}). Depending on the percentage of bamboo in the concrete, the total areas of bamboo required for the specified percentage beam specimen were calculated. Then the numbers of bamboo splices that required was determined for each percentage.

In tying the bamboo strips both steel and bamboo stirrups were used. In areas where shear force is pronounced, i.e areas between the support and the point of load application, steel stirrups were used. But in the middle part of the beam where shear force is zero bamboo stirrups were used. It was difficult to bend the bamboo stirrups into closed loops type. Because of this, U shaped stirrups were used. In the preparation of this stirrups the bamboo were splitted into 10mm - 15mm thick, then after immersing into the water at least for 6hrs to be flexible to bending into U shape was made. Totally 4 steel stirrups and 3 bamboo stirrups were used per specimen with arrangement as shown in the Figure 3.7, below.

For the treated bamboo specimen, a brush coat or a thin coat of AC-85/100 asphalt were used. After brushing the bamboo with the specified asphalt, coarser sand was pressed manually and was kept for 24hr to dry.

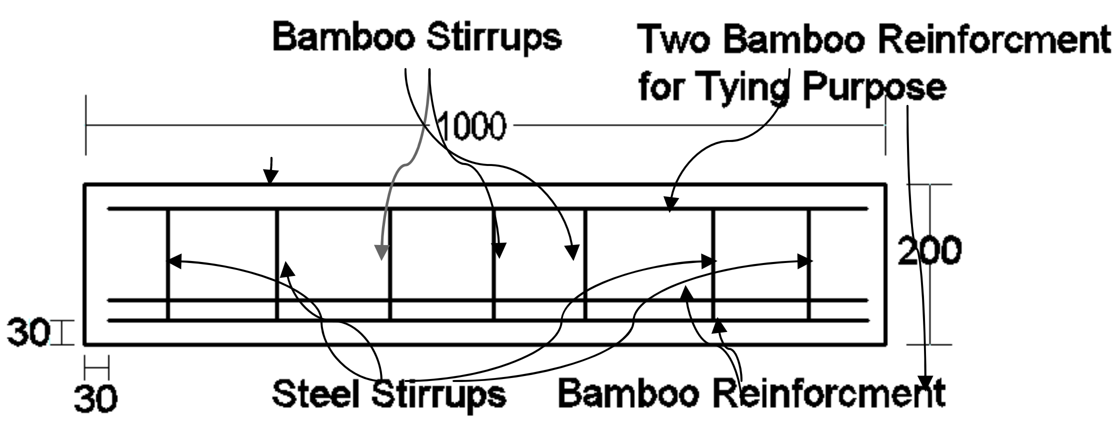


Figure 3.7 Beam Dimension and the Position of Steel and Bamboo Stirrups

As it was recommended in U.S Naval Civil Engineering Laboratory the bamboo reinforcements bars were place 30mm from the face of the concrete surface and the clear spacing between bamboo splits was 26mm which is 1.33 times of the maximum size of aggregate. The clear cover was chosen to be 30mm. By taking the concrete cover and clear spacing between bamboo splices into consideration, one row of bamboo for 2.5% and two row of bamboo for 3.5% and 4.5% were used as shown in the Figure 3.8. In addition to the bottom structural reinforcement two quarter section of bamboo were placed for tying purpose.

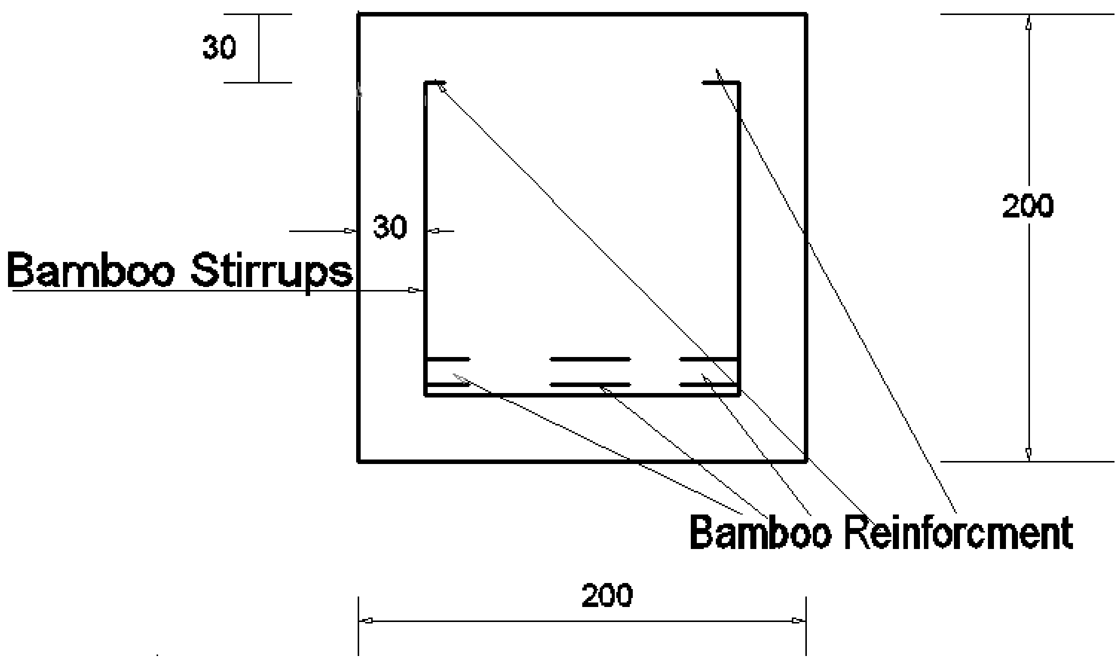


Figure 3.8 Beam Cross Section

3.5.2 Test Setup

Flexural tests were conducted on Universal Testing Machine with model 70-C0807/C. The test was conducted with two point loading. Test procedure listed on ASTM C 78-02 was used to perform flexural test. First the support with two lower rollers was positioned on the lower part of the middle frame cross beam and fasten then fitting of the upper roller bearer was made. After that, upper roller was positioned 286.7mm apart by placing them in equal distance from the centre. The support was indent 70mm from the left and right parts of the beam. Then, recessing was made for the remaining 860mm span of the beam by dividing into three parts. Afterwards, the beam was placed on the testing machine with respect to the side as the reinforcement lay. Then, by opening the UWT 8 program from the menu the transverse testing test key was selected. Then, on the pages that display descriptive data and test configuration data were entered. With PUMP and START TEST keys load application commenced until failure of the member is noticed by pattern of the first crack followed with excessive deflection. On the PC the ultimate load and the load deflection graph were recorded.

Figure 3.9 Flexural Test Specimens and Set Up

4 EXPERMENTAL TEST RESULTS

4.1 Introduction

This chapter presents the results of the tensile tests, compression tests, Pullout tests and four point flexural tests performed with Bamboo reinforced concrete for different percentage. Tensile and compression tests varied along the sections from bottom to top to see the effect of strength with height. The tensile test carried out with UTM machine with a constant rate of $1N/mm^2$ and the control PC automatically draw stress strain curve, from this the ductility and the modulus of elasticity were analyzed.

Pull out tests varied based on the sections as quarter section, half section, full section and quarter treated section to see the effect of section and treatment. Test designations were done by starting with “P” to represent pull out test followed by section type and treatment case. For example:- P-FS, Untreated-1 represents a untreated full section pull out test specimen.

Finally, flexural tests were made by varying the percentage of bamboo as of 2.5%, 3.5% and 4.5% and 2.5% of treated bamboo reinforced concrete beams to investigate the feasibility of bamboo as reinforcement and see the effect of treatment. The four point bending test used a load that was applied at a steady rate of 10 controlled with a PC automatically draw the Load verses deflection graph. Failures types and crack propagation were also recorded at the same time. Test designations were done by starting with “F” to represent flexural test followed with treatment case and then the percentage of reinforcement indicated in each case. For example: - F-Treated, 2.5-1 represents a flexural test specimen treated with asphalt and with 2.5% of bamboo reinforcement.

4.2 Tensile and Compression Test Results

a) Tensile Test Results

Tensile tests were conducted on specimens with nodes. Nodes are weak and brittle in resistance to tensile force as referred in ISO-22157. These tests were performed on fifteen specimens with nodes at gauge position and its main purpose was to determine the tensile strength, ductility and modules of elasticity of the specified species bamboo (which is Gumero bamboo). In the experimental test failures in most of the specimens occurred at the node. A few numbers of test specimens failed by splitting in to two parts and then followed by node failure as shown in the Figure 4.1, below and others show a combination of splitting, shear and node failure.

The general tensile test results are summarized in the Table 4.1, shown below

Table 4.1 Tensile Test Result

Specimen Code	Cross sectional Area [mm^2]	Ultimate Load [kN]	Stress [MPa]	Location	Mass per volume Kg/m^3]	Moisture content [%]	Lateral shrinkage [%]	Longitudinal shrinkage [%]	Type of Failure
TT1	50.8	6.3	124.0	T	0.43	14.29	3.83	-0.08	Node
TT2	54.4	7.5	137.9	M	0.81	15.24	4.74	0.21	Node splitting shear
TT3	59.7	10.9	182.7	B	0.75	12.81	3.65	0.77	Node plus Splitting
TT4	65.0	7.8	120.1	T	0.52	13.81	2.96	0.31	Node
TT5	64.9	8.7	134.0	M	0.62	15.08	3.30	0.18	Splitting shear failure
TT6	68.1	12.3	180.7	B	0.74	11.88	2.93	-0.81	Node
TT7	57.8	7.1	123.0	T	0.55	15.17	4.01	0.04	Node plus Splitting
TT8	69.3	10.8	155.9	M	0.81	16.00	3.54	-0.31	Node
TT9	65.0	13.2	203.0	B	0.87	13.35	1.94	-0.27	Node plus Splitting
TT10	54.1	5.7	105.7	T	0.39	16.87	5.01	0.26	Node
TT11	69.2	10.1	145.8	M	0.67	16.16	1.89	0.16	Node splitting shear
TT12	70.8	12.3	173.4	B	0.84	15.31	3.76	-0.21	Node
TT13	49.0	4.5	92.0	T	0.48	11.15	4.12	0.30	Node
TT14	56.7	7.8	138.0	M	0.78	13.01	5.32	0.07	Node splitting shear
TT15	59.6	13.3	223.0	B	0.80	9.41	1.44	-1.02	Node

*TT represent tensile test

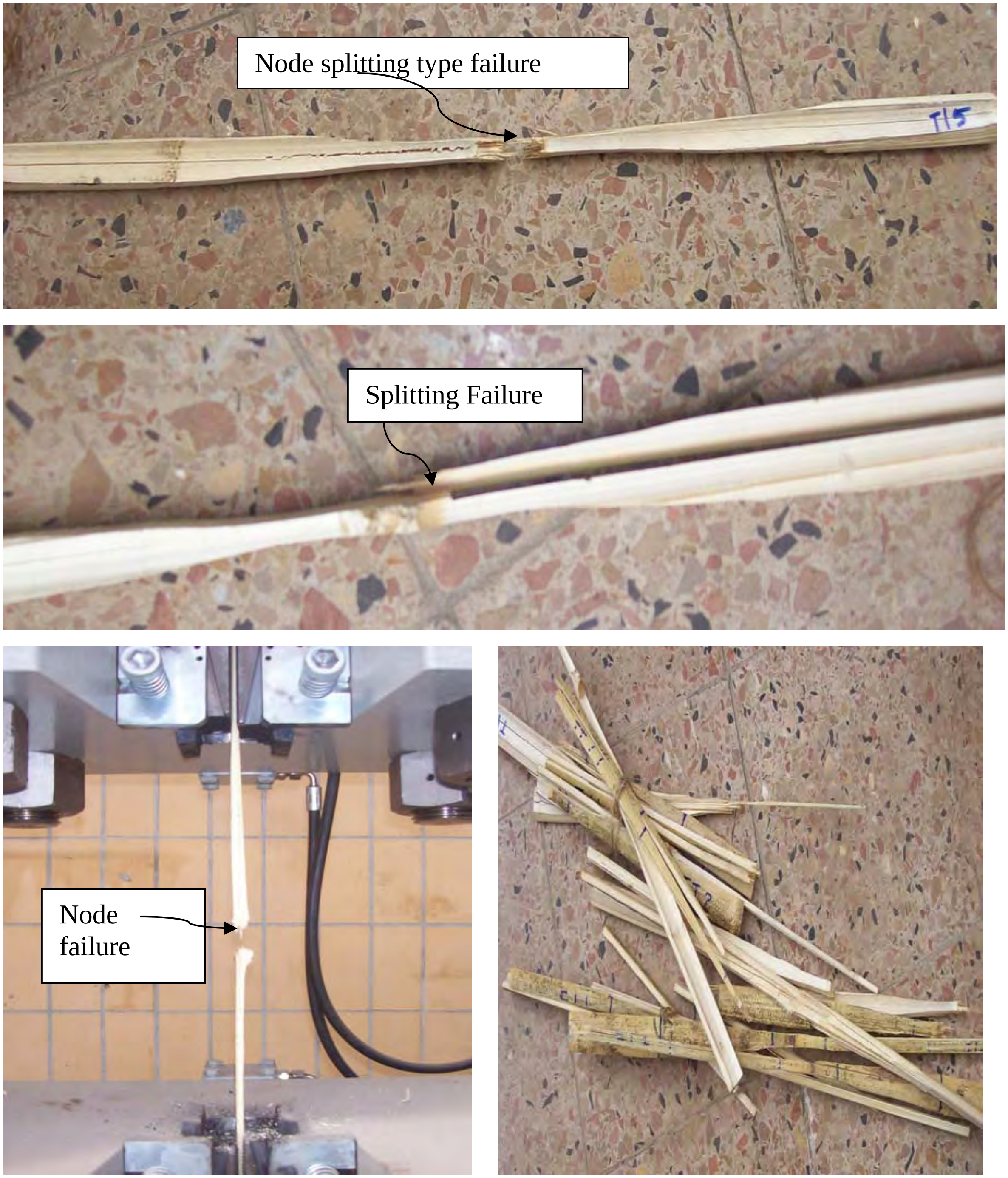


Figure 4.1 Failures of Tensile Test

b) Compression Test Results

Compression tests were conducted on specimens with nodes and without nodes for eighteen test specimens. From the test the ultimate compression resistance of the specified specie was recorded. Brooming or end-rolling type of failure was observed in most of the test specimen. The entire three specimens with node failed with the end-rolling type of failures. This type of failure is usually associated with excess moisture at the ends of the specimen or improper cutting of the specimen which is usually associated with a reduced load. The other type of failures which were observed in most of the specimens were splitting and shearing. Most samples failed by dividing in to two parts which is a splitting type of failure.

The general compression test results are summarized in the Table 4.2, shown below

Table 4.2 Compression Test Result

Specimen code	Location	X-sectional Area [mm$^{2]}$	Moisture content [%]	Mass per volume [Kg/m^3]	Lateral Shrinkage [%]	Failure load [kN]	Stress [MPa]	Type of failure
CT1	T	565.8	14.28	0.49	3.83	21.40	37.82	Splitting
CT2	M	754.0	15.24	0.78	4.74	29.20	38.73	Brooming
CT3	B	918.1	12.81	0.73	3.65	39.00	42.48	Brooming
CT4	T	741.5	13.81	0.53	2.96	29.20	39.38	Shearing
CT5	M	868.7	15.08	0.71	3.30	42.10	48.46	Splitting
CT6	B	1033.5	11.88	0.79	2.93	55.00	53.21	Brooming
CT7	T	505.8	15.17	0.51	4.01	20.20	39.94	Splitting
CT8	M	682.5	16.00	0.78	3.54	31.60	46.30	Brooming
CT9	B	765.0	13.35	0.86	1.94	47.10	61.57	Splitting
CT10	T	615.6	16.86	0.41	5.01	21.10	34.28	Shearing
CT11	M	889.9	16.15	0.69	1.89	34.30	38.54	Brooming
CT12	B	1100.2	15.30	0.80	3.76	50.70	46.08	Brooming
CT13	T	451.6	11.15	0.46	4.12	18.20	40.30	Shearing
CT14	M	562.0	13.01	0.71	5.32	25.40	45.20	Splitting
CT15	B	720.2	9.40	0.81	1.44	36.20	50.26	Brooming
CT16	M	624.6	14.28	6.36	4.50	23.20	37.03	Brooming
CT17	M	978.8	15.24	9.90	2.09	41.20	50.76	Brooming
CT18	M	733.4	12.81	8.90	4.06	30.30	45.97	Brooming

Figure 4.2 Compression Test Failure and Shrinkage Specimens after Oven Dry

4.3 Pullout Test Results

The bond strength between bamboo and concrete for different splits was determined in pull-out tests. In doing this a pulling force were applied at the end of the bamboo bar and from this the bond strength of bamboo were estimated. In the pull out test generally two types of failures were observed. Slippage of bamboo out of the concrete block was one of the failures which were observed in the majority of the test specimen. Here, pullout failures occurred due to the bond strength between the bamboo and the concrete which indicates bond failures of bamboo. During the first several seconds, the bamboo did not show any slippage. After the bamboo started slippage, the bamboo was pulled out smoothly with a small amount resistance. The other type of failure observed was due the splitting of the enclosing concrete. In this type of failure the concrete broke up into two parts while the bamboo slipped out as shown in Figure 4.3.

Figure 4.3 Failures of Pullout Test

The final bond strength depends on the embedment length and the geometrical properties of the bamboo. From the ultimate load, F, and the geometric properties of specimens, the average bond stress was calculated using the following equation (4.1):

$$\mu = F/A \qquad [4.1]$$

Where μ - The average bond stress,

F - Ultimate load resisted,

A - The shear area.

Table 4.3 Pull out Test Result

a) Pull out test for full bamboo culm

Specimen code	Concrete size L*b*h (cm)	Perimeters, P (mm)	Embedment height, h (mm)	Shear area P*h (mm^2)	Load at Failure (kN)	Stress, (MPa)	Type of Failure
P-FS, Untreated-1	15*15*15	94.1	130.0	12229.7	7.5	0.613	Slip
P-FS, Untreated-2	15*15*15	99.8	130.0	12972.6	10.3	0.794	Slip
P-FS, Untreated-3	15*15*15	119.9	130.0	15585.1	13.1	0.840	Slip
					Average Stress	0.749	

b) Pull out test for half section bamboo

Specimen code	Concrete size L/b/h (cm)	Perimeters P (mm)	Embedment height, h (mm)	Shear area P*h (mm^2)	Load at Failure (kN)	Stress, (MPa)	Type of Failure
P-HS, Untreated-4	15/15/15	104.0	125.0	13000	12.0	0.923	Slip
P-HS, Untreated-5	15/15/15	102.0	130.0	13260	10.1	0.762	Slip+ Splitting of concrete
P-HS, Untreated-6	15/15/15	112.0	125.0	14000	12.7	0.907	Slip
					Average Stress	0.834	

c) Pull out test for 1/4 section bamboo

Specimen code	Concrete size L/b/h (cm)	Perimeters P (mm)	Embedment height, h (mm)	Shear area P*h (mm^2)	Load at Failure (kN)	Stress, (MPa)	Type of Failure
P-1/4S, Untreated-7	15/15/15	69.0	95.0	6555	Incorrect loading.		
P-1/4S, Untreated-8	15/15/15	72.0	90.0	6480	6.0	0.926	Slip
P-1/4S, Untreated-9	15/15/15	66.0	90.0	5940	4.5	0.758	Slip + grip
Average Stress						0.842	

d) Pull out test for 1/4 section bamboo coated with asphalt and roughed with sand

Specimen code	Concrete size L/b/h (cm)	Perimeters P (mm)	Embedment height, h (mm)	Shear area P*h (mm^2)	Load at Failure (kN)	Stress, (MPa)	Type of Failure
P-1/4S, Treated-10	15/15/15	70.0	110.0	7700	8.2	1.06	Slip
P-1/4S, Treated-11	15/15/15	69.0	110.0	7590	8.6	1.13	Slip + Splitting of concrete
P-1/4S, Treated-12	15/15/15	79.0	100.0	7900	5.8	0.73	Slip + Splitting of concrete
Average Stress						0.933	

* Note that FS is to represent full section, HS is to represent half section and 1/4S is to represent 1/4th section of bamboo.

4.4 Flexural Test Results

From the experimental test the load deflection graph, ultimate carrying capacity and the type of failure were recorded. The deflection at first crack was recorded from the load and deflection curve which was found at the point where the stiffness of the beam changed. In addition the maximum deflection was read from this curve. Generally bond, pure flexural, shear and a combination of shear and flexure types of failures were observed. The flexure and shear combination failure were the most dominating occurrence.

Test F-treated, 2.5

These test beams contain 2.5% bamboo treated with AC-85/100 asphalt. Three test specimens were prepared for this percentage.

In the first test specimen beam, the first crack occurred vertically from the point of load application which was flexure crack and the crack was widened. Then, crushing of concrete at the point load application was observed. Longitudinal crack of concrete parallel to the reinforcing bar was also observed, which may be considered as a bond failure. Finally, the beam failed ultimate load of 66kN.

Figure 4.4 Failure pattern for F-treated, 2.5-1

In the second test beam initially a crack was observed vertically from the point of load application. Then, as the load increases the crack started at the point of load application which extended to the bottom of the beam with incline pattern. Then, the crack propagates longitudinal parallel to the positive reinforcing bars. This type of failure is a combination of bond and flexure-shear failure. At the end piece of concrete fell out from the bottom of the beam possessing the stamp of the bamboo reinforcement. This indicates a poor bond between the concrete and bamboo, leading to bond failure. The pattern of crack observed in this test beam is shown below in Figure 4.5. The ultimate load recorded from this test beam specimen was 57.7kN.

Figure 4.5 Failure pattern for F-treated, 2.5-1

In the third test beam specimen, the first crack was started from the load application point and propagates to the middle between support and load application as shown in Figure 4.6. Crushing of concrete at the point of application of load was observed which was a flexural failure. Crack was started from the point of load application and became inclined as the load application progressed, where the failure called shear bending failure occurred under a combination of bending moment and shear force. A piece of concrete fell out from the bottom part of the beam bearing the stamp of bamboo reinforcement. This indicates poor bond between the concrete and bamboo, leading to bond failure. Generally, this test specimen shows a combination of shear, bond and flexure failure. During setup a mistake of early loading noticed. When we jog up the supporting frame up wards a contact of the beam with the loading roller occurred. This induces an initial load on the beam. Due to that the specimen failed with less resistance than the actual. Finally, the test beam failed with an ultimate load of 47.5kN, which attributes to initial loading.

Figure 4.6 Failure pattern for F-treated, 2.5-3

F-untreated, 2.5%

These test beams contain 2.5% bamboo without treatment. Three test specimens were prepared for this percentage.

In the first beam specimen cracking started from the support by widening its width propagates diagonally to the point of load application. The concrete at the support was crushed. This failure is a type of diagonal tension failure which occurred under the action of large shear forces. Figure 4.7 shows the diagonal tension failure that was observed. Finally an ultimate load of 58.4kN was recorded.

Figure 4.7 Failure pattern for F-untreated, 2.5-4

In the second test specimen longitudinal crack parallel to the positive reinforcing bar had been observed before any other crack. As loading progressed, crushing of the concrete at the point of loading started. As further a large crack which propagates vertically down wards from the compression zone of the beam to the bottom of the beam was observed producing type of bending failure. In addition, cracks started beam propagated diagonally was also observed. Generally, a combination of bond and flexure failure was dominantly observed. The pattern of cracks observed in this test beam is shown in the Figure 4.8 below. Finally, the beam failed at an ultimate load of 64.5kN.

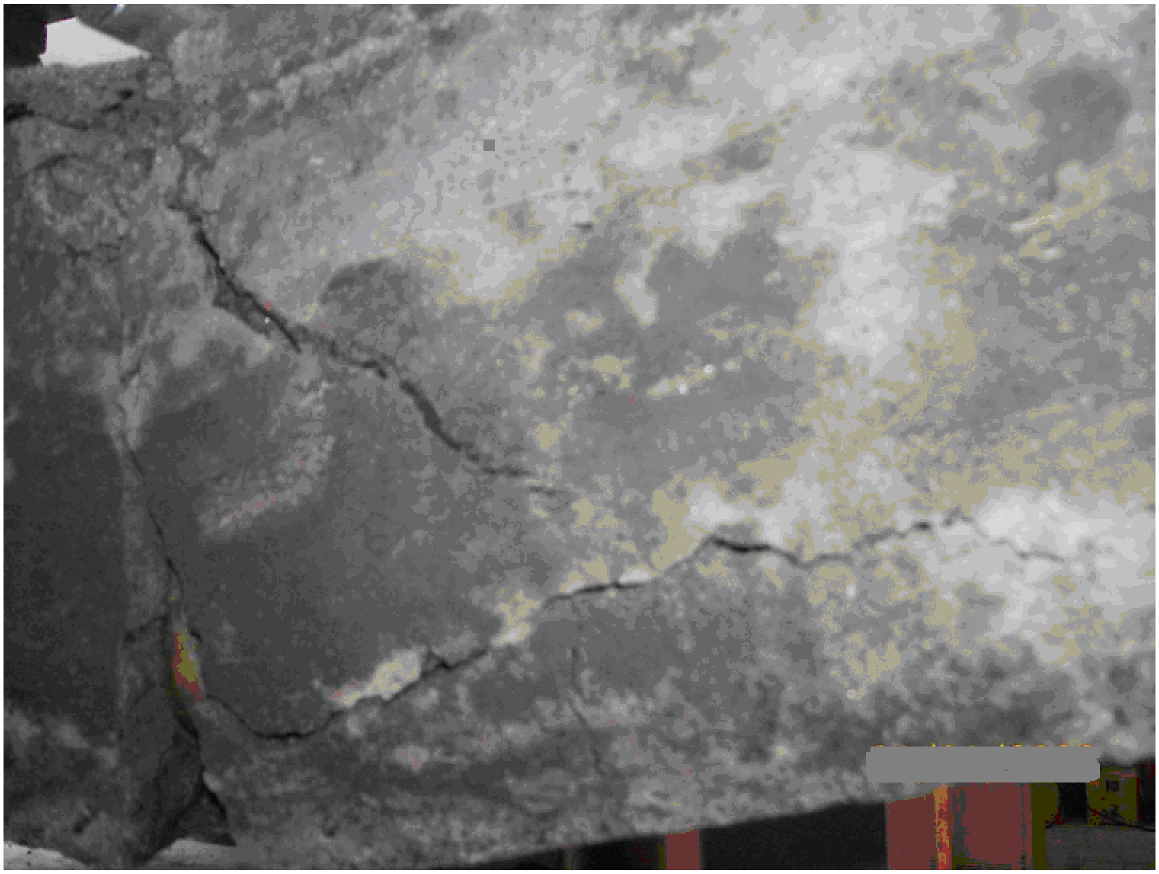


Figure 4.8 Failure pattern for F-untreated, 2.5-5

In the third beam specimen, diagonal cracking started from the support to the point of application of load. This failure is diagonal tension failure, which occurred under the action of large shear forces. Longitudinal cracks were also observed in this test specimen. Figure 4.9 shows the diagonal tension failure that was observed. Finally, an ultimate load of 58.4kN was recorded.

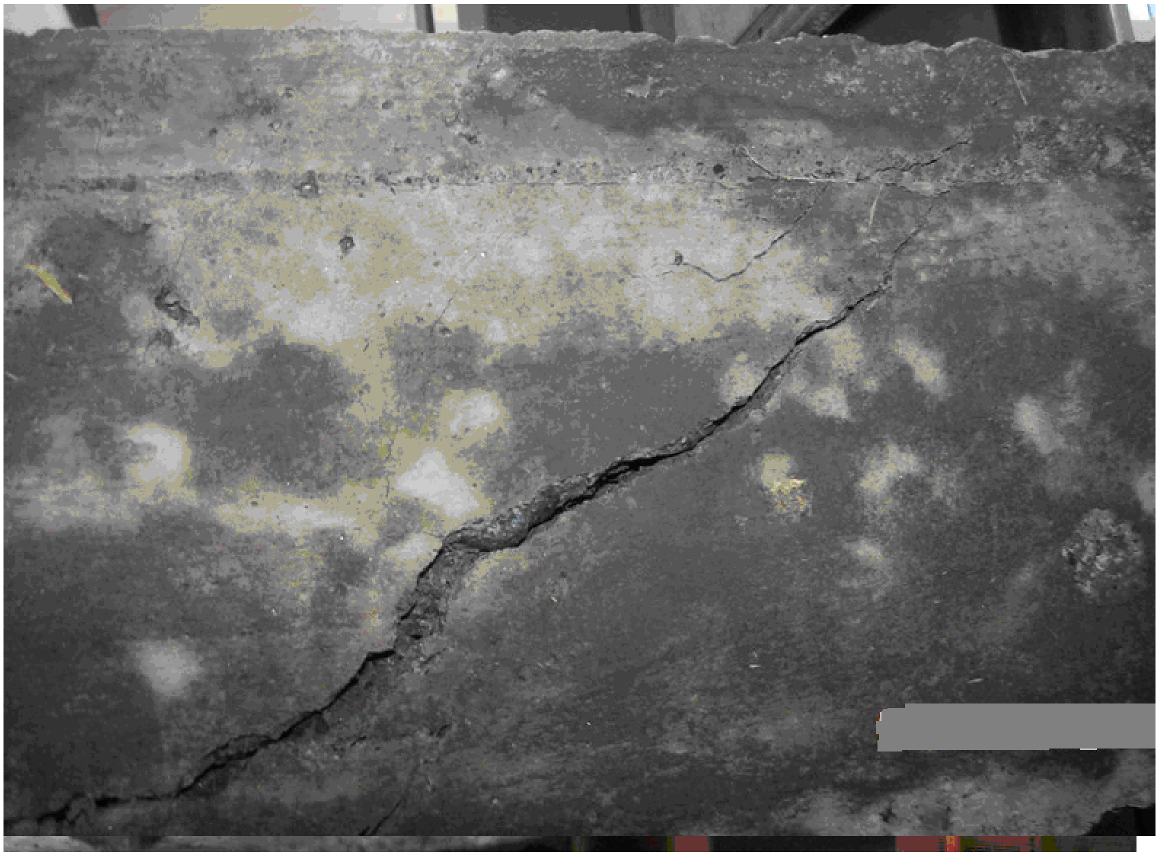


Figure 4.9 Failure pattern for F-untreated, 2.5-6

F-untreated, 3.5%

These test beams contain 3.5% bamboo without treatment. Three test specimens were prepared for this percentage.

In the first test beam, crack started at support by crushing of concrete and the crack propagated to the point of application of the load. The concrete fell out from the side of the beam bearing the stamp of bamboo reinforcement. A slippage of bamboo reinforcement about 40mm was also observed. This indicates a poor bond between the concrete and bamboo, leading to bond failure. Here, combinations of shear and bond failures were observed to be dominant. This test beam resists an ultimate load of 64.5kN.

Figure 4.10 Failure pattern for F-untreated, 3.5-7

In the second test beam, cracks started by crushing of concrete as the supports and then the crack propagate diagonally to the points of application of load. This was the diagonal tension failure due to shear force. The concrete around the support was detached and fell down and also there was a slippage of bamboo around the support. This was due to the poor bondage between the bamboo and concrete. In this test beam dominantly diagonal tension failure due shear forces occurred as shown in Figure 4.11, below. Finally, the beam failed with 69.8kN ultimate load with shear controlling failure.

Figure 4.11 Failure pattern for F-untreated, 3.5-8

In the third test beam, cracks started in the compression zone of the concrete with slightly diagonal pattern, which attributes to combination of shear-bending failure. But, when the loading progressed, crushing of concrete at the supports were also observed and then the crack propagate diagonally to the points of application of load. Finally, the beam failed with 60kN ultimate load.

Figure 4.12 Failure pattern for F-untreated, 3.5-9

F-untreated, 4.5%

These test beams contain 4.5% bamboo without treatment. Fine cracks were observed during curing period of the specimen. Three test specimens were prepared for this percentage.

In the first test beam, initial crack started from the support to the point of loading, which attributes to diagonal tension failure type due to shear force. As loading progressed crushing of concrete at the point of application of load was observed this was due to the bending moment. Longitudinal crack parallel to the reinforcing bar was also observed. After the test completed an average of 3cm slippage of bamboo reinforcement was observed in both directions which show the poor bondage between concrete and bamboo. Generally, a combination of shear-bond-flexure failures was observed in this test beam.

The final failed beam is shown in Figure 4.13, below. This test beam resists an ultimate load of 97.4kN.

Figure 4.13 Failure pattern for F-untreated, 4.5-10

Here, in the second test beam cracks started by crushing of concrete as the supports and then the crack propagates diagonally to the points of application of load. A slippage of bamboo around the support also observed. In this test beam a pure diagonal tension failure due to shear forces occurred as shown in Figure 4.14 below. Finally, the beam failed with 75.9kN ultimate load in shear.

Figure 4.14 Failure pattern for F-untreated, 4.5-11

In the third test beam, the crack started from the support propagates diagonally to the point of application of load. This failure was recorded as diagonal tension failure due to shear force as shown in the Figure 4.15 below. Moreover, an average of 2.5cm bamboo slippage was also observed. Finally, the beam failed at an ultimate load of 62.9kN. Relative to the other two test beams this beam failed with less load.

Figure 4.15 Failure pattern for F-untreated, 4.5-12

Generally for most of test specimens a combination of bond, shear and flexure failures were observed. As the percentage of bamboo reinforcement increases shear failure was more dominantly exhibited than flexure and bond. Moreover, the slippage of bamboo at the supports and a longitudinal crack parallel the reinforcement bars also observed in most of the test specimens especially for the lesser percentage occurred with widen cracks. The general revised test results are shown in Table 4.4 below.

Table 4.4 Flexural Test Results

Specimen code	Concrete size l/b/h in (cm)	Free span in (mm)	Deflection at max. load (mm)	Failure load (kN)	Type of failure
F-treated, 2.5-1	100/20/20	860	9.0	66.0	Flexure followed by bond failure
F-treated, 2.5-2	100/20.5/19.5	860	8.0	57.7	Flexure followed by shear and bond failure
F-treated, 2.5-3	100/20.5/20	860	10.0	46.0	Defective loading
F-untreated, 2.5-4	100/20.5/19.5	860	7.5	58.4	Shear followed by flexural failure
F-untreated, 2.5-5	100/20/19.5	860	7.5	64.6	Flexural followed by shear failure
F- untreated 2.5 -6	100/20.5/20	860	Not recorded	60.0	Shear followed by bond failure

F-untreated, 3.5-7	100/20.5/20.5	860	5.0	64.5	Shear followed by flexural failure
F-untreated, 3.5-8	100/20.5/20.5	860	5.0	69.8	Shear followed by bond failure
F-untreated, 3.5-9	100/20.3/20.4	860	Not recorded	60.0	Flexural followed by shear failure
F-untreated, 4.5-10	100/20.5/21.5	860	5.5	97.4	Shear followed by bond failure
F-untreated, 4.5-11	100/20/19.5	860	5.5	75.9	Shear
F-untreated, 4.5-12	100/19.5/20.5	860	5.0	62.9	Shear

5 ANALYSES AND DISCUSSION

5.1 Analyses

5.1.1 Tensile and Compressive Test

From these test results an average tensile strength of 149.5MPa parallel to the grain with node at gauge position was obtained. The variation of strength of bamboo was high relative to concrete and steel. This is because organic nature (vulnerable to termite attack and decay), natural growing (varied due to moisture content, weather condition, season etc.), Variation in cross sectional area, damage during transport and storage etc. In order that bamboo need higher factor of safety than steel and concrete. The United States Naval Civil Engineering Laboratory (1966) uses a partial safety of 4.5 for bamboo to obtain allowable tensile stress [3].

The results of the tensile tests show that the bottom and middle parts of the culm have high tensile strength than the top part of the culm. The top part of the culm has only one third of bottom part tensile strength. This indicates that the decrease in tensile strength is considerable as we go from bottom to top part of the culm. Considering only the results obtained from the bottom and middle part of a culm, an average tensile strength of 167.4MPa with a standard deviation of 30.3 was obtained. By avoiding the top parts of a culm greater strength with less variation was obtained. Hence it is better to use the bottom and middle part of a culm as reinforcement for better resistance.

On the other hand an average compressive strength of 44.17MPa with a standard deviation of 7.11 parallel to the grain without node was obtained. Relative to the tensile test results less variation was obtained. From samples with node for compression test, that were taken from the middle of a culm, average strength of 44.59MPa was obtained. From the experimental test result approximately equal compressive strength was obtained for samples taken with node and without node at gauge position.

The compressive strength was found to be much less than the tensile strength. This confirmed the fact that bamboo fiber grows in the longitudinal direction and it has less resistance in the transverse direction**.** Generally, the average mechanical test result obtained from this experimental program is shown in the Table 5.1 below:

Table 5.1 Mechanical Properties of Bamboo

No	Mechanical property	Average value	Standard Deviation
1	Ultimate Tensile Strength, MPa	149.50	36.8
2	Ultimate Compressive Strength, MPa	44.17	7.11
3	Mass per volume, Kg/m^3	0.68	0.16
4	Radial Shrinkage, %	3.50	1.13
5	Longitudinal Shrinkage, %	-0.03	0.45

In the table, the shrinkage of thickness and diameter is called radial shrinkage whereas the shrinkage in the direction of length is called longitudinal shrinkage. The result showed that a high shrinkage in the radial direction, while almost zero shrinkage was measured in the longitudinal direction.

i Mean Ultimate and Allowable Strength of the population

In a test series, we would like to determine the mean strength value of the population we actual determine the mean value f_{bym} of the sample. The mean value of samples however takes no account of the range of the strength in a population. According to ISO-22157 the mean strength value of the population can projected from the mean value samples as follow:

For the number of samples equal to 12 and above, $f_{by} = f_{bym} \pm 10.6$ where

Where f_{bym} = 149.50MPa, which is mean ultimate tensile strength of the samples

f_{by} is mean ultimate tensile strength of the population

Then, $f_{by} = 149.5 – 10.6 = 138.9$MPa

According to US Naval Civil Engineering Laboratory (1966) report [3], 4.5 factor of safety was selected to obtain allowable tensile strength of bamboo. For 138.90MPa mean ultimate tensile strength of the population an allowable tensile strength of 30.87MPa could be obtained.

ii Modulus of Elasticity from tensile test

Modulus of elasticity, E is among one of the most important parameters of mechanical properties of a material. In ISO 22157 modulus of elasticity E, can be determined from stress strain diagram based on the linear elastic behavior. From the samples with node at gauge position of the tensile test result, an average E of 19518.4N/mm^2 was recorded.

5.1.2 Pull out Test

From the test results the treated quarter sections have a slightly more bond strength than the untreated quarter section. On the other hand, the untreated quarter sections have more bond strength than the untreated half and full sections. Generally, the mean pull out test results obtained from this experimental program is shown in Table 5.2 below.

Table 5.2 Mean Pullout Test Result

No	Section Type	Avg. Bond stress, MPa	Standard Deviation	% deviation from quarter section
1	Quarter, treated	0.933	0.213	10.81
2	Quarter, untreated	0.842	0.119	0.00
3	Half, untreated	0.834	0.071	-0.95
4	Full culm	0.749	0.120	-11.05

The United States Naval Civil Engineering laboratory (1966) reported an allowable bond stress of 50Psi (0.345MPa) for ¾ in wide split. Coming to our case, it has been obtained an ultimate pull out strength of 0.842MPa for quarter sections. If 40% of the ultimate bond is taken for flexural allowable bond stress, the result will be approximately equal to result reported by the United States Naval Civil Engineering laboratory.

In other research made in the University of Texas at Arlington by Youngsi jung obtained a bond stress from 0.54MPa to 0.93MPa for solid bamboo which was in the same range from the Gumero solid bamboo species. On other pull out test research conducted by K. Ghavami 0.52MPa was obtained for full culm which is approximately equal to the full section of Gumero bamboo species. This shows that the experimental results obtained in pull out tests are comparable with other research results.

5.1.3 Flexural Tests

5.1.3.1 Theoretical Calculated Ultimate Strength of Bamboo Reinforced Concrete beam

For the purpose of comparison the experimental and theoretical moment resistances were calculated. All tests were performed with four point loading with load arrangement shown in Figure 5.1, below. The experimental ultimate moment is calculated using the failure load obtained from the test and the self weight of the beam by utilizing the law of statics with equation 5.1 below.

$$M_u = \frac{P_u L}{6} + \frac{WL^2}{8} \qquad \text{[Eq. 5.1]}$$

Where: P_u is failure load, L is the free span length, W is self weight of the beam and M_u is experimental ultimate moment.

The calculation of theoretical ultimate moment resistance of bamboo reinforced beams was made based on the design guidelines listed in the United States Naval Civil Engineering laboratory (1966) report by utilizing the assumptions [3]. The mechanical properties of bamboo obtained from the test result and the compressive strength obtained from the cube tests were used.

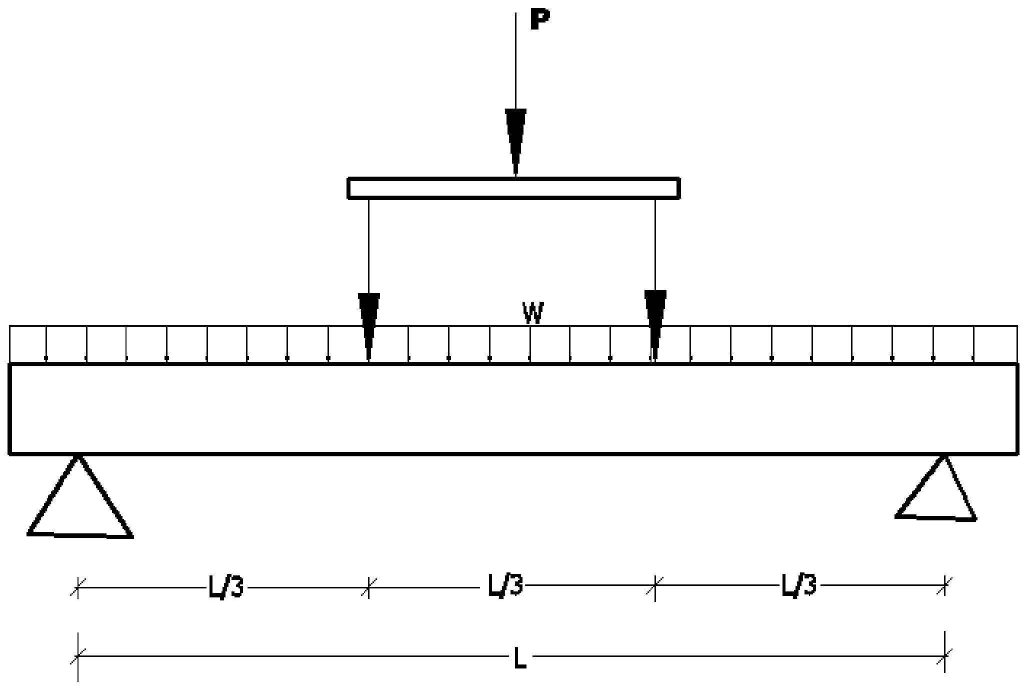


Figure 5.1 Two Point Loading System

Material Properties

f_{by} = 138.9MPa

$f_{bd} = \frac{f_{by}}{4.5}$ = 30.87MPa = 4477.16Psi

E_b = 19518.4N/mm^2

Where, f_{by} = Ultimate strength of bamboo

E_b = Modulus of Elasticity of bamboo

Concrete compressive cube strength C-15.03, f'_c = 2179.48Psi

f_c = 0.45*2179.48Psi = 980.77Psi

Cross section of concrete = 20cmx20cm

First by factoring the ultimate strength of concrete and bamboo to allowable stress the allowable resistance was determined. According to the design method specified in [3] the R (Coefficient of resistance) values was read from the graph of resistance coefficient for bamboo reinforced concrete beams and flexural members. Then, the allowable flexural resistances were calculated by multiplying with net area of the beam. Finally, the ultimate resistances were estimated by dividing with the factor that was used to factor the ultimate strength of the materials.

Table 5.3 Theoretical Ultimate Moment of Bamboo Reinforced Concrete Beams

Percentage of bamboo	2.5%	3.5%	4.5%
R = $\frac{M_{rd}}{bd^2}$ (figure-1 [3])	93	108	116
M_{rd}, lb-in	32,802.70	34,166.80	36,697.68
M_u (M_{rd}/0.45)	72,894.89	75,926.22	81,550.40
M_{ut}, kNmm	8237.12	8579.66	9215.20
P_{ut}, kN	56.83	59.24	63.81
P_u, kN (from test)	61.00	64.77	78.73
M_u, kNmm (from test)	8654.58	9194.95	11195.88
Variation from experimental ultimate moment, %	-4.82	-6.69	-17.69
Variation from experimental ultimate Load, %	-6.84	-8.54	-18.95

The experimental and theoretical ultimate loads and the percent of variation from the experimental ultimate moments are shown in Table 5.3 above for each percentage of bamboo. The result shows that ultimate loads obtained from the experimental test are greater than the theoretical calculated ones. Especially the results of experimental ultimate loads for 4.5% bamboo reinforced concrete beams are much higher than the theoretical calculated ultimate loads approximately by 18.95%. But in the case of 2.5% and 3.5% bamboo the theoretical ultimate moments are in close agreements with the experimental ultimate moment. This shows that as the percentage of bamboo reinforcement increase, the accuracy of ultimate moment estimation by United States Naval Civil Engineering laboratory (1966) report decreases. This report provides a set of instructions on how to properly design bamboo reinforced concrete members. Due to this a conservative theoretical calculated results were obtained.

5.1.3.2 Theoretical calculated ultimate moment resistant for minimum steel reinforced concrete beam

Ultimate strength method was used in the analysis of the ultimate strength of minimum steel reinforced concrete utilizing the usual assumption. In P.M. Ferguson it is noted that the ultimate strength of reinforced concrete beams can be predicted or calculated with quite satisfactory accuracy [23]. To calculate the ultimate moment strength, reference to Ferguson P.M. [23] is made.

The same grade of concrete obtained in the laboratory and cross section area were used for the analysis.

- Material Data

Concrete compressive cube strength C-15

Υ_c = 23.1kN/m^3 (from average unit weight of the concrete specimen obtained from cube test.)

Cross section of concrete = 20cmx20cm

Steel grade assumed S-260 and E_s = 200GPa

- Minimum Steel Reinforcement Requirement

The minimum reinforcement needed calculated from the reinforcement required to prevent shrinkage and change in temperature. Empirical relations are given in codes and standards. Our code EBSC-2 gives for beams:

$$\rho = \frac{0.6}{f_y} = \frac{0.6}{260} = 2.3x10^{-3} \text{ [16]} \qquad \text{[Eq. 5.2]}$$

Assuming 25mm cover and ϕ10

d = 200-25-6 = 170mm

$A_{smin} = \rho bd = 2.3x10^{-3}x200x170 = 78.2mm$ use 2 ϕ10

Therefore $A_s = 2x0.25x3.14xd^2 = 157mm^2$ and $\rho = 4.62x10^{-3}$

- Section capacity

For under reinforced beams the ultimate strength is analyzed below based on Whitney theory [23]. Whitney simplifies the distribution of compressive stress by an equivalent block of uniform stress of intensity $0.85f_c^{'}$ and height ‘a’ [Figure 5.2].

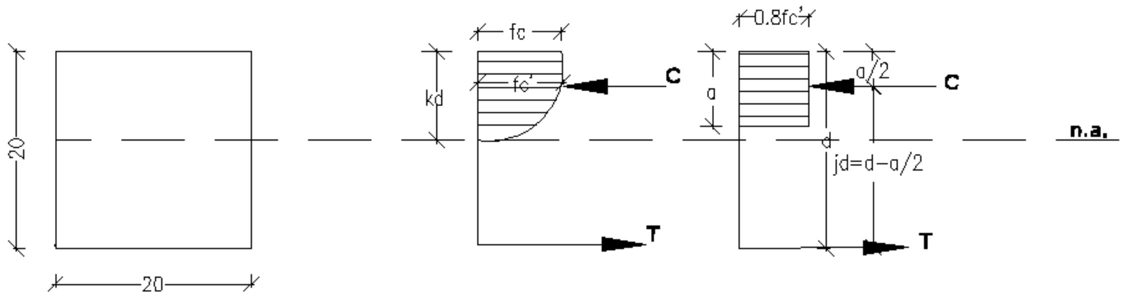


Figure 5.2 The Whitney Compressive Stress Block

Beams for less reinforcement than required for balanced section fails when compression force C equals with tension force T [23].

Therefore, C = T [Eq. 5.3]

Where, $T = A_sf_y$ and $C = 0.85\ f_c^{'}ab$

Then equating T and C, $a = \dfrac{A_s f_y}{0.85 f_c^{'} b}$

Then the lever arm jd between C and T is equal to d-a/2. Hence the ultimate resisting moment $M_{ut,m}$ is;

$M_{ut,m} = Tz = Cz = A_sf_y(d\text{-}a/2) = 170*260*(170 – 16/2) = 7160400\text{Nmm} = 7160.4\text{kNmm}$.

Therefore the minimum steel reinforced concrete can resist an ultimate moment of 7160.4kNmm. For two point loading system as shown in the Figure 5.1, the ultimate load $P_{ut,m}$ can be calculated from statical analysis.

From statical analysis;

$$M_{ut,m} = \frac{P_u L}{6} + \frac{WL^2}{8} \Rightarrow P_u = \frac{6M_u}{L} - \frac{3WL}{4}$$

Where W is self weight of concrete, W = 23.1*0.2*0.2 = 0.924kN/m and

L is free span length of the simple supported beam, L = 860mm.

Thus, $P_{ut,m}$ = 49.36kN

5.1.3.3 Theoretical calculated ultimate moment resistance for equivalent steel reinforced concrete beam

By using compressive strength obtained from the cube tests, the capacity of the beam was calculated by replacing the bamboo with equivalent stress of steel grade 260. Calculation of the area of equivalent steel was made based on their tensile strength with out factoring the ultimate tensile strengths of bamboo and steel. It has been obtained from the experimental test 138.9MPa average tensile strength of the population. Then using, S-260 steel grade the equivalent steel will be calculated as follow;

$$\rho_s = \frac{\rho f_{by}}{f_y} = \frac{\rho * 138.9}{260} \qquad \text{[Eq. 5.4]}$$

Table 5.4 Equivalent Steel Reinforced Concrete Beams Ultimate Moment

Bamboo percentage	Equivalent steel percentage	Area of steel, mm^2	Moment For Equivalent steel reinforced concrete beam, kNmm	Ultimate load resistance, kN
2.5%	1.336%	454.24	17,347.30	120.41
3.5%	1.870%	635.80	22,754.65	158.13
4.5%	2.404%	817.36	26,583.26	184.85

5.1.3.4 Comparison Ultimate Loads for Bamboo and Steel Reinforced Concrete Beams

Comparisons of the ultimate loads for minimum steel reinforced concrete beams calculated theoretically in section 5.1.3.2 above and the experimental ultimate loads of bamboo reinforced beams are given in Table 5.5 below. Moreover, comparisons of the theoretical calculated equivalent steel and the experimental ultimate moment bamboo reinforced concrete beams are also shown in Table 5.5 below.

Table 5.5 Comparison of Ultimate load of bamboo with steel reinforced concrete beams

Bamboo percentage	2.5% Untreated	3.5% Untreated	4.5% Untreated
Bamboo reinforced concrete ultimate load, kN	61.00	64.77	78.73
Equivalent steel reinforced ultimate load, kN	120.41	158.13	184.85
Minimum steel reinforced ultimate load, kN	49.36	49.36	49.36
Ratio of bamboo ultimate load to minimum steel reinforcement,	1.24	1.31	1.60
Ratio of bamboo ultimate load to equivalent steel reinforcement,	0.51	0.41	0.43

From the summary in Table 5.5, bamboo reinforced beams have more resistance of ultimate load than minimum steel reinforcement. From the summary a 2.5 % bamboo reinforced beam has ultimate load resistance by more than 20% than the minimum steel reinforced beam. It is also shown that the ultimate load capacity of bamboo was about 45% on average, when compared with equivalent steel reinforced concrete beam.

5.2 Discussions

5.2.1 Tensile and Compression Test

All tests for this thesis work were done with an average 22^0C of room temperature in dry condition. As analyzed above, the mean tensile strength of 149.5MPa parallel to the grain with node and 138.9MPa mean strength value of the population were obtained. Although, examination of the node structure shows that the fibers in the nodes are much denser than those of the internodal regions, the failure of test specimens were at nodes which indicate that, the node region is weak for tensile forces. Moreover, the stress strain graphs show the brittle character for bamboo at nodes. The average test result value obtained from test specimens with node would be taken as an average strength for Gumero bamboo species. Even though bamboo has low modules of elasticity, the tensile test result shows appreciable strength of bamboo. Comparing the ultimate tensile strength of bamboo with a steel of S-260, it has about half ultimate load resistance of that of steel reinforced, and the young's modulus of bamboo is 1/10 times that of steel.

During testing of tensile specimens a fluctuation of stress i.e. a sudden rise and drop of stress were observed as shown in the stress-strain graph of Figure 5.3. This is due to orthotropic nature of the bamboo i.e. bamboo has strong fiber in the outer surface whereas week in the inner surface. During testing it is assumed that it got strong outer fiber resulting in a rise of stress and then, when this fiber is broken the resistance would be lost and a decreasing of stress is observed.

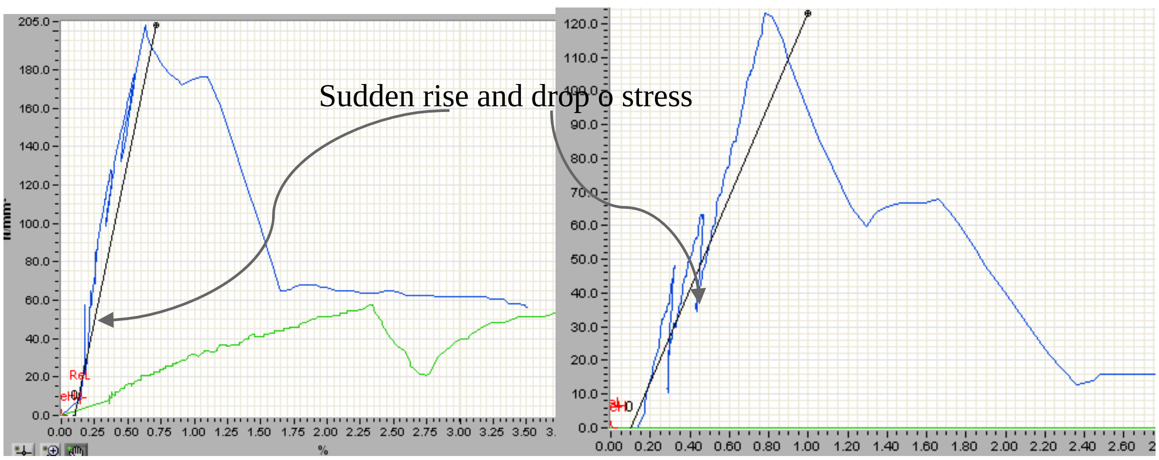


Figure 5.3 Typical Tensile Stress Strain Graph of Bamboo

Compression test results that were obtained from specimens with node from the middle location of bamboo were approximately equal to the internode test sample results. The average compression strength of 44.17MPa was obtained for internode specimens in this investigation. The average test result value obtained from internodal test specimens would be taken as an average strength for Gumero bamboo species.

5.2.2 Pullout Test

In the tension zone, the transfer of tension force from the reinforcement to the surrounding concrete is by shear at the bar-concrete interface. This interface shear is called bond stress. The mechanisms by which the bars develop this bond are by adhesion between the concrete and the bar surface and by friction in the first loading. As loading continues both the adhesion and friction effect would be lost and the bond will be transferred by the bearing on the deformation of the bars [13], [21]. On the contrary, bamboo has no deformed surfaces as steel bars had. Due to the smooth surface of bamboo slipping is the major problem in reinforcement.

In the pullout test it was observed that the contact between concrete and bamboo was rough at the nodes and smooth at the plain section. The presence of nodes in the reinforcement gives great assistance in maximizing the bond stress. As it was observed in the pull out test some of the test specimens except the full culm were failed by longitudinal splitting of the concrete. The splitting of concrete believed to occur due to an outward component of forces at the node during transferring bond stress through bearing action which produces a ring of tension. This lead splitting of concrete on weak planes along the bar. This type of failure is an evidence for the action of the node as a rib [23].

Generally, from the test results of quarter sections of bamboo have higher bond resistance than the other sections. This is due to 1) Exposure of the diaphragm at the nodes to act as a rib 2) Creating a more adhesion surface between the concrete and the bamboo surface. 3) Having larger contact surface area relatively.

5.2.3 Flexural Test

i Observations

During the first week of curing period, fine cracks were observed in the 3.5% and 4.5% flexural beam specimens. Especially in the 4.5% test specimens this fine cracks were observed clearly. These cracks were not clearly observed in 2.5% bamboo beam specimens. These cracks were expanded as the amount of bamboo reinforcement increases. The 4.5% reinforced bamboo has more visible cracks than 3.5%. This might be due to the swelling effect of bamboo during curing periods. As the percentage increases the number of bamboo that was swelling would be increased. This swelled bamboo pushes the concrete away and creates crack. In the 2.5% the swelling effect might be small to create visible cracks due to smaller bamboo-concrete area ratio.

Figure 5.4 Cracks That were Observed during Curing Period in 4.5% Beam Specimen

From the experimental results beam specimens with 4.5 percentages bamboo reinforcement sustained greater load than those specimens with 2.5 and 3.5 percentages. Furthermore, beam specimens with 3.5 percentages bamboo reinforcement sustained greater load than beams with 2.5 percentages. This result shows that as the percentage of reinforcement increases the carrying capacity of the beams was also increases. With this intention the carrying capacity of bamboo reinforced beam could be maximized by increasing the percentage of bamboo in the reinforcement.

The load carrying capacities of the treated 2.5% have the same carrying capacity with 2.5% untreated bamboo reinforced concrete beams. This indicates for short time the untreated bamboo strips did not affect by decaying and shrinkage problem. When the bamboo reinforced concrete beams exposed to drying cause the bamboo reinforcements to be shirnked and loose bondage. During curing period the degree of absorption of water for treated bamboo would be minimized. As a result the degree of shrinkage would be minimized when drying occur. But the untreated bamboo absorbs water in the curing period and loss in the drying period. Consequently shrinkage would occur in the drying period which results in a loss of bondage. At this time the effect of treatment would be dominate. Thus, treatment has a long term effect rather than short time.

ii Load-Deflection Curves

Generally depending on the percentage of reinforcement three types of failures would be occurred:

Case-1 When $\rho < \rho_b$, the tension failure would occurred, so that it is an under-reinforced case,

Case-2 When $\rho > \rho_{b,}$ compression failure would occur, so that it is an over-reinforced case,

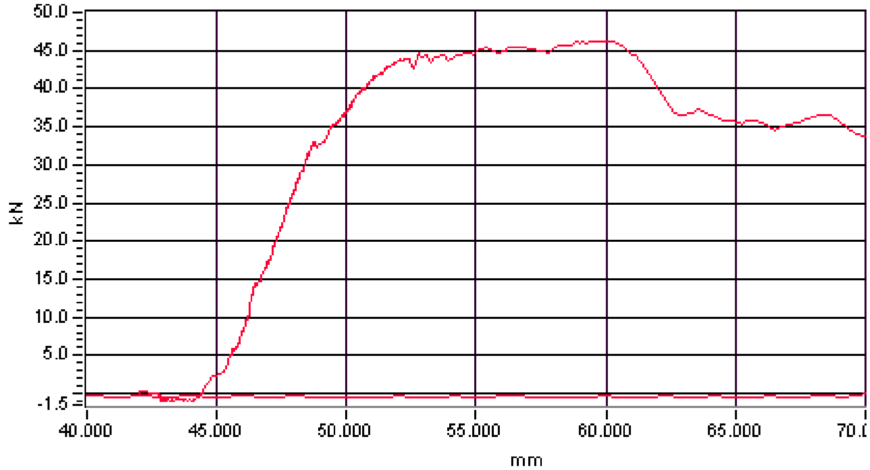
Case-3 When $\rho = \rho_b$ the concrete and the reinforcement could fail simultaneously, which termed as balanced case.

In the load-deflection graph obtained from the test, the above behaviors were clearly shown for the 2.5%, 3.5% and 4.5% percentage of beam specimens. As it is shown in the graph of load versus deflection, Figure 5.5 below, the 2.5% bamboo undergoes large deflection at the maximum load carrying capacity. In the 4.5% bamboo after the beam reaches to its ultimate carrying capacity, it showed a sudden drop of load resisting. In the case of 3.5% bamboo reinforced beam samples, even though it undergoes a deflection at the maximum load carrying capacity, the amount of deflection that undergoes was slightly less than the 2.5%. From this, the 2.5% bamboo shows a ductile type of failure which is analogues to the tension failure type in under steel reinforced beams. From this it can be concluded that the 2.5% reinforcement is less than the balanced reinforcement. But in the case of 4.5%, the section fails suddenly a brittle type failure manner. In this percentage the compression failure type of behavior was observed. 4.5% reinforcement is analogues to the behavior of over reinforcement. From this 4.5 % can be grouped from the over reinforced type of beams.

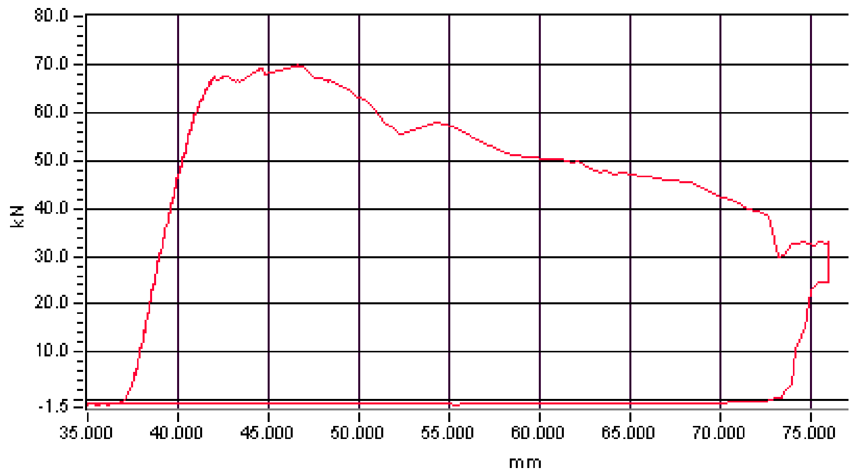
The 3.5% bamboo reinforced beams shows a behavior which is in between. In this percentage as explained above the deflection that undergoes at the maximum carrying capacity is less than from the 2.5% but much greater from the 4.5%. This leads to the assumption that the 3.5 % is a percentage that would be found around the optimum percentage.

Generally, from the load deflection graph it can be concluded that the bamboo reinforcement increases the ductility of the beams. Especially the 2.5 and 3.5 percentages specimen beams show the a ductile failure type of behavior which correspond to the tension type of failure. On the other hand the higher percentage bamboo reinforced concrete beams (4.5%) have a brittle type of failure which corresponds to the compression failure.

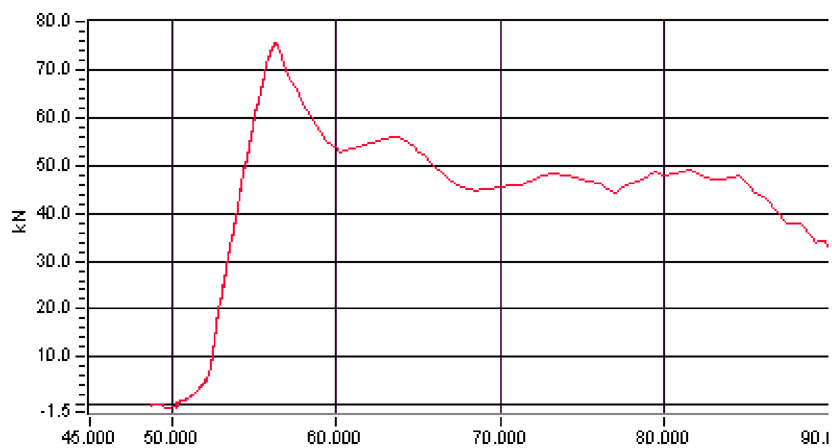
The other amazing behavior in the load deflection diagram is that there is a fluctuation of resistance especially around the maximum carrying capacity. This behavior was more happen in the 2.5% beam specimens. This fluctuation of resistance is believed that due to the bondage effect of bamboo. During initial loading the bond resistance is by adhesion and friction. As loading progress slip of bamboo will be occurred and the bond resistance by adhesion and friction would be lost. At this time the bond resistance would be transfer by nodes which act as bearing action, then the bondage increase and at the same time the resistance would be increased. Since there are an average of three nodes in one split of bamboo and there are a number of splits this action might happened for a number of times as it is seen in the diagram. Moreover, 2.5% beam specimens were under reinforced as described above; the reinforcements are efficiently utilized for resistance compared to the other percentages. Due to this the effect of fluctuation is more indicated in this percentage.



a) Typical Load deflection diagram for 2.5% of bamboo reinforced beams



b) Typical Load deflection diagram for 3.5% of bamboo reinforced beams



c) Typical Load deflection diagram for 4.5% of bamboo reinforced beams

Figure 5.5 Typical Load-Deflection Diagrams of Bamboo Reinforced Beams

5.2.4 Design Consideration and Applications

Bamboo used as reinforcement in the concrete has shortcoming. The major shortcomings are;

a. **Smooth surface of bamboo:-** Rough surface is important to enhance the bondage. Nevertheless, bamboo has smooth surface. Only around node has a rougher surface.

b. **Thermal Expansion:-** Close coefficient of thermal expansion of reinforcing bar and concrete is essential to control undesirable effect of differential thermal deformation. Researches on the determination of thermal coefficient of expansion of bamboo was made by Cox and Geymayer. From this researches one millionth per degree a cross and parallel to the fiber was obtained[7]. Whereas, concrete has an average of $10x10^{-6}$ per degree Centigrade [16] coefficient which is ten times more than bamboo so as this create a differential thermal deformation when ever there is temperature difference.

c. **Shrinkage and Swelling:-** During the casting and curing of concrete, reinforcing bamboo absorbs water and swells so that pushes the concrete away. Then, at the end of the curing period, the bamboo loses the moisture and shrinks back almost to its original dimensions.

d. **Durability:-** Due to organic nature of bamboo, the life span in concrete is uncertain. Concrete is very highly alkaline which destroys bamboo.

Many researches have been made to overcome these drawbacks for the application of bamboo as reinforcement. These drawbacks can be minimized by proper treatment methods. Application of thin layer of asphalt coating roughed with sand can be one of treatment methods. The asphalt coat used as a water-repellent which is used to prevent the absorption of water and exposure of bamboo to the alkaline environment. This helps minimizing swelling, shrinkage and decaying problems and maximizing durability. The sand used to roughen the smooth surface of bamboo and minimize the slippage problems. Moreover, concrete slump should be as low as workability will allow to minimize excess water and so reduce swelling of the bamboo and decrease thermal coefficient of concrete [2], [3].

Important Parameter during Design

i. Bond and anchorage

The length of embedment necessary to provide an adequate factor of safety against pullout failure is called anchorage length [23]. Reinforcement bars are anchored in concrete either by bond stress or hook + bond stress. The average bond strength obtained in pullout test is conservative and defective in several ways. According to Ferguson P. M., the ultimate flexural bond strength is considerably lower than the bond strength obtained from the pullout test by 25% to 50% [23]. Based on this estimation the anchorage length obtained by taking 35% of bond strength obtained in the pullout test will make conservative. Then, for a bar of perimeter p, area A, as it shown in the figure 5.6, and from equilibrium;

$A_b f_b = u\ L_d P$ [Eq. 5.5]

Where A_b is area of the bar,

F_b is tensile strength of bamboo

U is bond strength which is 35% of bond obtained from the pullout test

L_d is the anchorage length

P is perimeter of the bar

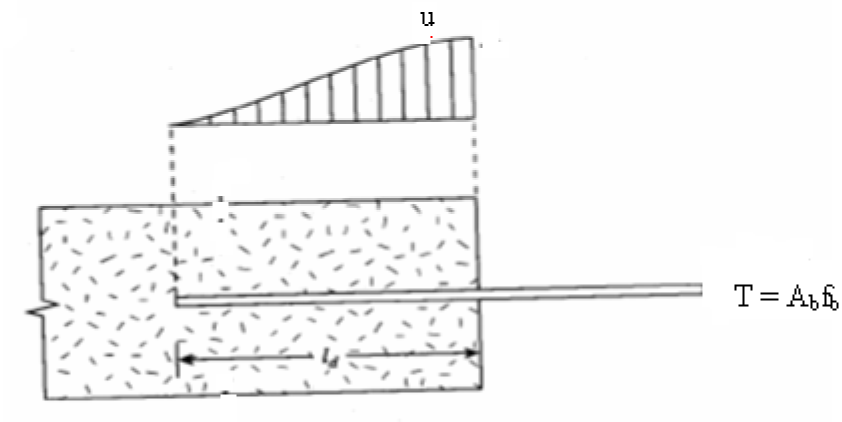


Figure 5.6 Bond Stress and Development Length

ii. Lapped Splices

When the available length of bamboo is less than provided length, extend reinforcement bars by lap splices. In lapped splices, the force in one bar is transferred to the surrounding concrete which in turn transfers the force to the adjacent bars. According to the United State Naval Civil Engineering report (1966) splicing reinforcement in any member should be overlapped at least 25 inches (63.5cm). Splices should never occur in highly stressed areas and in no case should more than 30 percent of the reinforcement be spliced in any one location [3].

iii. Concrete cover and spacing of reinforcement

Appropriate thickness of concrete cover is essential to ensure adequate fire resistance, sate transmission of bond forces and protection against corrosion or decay. Our code EBCS-2 recommends minimum concrete cover at least equal to the diameter of the bar for steel reinforcement. Due to low resistance of bamboo to fire appropriate concrete cover should be applied. According to Saucier K. L. and Smith E. F. and Khare L. recommendation a concrete cover not less than 25mm is recommended for bamboo reinforced beams.

EBCS-2 recommends a the spacing of bars should be at least equal to 20mm or the diameter of the largest bar or the maximum size of aggregate plus 5mm for steel reinforcement. On the other hand the United States Naval Civil Engineering laboratory

(1966) report recommends a clear spacing between bamboo rods or splints should not be less than the maximum size aggregate plus 1/4 inch (6mm). So that adopting the spacing recommended in EBCS-2 for steel reinforcement will not have problem.

iv. Stirrups

Due to the difficulty to bend bamboo into the desired shape it is recommended to use steel stirrups especially in critical zones (large tension zones).

In general, the test results indicated that bamboo reinforcement improved the load carrying capacity in average by 138% as compared to the minimum steel reinforced concrete beams. As the percentage of bamboo reinforcement increase, even though the fine cracks and brittle type of failure were observed, it was noticed that the load carrying capacity of the beams were also increased. In the calculation of the percentage of bamboo, cross sectional area and carrying capacity there is no empirical equations formulated till now. From the experimental program, as it was compared from the steel reinforcement, it was obtained that it can carry averagely about 45% of the equivalent steel carrying capacity. So that it can be deigned to bear 20% to 35% of equivalent steel reinforcement carrying capacity for the optimum percentage of bamboo by incorporating the above parameters in the design.

In general bamboo reinforced concrete will be applicable in areas like;

- Temporary building structures (structures which are not entirely precise or fixed)
- In areas where minimum reinforcement is needed by giving consideration on the life span of the structure.
- In the construction of detours such as temporary bridges, culvert etc
- For construction of low rise residential buildings
- For road base reinforcement
- For ground floor and manhole construction etc.

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Based on the experimental study of Gumero bamboo, the following conclusions can be drawn:

1. The node of bamboo is weak in tension. Almost all samples have failed at nodes.
2. The compressive stress was found to be much less than the tensile stress. This confirmed the fact that bamboo fiber grows in the longitudinal direction and it has less resistance in the transverse direction**.**
3. The ultimate tensile strength of bamboo decreases from bottom to top of the Culm.
4. Comparing the ultimate tensile strength of bamboo with a steel of S-260, it has 0.53 times resistance as that of equivalent steel, and the young's modulus of bamboo is 1/10 times that of steel.
5. Radial shrinkage is high whereas shrinkage in the longitudinal direction is almost zero.
6. Split bamboo performs better bond than whole culms when used for reinforcing. This is due to; 1) by avoiding internal cavity of the bamboo a more compact reinforcement is obtained 2) by exposing the diaphragm at the nodes makes to act as a rib in flexural action 3) by creating a more adhesion between the concrete and the bamboo surface.
7. Some of the pullout test failed by splitting of concrete longitudinally. This is an evidence that the node of bamboo has a bearing action in flexural action.
8. Treated bamboo has slightly better bond strength than the untreated.
9. The beam with 2.5% bamboo reinforcement shows under reinforced type of failure mode and 4.5% bamboo reinforcement shows a brittle type failure mode.
10. The beam with 3.5% bamboo reinforcement is approximately optimum percentage with respect to tests undertaken.

11. The treated reinforced beam had equally carrying capacity with the untreated beams for the same percentage. This is believed to be due to the swelling of bamboo during curing period push the concrete so that gave good bond resistance for the untreated case that may be equivalent to the effect of treatment.
12. The bamboo reinforcement has better resistance than the minimum steel reinforced concrete beams.
13. The ultimate load capacity of bamboo was about 45% when compared with equivalent steel reinforced concrete beam.
14. As the percentage of bamboo increase the load carrying capacity would be increase, but ductility would be decrease.

6.2 Recommendations

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This study initiate use of bamboo as reinforcement complement to previous studies but would like the following by studied in details for prompt use in the construction industry.

1. Tensile tests for different species of bamboo and investigation on the relationship between the tensile strength of bamboo of different species and performances as reinforcement in concrete should be conducted.
2. Development of factor of safety to calculate the allowable stress of bamboo for use in design calculation on basis of statical data be studied.
3. Experimental study be carried on different percentage of bamboo reinforced concrete columns to investigated bond strength, buckling behavior, carrying capacity and type of failures.
4. Extensive study be conducted on different treatment methods regarding the bond strength and economical aspects of bamboo in concrete members.
5. Durability analysis of bamboo should be made by exposing to drying and wetting frequently and to alkaline environment. Then mechanical properties of bamboo be conducted for different ages.
6. Long term studies on the durability and fatigue of bamboo reinforced concrete beam be performed.

7. The behavior of bond and flexure for bamboo concrete beam reinforced with 3.5%, with parameter varying the number of nodes and their locations be intensively investigated.
8. Thermal effect of bamboo by conducting pullout tests on different gradient of temperature.
9. Conducting pullout test with thermal treated and untreated bamboo to see the improvement of bond strength.
10. Short term and long term deflections on bamboo reinforced concrete beams be conducted.

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Statement of Declaration

I declare that this project work is my original work. It has not been submitted for any degree/Diploma in any University. In carrying out of the project work I have different sources and materials, which have been appropriately acknowledged.

Name: Fikremariam Mengistu

Signature: _______________