PERFORMANCE OF GLUE LAMINATED BAMBOO BEAMS AND TRUSSES

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Performance of Glue Laminated Bamboo Beams and Trusses

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DECLARATION

This thesis is my original work and has not been presented for a degree award in any other University.

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This thesis report has been submitted for examination with our approval as University supervisors;

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Dedication

This Research is dedicated to my dear parents who instilled in me the spirit of working hard and my entire family.

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SYMBOLS AND ABBREVIATIONS

MOE	Modulus of Elasticity
MOR	Modulus of Rupture
KeFRI	Kenya Forestry Research Institute
Kpa	Kilo Pascals
Gpa	Giga Pascals
Mpa	Mega Pascals
INBAR	International Network for Bamboo and Rattan
BCL	Bamboo Composites Lumber
BSB	Bamboo Strip Board
DG	Dendrocallamus Giganteous
LCA	Life Cycle Analysis
IB	Internal Bond
TRF	Tannin Resor cinol Formaldehyde
ASTM	American Society for Testing and Materials
LBL	Laminated Bamboo Lumber
LBB	Laminated Bamboo Beam

Abstract

Bamboo has been known to possess superior strength properties especially its tensile strength that compares well with that of mild steel, has positive environmental impacts of absorbing carbon dioxide and releasing oxygen and matures very fast in 3 to 4 years. However despite these advantages bamboo is not being used widely in construction one limitation being its natural occurrence in cylindrical and hollow form. This research evaluates the performance of glue laminated bamboo beams.

Anatomical features of bamboo internode and earlier studies that have shown that, strength properties of bamboo increase from inner to outer layer of the culm and so is the concentration of the cellulose fibers. Mature Bamboo of three and a half years was harvested, split, treated and dried for the study. Tensile test was carried out on strips with nodes, strips with outer skin removed and strips with outer skin intact. Laminated bamboo beams were made in various variations; two orientations, strips facing each other and strips facing same direction in respect to inner and outer face of culm, beams with coinciding nodes at the midpoint, beams made with jointed strips, beams with separated inner and outer parts of the culm, beams with different glue types and a Lattice truss model. Bending, shear and compression tests were performed on the specimens and the lattice truss model was also tested.

The results obtained show that orientation of bamboo strips and direction of loading has an effect on flexural strength of laminated bamboo beams, loading on the edge increased the strength by about 20%. Results also show that nodes have a reducing

effect on longitudinal tensile strength but have reinforced effect increasing flexural strength of beams, jointed beams have a lower flexural strength but compares well with commonly used timber, type of glue and dispersal affects the strength. In general laminated bamboo beams specimens portrayed superior structural strength properties with a higher MOR of 98 N/mm^2 than cypress timber with MOR of 83 N/mm^2. The lattice truss models which employed steel plates and bolted connections, did not fail on the joints but rather on excess deflection and deformation of members without rupture of the bamboo material.

CHAPTER 1

1.0 INTRODUCTION

1.1 Background Information

The International Network for Bamboo and Rattan (INBAR), in one of its publication (Ganapathy et.al 1999) reports that there are more than 28 types of bamboo composites lumber (BCL), also known as bamboo panel products, which have been developed by researchers in China and in other bamboo growing countries such as India, Indonesia, Japan, Laos, Malaysia, the Philippines, Taiwan, Thailand, Vietnam and Costa Rica.

BCL have been successfully used as materials for furniture making and for non-structural (non-load bearing) members in construction. Some of the bamboo composite lumber have proven to be comparable and even better than wood in certain cases and usages. For instance, the bamboo strip board (BSB), a strong and stiff material has already had an economic success in China for making platforms (floors) for transport vehicles like buses, trucks and train coaches, and for making concrete formworks in construction.

Another wide use of BCL is in the flooring industry. Laminated bamboo floor board has been regarded as a high value flooring material with properties better than a wooden floor board. However, up to date, laminated bamboo composite has not yet been used as load bearing structural members in the construction. However, many bamboo scientists and engineers around the world are eyeing at this possibility as manifested in the works by Bai et al (1999), Janssen (1981), Lee et al (1996, 1998, 1997), Mansur (2000) and Nareswoho (2000).

To use bamboo effectively in building industry also means to reduce the use of structural timber. This, in turn, will go a long way in helping the world to lift the burden on the environment due to excessive logging/cutting down of trees, especially of the reducing tropical forests. With this aim, bamboo scientists and engineers are striving to generate deeper knowledge on bamboo and better technology of manufacturing bamboo composite beams.

Timber has other uses and therefore there is competition for it. For instance, timber is a major raw material for making furniture and this is a big challenge to the construction industry because furniture builders are always willing to pay much more on timber. The reason why furniture developers are more willing to pay more for timber is that when used to make furniture, its return in terms of profit is much higher than when used for construction. In other words, for every cubic foot of timber used to make furniture, the amount of economic advantage is higher compared to the same amount of timber used for construction (American Institute of Timber Construction (2012). This means that the construction industry has to face strong competition in accessing timber for construction.

In Kenya, the Kenya Forestry Research Institute (KeFRI) has initiated manufacture of laminated bamboo beams, even though the production is not yet commercial or in large volumes, this forms a good platform for the country to start venturing into means of effecting efficient production of composite bamboo beams to supplement the limited construction materials, save on the environment by reducing pollution as a result of heavy use of steel and concrete that produce a lot of carbon dioxide in their production and reduce over reliance on timber that is has led to reduction in forest coverage.

1.2 Problem Statement

World's population growth has led to increased construction activities that have stretched the conventional building materials cement, steel and timber beyond limits. Furthermore the production of conventional materials cement and steel contributes a great deal in emissions of carbon dioxide in the atmosphere. Similarly, use of timber on the other hand has resulted to a decrease in forest cover and hence causing drought in many areas.

These problems necessitate the search for alternative or supplementary building materials. Bamboo offers a solution as it does the opposite of pollution by releasing fresh oxygen to the atmosphere during its growth and grows very fast, being the fastest growing plant currently known (Liese 1987) and matures in 3 to 4 years. Laminated bamboo beam is made of bamboo strips pressed and glued together to make a beam. Studies on the anatomy of bamboo internode cross-section (Wan Tarmeze et al 2005) have revealed that the strength properties change (increase) from inner to outer layer of the culm, this therefore means that the orientation of the strips in laminated bamboo beam and direction of loading affects the strength of the Beams.

Earlier works by Mahdavi et al (2011) concentrated on processing, performance and economic consideration of the development of laminated bamboo beam; however the processing does not take into consideration the orientation of the bamboo strips. Without exhaustive study on the effect of the orientation of the bamboo strips on the structural performance of laminated bamboo beams, optimum performance of the beams will not be achieved and hence full utility and use of beams, economy and other possible applications won't be appreciated. It is therefore imperative to carry out a research that explores various arrangement of the strips and techniques of manufacture against a certain direction of loading that gives optimal performance of laminated bamboo beam.

1.3 Research Questions

i. Does the orientation of bamboo strips and direction of loading in laminated bamboo beams have significant effect on strength?
ii. How do laminated bamboo beam with jointed strips perform?
iii. How do laminated bamboo beams perform in different types of glues?
iv. How do laminated bamboo beams structurally perform compared to cypress timber beams?
v. How do laminated bamboo lattice truss structurally perform?

1.4 Research Objectives

1.4.1 Main Objective

The main objective of this study is to evaluate the structural performance of glue laminated bamboo beams and lattice trusses.

1.4.2 Specific Objectives

i. To determine the effect of the orientation of bamboo strips and direction of loading on the structural performance of laminated bamboo beams.
ii. To assess the structural performance of glue laminated bamboo beams with jointed strips.
iii. To determine the effect of glue types on the structural performance of laminated bamboo beams.
iv. To assess structural performance of glue laminated bamboo beams compared to cypress timber beams
v. To assess structural performance of glue laminated bamboo lattice trusses.

1.5 Research Justification and Significance

With the growing population, the developing economies need millions of houses for this population of which a big part is homeless. In countries like Kenya, large population has been forced to stay in slums of the big cities while it is a very common sight of people sleeping on the road side especially in Nairobi City of Kenya.

The increased growth rate therefore necessitates infrastructure development in the form of suitable space for residential, offices and industries. While acknowledging the need for building more structures, it is also very important to consider the pertinent environmental issues at the forefront.

Engineered bamboo can therefore be of great value to civil engineers to alleviate the problem owing to several noteworthy features. From environmental consideration, every ton of bamboo produced consumes about a ton of the atmospheric CO_2 during photosynthesis, and in the process fresh oxygen is released into the atmosphere. Considering the structural aspect, bamboo has been found to have competitive strength characteristics. Bamboo species like dendrocallamus giganteus (DG) have been found to have tensile strength of about 120 MPa, compressive strength of about 55 MPa and Young's modulus of about 14 GPa (Bhalla et al 2008). These figures compare quite well with mild steel with an ultimate strength of 410 MPa, yield strength of 250 MPa and Young's modulus of 200 GPa (Bhalla et al 2008). Concrete which is widely used has much lower strength than those of bamboo listed here. In addition, bamboo has a low density typically 700 kg/m3, resulting in much higher strength to weight ratio as compared to steel with a density of 7800 kg/m^3 and concrete with a density of 2400 kg/m^3.

It is therefore justifiable to find means of utilizing bamboo in construction, further study of bamboo composite beams will ensure optimum methods are achieved that will give higher structural properties and lower cost of production to considerably replace steel, concrete and timber in the construction industry. Bamboo is also an attractive alternative to wood panels because of its physical similarities to hardwoods. Bamboo laminated panels are strong, durable, resistant to insects and molding.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

As availability of resource declines and demands increase in the modern industrialized world, it is becoming unavoidable to explore and research on opportunities for new and sustainable building materials in the construction industry (Meadows et al. 1992). For example wood has recently gained popularity in the green building owing to its environmentally beneficial and positive characteristics: wood has been promoted as biodegradable, re-newable, low in embodied energy, sequestering carbon from the atmosphere, and creating much less pollution in the production process and transport than concrete or steel (Falk 2009). Bamboo as well has similar positive environ-mental characteristics comparable to wood (Lee et al. 1994; van der Lugt et al. 2006; Nath et al. 2009; Rittironk and Elnieiri 2007 ;). Most notably, bamboo is highly renewable and its stalks mature in 3 to 4 years. Bamboo's strength is also comparable to that of wood. And as such, it makes an appealing and ideal candidate as a structural material to either supplement or replace wood, steel and concrete. With adequate and in-depth research, it is conceivable that bamboo has potential could become a sustainable alternative or supplement to current building materials in World.

Van der Lugt et al. (2006) carried out a study and presented an environmental life cycle analysis (LCA) of bamboo, with a view to quantify the environmental effects of using bamboo or its products as construction materials. The results of his analysis show that, in some applications, bamboo achieved “factor 20” on environmental impact, meaning that bamboo had 20 times less load on the environment than currently alternatives being used. In the study, environmental impact is expressed in units of environmental cost, that is: “fictitious societal costs (monetary factors) that are meant to express the prevention of environmental damage and pollution by certain interventions (e.g., emissions)” (van der Lugt et al. 2006). Lack of knowledge, expertise and experience with bamboo and its uses were seen as the contributors to much inefficiency and unnecessary cost currently associated with bamboo processing and construction. The inefficiencies and costs are expected to reduce as familiarity with this bamboo increases and its advantages accept in the society.

As hollow tube, bamboo is efficient in resisting bending forces as a whole, it has large ratio of moment of inertia to cross-sectional area. However it is difficult, to create connections for this shape, and furthermore tubes cannot be used in specific applications where flat surfaces are required. Laminated bamboo lumber (LBL) comes in handy to resolve these deficiencies in the natural shape of bamboo as it is formed in rectangular sections that are more suitable and easier to use in the common traditional structural applications. The beams have been created in research studies by using glue to join strands or flattened surfaces extracted from the culm (i.e., bamboo stem). This result to a composite rectangular structural member with highly renewable characteristics that make it very competitive and practical, in this regard, with commonly used building materials.

2.2 Growth of Bamboo

Bamboo is a tribe of flowering evergreen plants and the largest members in the grass family are the giant bamboos, they have been profiled as some of the fastest growing plants on earth owing to their unique rhizome dependent system with a reported growth rates of 100cm in 24 hours depending on climatic conditions and local soils, (Farrelly, 1984). A more typical growth rate of bamboo cultivated in temperate climates ranges between 3 to 10 cm per day in the growing season. Some of the largest species of bamboos grow over 30m in height and 15cm to 20cm in diameter depending on the species.

The bamboo plant is made up of an underground axis that comprise rhizomes, roots and buds and above ground axis comprising of stem, branches and foliage as shown in Figure 2.1. Buds from the rhizome develops into new shoot that grows into a new stem after emerging from the ground, this property enables the bamboo to multiply very fast as the rhizome elongates underground producing more and more shoots on the surface.

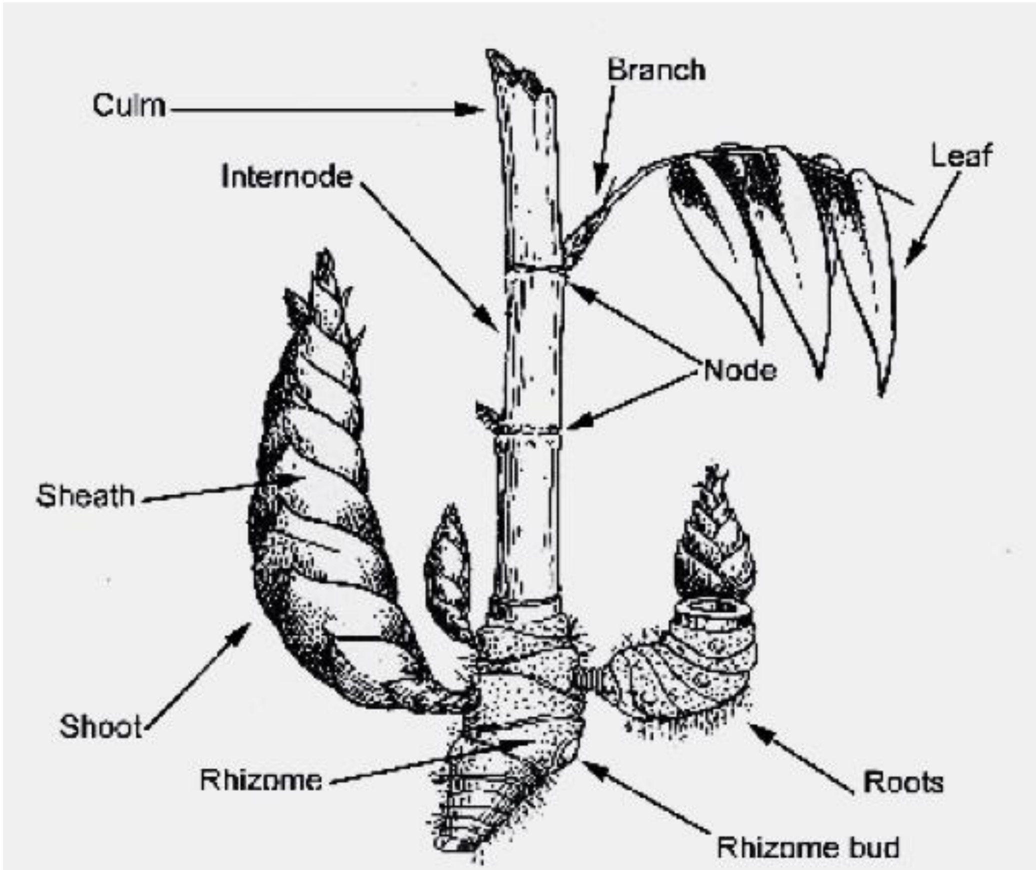


Figure 2.1 Parts of Bamboo plant (Kigomo N 2007).

Unlike common trees that grow in rings annually, individual bamboo stems shoot from the ground in their full diameter and grow to the full height in a single growing season that lasts from 3 to 4 months. In these months each shoot grows vertically into a stem/culm without branching and until a majority of the shoots reaches the maturity height and thereafter branching starts. In the subsequent period the culm starts hardening and is ready for harvesting in use for construction within 3 to 7 years depending on the species.

2.3 Bamboo Resources

The total bamboo area in the world is estimated to be 36 million hectares or an average of 3.2% of the total forest area. The bamboo is naturally distributed in the tropical and subtropical zone at latitudes from approximately 46° North to 47° South latitude, and from sea level to as much as 3,000 meters in elevation where there is a warm climate, abundant moisture, and productive soil. Naturally, bamboo is mostly distributed in the tropics, subtropical and temperate zones of all continents except Europe and North America. In recent years, bamboo has been introduced into North America, Europe and Australia. (Lobovikov, Paudel, Piazza, Ren, & Wu, 2007; Zhang et al., 2002; Jiang, 2007).

2.3.1 Asia and Oceania

Asia is the richest bamboo producer with approximately 65% of total world bamboo resources or about 24 million hectares as reported by Jiang (2007). In Asia there are about nearly 900 species and about 40 to 50 genera, accounting for about 80% of bamboo species in the world. Five of the six countries where are the largest extent of bamboo forests occur, are in Asia; India, China, Indonesia, Myanmar and Vietnam. In addition, Southeast Asia has been postulated to be the bamboo origin and hence presents the center of bamboo distribution. (Chaowana 2013).

India is the major bamboo producing country, possessing about 145 species; the area of bamboo growth exceeds 11.4 million ha, 17% of the country’s total forest area. Another major bamboo-producing country is China having the highest bamboo biodiversity in Asia, with over 500 species, covering 5.4 million ha or about 3% of its total forested area. The bamboo area in China has been rapidly increasing by about

50,000 hectares per year. Moso bamboo (*Ph. heterocycla*), the most important bamboo species with high economic value, covers an area of 3.4 million hectares or about 70% of total bamboo area in China (Lobovikov et al., 2007).

2.3.2 Latin America

In Latin America, bamboo occupies 10 million hectares or 28% of the total bamboo area in the world. According to Jiang (2007), there are around 270 bamboo species within 18 genera. Guadua spp. is the most well-known bamboo species because it has a large culm favorably used in construction and industry.

2.3.3 Africa

Africa has the smallest bamboo area covering an area of 2.7 million hectares or 7% of the total bamboo area in the world. There are totally about 40 species within 13 genera which mostly distribute in tropical rainforest and evergreen broadleaved mixed forest. The main species are *Arundinaria alpine*, *B. vulgaris* and *Oxytenanthera abyssinica*.

2.3.4 Kenya

Most of the bamboo resources in Kenya comprise one indigenous species, *Yushania alpina*, which was formerly known as *Arundinaria alpina*. This species, which is commonly known as “alpine bamboo”, occurs naturally on the main mountains and highland ranges of Kenya and eastern Africa. The species is estimated to cover between 145,000 - 150,000 ha, located mainly at altitudes ranging from 2400 m to about 3400 m above sea level (Kigomo N. 2007).

Most of the bamboo resources in Kenya are found within government forests and in trust-lands and farmlands, which were once within the Government forests but have since been degazetted.

Another small proportion is found domesticated by farmers with Bambusa vulgaris as the dominant species. The Kenya Forestry Research Institute (KeFRI) has introduced other bamboo species from Asian countries within forest areas and on farmlands on an experimental basis

KeFRI has carried out research on selection and growth of bamboo species in collaboration with Asian Research and Development Institutions since 1986. Through this research initiative, over twenty Asian bamboo species have been introduced into the country. Emergence of private farms in Kenya will increase the bamboo resources in Kenya, Kitil farm in Kitengela sells bamboo seed lings to farmers and promotes cultivation of bamboo for various uses like, food, craft work, charcoal and production of laminated beams.

2.4 Physical Properties of Bamboo

Knowledge on the physical properties of bamboo in strip forms (strip or strand) is pertinent since Glue Laminated bamboo beams contain bamboo in these forms. Studies done on the anatomy of bamboo internode cross-section have revealed that the strength properties of the bamboo strip increase from inner to outer layer of the culm (Wan Tarmeze et al 2005). Figure 2.2 shows the increase in concentration of the cellulose fibers from the inner layer to the outer layer.

According to Yu et al. (2008), the dimensional stability and properties of Moso bamboo is dependent on “layer,” referring to the radial location within the wall of the culm between the inner and outer radii. As is the case in many wood species, the test results by Yu et al (2008) on specific gravity based on ASTM D2395 gave values of between 0.553 and 1.006 (ASTM 2002) and tangential shrinkage tests from green to oven dried gave values of between 4.9 and 7.8% to be greater at the outer layers and increasing with longitudinal position of the stem or height. On the other hand, a decrease in longitudinal shrinkage was observed with values from 0.30 to 0.09% varying from inner to outer layers. As noted the effects that height and layer have on tangential shrinkage, longitudinal shrinkage, and specific gravity are statistically significant and independent of one another in a bamboo strip.

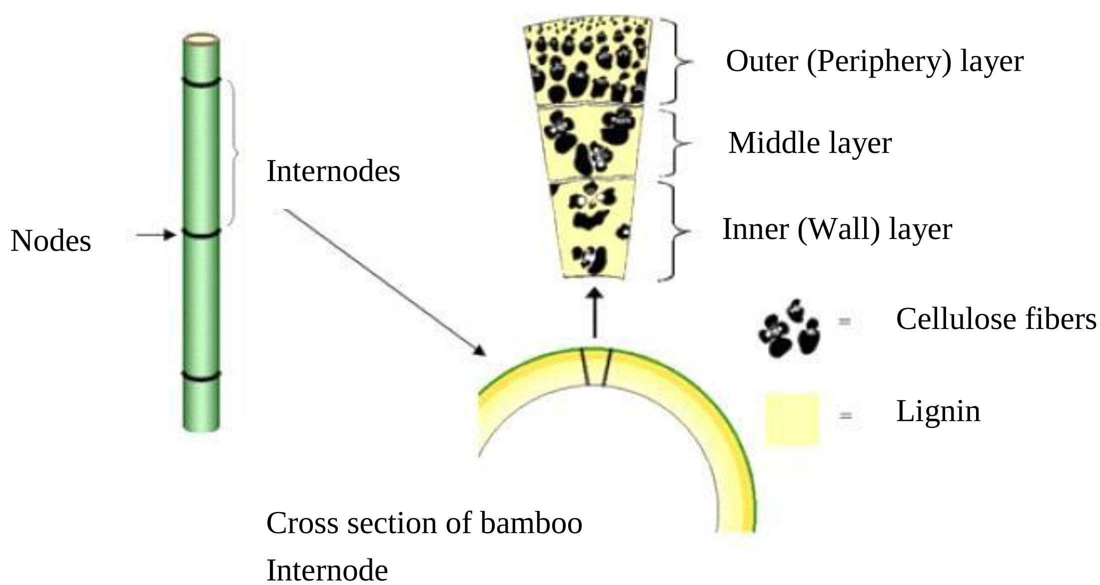
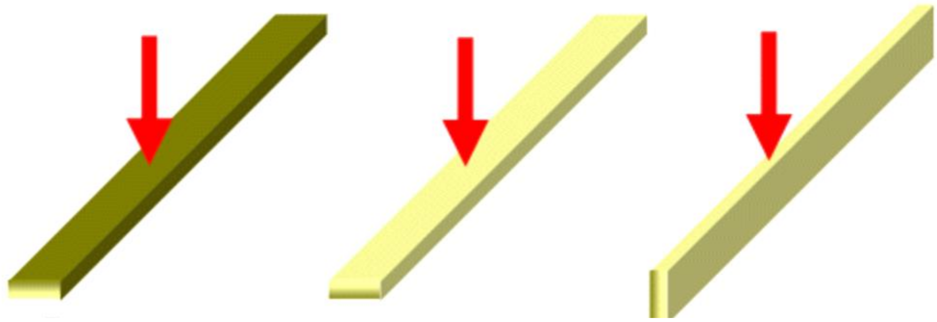


Figure 2.2 Anatomical features of Bamboo Internode

From the studies done, it is evident that the microstructure features of bamboo strip cause it to behave different under different bending modes depending on the direction of loading i.e. with load on top of outer layer (Figure 2.3 A), on top of inner layer (Figure 2.3 B) and when loading is on side (Figure 2.3 C).



Type A:
Outer Layer on top

Type B:
Inner Layer on top

Type C:
Vertical Bending

Figure 2.3 Different modes of loading a bamboo strip

2.5 Mechanical Properties

Yu et al. (2008) provided test results indicating that tensile strength and longitudinal elastic modulus of Moso bamboo are clearly dependent on radial position. It was found that tensile strength and elastic modulus at the outer layer averaged over height are 295.6 MPa and 26.9 GPa, respectively were almost triple those of the inner layer also averaged over height, of 113.4 MPa and 9.7 GPa respectively. As height increased from 1.3 to 4 m, tensile modulus of elasticity had a mean increase across all layers of 12.8% while same mean change for tensile strength was only 1.25%, showing that tensile strength is not dependent on height.

The study by Lee et al. (1994) was aimed to investigate the influences of height, moisture content and the presence of nodes on mean strength and stiffness properties on giant timber bamboo. Unlike Yu et al. (2008), it was found that strength properties of giant bamboo increased with height, the diversion is likely being a result of the use of different bamboo species. Consistent with structural wood species, however, strength was found to increase with decreasing moisture content.

The data by Lee et al. (1994) showed a consistent increase in compressive strength, tensile strength, elastic modulus, and modulus of rupture (MOR) by 37.6, 19.4, 48.2, and 47.7%, respectively; when comparison tests were carried out in air-dry conditions versus green conditions. For loblolly pine timber, the same properties increased with decreasing moisture content by 102.9, 75.3, 27.9, and 75.3%, respectively. This result shows that the effect of moisture content on the mechanical properties of giant timber bamboo is much less than the effects of moisture content on the mechanical properties of wood. It is therefore noted that, in the case of bamboo for structural applications, precautions must be taken into consideration for dimensional stability in wet service conditions as it is done in timber. The presence of nodes/rings on bamboo weakened the material and had the most significant influence on tensile strength, tensile strength decreased by 26.6% when nodes were present.

Table 2.1 compares giant timber bamboo and other bamboo species strength properties with those of common building materials. Giant timber bamboo is one of the weaker bamboo species listed but its strength properties are comparable to those of structural wood species like loblolly or pine Douglas-fir. From the data provided it is seen that bamboo is stronger in bending than timber, and its strength-to-weight ratio expressed as MOR/specific gravity is higher than that of all materials listed except carbon fiber. Bamboo is not only a fast-growing plant, but is also highly efficient as expressed by its strength-to-weight ratio in comparison to other raw structural materials.

Table 2.1 Comparison of Bending Properties of Bamboo to other Common Building Materials (Mahdavi et al. 2011)

	Specific gravity	**Modulus of elasticity (MOE) (GPa)**	**Modulus of Rupture (MOR) (MPa)**	**MOR to specific gravity ratio (MPa)**
Giant timber bamboo	0.52	10.7	102.7	197.5
Other bamboo	_	9.0 – 20.7	97.9 – 137.9	_
Loblolly pine	0.51	12.3	88	172.5
Douglas fir	0.45	13.6	88	195.6
Cast iron	6.97	190	200	28.7
Aluminum alloy	2.72	69	200	73.4
Structural steel	7.85	200	400	50.9
Carbon fiber	1.76	150.3	5,650	3,205.10

2.6 Glue Laminated Bamboo Beams

According to Wan Tarmeze et al. (2005), the parameters that affect the strength and stiffness of laminated bamboo or any other laminated product are:

1. Presence of voids
2. Glue imperfections
3. Orientation of bamboo material

Most of the research done on laminated bamboo beams has concentrated on improving compaction to reduce presence of voids and treatment of surfaces to enhance bonding of the glue though none has so far addressed the issue of orientation exhaustively.

2.6.1 Processing Techniques

2.6.2 Method 1

Nugroho and Ando (2001) investigated a technique to process Glue laminated bamboo beams by progressively crushing Moso bamboo culms to produce strips using roller press crushers and create zephyr strand mats. The mats were then hot-pressed between 150°C and 180°C in order to achieve dimensional stability of the strips and create a smoother surface reducing the irregularity and fewer voids, since spaces between strands are likely to weaken the material. Dipping specimens in boiling water for 1 min was found to aid in the flattening of fibers at lower press temperatures ranging between 100°C and 130°C but had less effectiveness at higher press temperatures ranging between 150°C and 180°C. After hot-pressing, the mats were then passed through a planer to remove their inner and outer layers that contains wax and silica known for weakening adhesive bonding. The mats were then coated with resorcinol-based adhesive and placed on top of each other. Inner surfaces of the strips were bonded to inner or outer surfaces. Three glue spreading rates were tested for optimal internal bond (IB) strength. Internal bond strength was optimal when using a glue spreading rate of approximately 300 g/m^2 and joining outer to inner surfaces of the mats. After applying the adhesive, the stacks of zephyr mats were cold pressed until the adhesive was fully bonded with the strips. The final product was then conditioned at 25°C and 65% relative humidity for a period of at least two weeks.

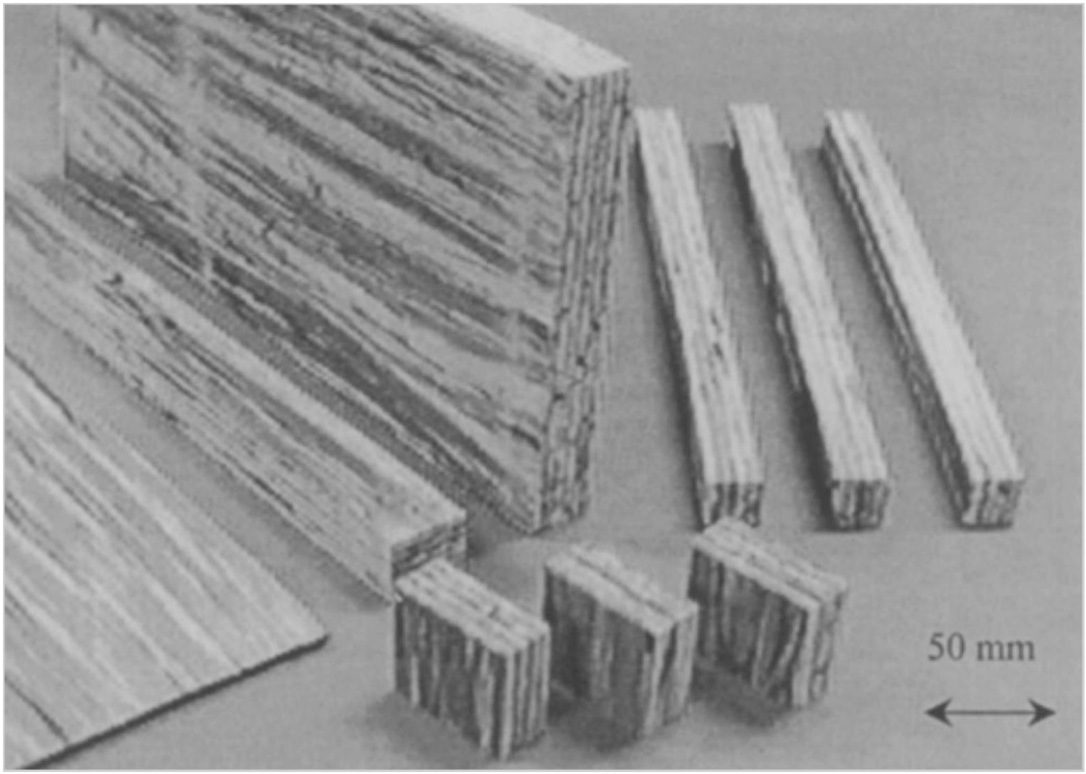


Figure 2.4 Samples of laminated bamboo lumber (LBL) (Nugroho and Ando 2001)

The effect of varying ply arrangement for Moso bamboo on strength properties was considered in this method, based on inner surface versus outer surface contact at interfaces where mats meet while joining in the presence of adhesive. Specimens made for testing were 4-ply, so, for each specimen, there were three interfaces to be glued, one at the center of the mats and two on either side of the center. Three variations were tested in this case:-

1. **Types I -** Inner surfaces of culm were glued to outer surfaces of the mats at all interfaces.
2. **Type II -** Outer surfaces of culm were glued together at the center interface of the mats, and at the outer interfaces inner surfaces were glued together.

3. **Type III** - Inner surfaces of culm were glued together at the center interface of the mats, and at the outer interfaces, inner surfaces were glued together.

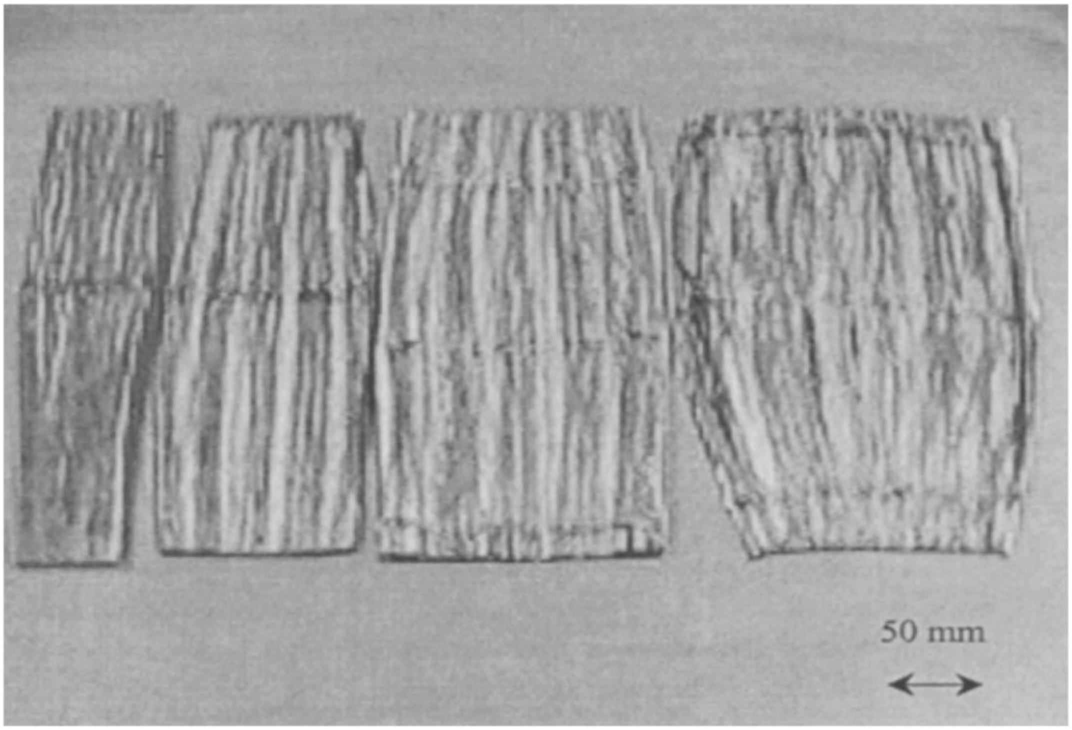


Figure 2.5 Bamboo zephyr strand mat made from Moso bamboo after a prehot-pressed treatment (Nugroho and Ando 2001).

2.6.3 Method 2

Another technique of processing glue laminated bamboo beams was investigated by Sulastiningsih and Nurwati (2009), Rittironk and Elnieiri (2007). In this case bamboo strips were produced by feeding bamboo culms through a splitter machine that cut the bamboo culm into slender strips. Both surfaces of the strips were scraped and planed to remove the wax and silica and create rectangular cross sections for ease of use. Adhesive was then applied to the strips that were then neatly arranged on top of one another to create the final product. Based on the approach by Sulastiningsih and Nurwati (2009), the strips were left to air-dry at room temperature for a period of one week after cutting them. The air dried strips were then immersed in a boron solution and left to dry in the sunlight to reduce their moisture content to 12%. By placing bamboo strips side-by-side and edge-gluing them using tannin resorcinol formaldehyde (TRF) extracted from black wattle, bamboo sheets were produced. The sheets were then stacked on top of one another, while keeping the grains parallel and using the same adhesive clamping them with no heat for 4 hours.

This method considered two different bamboo species namely:-

1. Bamboo tali [Gigantochloa apus (Schult. & Schult. f.) Kurz] and
2. Awi mayan (Gigantochloa robusta Kurz).

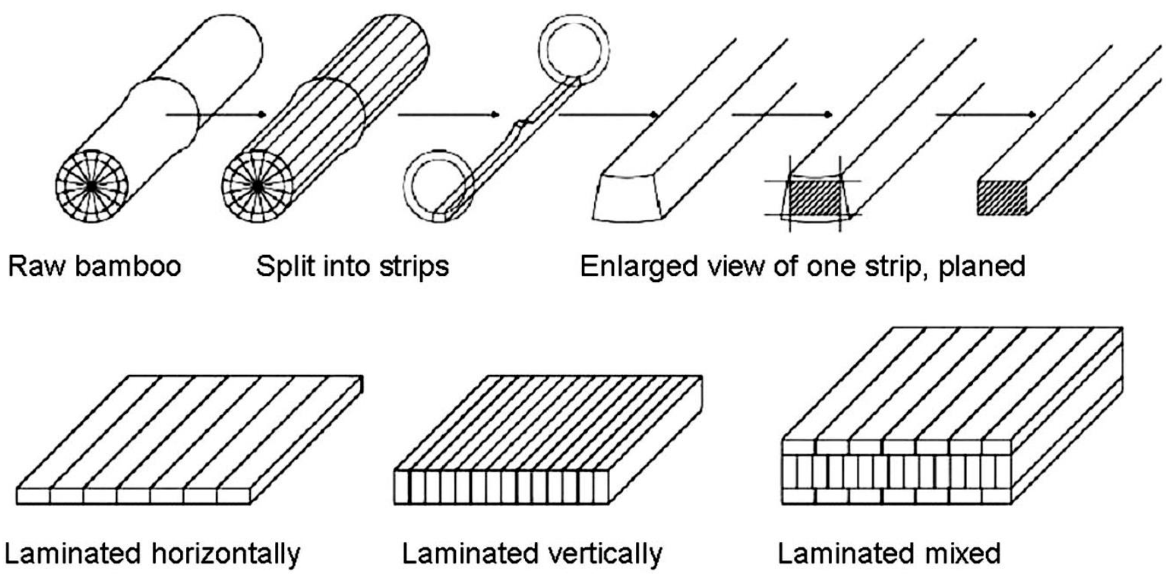


Figure 2. 6 The Manufacturing process of LBL using bamboo strips as done by Rittironk and Elnieiri 2007

2.6.4 Method 3

A third technique was investigated by Lee et al. (1998). First Moso bamboo culms were split in half longitudinally. The splits were then flattened at a pressure of 690 kPa for 1 to 4 minutes. The curvature and thickness of the bamboo splits achieved determined whether or not to increase or decrease the amount of time during pressure application. The inner and outer layers of the flattened bamboo were passed through a planer in order to remove the wax and silica usually contained in these layers. Resorcinol based adhesive was then applied to the flattened and planed surfaces of the bamboo splits. The splits were then carefully stacked on top of one another and the stack placed under a pressure of 1,380 kPa for 12 hours. The resulting product was then conditioned at 25°C and 65% relative humidity for a period of at least two weeks.

This method considered a 2 × 3 factorial design where two moisture contents and three glue-spread rates with Moso bamboo were varied.

2.6.5 Comparison of LBL Processing Methods

The specimens of final products of Method 1 (Nugroho and Ando 2001), Method 2 (Sulastiningsih and Nurwati 2009), and Method 3 (Lee et al.1998) were then tested in accordance with JIS Z-2113 (Japanese Industrial Standards 1997), ASTM D1037 (ASTM 1993), and ASTM D198 (ASTM 1994), respectively. Selected results of these tests are displayed in the Table 2.2 below for purposes of comparing the effectiveness of the three methods where the physical and mechanical properties are compared. .

Table 2.2 Physical and Mechanical Properties of Three Bamboo Processing Methods

LBL product			MC (%)	Specific gravity	Thickness Swell (%)	Linear Exp. (%)	MOE (Gpa)	MOR (MPa)
Method 1 4–ply LBL (2x2x32 cm^3)	Mat layup	Type I	-	0.9	12.1	0.5	11.9	83.5
		COV (%)	-	-	30.6	25	13.1	10.3
		Type II	-	0.9	12.4	0.5	12.1	86
		COV (%)	-	-	6.7	37.5	9.7	10.1
		Type III	-	0.9	11.9	0.5	10.9	74
		COV (%)	-	-	31.2	35.4	9	5.7
Method 2 3–ply LBL (7.6x1.5x41cm^3)	Species	G. *apus*	13.1	0.8	2.5	0.1	10	95.1
		COV (%)	8.9	1.3	11.7	9.1	8	9.7
		G. *robusta*	12.8	0.7	4.1	0.1	9.8	87.8
		COV (%)	12.3	2.8	16.9	14.3	5	13.8
Method 3 (2.5 x 2.5 x 40.6 cm^3)	Glue-spread rate (g/m^2 for a single glue line)	220	10	0.6	4.4	0.3	8	86.3
		COV (%)		-	18.9	26.7	9.5	11.9
			15	0.6	5.2	0.4	8.1	85.2
		COV (%)		-	20.1	30.3	14	21
		320	10	0.6	3.3	0.2	8.4	97.7
		COV (%)		-	13.4	22.5	10.2	7.5
			15	0.6	4.2	0.5	8.3	91.9
		COV (%)		-	15.3	31.5	13.6	13.5
		420	10	0.6	2.2	0.1	9.1	107.2
		COV (%)		-	14	30.3	11.7	10.1
			15	0.6	2.5	0.1	8.7	104.8
		COV (%)		-	15.4	41.6	8.5	6.4

2.6.6 Literature Review Summary

As analyzed from the data, method 3 was found to be the most effective comparing the process involved and strength parameters achieved. The various treatments applied in method 1 and 2 do not seem to have any significant effect on the strength achieved.

Although not very well elaborated, orientation of the bamboo strips shows some variation in strength achieved.

2.6.7 Conclusion

From the results, it is evident that the strength and stiffness of bamboo are comparable to those of timber; it is therefore capable of replacing timber in construction from load bearing point of view. Also it was noted that the strength to weight ratio of bamboo is far much better than that of structural steel, concrete, timber and cast iron showing that it has a very efficient load bearing capacity.

However, from the research done by others as reviewed, there is still research gaps be covered to enhance usage of bamboo in construction as summarized below:-

2.6.8 Research Gaps

- Even though Nugroho and Ando (2001) attempted to establish the effect of orientation of bamboo strips on strength, the aspect is not conclusively covered and only 3 configurations are covered in their scope, the other configurations ought to be investigated to identify the optimum performance of glue laminated bamboo beams.

- In the three configurations evaluated, the researcher does not specify the direction of loading; it is hence not clear on which side the specimen was loaded and the data that would have been obtained if other sides were loaded as well.

- Theoretical literature identifies that strength properties of bamboo vary lengthwise from the base to the top, this aspect and the possible effect on the strength of glue laminated bamboo beams has not yet been investigated through testing.

- To be able to utilize glue laminated bamboo beams, typical connections ought to be investigated and recommended, unlike timer bamboo tends to spilt along the grains when nailed and this poses challenges on its usage.

- So far only specimens have been tested, it is therefore necessary to manufacture typical structural systems of glue laminated bamboo beams and establish their performance as a system, example of a truss and an I-beam.

- It is important to appraise the economic viability by analyzing the cost involved in the manufacture of glue laminated bamboo beams vis a vis the strength achieved.

- We don’t have a formal design code for glue laminated bamboo beams, to be able to market its use it will be important to start developing one which requires detailed research on the topic.

This research therefore has targeted to investigate on the various parameters as analyzed above that have not yet been dealt with in the earlier research and as well try to employ glue laminated bamboo beams to practical use by testing trusses and beams made from glue laminated bamboo beams.

CHAPTER 3

3.0 MATERIALS AND METHODS

3.1 Introduction

The research project was conducted at Kenya Forestry Research Institute (KeFRI) using advanced machinery installed in the year 2012 as part of Bamboo craft (Bamcraft) project at KeFRI Industrial Bamboo Processing & Training Centre at Karura, the latest state-of –art training center of bamboo applications in Eastern Africa.

Kenya has vast bamboo reserves and the potential of developing plantations using indigenous and exotic species has been demonstrated by KeFRI (Kigomo N 2007). The development of bamboo industries has to be sustained through expansion and management of bamboo plantations and forests. Already private farms has picked up the idea of investment in bamboo plantations as seen in Kitil farm located in Kitengela that is not only growing bamboo commercially but also supplying seedlings to other farmers.

In this study, laminated bamboo beams were subjected to testing similar to timber. Tests carried include; - Tensile test, bending test, Compression test and Shear test on small clear specimens in accordance to BS 373:1957 Methods of Testing small clear specimens of timber. Other Tests done were bending test of large scale beams and testing lattice truss girder models.

3.2 Materials

3.2.1 Bamboo

Bamboo was the main raw material used in this research; *Yushania alpina* species was used where age and size were the most important factors considered when selecting the materials for research. The bamboo harvested from Kamae, Kenya was three and half years old and the culms were selected from diameter greater than 80mm and wall thickness greater than or equal to 10mm in the lower section of the culm. Erect and straight culms were selected while withered, deformed or mildewed culms were rejected for better quality of laminated beams.

3.2.2 Adhesive

Polyvinyl Acetate Adhesives were used in this research; two types of adhesives most common ones in Kenyan market were used

a) Type I - High Strength Polyvinyl Acetate Glue – the most superior glue in the market used in furniture and structural works. Trade Mark name is *Ponal Professional White Wood Glue*.

b) Type II – Normal strength Polyvinyl Acetate Glue – the most common glue in the Kenyan market and used widely in furniture and light works. Trade Mark Name is *Ponal Mitiplast White Wood Glue*.

3.3 Materials Preparation

3.3.1 Cross Cutting

To obtain shorter and workable pieces, the culms were cut using the cross cutting machine to lengths of 2m to suite the dimensional requirements of the pressing machine that takes a minimum length of board of 1m and a maximum of 2m. Plate 3.1 shows some of the Bamboo material after cross cutting.

Plate 3.1 Bamboo Material after cross Cutting

3.3.2 Splitting

Splitting was the first stage in the process of converting round bamboo poles into flat strips, the splitting machine with parallel rotary blades was used for this purpose. The hollow poles were longitudinally split into segments of 22mm. Splitting of the cylindrical bamboo stems produced slightly curved strips.

Plate 3.2 Splitting of Bamboo in progress

3.3.3 Bamboo Strip 2 sides removal

The Bamboo strips were flattened and pre-shaped before being boiled and dried; shaping was done using the 2-side removal machine. Shaping involved removal of the shiny and silky outer skin and the inner knot of the strips, care was taken in removing the outer side of the strips (i.e. the culm epidermis) since it is the strongest part of the bamboo culm and hence only shaping and removal of the silky layer was done. In this stage the minimal curvature on slips is reduce to obtain a square cross section.

Plate 3.3 Bamboo after splitting

3.3.4 Preservation

The formed strips were disinfected and bleached, this was important for protecting bamboo materials and ensuring the quality of products. The strips were boiled in a tank for 3 hours to bleach them and protect them against pests in a single process using the chemicals in Table 3.1.

Bleaching was achieved by boiling the strips for three hours a solution containing hydrogen peroxide. Hydrogen peroxide is a strong oxidizer in both acid and alkaline media, and also functions as a reducing agent that extracts starch, protein and other nutrients thereby bleaching the surface of bamboo material.

Table 3.1 Preservation and Treatment Chemicals

Chemical Composition for preservation and Bleaching of Bamboo Strips		
Chemical Agent	**% in Solution**	**Quantity per 1000 L of Water**
Hydrogen peroxide (80%)	0.5	5 L
Borax oxide	0.8	8 Kg
Boric acid	0.2	2 Kg

The preservation agent was in the mixture of boric acid and borax oxide which resulted in the formation of disodium octaborate. Boron salts are dissolved in water and are effective against borers, termites and fungi. After treatment, the water evaporates during leaving the salts inside the bamboo.

Plate 3.4 Boiling of Bamboo

3.3.5 Drying

The bleached and treated bamboo strips were dried in air for 3 months while monitoring the moisture content until moisture content of below 12% was achieved. Moisture content of the strips was checked weekly to monitor and achieve the required moisture content of below 12%.

3.3.6 4 Side Planning

Size of the strips and moisture content were most important in this stage to achieve stable laminated beams, the moisture content of the bamboo strips was rechecked to confirm it was below 12%. In order to achieve a stable laminated beam the strips had to be rectangular and flat on each side and hence ensure proper bonding of the strips on all the four sides.

A 4 side Moulding Machine was used to shape the strips into fixed width and thickness to ensure that they bonded into a solid beam after laminating; strips of half widths were also prepared for staggering the straight joints during lamination.

The Strips were marked on the outer side with red ink immediately after planning to ensure identification of inner and outer faces of the strips for the purpose of varying orientation during lamination.

3.3.7 Assembling and Pressing

After four sides planning, the bamboo strips were sorted in kept in order of the markings showing inner face/outer face, the bamboo strips were laminated horizontally while varying their orientation, a half width strip was introduced in each layer on alternating sides to break vertical straight joints on adjacent layers.

a) The first layer of bamboo strips was laid on a flat table and glue applied on one face and one edge while joining the edges.

b) The second layer of bamboo strips was glued on the edges and placed on the 1st layer.

c) The two layers were tied with a manila string to maintain the arrangement prior to placing of other layers.

d) Glue was applied on the surface of the second layer and the third layer place after gluing on the edges.

e) The three layers were again joined with a manila string and the first manila string joining layer 1 and layer 2 removed.

f) The process was repeated until the desired thickness was achieved while ensuring proper application of glue on the surfaces and placement of a half width strip on alternating sides of each layer to break the straight joint.

g) The laminated bamboo panels were then cold pressed at 0.5 N/mm^2 top pressures and 9.81 N/mm^2 side pressure. The panels were left in the pressing machine overnight to bond at a room temperature of 22°C.

Plate 3.5 Gluing of Bamboo Strips

Plate 3.6 Cold Pressing Laminated Panel

3.4 Test Specimens

3.4.1 Tensile Test Specimens

To determine the tensile strength of the bamboo material, it was necessary to prepare tensile test specimens from bamboo strips. For Tensile test the specimens were prepared in accordance to BS 373:1957 as shown in Figure 3.1. Samples were prepared in three categories:-

i. Samples with node at the center.
ii. Samples with no nodes but with outer layer removed.
iii. Samples with no nodes and with outer layer.

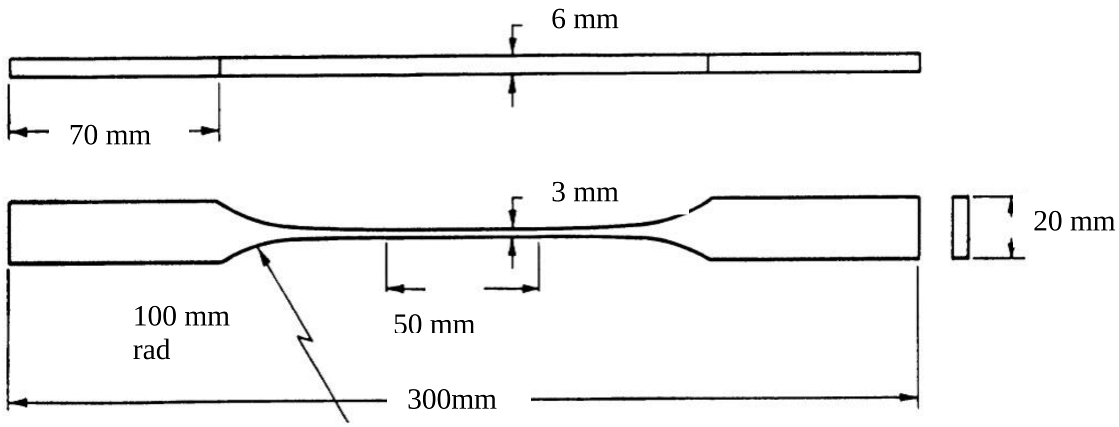


Figure 3.1 Tensile Test Specimen

3.4.2 Test Specimens for Different orientations

Various test specimens were laminated by orienting the strips in a predetermined pattern with respect to the outer and inner side of the culm. In order to establish if the orientation of bamboo strips has significant effect on the structural performance of laminated bamboo beams, bamboo panels were laminated in various orientations as outlined below:-

3.4.2.1 Orientation one

For orientation 1 the strips were laminated the with the inner surface of the bamboo culm facing each other for every pair of strips, the outer surface of each pair of strips was then laminated with outer surface of another pair to build up the required thickness.

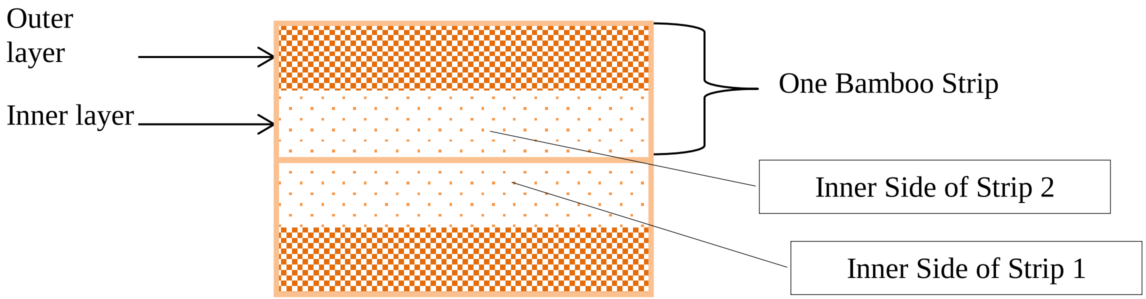


Figure 3.2 Orientation 1 – Bamboo Strips inner face glued together

3.4.2.2 Orientation two

For Orientation 2 the strips were laminated facing the same side, the inner surface of the bamboo culm for one layer was glued to outer face of the adjacent layer. Figure 3.3 illustrates the arrangement of strips in this orientation; every glue line interface had an outer layer glued to an inner layer of the adjacent strip.

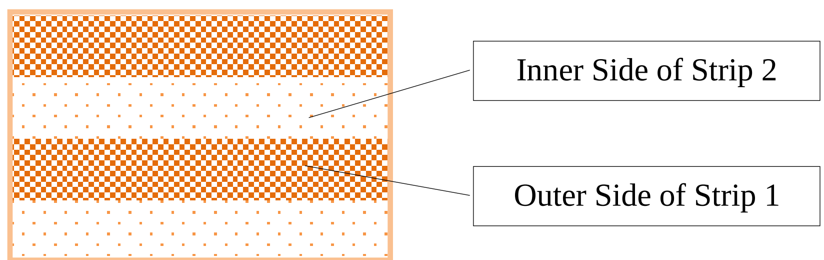


Figure 3.3 Orientation 2 – Bamboo Strips facing the same side

3.4.2.3 Coinciding Nodes at beam Mid-point

To establish the effect of coinciding nodes in laminated bamboo beams, specimens were made with coinciding nodes at the mid-point of the beams. This was achieved by selecting strips and placing them with the nodes falling on the same line as shown in Plate 3.7. The strips were then cut to uniform length while ensuring the nodes were in the same line and hence coinciding nodes at the center were achieved after lamination. Specimens for testing were extracted while ensuring the nodes formed the center part of the beams, this would give an indication of the effect of nodes on bending strength since the center part of a beam is the most critical part in bending.

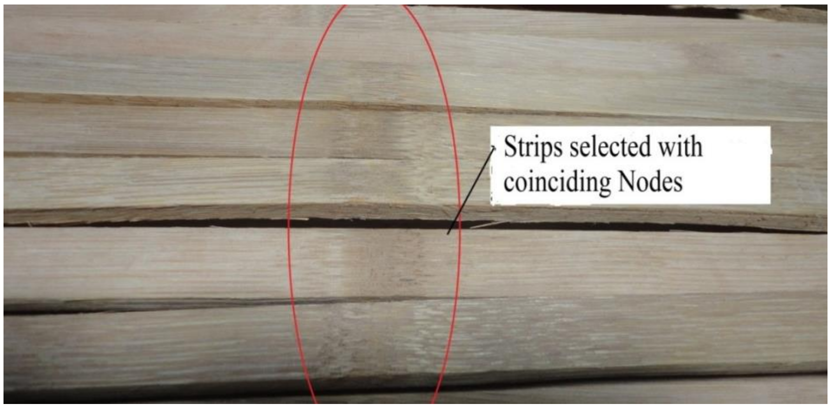


Plate 3.7 Bamboo Strips arranged with the nodes at the mid-point

3.4.2.4 Specimens with outer layer and inner layers of the bamboo culm separated

Splitting machine was used to split bamboo strips into two halves to separate the inner and the outer layer. The outer layer was assumed to have uniform properties of high concentration of cellulose fibers and the inner layer assumed to have uniform properties of less concentration of cellulose fibers and more lignin. To evaluate the effect of removing the inner layer of the bamboo culm on the performance of bamboo beams, the split bamboo strips were used to laminate panels as follows:-

3.4.2.4.1 Outer Layers Only

The outer half of the bamboo strips obtained by splitting a bamboo culm at the center were used to laminate bamboo beams, Figure 3.4 illustrates lamination of beams using the outer layers with higher concentration of cellulose fibers. The strips used in lamination were half size in thickness as compared to full size strips, and therefore in an equivalent cross section of a beam had double the number of strips and double glue line interfaces.

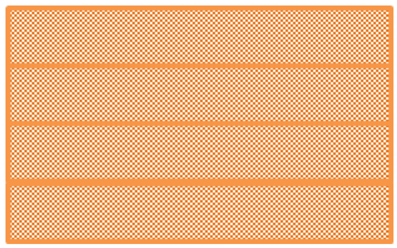


Figure 3.4 Lamination with Outer layers only

3.4.2.4.2 Inner Layers only

The inner half of the bamboo strips obtained by splitting a bamboo culm at the center were used to laminate bamboo beams, Figure 3.5 illustrates lamination of beams using the inner layers with lower concentration of cellulose fibres and higher concentration of lignin as compared to outer half strips. The strips used in lamination were half size in thickness as compared to full size strips, and therefore in an equivalent cross section of a beam had double the number of strips and glue line joints.

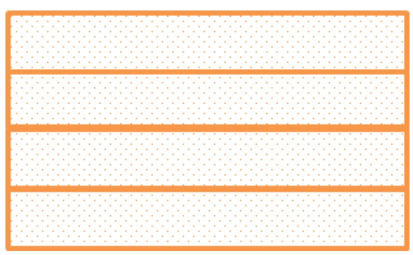


Figure 3.5 Lamination with Inner layers only

3.4.2.4.3 Outer Layers on extreme edges and Inner layers at the center

A beam experiences stress on the extreme fibers at the bottom and the top. The Bottom zone experiences tension and the top zone experience compression when bending. Outer layers were placed on the extreme edges to determine if rearranging of an equivalent volume of bamboo strips, to have the stronger outer layers on the extreme edges of the beam and the inner layers at the center would increase the strength. Figure 3.6 illustrates the arrangement of outer layers on extreme edges and inner layers at the center.

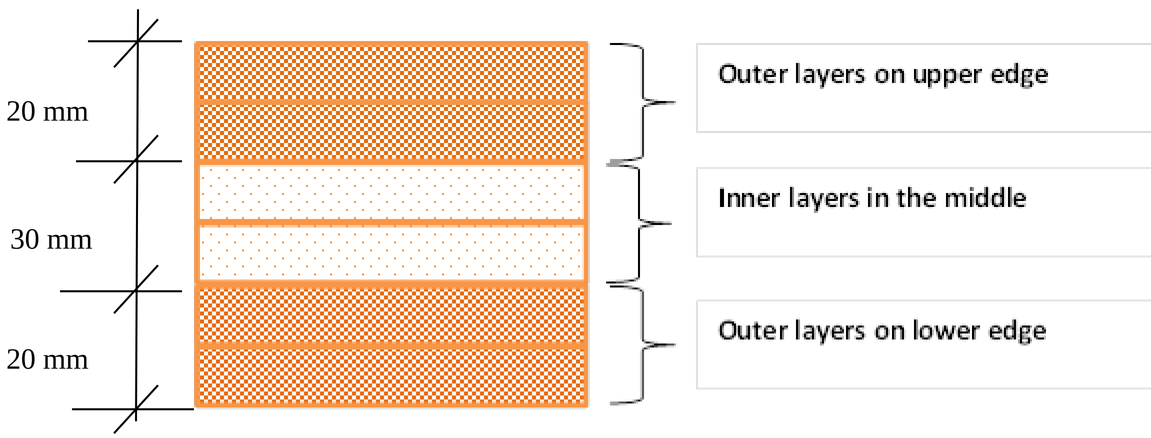


Figure 3.6 Lamination with Outer layers on extreme edges and Inner layers at the Centre

To investigate the performance of jointed beams in cases of laminating longer beams than the available material length, specimens were made from strips pieces with staggered joints. Plate 3.8 shows the process of introducing staggered joints in the bamboo strips and the laminated bamboo panel with the joints. Test specimens with jointed strips were obtained from the laminated panel.

Plate 3. 8 Bamboo Panel Laminated with alternate joints

3.4.2.6 Laminated Bamboo Beams with different Glue Types

To assess the performance of laminated bamboo beams in different types of glues, outer layers of the bamboo culm were used to laminate panels using the two types of glues. Glue Type I and Glue Type II were used in lamination, all other factors like type and size of bamboo strips, pressing force, time of application of the pressing force, rate of glue application and size of the laminated panels were kept constant with the Type of Glue being the only variable.

3.4.2.7 Glue Laminated bamboo Lattice Girder specimens

To evaluate the structural performance of glue laminated bamboo lattice girder a half scale lattice girders trusses were made from laminated bamboo beams and bolted joints with steel plates adopted. Plate 3.9 shows an assembled truss model, 25mm x 25mm laminated bamboo sections were used as truss members. 3mm thick steel plates and 6mm diameter high tensile strength black bolts were used for the connections.

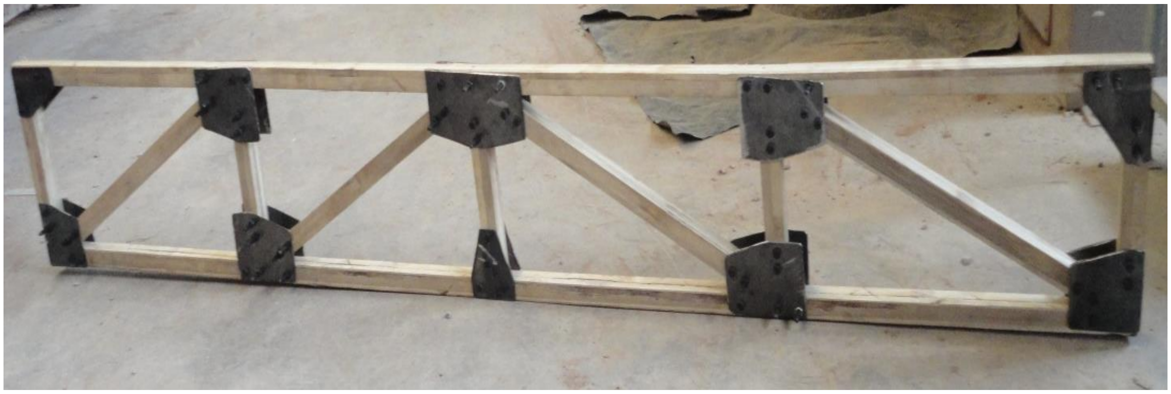


Plate 3.9 Glue Laminated Bamboo Beams Lattice Girder Truss Model

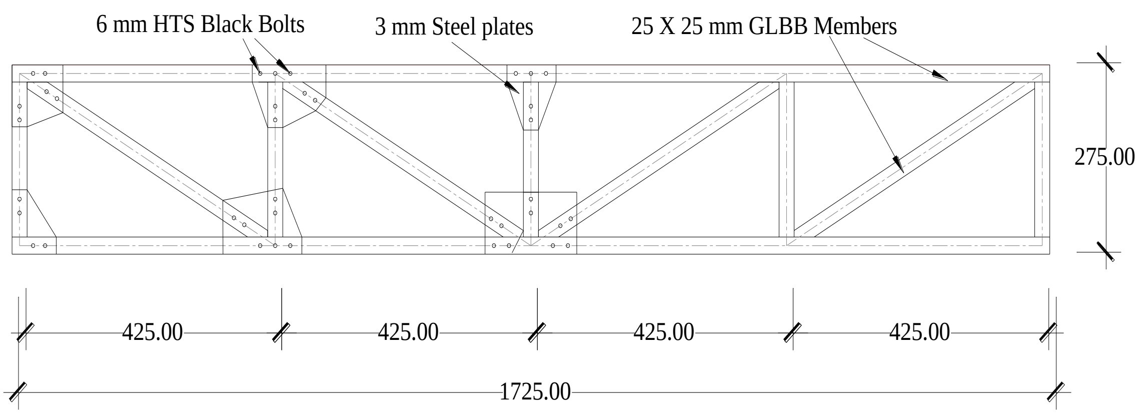


Figure 3.7 Glue Laminated Bamboo Beam lattice Truss Model Details

3.5 Test Setup

3.5.1 Tensile Test

Tensile Test was done in accordance to BS 373:1957 using the Universal Testing Machine by applying the load parallel to the grain on the specimens prepared as per Figure 3.1 at a constant speed of 0.05in/min. The Specimens were gripped on the wider edges as shown in Figure 3.11. Load was applied gradually until failure and the maximum load recorded.

Plate 3.10 Tensile Test Set up

3.5.2 Static Bending Test

Static bending test for small clear specimens was carried out in accordance to BS 373:1957 using the central loading method. The Standard specimens of 2cm by 2cm by 30cm extracted from laminated panels were placed on the universal testing machine with the distance between the points of support being 28cm; a dial gauge was fixed to measure deflection at mid length and loading was done at a constant speed of 0.26 in/min.

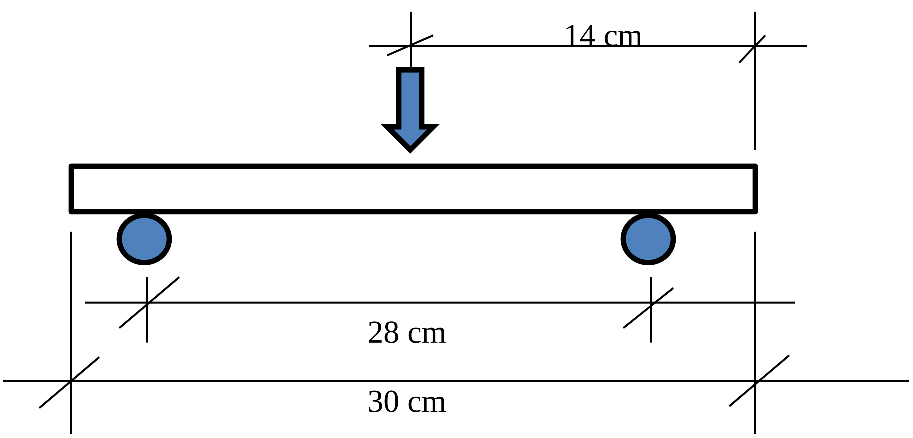


Figure 3.8 Static Bending Test Setup Dimensions

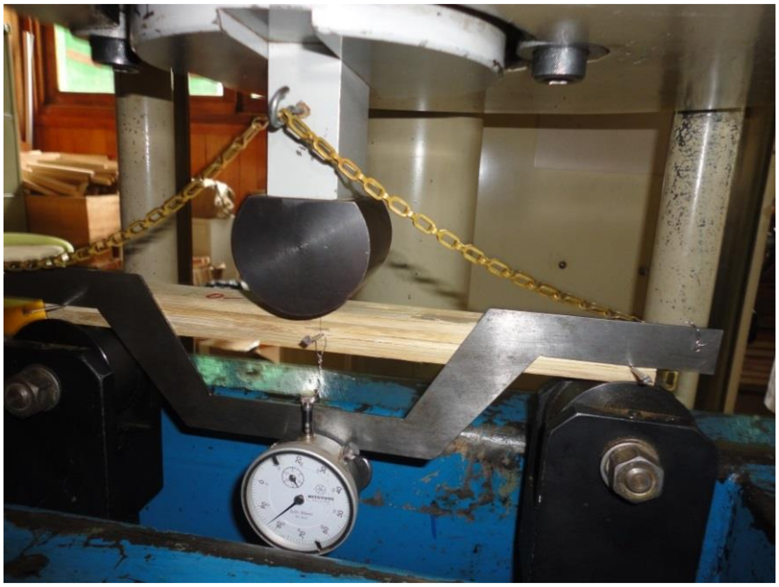


Plate 3.11 Static Bending Setup, Dial Gauge measures deflection

Loading was done in two ways, loading on the face and loading on the edges for all symmetrical specimens as illustrated in Figure 3.9. Loading for Orientation 2 specimens was done in three ways; - loading on the upper face with the outer layer, loading on the lower face with the inner layer and loading on the edge as illustrated in Figure 3.10.

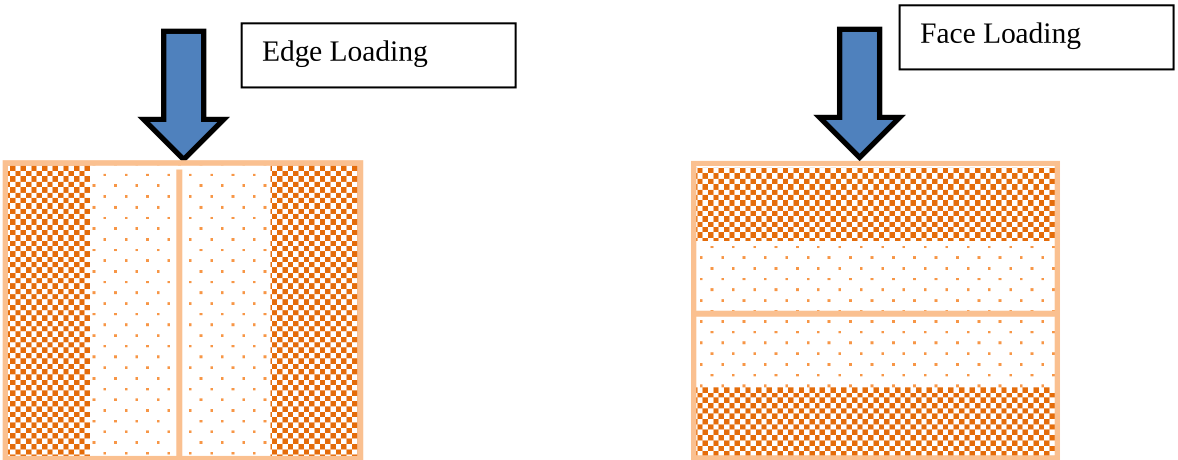


Figure 3. 9 Direction of Loading for orientation 1

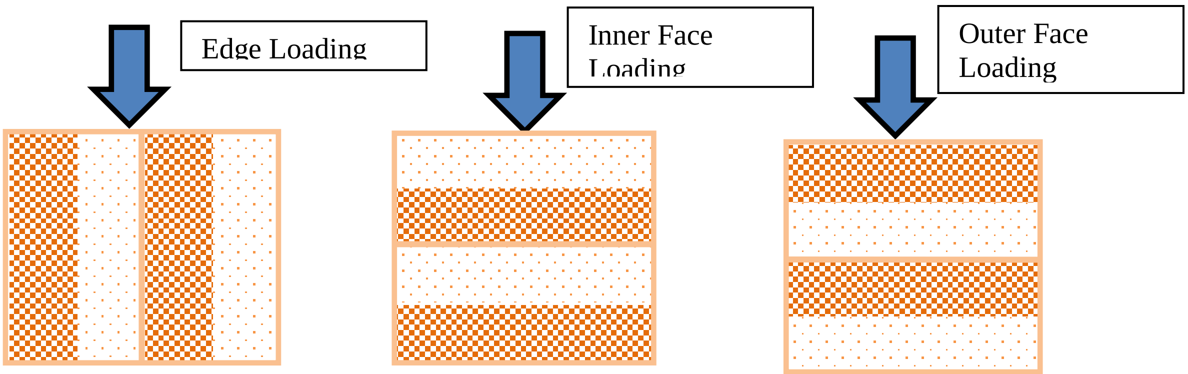


Figure 3.10 Direction of Loading for orientation 2

3.5.3 Compression Parallel to grain

Compression parallel to grain was carried out in accordance to BS 373:1957 on the Standard specimens of 2cm by 2cm by 6cm. Loading was done at constant speed of 0.025 in/min until failure and the maximum load recorded. The specimen was placed in the jig and the set up positioned in the universal testing machine as shown in Plate 3.12.

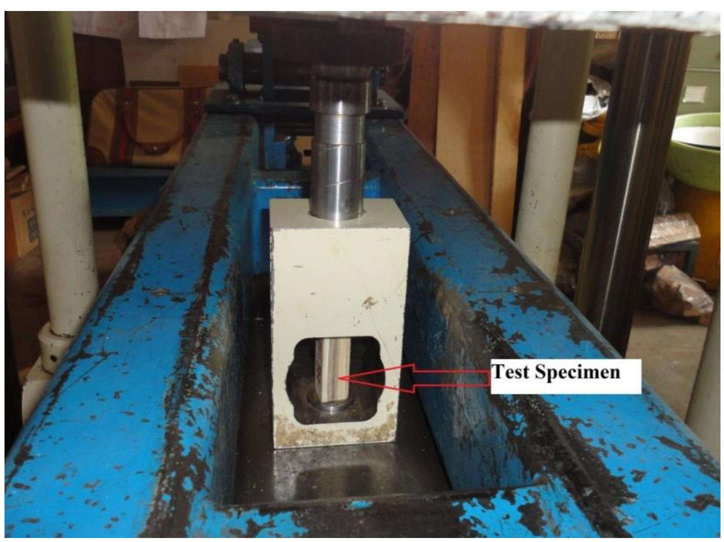


Plate 3.12 Compression Parallel to grain test Setup

3.5.4 Shear Parallel to grain

Samples for Shear Parallel to grain test were prepared in accordance to BS 373:1957; standard specimens of dimensions 2cm by 2cm by 2cm were extracted from the laminated panels.

The test was done in accordance to BS 373:1957 on 2cm cube specimens parallel and perpendicular to the strips while applying the load at a constant rate of 0.025in/min until failure and the maximum load recorded.

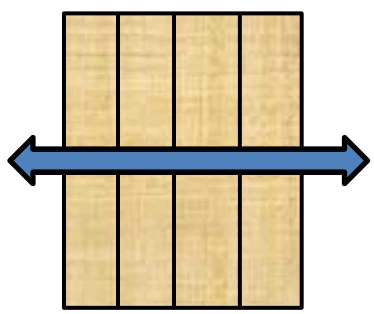


Figure 3. 11 Shear test perpendicular to strips

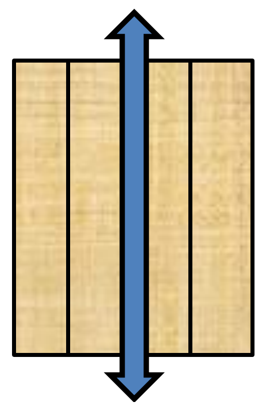


Figure 3.12 Shear Test Parallel to strips

3.5.5 Bending - Four Point Loading Method

Bending test for full scale beams was carried out in accordance to EN 408:2003 on specimens of 1200mm length as illustrated in Figure 3.13. The beams were gradually loaded with two point’s loads at a rate of 0.1 Mpa/Sec until failure while recording the deflection at the center and the corresponding load.

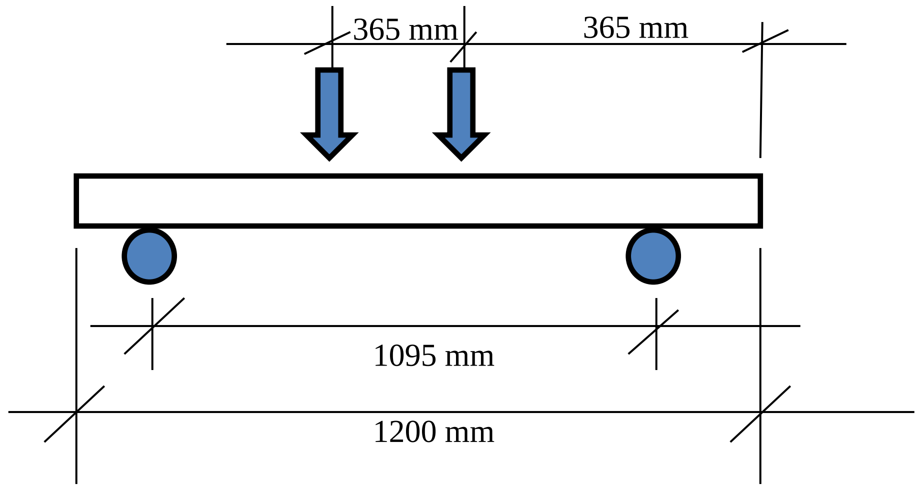


Figure 3.13 Four Point loading for 1200mm Beams

Bending test for full scale beams to determine strains on extreme bottom fibers and compare behavior of laminated bamboo beams with cypress beams was carried out on 600mm length beams, the beams were loaded with two point loads at a rate of 0.1 Mpa/Sec until failure as illustrated in the set up below Figure 3.14. Load was applied gradually until failure while recording deflection, strain at the bottom center and the corresponding load using the data logger.

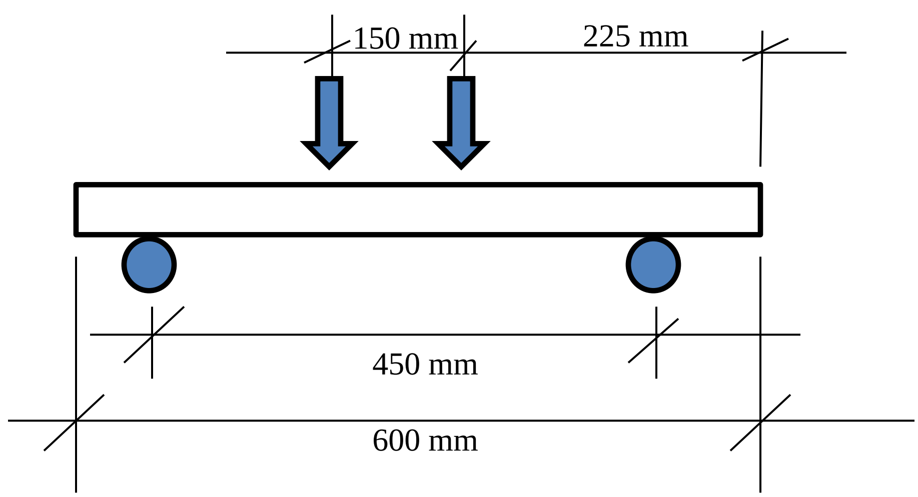


Figure 3.14 Four Point Loading Method- Setup for 600mm length Beams

3.5.6 Truss Model Test Set Up

Truss models were set up for loading as shown in Figure 3.15 and Plate 3.13. A single point load from the loading jack was distributed into 3 point loads on the truss joints; this was done by using a stiff square hollow section to distribute the load via raised timber sections at the joints. The truss model were simply supported by placing rollers on the two supports, a loading from the jack was transferred to the square hollow section through a load cell connected to a data logger for recording the loading at intervals. The load was then distributed from the square hollow section to the truss in 3 point loads. A deflection meter was placed at the bottom center of the truss to measure deflection. The load cell, deflection meter and strain gauges connected in the members were all connected in a data logger. Loading was done gradually until failure while recording the load, deflection and strains at intervals.

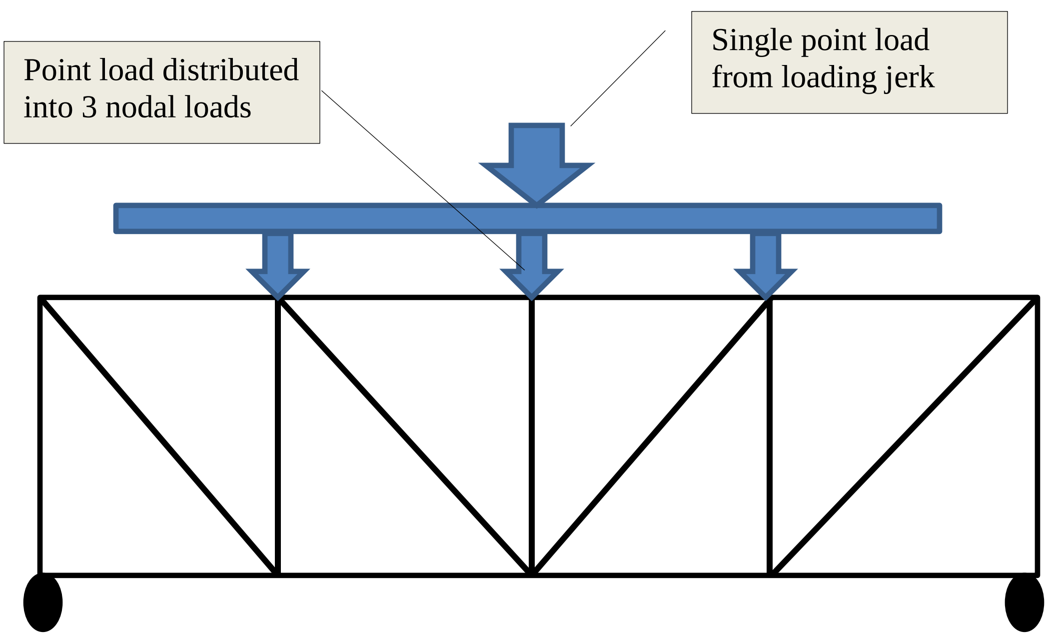


Figure 3.15 Truss Model Setup

Plate 3.13 Truss Model Loading Setup

CHAPTER 4

4.0RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the analysis and detailed discussion of the experimental results. Results obtained from the various test carried out were presented and discussed in detail. Tensile strength for the bamboo material was discussed in three cases, with node, without a node but with outer skin removed and without a node but with the outer skin intact. Bending, Compression and shear tests results were discussed for specimens tested to achieve the objectives; the variables in the study included orientations of bamboo strips, presence of nodes, type of glue used and presence of voids in laminates and presence of joints in laminates. In addition the results of lattice truss models loaded with 3 three point loads at the joints were discussed.

4.2 Tensile Test

To determine the tensile strength of the bamboo material, Tensile Test was carried out on random samples of the bamboo material. Samples were prepared in three categories;- Bamboo strips with node at the center, bamboo strips with outer surface removed but without a node and bamboo strips with outer surface intact and without a node. Total no of 10 specimens for each category were tested and the tensile stress at maximum load was calculated in accordance to BS 373:1957, the mean tensile stress was tabulated in Table 4.1.

Table 4.1 Tensile Stress Results

Part of Bamboo Strip	Tension Parallel to Grain (N/mm^2)
Bamboo Strips With Node at Centre	151.67 ± 0.71
Bamboo Strips with outer surface removed	253.06 ± 0.87
Bamboo Strips with outer surface	363.89 ± 0.52

Bamboo Strips with nodes at the center had the least tensile stress of 151.67 N/mm^2 compared to the others. Plate 4.1 shows the mode of failure was by separation of fibers, showing that the node is a point of fiber discontinuity, the fibers contribute to the high tensile strength of bamboo and hence the nodes forms a point of weakness in tension. Results of a study done by Shao et al (2010) also found out that presence of nodes reduces the tensile strength of bamboo culm.

Plate 4. 1 Tensile failure of a bamboo strip with node at the center

Strips with the outer surface removed failed by splitting and shearing diagonally as seen in Plate 4.2, the strips were much stronger than the strips with node at the center achieving a mean tensile stress of 253.06 N/mm^2. Comparing to the strips with the outer surface intact, removing the outer skin of the bamboo culm reduced the tensile strength by about 30%.

Plate 4.2 Tensile failure of a bamboo strip with outer skin removed

Bamboo strips with the outer skin intact and without nodes had the highest tensile stress of 363.89 N/mm^2 and failed by shearing parallel to the grains as seen in Plate 4.3. This confirmed that the outer skin of bamboo culm is the strongest in tension (Shao et al 2010). Concentration of cellulose fibers is highest on the outer layer of the bamboo culm (Wan Tarmeze et al 2005), this contributed to the high tensile strength on the outer layer strips without nodes and hence continuous fibers throughout the specimens. The mode of failure shows that the bamboo fibers did not break but rather separated from the lignin matrix.

Plate 4.3 Tensile failure of a bamboo strip with outer skin intact and no node

4.3 Test Results for Different Orientations

4.3.1 Static Bending Test Results

To determine the effect of orientation of bamboo strips on the structural performance of laminated bamboo beams, static bending test using the central loading method was carried out on the standard test specimens of 20mm x 20mm x 300mm.Loading was done gradually at a constant speed of 0.26 in/min until failure while recording the load, deflection. Direction of loading was also varied.

4.3.2 Bending for orientation 1 and 2

Three (3) Point flexural test on small clear specimens was carried out and average of at least three specimens on each case reported, results for load and deflection on bending test for the various orientations and loading directions were plotted in Figure 4.1. A summary of loading surface, mid span deflection at maximum load, Modulus of Elasticity and Modulus of Rupture are given in Table 4.2.

From the results, the maximum flexural strength was obtained for orientation 1 with a Modulus of Rupture of 103.5 N/mm^2 loaded on the edge, Orientation 1 also had the highest flexural strength while loaded on the face compared to orientation 2 by 2.5%, in this orientation the bamboo strips are arranged facing each other and therefore each pair of strips forms a beam with the strong outer layers on the extreme fibers which experience tension on the lower side and compression on the upper side while bending. Also when loaded on the edge, orientation 1 is more stable and achieves a little more strength than orientation 2.

While loaded on the face, orientation 2 had a major difference on flexural strength depending on the face loaded; loading on the inner face gave an increase in strength by 11% and a higher mid span deflection at maximum load as compared to loading on the outer face. When the beam in orientation 2 is loaded on the inner face, all the outer face of the strips are much closer to bottom axis of the beam and also the extreme fiber on the bottom is the outer face of the bamboo strip which is stronger in tension, in this case the beams had 11% increase in strength as compared to loading on the outer face which exposes the weaker inner face to tension on the bottom of the beam and also the arrangement places the outer stronger face of other strips further away from the bottom tension zone of the beams while bending.

In both orientations, it was noted that loading the beams on the edge gave higher values of Modulus of Rupture and Modulus of Elasticity by about 22%, the beams are much stiffer while loaded on the edge and hence the increased load carrying capacity. However the balanced arrangement of orientation 1 gives it an advantage of less mid span deflection at the maximum load and slightly higher flexural strength as compared to orientation 2. Correal et al (2014) carried out a study on Guadua bamboo laminated beams loaded on the edge and on the face, results indicated that loading on the edge presented 12% higher values of modulus of rupture (MOR), and 9% higher values of modulus of elasticity (MOE) compared to equivalent results for loading on the face. The increase in bending strength when loading on the edge of the bamboo strips id therefore consistent.

Even though orientation 1 has higher strength (2.5%) while loaded on the face as compared to orientation 2, orientation 2 has a higher modulus of elasticity (7.1%) when loaded on the inner face than orientation 1. The strengths when the beams were loaded on the face compared well with the results of Nugroho and Ando (2001), who used Moso bamboo, however Nugroho and Ando (2001) did not specify the direction of loading.

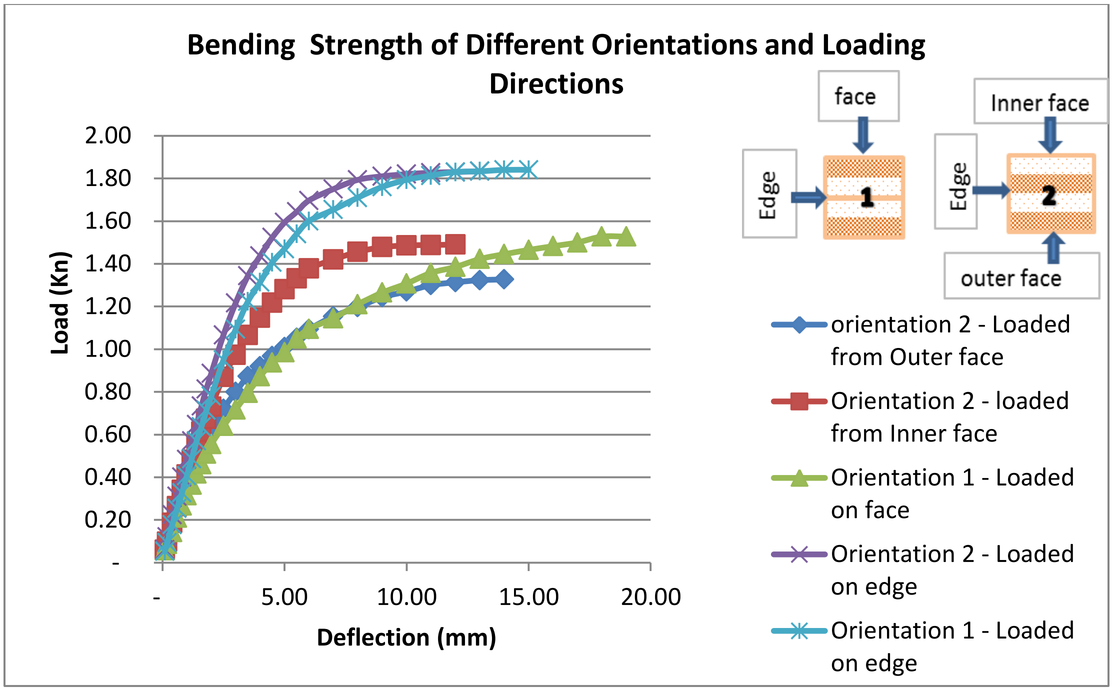


Figure 4.1 Bending Strength of different Orientations and Loading Directions

Table 4.2 Summary of Bending Test Result for Orientation 1 and 2 beams

Beam	Loading Surface	Mid Span Deflection at Maximum Load (mm)	Modulus of Elasticity (N/mm^2)	Modulus of Rupture (N/mm^2)
Orientation 1	face	2.00	12,656.25	85.92
Orientation 1	edge	3.20	15,820.31	103.50
Orientation 2	face - Outer	2.00	12,656.25	74.63
Orientation 2	face - Inner	3.00	14,062.50	83.81
Orientation 2	edge	3.00	17,015.63	103.13

4.3.3 Bending for beams with coinciding nodes at mid-point

Three (3) Point flexural test on small clear specimens was carried out and average of Four specimens, results for load and deflection on bending test for the two loading directions were plotted in Figure 4.2. A summary of loading surface, mid span deflection at maximum load, Modulus of Elasticity and Modulus of Rupture are given in Table 4.3.

The beams with coinciding nodes at the center performed better and had slightly higher values of Modulus of Elasticity by 8% when loaded on the face and Modulus of Rupture by 14 % when loaded on the face compared to other beams in Table 4.2, this is despite the fact that strips with nodes at the center had the least tensile strength (Table 4.1) and the failure was at the nodes by separation of grains, a study done by (Shao et al 2010) indicated that in both planed and non-planed samples, the node did not have a reduced effect on bending strength, longitudinal shearing strength and compressive strength. Instead, the node had a reinforced effect of different degrees. However, the node reduced the longitudinal tensile strength. Occurrence of coinciding nodes in laminated bamboo beams is however an ulikely case considering bamboo being a natural material that varies in internode length and very many strips from different stems are used in lamination process.

Plate 4.4 Beam with coinciding nodes at centre

Table 4.3 Load - Summary of Bending Test Result Central node beams

Beam	**Loading Surface**	**Mid Span Deflection at Maximum Load (mm)**	**Modulus of Elasticity (N/mm^2)**	**Modulus of Rupture (N/mm^2)**
Central Node	face	2.90	13,092.67	98.44
Central Node	edge	3.00	16,875.00	109.69

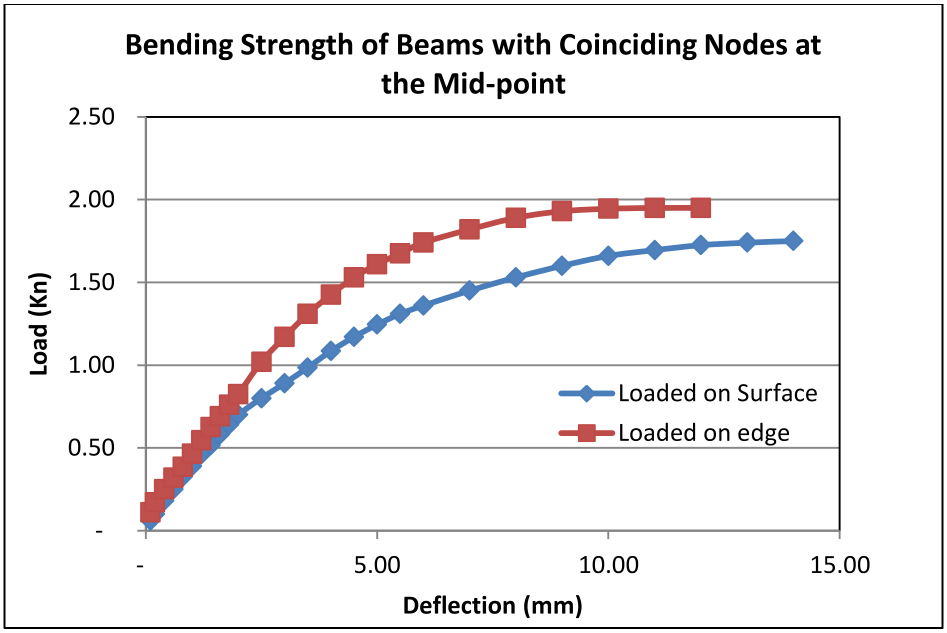


Figure 4.2 Load - Deflection Curves for beams with coinciding nodes at the mid-point at different loading directions

4.3.4 Bending for beams with outer layer and inner layers of the bamboo culm separated

Three (3) Point flexural test on small clear specimens was carried out and average of at least four specimens on each case of beams made from separated inner parts and separated outer parts, results for load and deflection on bending test for the various the two cases and two loading directions were plotted in Figure 4.3. A summary of loading surface, mid span deflection at maximum load, Modulus of Elasticity and Modulus of Rupture are given in Table 4.4.

Results for bending while loading on the surface compared for the inner and outer layer beams, while loading on the edge, outer layers had a considerable increase in strength by 42.5% while the inner layers had no much difference in strength while loaded on the surface or on the edge.

Beams laminated with inner or outer layers had more glue lines than other beams since the strips had half the thickness compared with the entire strip width, this contributed to additional stiffness and hence the little difference in bending strength for both inner and outer layers when loaded on the surface. While loaded on the edge, the outer layers gained strength by 42.5% due to the increased stiffness while the inner layer remained the same, inner layers having less cellulose fibers and more lignin were much weaker irrespective of the loading direction.

Bamboo material has been found to be very strong in tension but weak in compression, since bending action in beams involves tension at the bottom fibers and compression at the top fibers, relative low compression strength of bamboo and high tensile strength renders the beams a ductile behavior, where the beams achieves a very high deflection without breaking the fibers and failure occurs when the curvature under load is too large to take any more increment in loading.

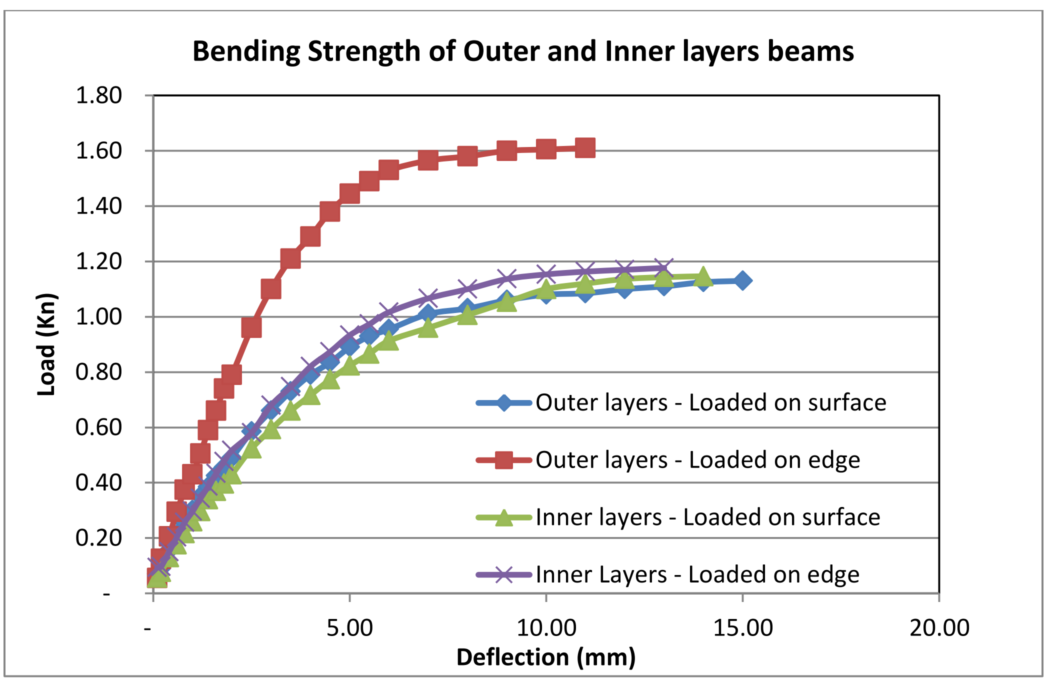


Figure 4.3 Load-Deflection curves for Inner and Outer parts Beams

Table 4.4 Summary of Bending Test Results for Inner and Outer Layer Beams

Beam	Loading Surface	Mid Span Deflection at Maximum Load (mm)	Modulus of Elasticity (N/mm2)	Modulus of Rupture (N/mm^2)
Outer Layers	face	2.50	10,125.00	63.56
Outer Layers	edge	3.20	15,820.31	90.56
Inner Layer	face	3.00	8,437.50	64.50
Inner Layer	edge	2.50	10,125.00	66.19

4.3.5 Bending for Beams with outer layers on extreme fibers and inner layers at the center

In this category full scale beams of dimensions 45mm x 70mm x 600mm length with outer layers comprising 20mm on either extreme fibers and inner layers comprising 30mm of the central fibers (Fig 3.6) were tested as illustrated in Figure 3.6, a total of three beams were tested and the average load – deflection curve plotted in Figure 4.4.

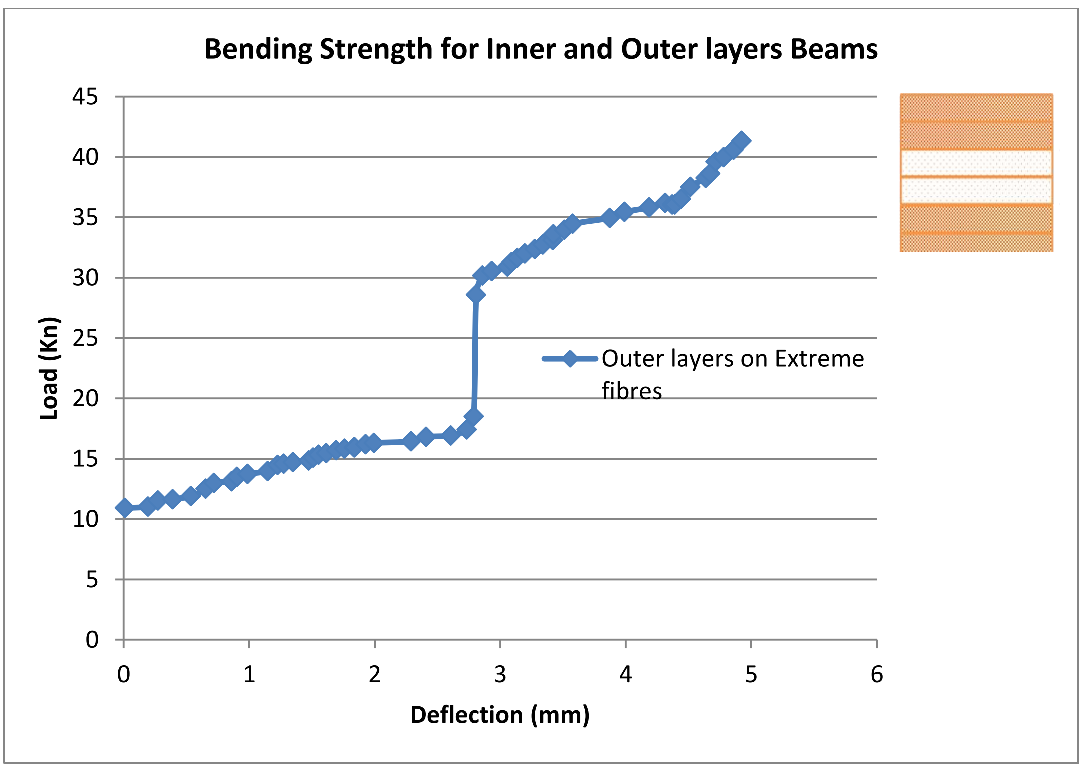


Figure 4.4 Bending Strength for Beams with Outer layers on extreme fibers

The beams had an average flexural strength of 84.8 N/mm^2 at maximum load, the load – deflection curve in Figure 4.4 show a linear relationship of increase in deflection with increase in load upto a deflection of 3 mm where the rate of increase in load with deflection increase significantly, at the initial stage the beam takes load with the upper zone taking compression and lower zone of the beam taking tension, after a while since bamboo is very strong in tension, the lower zone fibers resist the load and the beam starts deforming by depressing on the loading points, this is because the central material in the beam from the inner parts of the bamboo culm is much easier to compress as it is spongy due to higher volume of lignin as compared to cellulose fibres. This arrangement was noted to not only increase the flexural strength but also the beams did not break any fibres after failure, the beams regained most of the deflection but were slightly deformed with depressions at the point of loading. The beams showed an elastic and ductile behavior, by taking the loading and regaining much of the deflection after loading.

Plate 4.5 Beam under loading and after loading

Plate 4.6 Specimens after failure

Although failed specimens shows deformation, the fibres were not broken and about 90% of the deformation experienced during loading had been regained. Plate 4.6 shows the specimen being loaded and Plate 4.7 shows the beams after testing.

4.3.6 Compression Test results

Compression parallel to grain was carried out in at least 8 specimens of 2mm x 2mm x 6mm for each case and an average of the maximum load presented in bar graphs.

For orientation 1 and 2 specimens, although orientation 2 had a slightly higher maximum load by 7%, compression strength did not seem to depend on orientation of bamboo strips, bamboo outer skin is strong in tension and hence it's positioning in compression does not affect the compression strength.

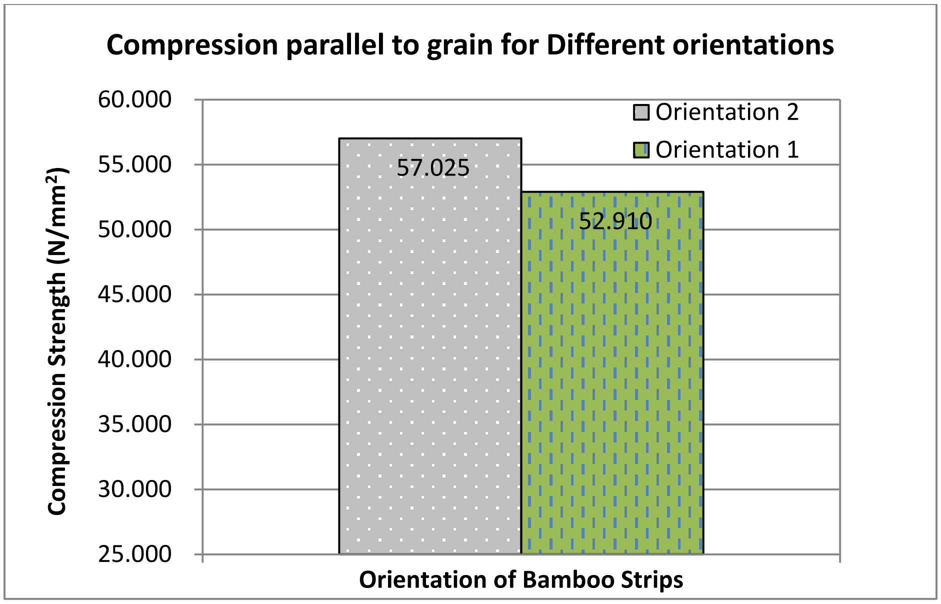


Figure 4.5 Compression Parallel to grain for Orientations 1 and 2.

For specimens made from separated inner and outer layers, the inner layers were very weak in compression and an increase in maximum load of 54% was noted while comparing the inner and outer layers (Fig 4.6). The inner layers have less fibers and more lignin, the lignin has less resistance to load and the cells collapses under loading. The outer layers has more cellulose fibers that even though the fibers are not very strong in compression as compared to other materials, they contribute to an increase in the compression strength to the outer layers as compared to the inner layers. The mode of failure in all the cases was similar by buckling shearing across the grains as the cells collapsed (Plate 4.7)

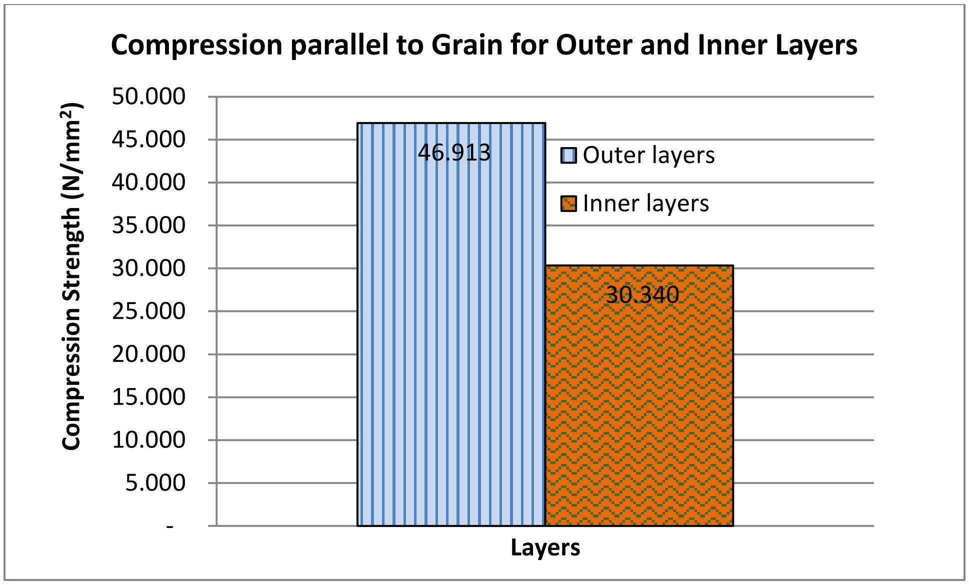


Figure 4.6 Compression parallel to grain for inner and outer layers

Plate 4.7 Failure mode under compression

4.3.7 Shear Test results

Shear test parallel to strips and perpendicular to strips was carried out in at least 10 specimens of 2mm x 2mm x 2mm for each case and an average of the maximum load presented in bar graphs. The specimens were placed in a shear test Jig, loading was done gradually at a constant rate of 0.025in/min until failure and the maximum load recorded.

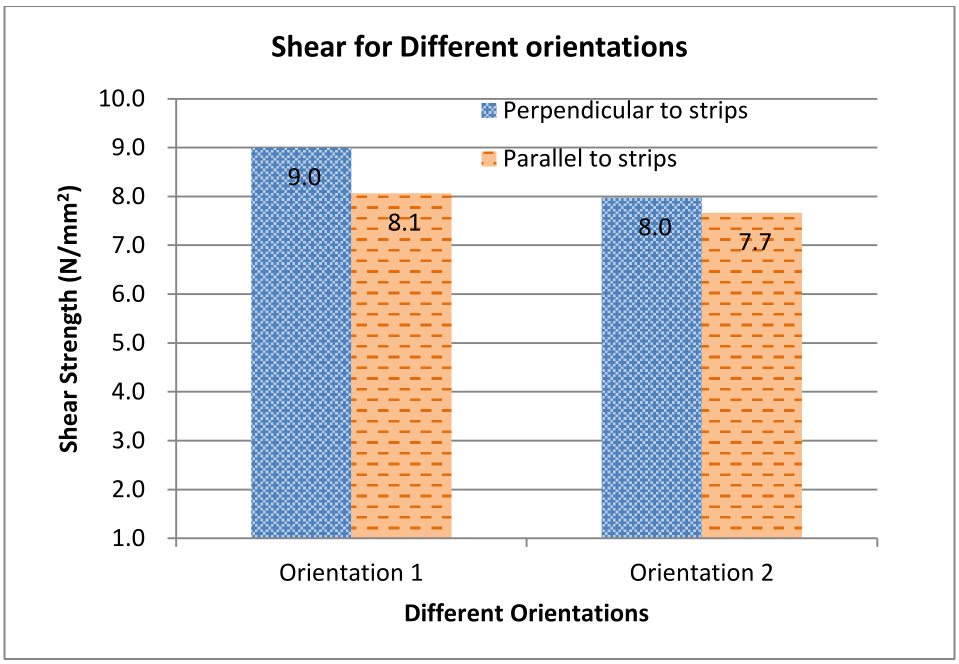


Figure 4.7 Shear Strength for orientation 1 and 2

For orientation 1 and 2, shear strength was higher in orientation 1 than in orientation 2 for both cases of loading parallel and perpendicular to the strips. In orientation 1 the outer layers of the bamboo culm were at the centre of the specimen and hence more shear strength in the specimens since the shearing plane was within the outer layers. However in the arrangement of orientation 2, outer part of bamboo culm and inner part formed the interface at the center of the specimen and hence the inner layer resulted to lower shear strength as it contains more of lignin and less of cellulose fibers.

When comparing shearing parallel to the strips and shearing perpendicular to the strips, shearing perpendicular the strips had a higher shear strength as compared to shearing parallel the strips, in perpendicular loading sharing occurred through the inner parts and outer parts of the strips, however when shearing parallel to strips the shear plane followed the weaker inner layer and hence less shear strength was achieved. It was noted that the difference in the strength was by a small margin of about 11 %, this is due to the fact that shearing was parallel to the grains and hence the lignin matrix played the major role in resistance while the areas of high fiber concentration contributed to a slight increase in the resistance as a result of the friction between the fibers and lignin matrix.

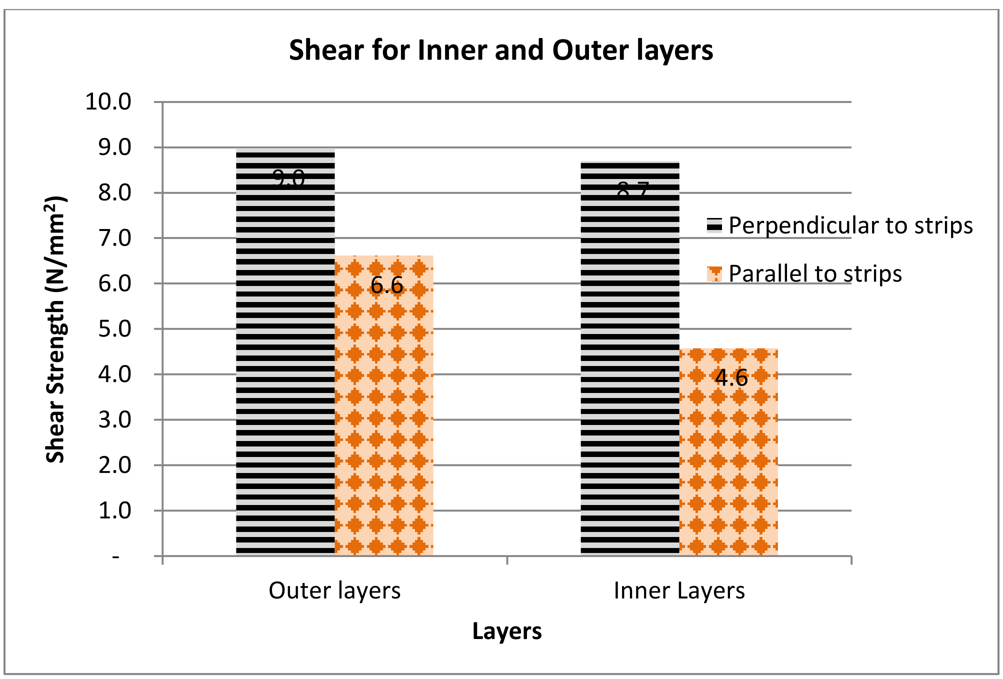


Figure 4.8 Shear Strength for Inner and Outer layers

For Inner and outer layers, shear strength perpendicular to the strips was slightly higher in outer layers by 3%, more layers were used on specimens since the strips were half the thickness, the additional glue lines interface increased the stiffness and hence the little difference in shear strength for inner and outer layers specimens.

For shear parallel to the strips, outer layers had a considerable higher strength as compared to inner layers by 46%, in this case shear plane occurred through the lignin material of the inner layers which is much weaker while the outer layers are fibrous and hence much stronger.

Plate 4.8 Specimens tested perpendicular to strips

Plate 4.9 Specimens tested parallel to strips

4.4 Test Results for Jointed Beams

4.4.1 Bending Test results for beams with jointed strips

The beams with jointed strips gave much lower flexural strength than other beams by about 20%, however the beams achieved a Modulus of Rupture of 68.34 N/mm^2 that compares well with commonly used timber like cypress timber with a Modulus of

Rupture of 68 N/mm^2 as given by Lavers (2002) and can therefore be used in construction creating a possibility of using shorter strips to engineer a longer beam as required. The average results of five specimens tested are presented in Figure 4.9 and a summary of loading surface, mid span deflection at maximum load, Modulus of Elasticity and Modulus of Rupture are given in Table 4.5. The beams failed by tension and compression, the bottom fibers ruptured in tension while the top fibers collapsed under compression. This was an indication that the adhesive bond was strong enough since failure did not occur on the joints; however the reduction of strength by 20% was as a result of the discontinuity of the fibers in the strips that contribute to high tensile strength of bamboo.

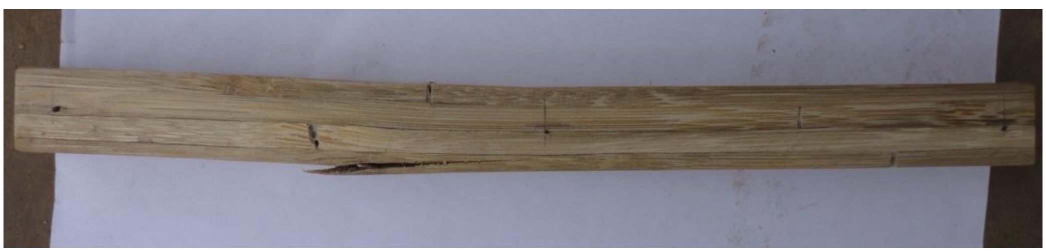



Plate 4.10 Tested jointed beam

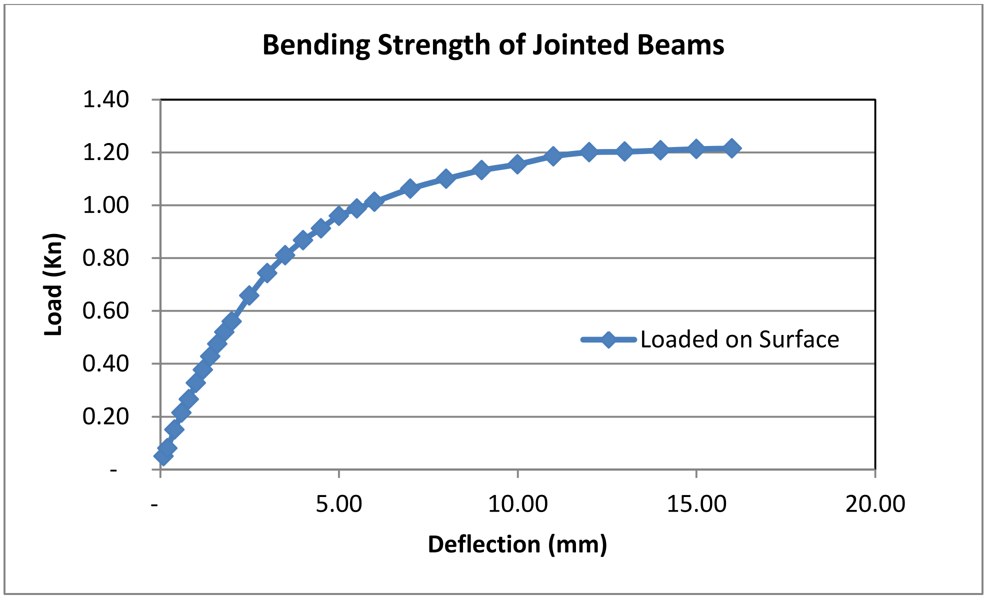


Figure 4.9 Load - Deflection Curves for Jointed beams

Table 4.5 Summary of Bending Test Results for Jointed Beams

Beam	**Loading Surface**	**Mid Span Deflection at Maximum Load (mm)**	**Modulus of Elasticity (N/mm2)**	**Modulus of Rupture (N/mm^2)**
Jointed Beams	face	2.50	11,812.5	68.34

4.5 Test Results for Beams with different glue types

4.5.1 Bending Test results for beams laminated with different glue types

Static bending test was done on specimens laminated with two different types of Polyvinyl Acetate Glue available in Kenyan markets, outer parts bamboo strips and the only variation was the type of glue used. The average results for a total of 10 specimens tested in each case are presented in Figure 4.10 and a summary of loading surface, mid span deflection at maximum load, Modulus of Elasticity and Modulus of Rupture are given in Table 4.6.

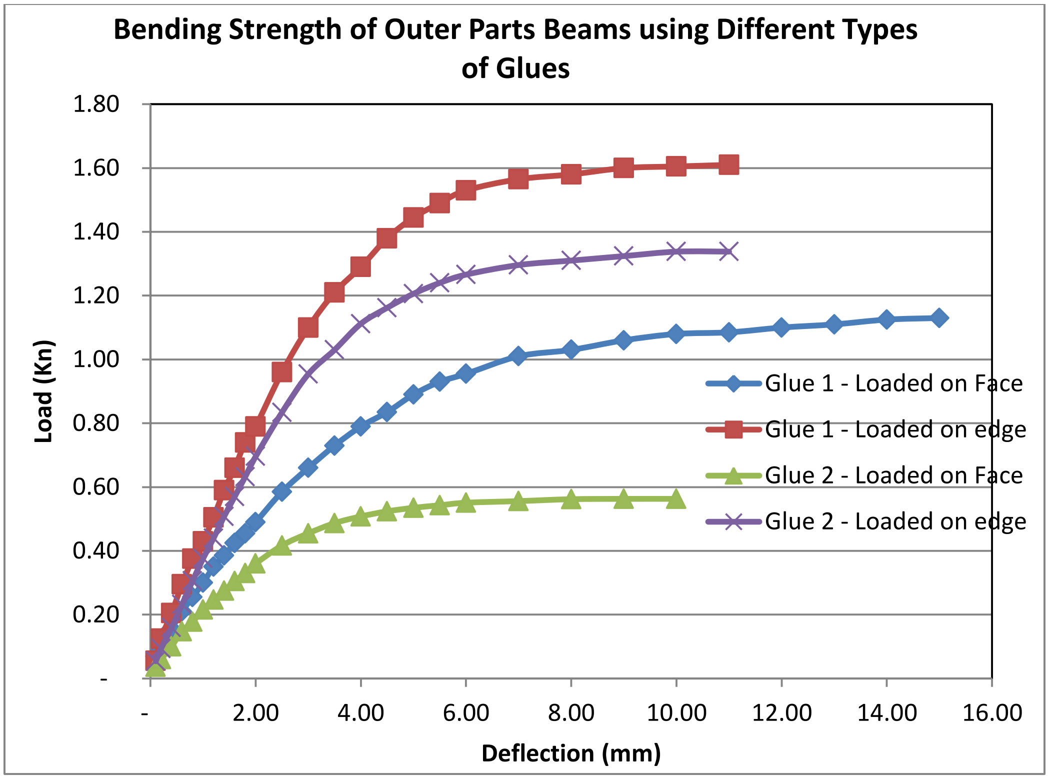


Figure 4.10 Bending Strength of Beams with different types of glues

In both modes of loading, specimens made from glue Type 1 had the higher flexural strength than specimens from glue type 2, specimens of glue type 2 failed by shearing along the glue line leading to separation of bamboo strips and hence the low strength values. However specimens made from glue type 1 remained intact and failed by excess deflection of breaking of fibers as seen in Plates 4.11 and 4.12.

Table 4.6 Summary of Results for Different types of Glues

Beam	**Loading Surface**	**Mid Span Deflection at Maximum Load (mm)**	**Modulus of Elasticity (N/mm2)**	**Modulus of Rupture (N/mm^2)**
Glue Type 1	face	2.50	10,125.00	63.56
Glue Type 1	edge	3.00	15,468.75	90.56
Glue Type 2	face	2.50	6,750.00	31.67
Glue Type 2	edge	3.00	13,359.38	75.26

Beams for Glue Type 2 did not reach their maximum strength due to separation of the strips, the low values of modulus of elasticity and modulus of rupture show that the bamboo material was not fully utilized as a unit in the load bearing.

Similar to other cases, both type of beams had their higher flexural strength when loaded on the edge as compared to loading on the face. Loading on the edge was consistent in being stiffer and hence much stronger.

Plate 4.11 Beam specimen of Glue type 2

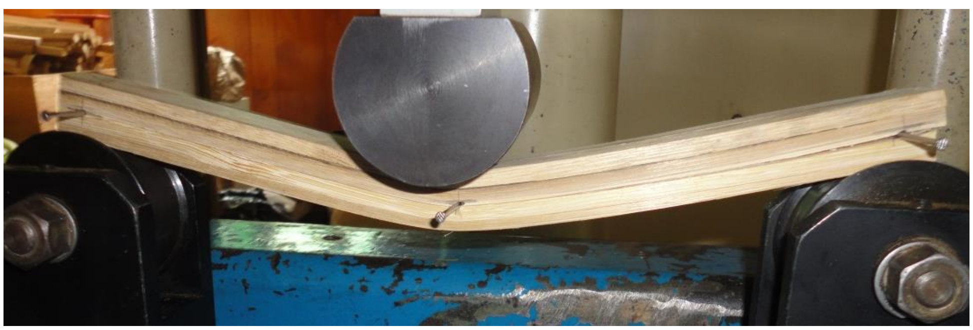


Plate 4.12 Beam specimen of Glue type

4.5.2 Compression Test results for beams laminated with different glue types

Compression parallel to grain was carried out in 10 specimens of 2mm x 2mm x 6mm for each case and an average of the maximum load presented in bar graphs Figure 4.11, Beams from Glue type 1 had higher compressive strength than beams from Glue Type 2, Glue Type 1 beams failed by buckling and shearing across the grains and the strips remained intact while Glue Type 2 beams failed by separation and buckling of the strips. Glue Type 1 was strong enough to maintain an a glue line interface stronger than the parent material while glue Type 2 was weak in bonding and resulted to a glue line interface weaker than the parent material and therefore the bond could not take more load than the parent material leading to a pre mature failure.

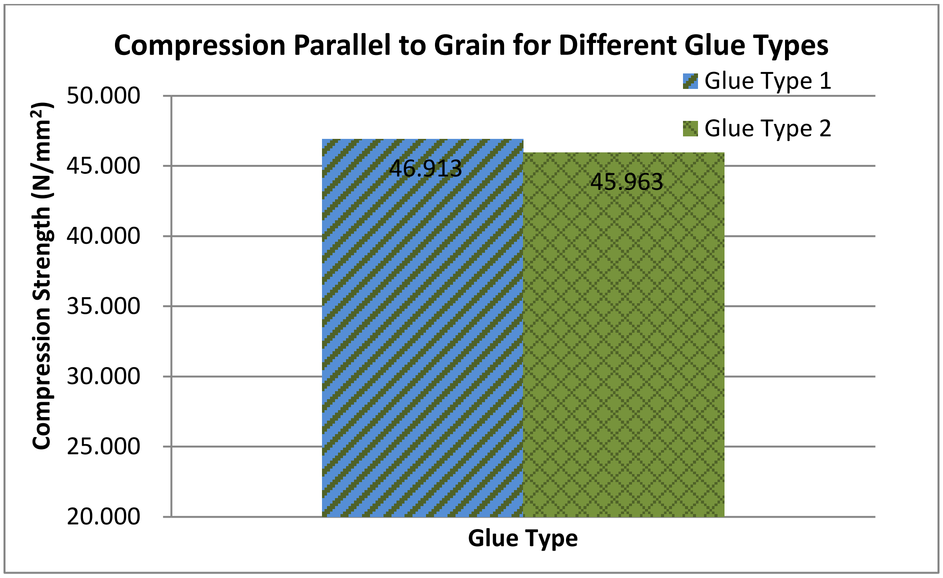


Figure 4.11 Compression Parallel to Grain for Different Glue types

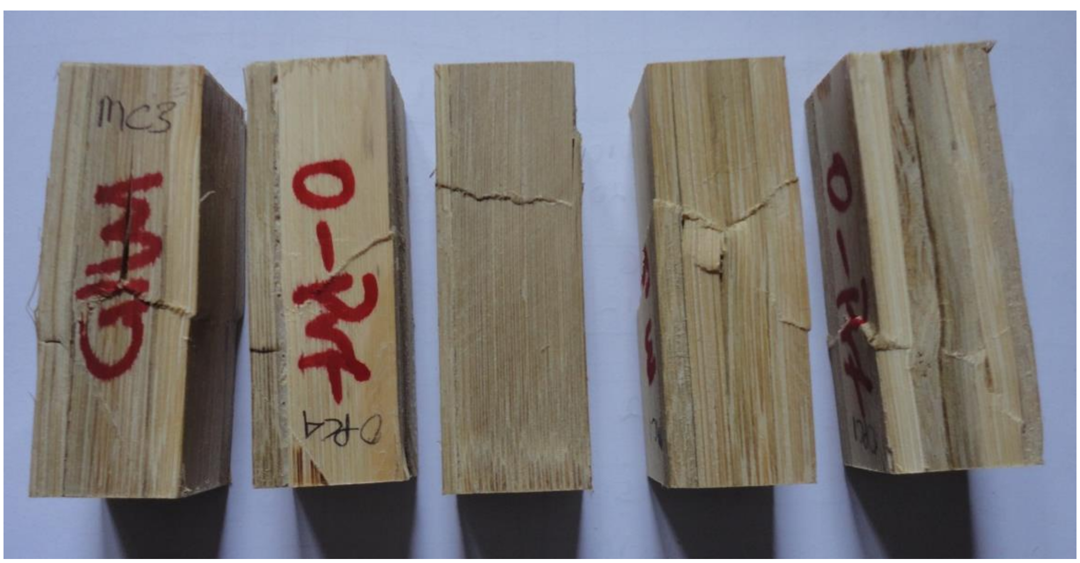



Plate 4.13 Specimens Failed by buckling – Glue Type 1

Plate 4.14 Specimens failed by delamination - Glue Type 2

4.5.3 Shear test results for beams laminated with different glue types

Shear test parallel to strips and perpendicular to strips was carried out in at least 10 specimens of 2mm x 2mm x 2mm for each case and an average of the maximum load presented in bar graphs.

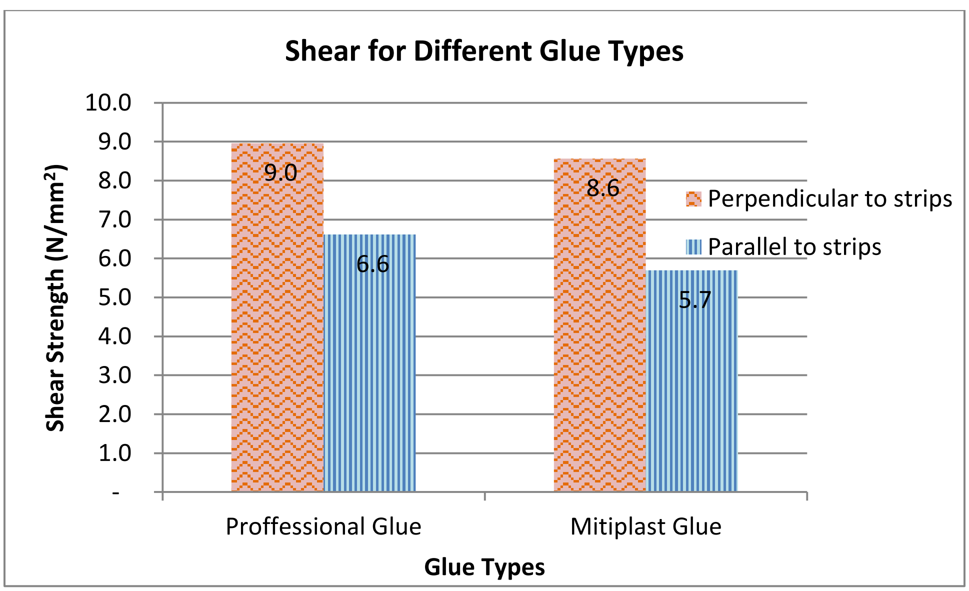


Figure 4.12 Shear results for different types of glues

Although glue Type 1 specimens had a higher average value, shear strength results showed a very little dependent on the type of glue used, this is because of the size of specimen used and its placing in the shear test Jig that rarely exposes the glue line to shearing but rather the material that is at the center.

4.5.4 Bending test results for beams with varying glue dispersal

It was during the pressing that there was bleeding of excess glue on the edges after application of both top and side pressure (Plate 4.15), even though this was a sign of proper pressing of the strips, further observation of the laminated panels showed that more gaps appeared on the ends of the panels while the central part was intact (Plate 4.16). Static bending Tests were done on at least four specimens extracted from the end part of the panels and central parts of the panel and plotted in Figure 4.13.

Plate 4. 15 Bleeding of glue under pressure

Plate 4.16 Voids on either ends of laminated panels

Plate 4.17 Proper bonding at the centre of Laminated panel

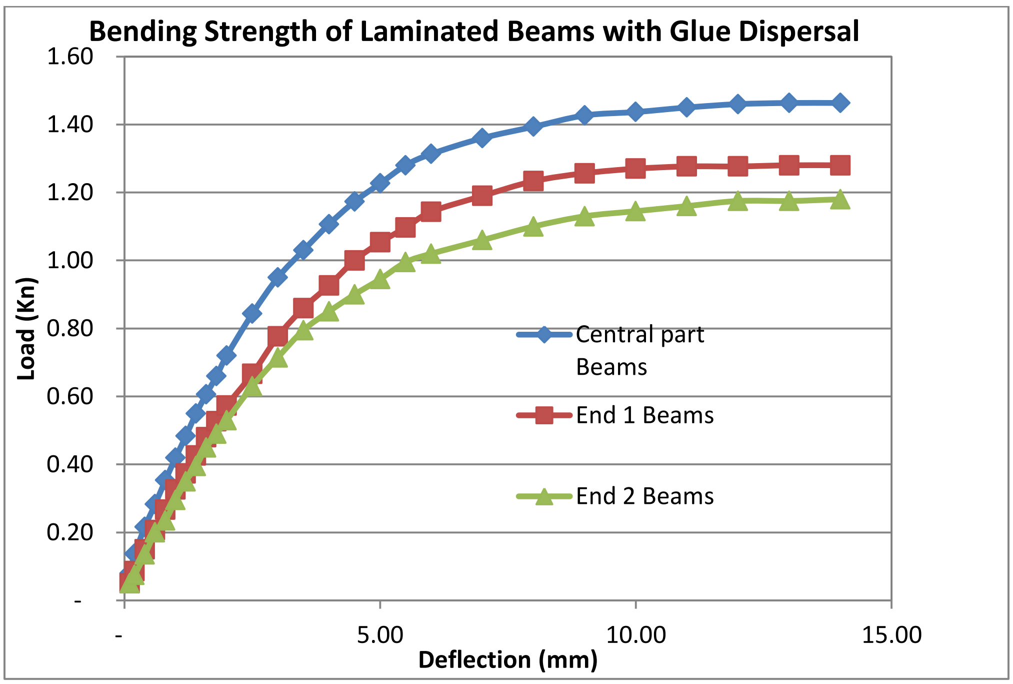


Figure 4.13 Bending strength of beams in different glue dispersal

From the bending results, samples from the central part had the highest flexural strength while samples from either ends. This shows that the bleeding of glue under pressure caused formation of voids at the ends and hence weaker bonding resulting to lower strengths. Wan Tarmeze et al (2005) listed glue imperfections and presence of voids among the parameters that affect strength and stiffness of glue laminated bamboo beams.

4.6 Test Results for Full Scale Beams and Truss Model

4.6.2 Bending Strength of Laminated bamboo beams and cypress

To evaluate the performance of full scale laminated bamboo beams, 6 beams of 45mm x 95mm x 600mm were tested and an average of the results reported, 3 beams of cypress timber of equivalent dimensions were also tested and the average results compared to those of laminated bamboo beams.

A strain gauge was attached at the bottom centre of the beams to read the strains on the extreme fibers of the material.

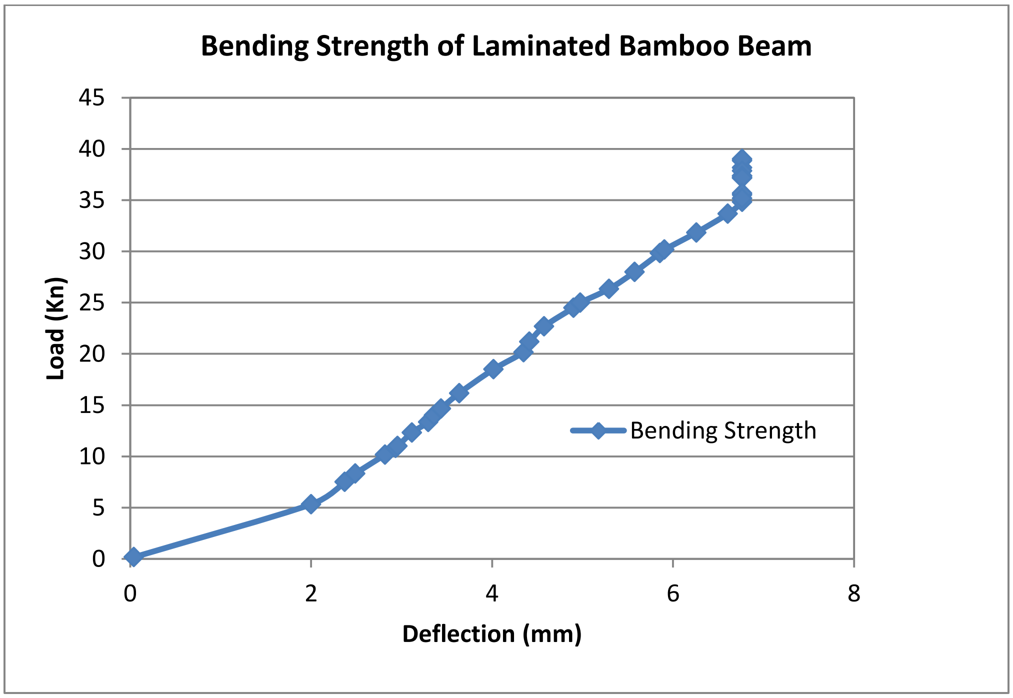


Figure 4.14 Bending Strength of laminated bamboo beams

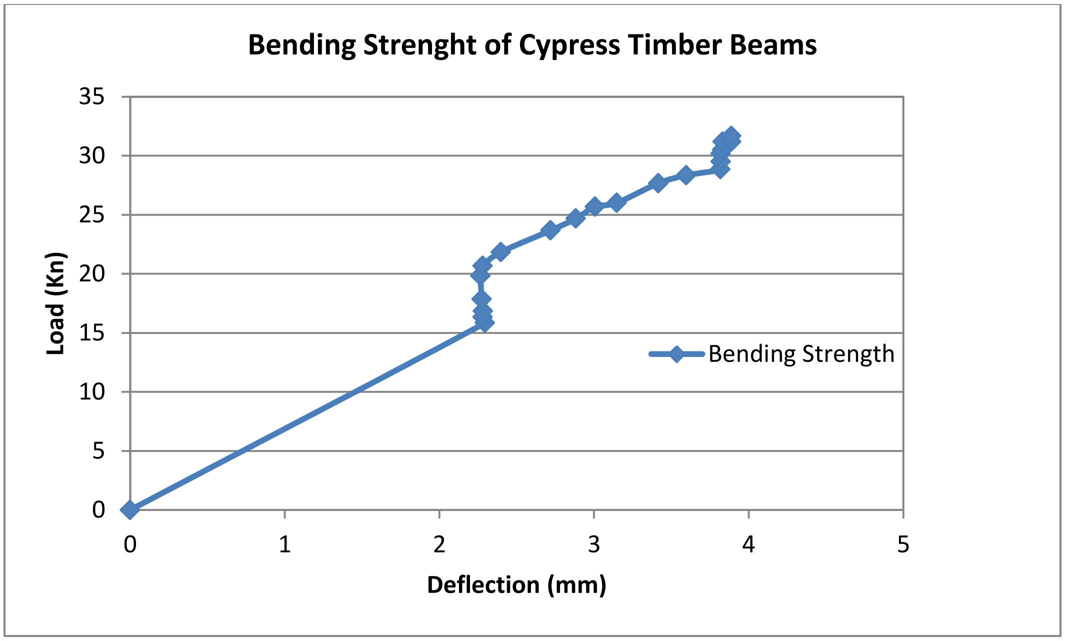


Figure 4.15 Bending strength of Cypress beams

Laminated bamboo beams had a mean flexural strength of 98 N/mm^2 while cypress timber had an a mean of 83 N/mm^2, laminated bamboo beams showed a constant rate of deflection with increase in load upto a load of 35 Kn and a deflection of 7mm where the increase in load continued with no deflection recorded until failure, the beams failed by breaking of the bottom strips and shearing along the grains, after failure the beams regained much of the deflection undergone since the inner strips did not break. Unlike cypress timber that failed by cracking and was less elastic, in both cases the beams buckled on the upper compression layer forcing the neutral axis to move downwards during the test so that ultimately the lower part of the specimens failed in tension. A study done by Sinha et al (2014) concluded that the laminated bamboo beam does possess higher allowable and average strength values in tension and bending and comparable stiffness values, with much less variability to a commonly used structural species of wood, Douglas fir.

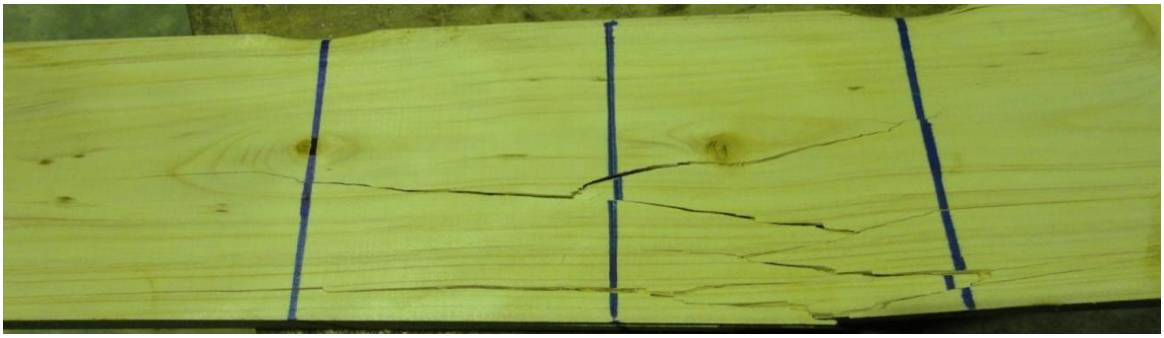


Plate 4.18 Mode of Failure in Cypress Beam

From Plate 4.19 the failure mode in cypress is flexural and the cracks are major, the beam failed abruptly by snapping and could not take any more load or regain from the deflection failure.

Plate 4.19 Mode of Failure in Laminated Bamboo Beam

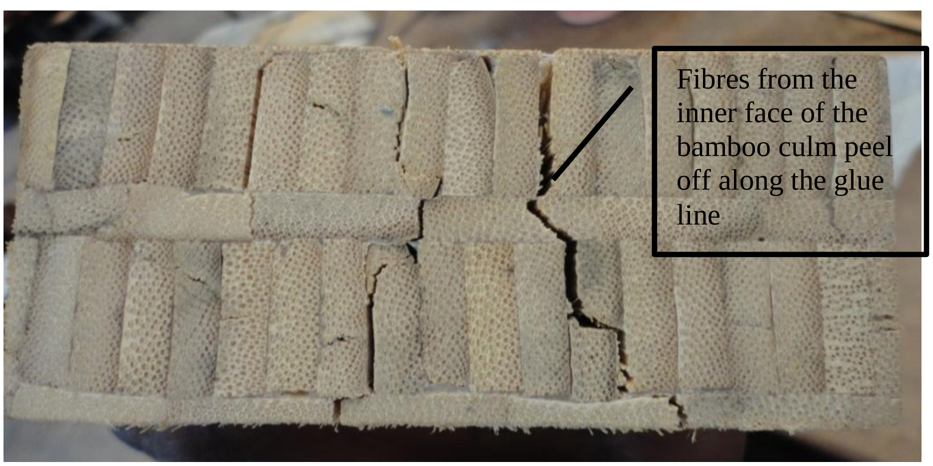


Plate 4.20 Edge Mode of failure in laminated bamboo beam

The failure mode for laminated bamboo beam was by tension on the lower part of the beams and shear along the grains, the shear occurred by separation of fibres from the inner faces of bamboo culm that were strongly bonded on the outer face of the culm. Due to the low concentration of fibres in the inner side of the culm and more lignin, the fibres tend to peel off under very loads, however this created two separate beams parallel on top of each other and the beams were able to take more load after the breaking of the bottom strips under tension and as well contributed to the elastic behavior where the beam springs back to almost its original state after the load is removed. Zhang et al (2014) observed that when laminated bamboo beams were loaded, the specimen was in elastic state at the begging of the loading. With increase in loading, the specimen showed a certain plastic deformation and the stiffness of the beam decreased. Once the outer most layer of bamboo fiber was pulled apart, the longitudinal splitting caused by tensile of the horizontal grain lead to the whole specimen being damaged in an instant. All beams crushed at eh bottom surface and split up the middle along the depth of the beam.

Graphs of load over time were plotted as below:-

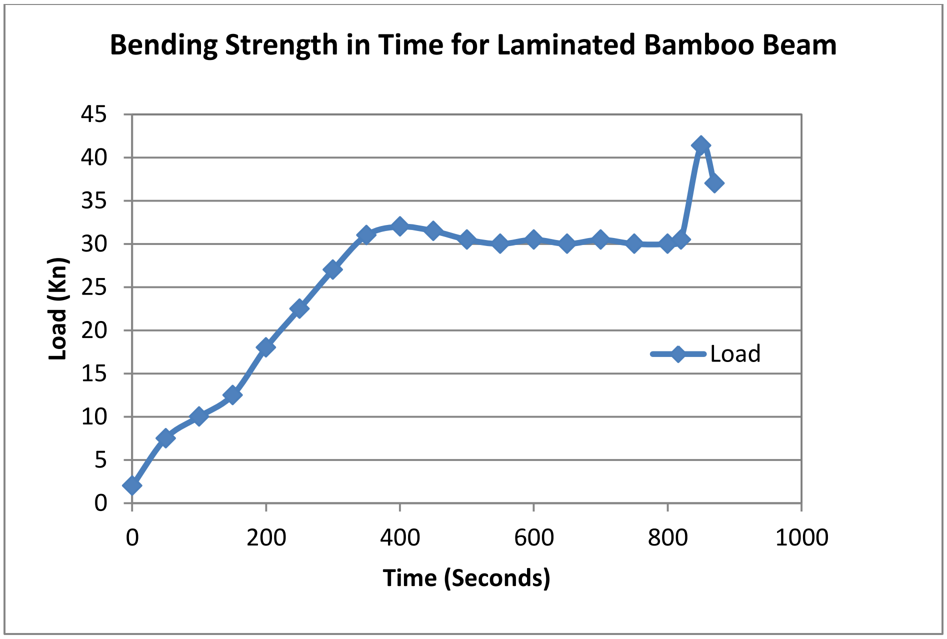


Figure 4.16 Laminated bamboo beam bending strength in Time

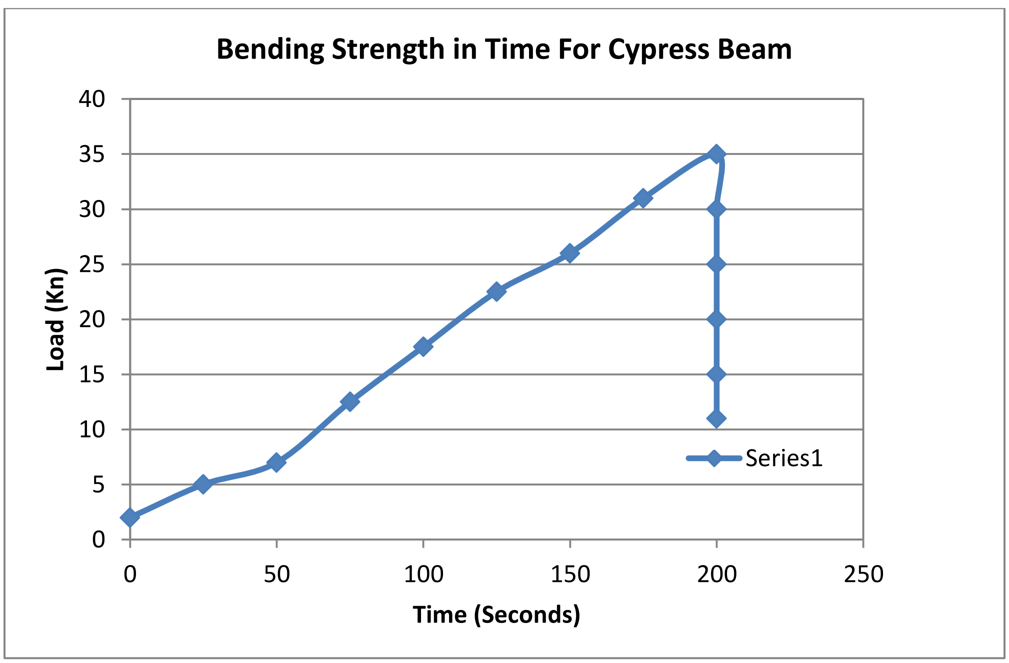


Figure 4.17 Cypress beam bending strength in time

As noted from the graphs of load in time for laminated bamboo beams and cypress, laminated bamboo beams had an increase in load over time up to a 35 Kn where the load is constant for a period of about 400 seconds and then a sudden increase in load till failure, the beams are able to take in more energy during deformation and due to fact that bamboo is very strong in tension, the beams take load for a long period of time until the bottom fibers break.

Apart from achieving low flexural strength, cypress timber beams were noted to fail very quickly in about 20% of the time the laminated bamboo beams takes. Cypress and most commonly used timber are not strong in tension and hence after the top compression zone of the beam buckles, the bottom tension zone gives in fast and snap. The failure in cypress timber was abrupt and they made a loud noise when cracking.

Graphs of strains on extreme bottom center fibers were plotted in the graphs below:-

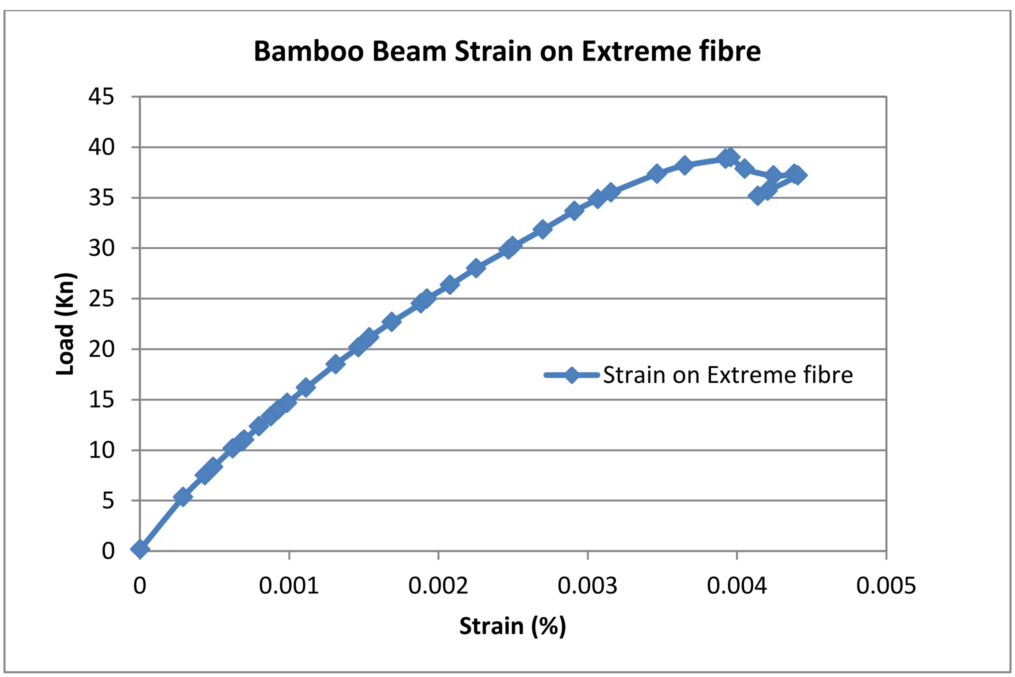


Figure 4.18 Load - Strain Curve on extreme fiber for Laminated Bamboo Beam

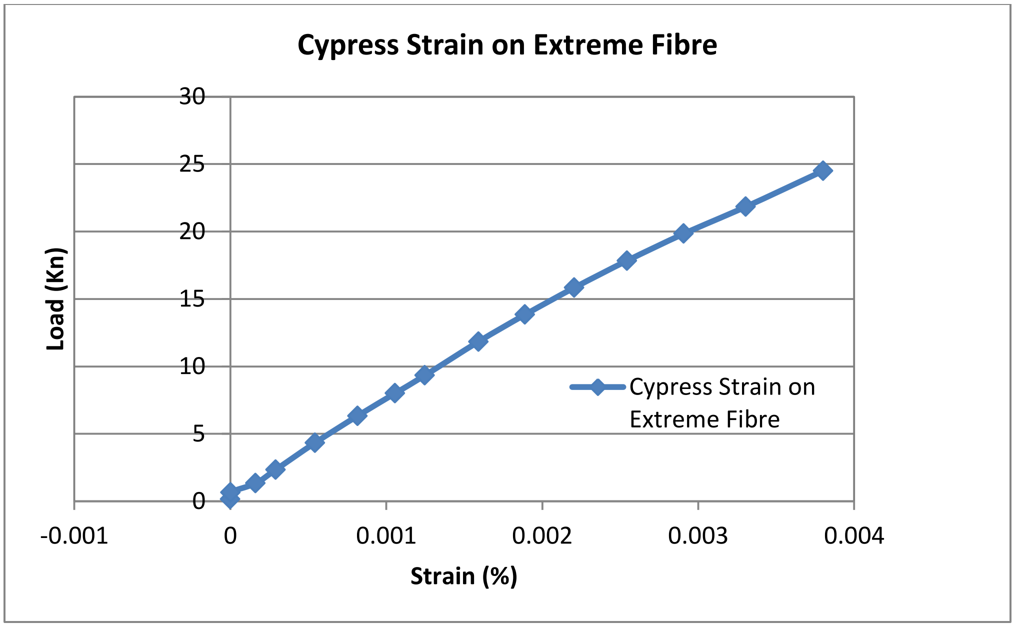


Figure 4.19 Load - Strain Curve on extreme fiber for Cypress beam

Increase in strains in laminated bamboo beams with increase in load was at a decreasing rate, this shows that the beams are stronger in tension and are able to take in energy, as compared to cypress beams, the load – strain curve is linear upto point of failure, showing that increase in load results to proportional strain on the extreme bottom fibers of the material and hence cypress does not resist tension at the bottom as compared to bamboo.

4.6.3 Test results of Lattice Girder Truss Model

Truss models from laminated bamboo members were made from members of 25mm x 25mm and had a span of 1.725m being a half scale model, the Joints were made of 3mm steel plates and 6mm high tensile strength bolts with two bolts on each member Average load deflection curve for the 3 truss models tested was plotted in Figure 20 Load – Strains curve for the members is Figure 21.

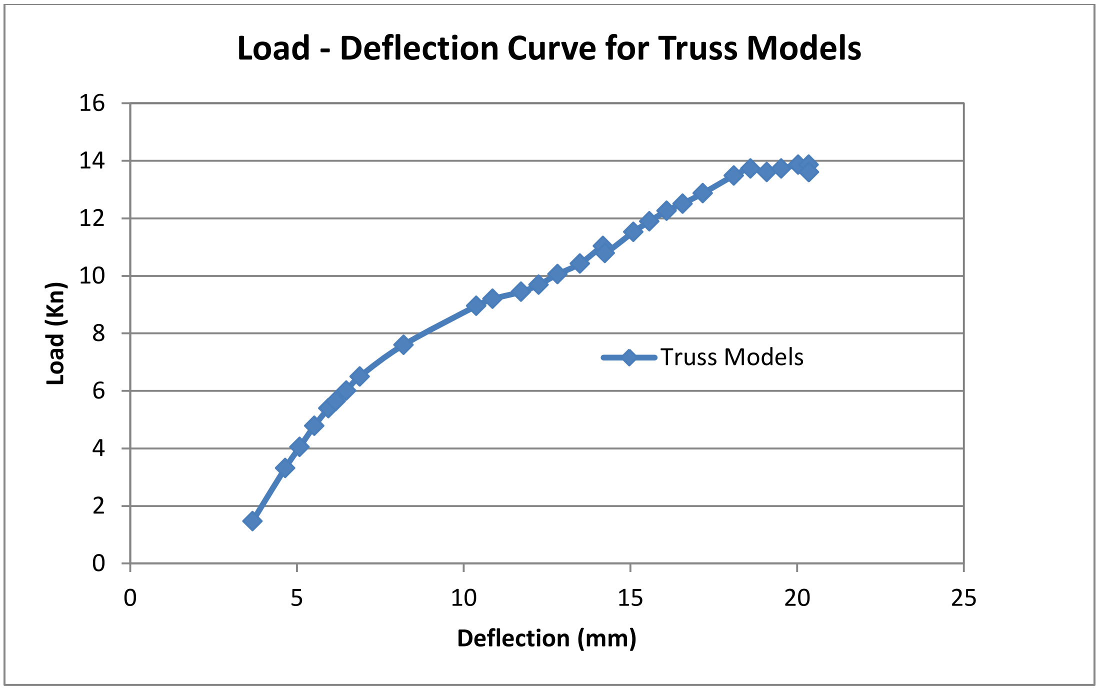


Figure 4.20 Load - Deflection curve for truss model

Truss models from laminated bamboo members had a large deflection without failure in members by breaking, the capacity of the deflection meter was exceeded and truss started twisting on increased load. The members are very strong in tension and the mode of failure was by deformation of members.

Plate 4.21 Deflected truss model under loading

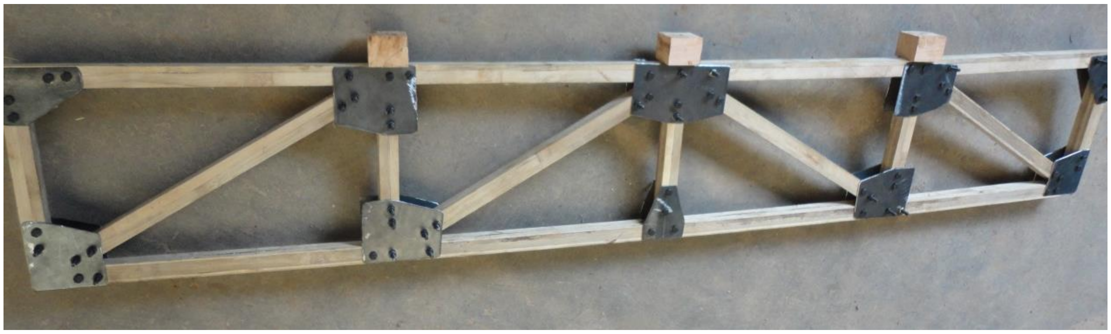


Plate 4.22 Truss model after testing

After the removal of the loading, the failed truss showed very little signs of failure, the members and joints were intact and only slight deformation was noticeable on the members. Since truss members are is axially loaded, they were under tension and compression, members under compression buckled and regained their status after removal of load while members under tension were too strong to break and hence the twisting effect of the truss during the loading. Figure 4.21 shows the members fixed with strain gauges.

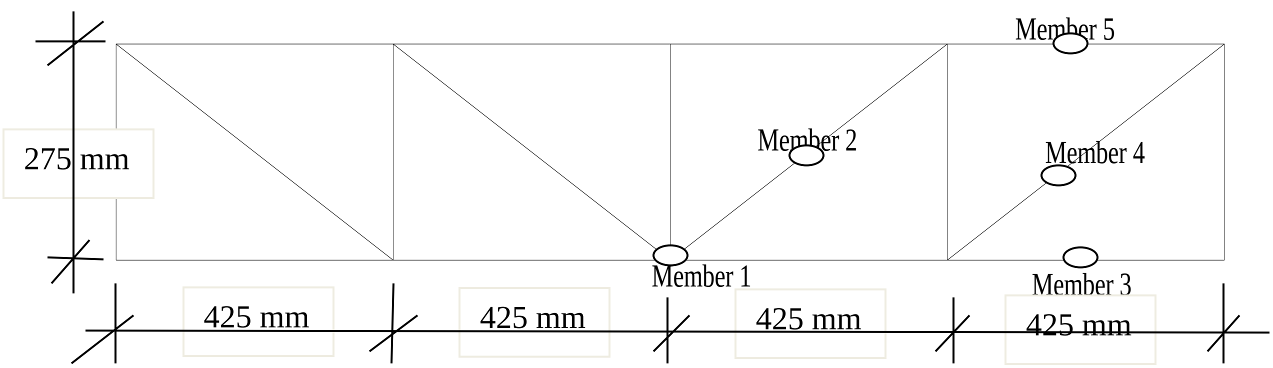


Figure 4.21 Lattice Truss members with Strain gauges

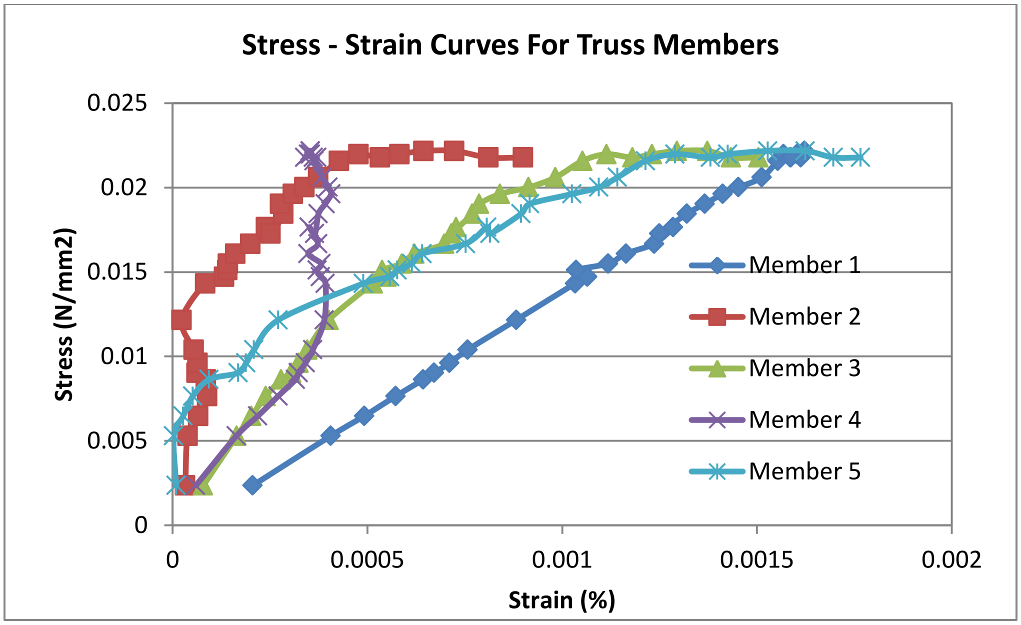


Figure 4. 22 Stress - Strain curves for Lattice truss members

From the Stress – Strain curves of the various truss members; member 1 which is the bottom chord at the mid-point was noted to have a linear relationship of strain stress curve, the member experiences continuous tension during the loading.

The connections used of bolts and steel plates performed well and showed no point of weakness, bamboo splits when nailed as nails separate the fibers longitudinally but drilling and bolting worked well for the connections.

Driving of nails through the bamboo culm results to splitting of the culm, this is because the grains in bamboo are parallel. The study satisfied that drilling holes and using bolts for connections or other fasteners driven through the drilled holes works better for bamboo. This has been one of the weaknesses of using bamboo in construction.

4.7 Summary of Results compared with other Timber Species

Table 4.7 Comparison of Mechanical Properties of LBB to other Common Timber species

Building Material	Loading Surface	Specific Gravity	Modulus of Elasticity (N/mm2)	Modulus of Rupture (N/mm^2)	Compression parallel to grain (N/mm^2)	Shear parallel to grain (N/mm^2)
Bamboo Orientation 1	face	0.74	12,656.25	85.92	132.28	22.49
Bamboo Orientation 1	edge	0.74	15,820.31	103.50	-	-
Bamboo Orientation 2	face - Outer	0.74	12,656.25	74.63	142.56	19.93
Bamboo Orientation 2	face - Inner	0.74	14,062.50	83.81	-	-
Bamboo Orientation 2	edge	0.74	17,015.63	103.13	-	-
Jointed Beam	face	0.74	11,812.50	68.34	-	-
Loblolly pine (Soft Wood)	-	0.51	12,300.00	88.00	49.20	9.60
Douglas fir (Soft Wood)	-	0.45	13,600.00	88.00	49.90	7.80
Bald cypress (Soft Wood)	-	0.46	9,900.00	68.00	43.90	6.90
Red Oak (Hard Wood)	-	0.61	11,300.00	96.00	45.00	13.20
Butternut (Hard Wood)	-	0.38	8,100.00	56.00	36.20	8.10
Walnut (Hard Wood)	-	0.55	11,600.00	101.00	52.30	9.40
Mangrove	-	0.89	16,689.89	134.83	79.96	22.62

Table 4.7 above gives a summary of Mechanical properties of Glue Laminated bamboo beams compared to other common timber species (Wood Handbook 2010, Manguriu et al (2013)). Bamboo has been compared in the various orientations and loading directions as tested. Orientation 1 loaded on the edge and on the face and orientation 2 loaded on the outer face, inner face and on the edge.

Laminated bamboo beams had the highest bending strength than the softwoods and hardwoods, except for mangrove that had the highest modulus of rupture than laminated bamboo beams in both orientation and loading directions. However laminated bamboo beams in orientation 2 and loaded on the edge had the highest modulus of elasticity compared to all other materials presented. The modulus of elasticity is a measure of stress and strain within limit of proportionality which provides a convenient model of expressing the stiffness or flexibility of a material; the higher it is the stiffer is the material Manguriu et al (2013).

In compression strength parallel to grain, laminated bamboo beams had higher strength than the soft woods and the hard woods by about three times, the beams had also higher strength than mangrove by about 2 times. Laminated bamboo beams compared well with mangrove in shear strength parallel to the grains, tripled the shear strength of the soft woods, and doubled the shear strength of the hard woods.

The comparison of the mechanical properties of laminated bamboo beams to other common hard wood and soft wood gives an indication of a superior engineered material. By varying the orientation it is possible to engineer a material with superior structural properties for specialized works, this optimizes the utilization of bamboo. The study aimed at evaluating various methods of optimizing laminated bamboo beams, from the results and discussion it’s clear that laminated bamboo beams can be engineered to suite special needs in constructions. By varying the orientations, higher strengths than that of common timber are achieved; this was seen in bending strength, compression strength and shear strength of laminated bamboo beams. In addition to increased strength, special treatment of laminated bamboo beams by using outer layers on the extreme edges of beams, increased the loading time to failure compared to cypress timber, this is an added advantage in the factor of safety while using the beams. The mode of failure was also by deflection and hence more safe.

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

Utilization of bamboo in construction will result in massive gains of protecting the environment. One of the bamboo species has been categorized by the Guinness World Records as the fasted growing plant currently known on earth; the fast growth rate means a high rate of replenishment of bamboo used. Although lamination of bamboo beams is a lengthy process, it was effectively achieved using advanced technology machinery at KeFRI, the latest state of art in the upcoming field. The research analyzed the process of engineering structural beams using strips from bamboo culm and the structural usage of the beams as joists and truss members. Although adoption of bamboo has not been fully embraced in the construction industry to replace or supplement the traditional construction materials namely timber, steel and concrete, the research found laminated bamboo beams is a viable construction material and the following conclusions and recommendations are drawn from the research;-

5.1 Conclusions

The following conclusions are made from the study:

a) Orientation of bamboo strips in laminated bamboo beams and direction of loading affects the flexural strength of the beams as follows:-
    - Loading on the edge gives the highest flexural strength by 22% in either orientation of bamboo strips in laminated bamboo beams.

- When loading on the face, arranging strips facing the same direction and loading on the inner face gives the highest Modulus of Elasticity by 11% than arranging the strips facing each other and loading on the face.

b) Nodes reduce the longitudinal tensile strength of bamboo strip, however the presence of coinciding nodes at the midpoint of beam does not have a reduced effect on bending strength but instead the nodes has a reinforced effect increasing the flexural strength in both loading cases than in other beams by 14%.

c) Introduction of jointed strips in laminated bamboo beams reduces the flexural strength but the strength achieved is sufficient for normal construction works, Modulus of Rupture of 68 N/mm^2 which compares to that of commonly used timber species. Joining of staggered shorter strips can be adopted in engineering of longer laminated bamboo beams than available material.

d) The outer skin of bamboo strip contributes the most in tensile strength, removal of the outer skin reduces the tensile strength by about 30%, and the outer skin should therefore have minimum disturbance in the making of laminated bamboo beams. Concentration of cellulose fibers is more on the outer skin contributing to the higher tensile strength compared to the inner skin that has more of lignin and less of cellulose fibres and hence weaker in tension.

e) The type of glue used has an effect on strength of laminated bamboo beams; the glue line interface should be stronger than the bamboo material to ensure maximum utilization of the bamboo in load bearing. Using of low quality glue leads to delamination during testing and reduces strength properties by about 50%.

f) Laminated bamboo beams are stronger than cypress beams by 15% in flexural strength, take more time to fail than cypress by about 400%, are more elastic and hence a superior building materials. Laminated bamboo beams achieved a MOR of 98 N/mm^2 while cypress timber achieved a MOR of 83 N/mm^2.

g) Laminated bamboo beams can be adopted in trusses by using steel plates and bolts for connections.

5.2 Recommendations

From what was deduced from the research and the results analysis, the following recommendations for further research on laminated bamboo beams are made:-

a) Laminated bamboo beams are recommended to be used as structural beams or truss members; they have superior strength properties compared to timber. Bolts and Steel plates are recommended for connections.

b) The prototype beams failed by shear along the grains which was by separation of the fibers on the inner face of the bamboo culm, a study should therefore be carried out on reinforcing the inner parts of the bamboo culm to strengthen the lignin matrix,

c) The study was done by cold pressing the strips at a constant pressure of 0.5 N/mm2 top pressures and 9.81 N/mm2 side pressure, a detailed study should be carried out on the effect of hot pressing and pressure variation on the strength of laminated bamboo beams.

d) The laminated bamboo beams showed properties of being elastic, they should therefore be investigated on their suitability in dynamic forces or areas of high vibrations like machinery supports.

e) Bamboo was found to be very strong in tension and hence the beams were equally stronger, a study on composite beam using bamboo on the tension zone and another material with better compression properties on the compression zone should be carried out to investigate the optimization of bamboo in structural works.

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APPENDICES

BENDING TESTS RESULTS FOR SMALL CLEAR SPECIMENS

Table A. 1: BENDING TEST RESULTS FOR ORIENTATION ONE

	Load Kn							
Deflection (mm)	**OO7**	**OO8**	**OO9**	**OO10**	**OO11**	**OO12**	**OO13**	**Average**
0.1	0.06	0.04	0.05	0.04	0.08	0.04	0.05	0.05
0.2	0.09	0.07	0.07	0.06	0.13	0.06	0.08	0.08
0.4	0.16	0.12	0.12	0.11	0.18	0.11	0.12	0.13
0.6	0.25	0.16	0.2	0.16	0.24	0.15	0.18	0.19
0.8	0.32	0.2	0.25	0.21	0.32	0.18	0.22	0.24
1	0.36	0.27	0.3	0.26	0.38	0.22	0.27	0.29
1.2	0.42	0.31	0.34	0.3	0.44	0.26	0.31	0.34
1.4	0.49	0.36	0.39	0.34	0.5	0.29	0.35	0.39
1.6	0.54	0.4	0.43	0.38	0.55	0.32	0.39	0.43
1.8	0.59	0.44	0.49	0.42	0.61	0.35	0.43	0.48
2	0.64	0.5	0.53	0.46	0.66	0.39	0.47	0.52
2.5	0.76	0.6	0.62	0.55	0.72	0.46	0.56	0.61
3	0.83	0.68	0.71	0.62	0.8	0.53	0.64	0.69
3.5	0.89	0.75	0.78	0.69	0.92	0.59	0.73	0.76
4	0.96	0.82	0.86	0.75	1.02	0.65	0.77	0.83
4.5	1.02	0.88	0.92	0.8	1.11	0.7	0.81	0.89
5	1.07	0.94	0.92	0.84	1.19	0.76	0.86	0.94
5.5	1.12	0.97	1.02	0.88	1.26	0.8	0.89	0.99
6	1.16	1.03	1.06	0.93	1.32	0.84	0.93	1.04
7	1.24	1.11	1.09	0.96	1.37	0.88	1	1.09
8	1.29	1.16	1.16	1.02	1.46	0.93	1.02	1.15
9	1.34	1.21	1.22	1.06	1.52	0.98		1.22
10	1.37	1.25	1.26	1.1	1.58	1.02		1.26
11	1.42	1.28	1.31	1.15	1.64	1.06		1.31
12	1.44	1.28	1.34	1.18	1.66	1.1		1.33
13	1.46		1.38	1.18	1.72	1.13		1.37
14	1.47		1.4		1.75	1.16		1.45
15	1.48		1.42		1.78	1.18		1.47
16	1.49		1.44		1.8	1.2		1.48
17	1.52		1.45		1.82	1.21		1.50
19						1.22		1.22

Table A. 2: BENDING TEST RESULST FOR ORIENTATION ONE - LOADED ON THE EDGE

	Load Kn						
Deflection (mm)	**OO1**	**OO2**	**OO3**	**OO4**	**OO5**	**OO6**	**Average**
0.1	0.05	0.04	0.07	0.07	0.05	0.06	0.06
0.2	0.09	0.06	0.13	0.14	0.09	0.08	0.10
0.4	0.16	0.14	0.22	0.21	0.17	0.18	0.18
0.6	0.22	0.19	0.31	0.29	0.26	0.24	0.25
0.8	0.33	0.25	0.39	0.35	0.34	0.32	0.33
1	0.39	0.33	0.47	0.43	0.42	0.4	0.41
1.2	0.44	0.41	0.56	0.51	0.49	0.46	0.48
1.4	0.49	0.48	0.67	0.58	0.56	0.55	0.56
1.6	0.55	0.54	0.73	0.64	0.64	0.6	0.62
1.8	0.6	0.61	0.81	0.71	0.72	0.68	0.69
2	0.72	0.66	0.9	0.77	0.78	0.76	0.77
2.5	0.81	0.81	1.1	0.89	0.94	0.91	0.91
3	0.89	0.94	1.25	1.03	1.09	1.08	1.05
3.5	0.96	1.06	1.39	1.13	1.22	1.18	1.16
4	1.02	1.13	1.49	1.21	1.32	1.21	1.23
4.5	1.07	1.22	1.61	1.29	1.39	1.34	1.32
5	1.13	1.26	1.68	1.35	1.47	1.41	1.38
5.5	1.17	1.34	1.75	1.41	1.53	1.45	1.44
6	1.23	1.4	1.81	1.45	1.59	1.49	1.50
7	1.29	1.47	1.87	1.49	1.62	1.53	1.55
8	1.34	1.53	1.92	1.53	1.68	1.56	1.59
9	1.36	1.58	1.98	1.57	1.72	1.59	1.63
10	1.37	1.61	2.02	1.58	1.75	1.6	1.66
11	1.37	1.65	2.03	1.59	1.76	1.6	1.67
12	1.37	1.67	2.04	1.59	1.78	1.6	1.68
13	1.37	1.68	2.04	1.59	1.78	1.6	1.68
14	1.37	1.7	2.04	1.59	1.78	1.6	1.68
15	1.37	1.7	2.04	1.59	1.78	1.6	1.68

Table A. 3: BENDING TEST RESULTS FOR ORIENTATION TWO - LOADED ON THE EDGE

	Load Kn					
Deflection (mm)	**SST5**	**SST10**	**SST11**	**SST14**	**SST15**	**Average**
0.10	0.04	0.08	0.06	0.05	0.07	0.06
0.20	0.10	0.14	0.12	0.12	0.12	0.12
0.40	0.18	0.27	0.22	0.21	0.23	0.22
0.60	0.27	0.37	0.29	0.31	0.30	0.31
0.80	0.36	0.46	0.38	0.38	0.42	0.40
1.00	0.44	0.55	0.46	0.50	0.46	0.48
1.20	0.52	0.65	0.54	0.57	0.55	0.57
1.40	0.59	0.72	0.63	0.65	0.64	0.65
1.60	0.68	0.82	0.70	0.73	0.74	0.73
1.80	0.76	0.91	0.77	0.81	0.82	0.81
2.00	0.83	0.99	0.84	0.89	0.90	0.89
2.50	1.00	1.19	1.01	1.07	1.05	1.06
3.00	1.16	1.35	1.14	1.22	1.20	1.21
3.50	1.30	1.49	1.24	1.34	1.33	1.34
4.00	1.39	1.60	1.32	1.44	1.42	1.43
4.50	1.48	1.69	1.40	1.52	1.48	1.51
5.00	1.56	1.76	1.46	1.59	1.56	1.59
5.50	1.62	1.80	1.51	1.64	1.62	1.64
6.00	1.68	1.86	1.55	1.70	1.68	1.69
7.00	1.74	1.89	1.62	1.75	1.74	1.75
8.00	1.80	1.91	1.67	1.79	1.80	1.79
9.00	1.80	1.92	1.71	1.81	1.80	1.81
10.00		1.92	1.74	1.82		1.83
11.00			1.76	1.83		1.79
12.00			1.77	1.83		1.80
13.00			1.78	1.83		1.81
14.00			1.78			1.78
15.00						

Table A. 4 BENDING TEST RESULTS FOR ORIENTATION TWO - LOADED ON INNER FACE

	Load Kn					
Deflection (mm)	**SST2**	**SST3**	**SST8**	**SST9**	**SST4**	**Average**
0.10	0.07	0.04	0.07	0.06	0.06	0.06
0.20	0.10	0.10	0.09	0.12	0.08	0.10
0.40	0.19	0.16	0.16	0.21	0.21	0.19
0.60	0.26	0.23	0.22	0.30	0.31	0.26
0.80	0.33	0.30	0.29	0.38	0.40	0.34
1.00	0.40	0.36	0.36	0.46	0.48	0.41
1.20	0.47	0.42	0.42	0.53	0.57	0.48
1.40	0.52	0.48	0.48	0.60	0.66	0.55
1.60	0.57	0.54	0.52	0.70	0.74	0.61
1.80	0.62	0.59	0.59	0.75	0.82	0.67
2.00	0.66	0.65	0.64	0.80	0.90	0.73
2.50	0.80	0.77	0.77	0.95	1.06	0.87
3.00	0.90	0.87	0.86	1.06	1.18	0.97
3.50	0.99	0.96	0.94	1.15	1.29	1.07
4.00	1.08	1.04	1.02	1.22	1.38	1.15
4.50	1.16	1.11	1.08	1.30	1.44	1.22
5.00	1.22	1.18	1.14	1.35	1.51	1.28
5.50	1.29	1.22	1.19	1.40	1.56	1.33
6.00	1.34	1.27	1.23	1.45	1.60	1.38
7.00	1.42	1.31	1.26	1.49	1.62	1.42
8.00	1.48	1.34	1.32	1.52		1.42
9.00	1.52	1.36	1.34	1.55		1.44
10.00	1.53	1.39	1.34	1.55		1.45
11.00		1.40				1.40
12.00		1.41				1.41
13.00						1.81
14.00						1.78

Table A. 5: BENDING TEST RESULTS FOR ORIENTATION TWO - LOADED ON OUTER FACE

	Load Kn			
Deflection (mm)	**SST1**	**SST6**	**SST7**	**Average**
0.10	0.08	0.02	0.08	0.06
0.20	0.16	0.06	0.12	0.11
0.40	0.24	0.12	0.21	0.19
0.60	0.32	0.19	0.27	0.26
0.80	0.39	0.24	0.33	0.32
1.00	0.46	0.28	0.38	0.37
1.20	0.55	0.32	0.42	0.43
1.40	0.62	0.36	0.46	0.48
1.60	0.68	0.40	0.52	0.53
1.80	0.72	0.43	0.55	0.57
2.00	0.78	0.46	0.59	0.61
2.50	0.93	0.54	0.69	0.72
3.00	1.02	0.60	0.78	0.80
3.50	1.12	0.65	0.85	0.87
4.00	1.18	0.67	0.91	0.92
4.50	1.27	0.67	0.96	0.97
5.00	1.32	0.68	1.03	1.01
5.50	1.38	0.71	1.07	1.05
6.00	1.42	0.74	1.12	1.09
7.00	1.48	0.80	1.18	1.15
8.00	1.52	0.82	1.25	1.20
9.00	1.58	0.86	1.29	1.24
10.00	1.60	0.88	1.33	1.27
11.00	1.62	0.91	1.37	1.30
12.00	1.63	0.92	1.39	1.31
13.00	1.64	0.93	1.40	
14.00		0.94	1.40	
15.00				

Table A. 6: BENDING TEST RESULTS FOR JOINTED BEAMS - LOADED ON FACE

	Load Kn					
Deflection (mm)	**J1**	**J2**	**J3**	**J4**	**J5**	**Average**
0.10	0.05	0.07	0.04	0.04	0.05	0.05
0.20	0.08	0.09	0.08	0.07	0.08	0.08
0.40	0.14	0.16	0.15	0.15	0.15	0.15
0.60	0.22	0.23	0.20	0.21	0.21	0.21
0.80	0.27	0.29	0.24	0.26	0.26	0.26
1.00	0.34	0.36	0.29	0.32	0.32	0.33
1.20	0.38	0.41	0.34	0.38	0.37	0.38
1.40	0.43	0.46	0.38	0.44	0.42	0.43
1.60	0.48	0.51	0.43	0.48	0.48	0.48
1.80	0.52	0.56	0.46	0.54	0.52	0.52
2.00	0.56	0.62	0.49	0.57	0.56	0.56
2.50	0.65	0.74	0.55	0.69	0.66	0.66
3.00	0.72	0.83	0.65	0.77	0.74	0.74
3.50	0.78	0.91	0.72	0.83	0.81	0.81
4.00	0.83	0.97	0.77	0.90	0.86	0.87
4.50	0.86	1.02	0.82	0.95	0.91	0.91
5.00	0.89	1.07	0.87	1.01	0.96	0.96
5.50	0.92	1.10	0.91	1.02	0.99	0.99
6.00	0.93	1.13	0.95	1.04	1.01	1.01
7.00	0.95	1.20	1.01	1.09	1.06	1.06
8.00	0.97	1.28		1.14	1.10	1.12
9.00	0.97	1.37		1.18	1.13	1.16
10.00		1.43		1.21	1.16	1.27
11.00		1.54		1.22	1.18	1.31
12.00		1.59		1.23	1.20	1.34
13.00		1.59		1.24	1.20	
14.00		1.61			1.21	
15.00		1.63			1.21	
16.00		1.64			1.21	

Table A. 7: BENDING TEST RESULTS FOR BEAMS WITH COINCIDING NODES - LOADED ON EDGE

	Load Kn				
Deflection (mm)	**CN2**	**CN4**	**CN6**	**CN8**	**Average**
0.10	0.14	0.08	0.10	0.11	0.11
0.20	0.20	0.14	0.18	0.17	0.17
0.40	0.28	0.22	0.24	0.25	0.25
0.60	0.34	0.30	0.31	0.32	0.32
0.80	0.40	0.37	0.38	0.39	0.38
1.00	0.47	0.46	0.46	0.47	0.46
1.20	0.55	0.54	0.56	0.55	0.55
1.40	0.63	0.62	0.63	0.63	0.63
1.60	0.69	0.69	0.70	0.69	0.69
1.80	0.76	0.76	0.78	0.76	0.77
2.00	0.81	0.84	0.85	0.83	0.83
2.50	0.98	1.06	1.04	1.02	1.03
3.00	1.12	1.22	1.23	1.17	1.19
3.50	1.24	1.38	1.32	1.31	1.31
4.00	1.35	1.50	1.45	1.43	1.43
4.50	1.44	1.62	1.54	1.53	1.53
5.00	1.51	1.71	1.62	1.61	1.61
5.50	1.56	1.79	1.69	1.68	1.68
6.00	1.61	1.87	1.74	1.74	1.74
7.00	1.66	1.98	1.80	1.82	1.82
8.00	1.71	2.07	1.88	1.89	1.89
9.00	1.76	2.10	1.92	1.93	1.93
10.00	1.77	2.12	1.94	1.95	1.94
11.00	1.78	2.12	1.95	1.95	1.95
12.00	1.78		1.95	1.95	1.89

Table A. 8: BENDING TEST RESULTS FOR BEAMS WITH COINCIDING NODES - LOADED ON FACE

	Load Kn				
Deflection (mm)	**CN1**	**CN3**	**CN7**	**CN5**	**Average**
0.10	0.06	0.06	0.05	0.06	0.06
0.20	0.10	0.10	0.09	0.10	0.10
0.40	0.20	0.16	0.18	0.18	0.18
0.60	0.26	0.24	0.22	0.25	0.24
0.80	0.34	0.31	0.32	0.33	0.32
1.00	0.42	0.36	0.37	0.39	0.39
1.20	0.50	0.42	0.44	0.46	0.46
1.40	0.55	0.48	0.46	0.52	0.50
1.60	0.62	0.54	0.56	0.58	0.58
1.80	0.70	0.60	0.62	0.64	0.64
2.00	0.74	0.66	0.68	0.70	0.70
2.50	0.89	0.71	0.76	0.80	0.79
3.00	1.02	0.76	0.84	0.89	0.88
3.50	1.12	0.85	0.96	0.99	0.98
4.00	1.23	0.94	1.08	1.09	1.08
4.50	1.30	1.04	1.20	1.17	1.18
5.00	1.38	1.11	1.26	1.25	1.25
5.50	1.44	1.18	1.34	1.31	1.32
6.00	1.50	1.22	1.35	1.36	1.36
7.00	1.60	1.30	1.44	1.45	1.45
8.00	1.68	1.38	1.52	1.53	1.53
9.00	1.75	1.45	1.62	1.60	1.61
10.00	1.82	1.50	1.68	1.66	1.67
11.00	1.85	1.54	1.74	1.70	1.71
12.00	1.89	1.56	1.76	1.73	1.73
13.00	1.89	1.59	1.75	1.74	1.74
14.00	1.90	1.60	1.75	1.75	1.75

Table A. 9: BENDING TEST RESULTS FOR END 2 BEAMS - LOADED ON FACE

	Load Kn				
Deflection (mm)	**T1**	**T2**	**T3**	**T4**	**Average**
0.10	0.05	0.05	0.05	0.05	0.05
0.20	0.08	0.07	0.07	0.08	0.08
0.40	0.15	0.12	0.14	0.13	0.14
0.60	0.21	0.19	0.20	0.20	0.20
0.80	0.25	0.22	0.23	0.24	0.24
1.00	0.32	0.27	0.29	0.30	0.30
1.20	0.38	0.32	0.35	0.35	0.35
1.40	0.43	0.36	0.39	0.40	0.40
1.60	0.49	0.41	0.45	0.45	0.45
1.80	0.54	0.44	0.49	0.49	0.49
2.00	0.59	0.47	0.53	0.53	0.53
2.50	0.69	0.57	0.63	0.64	0.63
3.00	0.80	0.63	0.71	0.72	0.72
3.50	0.89	0.70	0.79	0.80	0.80
4.00	0.96	0.74	0.85	0.86	0.85
4.50	1.02	0.78	0.90	0.90	0.90
5.00	1.07	0.82	0.94	0.95	0.95
5.50	1.12	0.87	0.99	1.00	1.00
6.00	1.15	0.89	1.02	1.02	1.02
7.00	1.19	0.93	1.06	1.07	1.06
8.00	1.23	0.97	1.10	1.11	1.10
9.00	1.25	1.01	1.13	1.13	1.13
10.00	1.26	1.03	1.14	1.15	1.15
11.00	1.26	1.06	1.16	1.16	1.16
12.00	1.26	1.09	1.17	1.18	1.18
13.00	1.26	1.09	1.17	1.18	1.18

Table A. 10: BENDING TEST RESULTS FOR END 1 BEAMS - LOADED ON FACE

	Load Kn				
Deflection (mm)	**B1**	**B2**	**B3**	**B4**	**Average**
0.10	0.06	0.04	0.05	0.05	0.05
0.20	0.10	0.08	0.08	0.08	0.09
0.40	0.16	0.14	0.15	0.15	0.15
0.60	0.22	0.18	0.22	0.21	0.21
0.80	0.30	0.24	0.26	0.26	0.27
1.00	0.36	0.30	0.32	0.31	0.32
1.20	0.42	0.34	0.36	0.37	0.37
1.40	0.48	0.38	0.42	0.42	0.43
1.60	0.52	0.44	0.48	0.48	0.48
1.80	0.58	0.48	0.52	0.52	0.53
2.00	0.64	0.52	0.56	0.57	0.57
2.50	0.69	0.62	0.69	0.66	0.67
3.00	0.86	0.70	0.77	0.77	0.78
3.50	0.95	0.78	0.85	0.86	0.86
4.00	1.02	0.86	0.90	0.93	0.93
4.50	1.10	0.92	0.98	1.00	1.00
5.00	1.16	0.98	1.02	1.05	1.05
5.50	1.21	1.02	1.06	1.09	1.10
6.00	1.27	1.08	1.08	1.14	1.14
7.00	1.34	1.12	1.11	1.19	1.19
8.00	1.40	1.19	1.11	1.23	1.23
9.00	1.42	1.24	1.11	1.25	1.26
10.00	1.42	1.28	1.11	1.27	1.27
11.00	1.42	1.30	1.11	1.27	1.28
12.00	1.42	1.30	1.11	1.28	1.28

Table A. 11: BENDING TEST RESULTS FOR CENTRAL PARTS BEAMS - LOADED ON FACE

	Load Kn				
Deflection (mm)	**M1**	**M2**	**M3**	**M4**	**Average**
0.10	0.08	0.08	0.08	0.07	0.08
0.20	0.13	0.14	0.14	0.13	0.14
0.40	0.19	0.22	0.24	0.21	0.22
0.60	0.25	0.32	0.28	0.28	0.28
0.80	0.30	0.41	0.35	0.35	0.35
1.00	0.38	0.48	0.40	0.42	0.42
1.20	0.43	0.56	0.46	0.47	0.48
1.40	0.48	0.64	0.53	0.55	0.55
1.60	0.52	0.72	0.58	0.60	0.61
1.80	0.56	0.78	0.64	0.66	0.66
2.00	0.62	0.86	0.68	0.72	0.72
2.50	0.72	1.02	0.79	0.83	0.84
3.00	0.80	1.18	0.87	0.95	0.95
3.50	0.88	1.30	0.91	1.02	1.03
4.00	0.94	1.42	0.96	1.11	1.11
4.50	1.01	1.50	1.01	1.17	1.17
5.00	1.06	1.58	1.04	1.23	1.23
5.50	1.12	1.64	1.08	1.28	1.28
6.00	1.16	1.69	1.09	1.31	1.31
7.00	1.22	1.74	1.12	1.36	1.36
8.00	1.28	1.78	1.12	1.39	1.39
9.00	1.34	1.82	1.12	1.43	1.43
10.00	1.37	1.82	1.12	1.44	1.44
11.00	1.41	1.82	1.12	1.45	1.45
12.00	1.44	1.82	1.12	1.46	1.46
13.00	1.45	1.82	1.12	1.46	1.46
14.00	1.45	1.82	1.12	1.46	1.46

Table A. 12: BENDING TEST RESULTS OF OUTER LAYERS BEAMS - LOADED ON THE FACE

	Load Kn				
Deflection (mm)	**OP1**	**OP2**	**OP3**	**OP4**	**Average**
0.10	0.08	0.06	0.07	0.07	0.07
0.20	0.11	0.07	0.10	0.08	0.09
0.40	0.19	0.12	0.17	0.15	0.16
0.60	0.23	0.19	0.20	0.21	0.21
0.80	0.29	0.22	0.26	0.24	0.25
1.00	0.34	0.26	0.28	0.30	0.30
1.20	0.40	0.30	0.35	0.34	0.35
1.40	0.44	0.33	0.37	0.39	0.38
1.60	0.49	0.36	0.43	0.45	0.43
1.80	0.53	0.38	0.46	0.46	0.46
2.00	0.58	0.40	0.48	0.50	0.49
2.50	0.69	0.48	0.56	0.59	0.58
3.00	0.78	0.54	0.66	0.68	0.67
3.50	0.86	0.60	0.71	0.73	0.73
4.00	0.93	0.65	0.79	0.80	0.79
4.50	0.99	0.68	0.82	0.84	0.83
5.00	1.06	0.72	0.89	0.90	0.89
5.50	1.12	0.74	0.91	0.93	0.93
6.00	1.15	0.76	0.96	0.98	0.96
7.00	1.24	0.78	0.99	1.01	1.01
8.00	1.28	0.78	1.03	1.05	1.04
9.00	1.34		1.05	1.06	1.15
10.00	1.38		1.08	1.09	1.18
11.00	1.39		1.09	1.10	1.19
12.00	1.42		1.10	1.11	1.21
13.00	1.44		1.11	1.12	1.22
14.00	1.47		1.13	1.13	1.24
15.00	1.48		1.13	1.13	

Table A. 13: BENDING TEST RESULTS OF OUTER LAYERS BEAMS - LOADED ON THE EDGE

	Load Kn				
Deflection (mm)	**OP1**	**OP2**	**OP3**	**OP4**	**Average**
0.10	0.08	0.03	0.06	0.05	0.05
0.20	0.18	0.07	0.12	0.13	0.12
0.40	0.26	0.15	0.21	0.19	0.20
0.60	0.35	0.24	0.29	0.30	0.29
0.80	0.44	0.31	0.38	0.40	0.38
1.00	0.50	0.36	0.41	0.43	0.43
1.20	0.56	0.45	0.51	0.50	0.50
1.40	0.66	0.52	0.58	0.59	0.59
1.60	0.72	0.60	0.66	0.67	0.66
1.80	0.80	0.68	0.70	0.74	0.73
2.00	0.86	0.72	0.79	0.82	0.80
2.50	1.04	0.88	0.98	0.96	0.97
3.00	1.17	1.03	1.00	1.10	1.08
3.50	1.29	1.13	1.21	1.20	1.21
4.00	1.38	1.20	1.26	1.29	1.28
4.50	1.48	1.28	1.38	1.36	1.38
5.00	1.56	1.33	1.43	1.45	1.44
5.50	1.60	1.38	1.49	1.48	1.49
6.00	1.65	1.41	1.52	1.53	1.53
7.00	1.70	1.43	1.57	1.55	1.56
8.00	1.72	1.44	1.59	1.58	1.58
9.00	1.73	1.47	1.60	1.59	1.60
10.00	1.73	1.48	1.61	1.60	1.60
11.00		1.49	1.61	1.61	1.57

Table A. 14: BENDING TEST RESULTS INNER LAYERS BEAMS - LOADED ON THE FACE

	Load Kn					
Deflection (mm)	**IL1**	**IL2**	**IL3**	**IL4**	**IL5**	**Average**
0.10	0.05	0.05	0.07	0.06	0.06	0.06
0.20	0.07	0.08	0.08	0.07	0.09	0.08
0.40	0.12	0.13	0.14	0.12	0.14	0.13
0.60	0.17	0.17	0.19	0.16	0.20	0.18
0.80	0.21	0.21	0.23	0.23	0.21	0.22
1.00	0.25	0.25	0.28	0.29	0.23	0.26
1.20	0.29	0.29	0.31	0.32	0.28	0.30
1.40	0.33	0.34	0.35	0.36	0.32	0.34
1.60	0.36	0.36	0.39	0.39	0.35	0.37
1.80	0.38	0.39	0.42	0.40	0.38	0.39
2.00	0.41	0.43	0.45	0.44	0.42	0.43
2.50	0.50	0.52	0.55	0.53	0.51	0.52
3.00	0.57	0.59	0.62	0.60	0.58	0.59
3.50	0.63	0.66	0.69	0.65	0.67	0.66
4.00	0.68	0.72	0.75	0.70	0.72	0.71
4.50	0.72	0.79	0.81	0.77	0.77	0.77
5.00	0.77	0.83	0.87	0.81	0.83	0.82
5.50	0.80	0.88	0.92	0.85	0.87	0.86
6.00	0.84	0.93	0.97	0.90	0.92	0.91
7.00	0.88	0.96	1.04	0.98	0.94	0.96
8.00	0.90	1.03	1.09	1.01	0.90	0.99
9.00	0.95	1.06	1.15	1.06	1.04	1.05
10.00	0.99	1.08	1.23	1.11	1.08	1.10
11.00	1.02	1.09	1.25	1.14	1.10	1.12
12.00	1.05	1.09	1.27	1.14	1.13	1.14
13.00	1.07	1.09	1.27	1.14	1.14	1.14
14.00	1.08	1.09	1.27	1.15	1.15	1.15

Table A. 15: BENDING TEST RESULTS INNER LAYERS BEAMS - LOADED ON THE EDGE

	Load Kn					
Deflection (mm)	**IL6**	**IL7**	**IL8**	**IL9**	**IL10**	**Average**
0.10	0.04	0.04	0.20	0.09	0.08	0.09
0.20	0.07	0.15	0.07	0.11	0.12	0.10
0.40	0.10	0.23	0.12	0.15	0.14	0.15
0.60	0.15	0.29	0.17	0.21	0.22	0.21
0.80	0.19	0.36	0.22	0.25	0.24	0.25
1.00	0.22	0.41	0.26	0.31	0.29	0.30
1.20	0.25	0.47	0.31	0.33	0.34	0.34
1.40	0.28	0.52	0.36	0.37	0.30	0.37
1.60	0.33	0.57	0.40	0.44	0.43	0.43
1.80	0.35	0.63	0.45	0.47	0.45	0.47
2.00	0.37	0.69	0.49	0.52	0.50	0.51
2.50	0.40	0.80	0.54	0.57	0.58	0.58
3.00	0.49	0.91	0.64	0.68	0.67	0.68
3.50	0.53	1.00	0.71	0.76	0.78	0.76
4.00	0.59	1.08	0.79	0.81	0.80	0.81
4.50	0.63	1.14	0.85	0.89	0.87	0.88
5.00	0.69	1.20	0.91	0.93	0.91	0.93
5.50	0.72	1.25	0.95	0.98	0.97	0.97
6.00	0.77	1.30	0.98	1.03	1.04	1.02
7.00	0.82	1.38	1.00	1.07	1.06	1.07
8.00	0.86	1.42	1.02	1.12	1.13	1.11
9.00	0.91	1.46	1.04	1.14	1.15	1.14
10.00	0.93	1.49	1.04	1.15	1.16	1.15
11.00	0.95	1.50		1.16	1.17	1.20
12.00	0.97			1.17	1.18	1.11
13.00	0.99			1.18		1.09
14.00	1.01					1.01
15.00	1.01					1.01

Table A. 16: BENDING TEST RESULTS OF OUTERLAYERS BEAMS - GLUE TYPE 2 - LOADED ON THE EDGE

	Load Kn								
Deflection (mm)	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**	**Average**
0.10	0.02	0.04	0.04	0.04	0.02	0.04	0.03	0.05	0.04
0.20	0.02	0.08	0.05	0.07	0.03	0.07	0.06	0.08	0.06
0.40	0.04	0.14	0.08	0.13	0.05	0.12	0.10	0.13	0.10
0.60	0.05	0.19	0.11	0.17	0.06	0.18	0.16	0.19	0.15
0.80	0.06	0.24	0.13	0.21	0.08	0.23	0.20	0.24	0.18
1.00	0.07	0.29	0.15	0.25	0.09	0.28	0.24	0.30	0.22
1.20	0.08	0.33	0.16	0.28	0.11	0.32	0.30	0.33	0.25
1.40	0.08	0.37	0.18	0.32	0.12	0.36	0.32	0.37	0.28
1.60	0.10	0.41	0.20	0.36	0.13	0.40	0.32	0.41	0.31
1.80	0.11	0.44	0.22	0.38	0.13	0.43	0.35	0.45	0.33
2.00	0.12	0.47	0.23	0.42	0.14	0.48	0.38	0.49	0.36
2.50	0.16	0.56	0.27	0.46	0.17	0.55	0.40	0.58	0.42
3.00	0.17	0.57	0.28	0.48	0.19	0.62	0.42	0.66	0.46
3.50	0.19	0.58	0.29	0.53	0.21	0.66	0.42	0.72	0.49
4.00	0.21	0.58	0.29	0.55	0.22	0.68	0.44	0.77	0.51
4.50	0.22	0.58	0.29	0.56	0.23	0.68	0.47	0.82	0.52
5.00	0.24	0.60		0.56	0.24	0.68	0.50	0.85	0.56
5.50	0.25	0.64	.		0.24		0.52	0.85	0.49
6.00	0.26	0.67			0.24		0.54	0.87	0.50
7.00	0.26	0.69			0.25		0.56	0.87	0.53
8.00	0.27				0.28		0.58		0.38
9.00	0.28						0.58		0.43
10.00	0.28								0.28

Table A. 17: BENDING TEST RESULTS OUTERLAYERS BEAMS -GLUE TYPE 2 - LOADED ON THE EDGE

	Load Kn					
Deflection (mm)	**G11**	**G12**	**G13**	**G14**	**G15**	**Average**
0.10	0.08	0.06	0.05	0.07	0.01	0.05
0.20	0.12	0.12	0.07	0.11	0.05	0.09
0.40	0.20	0.19	0.12	0.16	0.13	0.16
0.60	0.28	0.26	0.17	0.23	0.22	0.23
0.80	0.37	0.33	0.23	0.28	0.32	0.31
1.00	0.43	0.41	0.30	0.33	0.41	0.38
1.20	0.51	0.48	0.34	0.38	0.49	0.44
1.40	0.59	0.56	0.40	0.43	0.56	0.51
1.60	0.66	0.62	0.44	0.48	0.65	0.57
1.80	0.74	0.69	0.48	0.52	0.73	0.63
2.00	0.80	0.76	0.54	0.56	0.82	0.70
2.50	0.96	0.91	0.66	0.65	0.99	0.83
3.00	1.10	1.04	0.74	0.70	1.19	0.95
3.50	1.21	1.14	0.81	0.71	1.28	1.03
4.00	1.30	1.23	0.88	0.75	1.40	1.11
4.50	1.38	1.29	0.90	0.78	1.46	1.16
5.00	1.45	1.34	0.90	0.82	1.52	1.21
5.50	1.51	1.39		0.83	1.57	1.33
6.00	1.56	1.42		0.86	1.59	1.36
7.00	1.63	1.44		0.89	1.62	1.40
8.00	1.67	1.45		0.91	1.62	1.41
9.00	1.69	1.46		0.92	1.65	1.43
10.00	1.69	1.46		0.98	1.66	1.45
11.00		1.46		0.98		

TENSILE TESTS RESULTS FOR SMALL CLEAR SPECIMEN

Table A. 18: TENSILE TEST DATA – OUTER SURFACE REMOVED

Description	**Sample No.**	**Strength (Kn)**
Bamboo Strip with outer surface removed	TO1	4.99
	TO2	4.14
	TO3	5.71
	TO4	3.38
	TO5	3.28
	TO6	5.7
	TO7	4
	TO8	5.13
	TO9	4.4
	TO10	4.6
Average		**4.53**

Table A. 19: TENSILE TEST DATA - WITH OUTER SURFACE

Description	**Sample No.**	**Strength (Kn)**
Bamboo Strip with outer surface	TC1	7.06
	TC2	4.99
	TC3	4.14
	TC4	5.83
	TC5	6.76
	TC6	5.71
	TC7	3.38
	TC8	5.3
	TC9	5.52
	TC10	5.4
Average		5.41

Table A. 20: TENSILE TEST DATA – WITH NODES

Description	Sample No.	Strength (Kn)
Bamboo Strips with Nodes at the Centre	TN1	1.78
	TN2	3.76
	TN3	2.9
	TN4	2.48
	TN5	1.8
	TN6	3.74
	TN7	3.2
	TN8	2.18
	TN9	2.7
	TN10	2.76
Average		**2.73**

COMPRESSION TEST RESULTS FOR SMALL CLEAR SPECIMEN

Table A. 21: BENDING TEST RESULTS - 1

TABLE A21-1:				
ORIENTATION 2 - BEAMS			**ORIENTATION 1 – BEAMS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
OO1	21.94		SST1	25.01
OO2	21.55		SST2	23.57
OO3	19.46		SST3	21.36
OO4	21.6		SST4	25.64
OO5	21.68		SST5	22.88
OO6	19.6		SST6	19.59
OO7	20.63		SST7	23.11
OO8	20.97		SST8	21.32
OO9	21.21		**Average**	22.81
OO10	23			
Average	**21.16**			
CENTRAL PART - BEAMS			**END 1 - BEAMS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
M1	24.88		B1	18.27
M2	24.05		B2	19.11
M3	25.98		B3	18.75
M4	26.88		**Average**	**18.71**
Average	**25.45**			

Table A. 22: BENDING TEST RESULTS - 2

TABLE A21-2:				
END 2 - BEAMS			**GLUE TYPE 1 - BEAMS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
T1	23.88		OP1	18.29
T3	21.37		OP2	17.4
T2	21.16		OP3	15.26
Average	**22.14**		OP4	19.24
			Average	**17.55**
INNER LAYERS - BEAMS			**GLUE TYPE 2 - BEAMS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
IC1	13.18		OPM1	20.51
IC2	12.79		OPM2	16.23
IC3	11.79		OPM3	19.76
IC4	9.9		OPM4	17.83
IC5	8.42		OPM5	19.64
IC6	14.66		OPM6	18.12
IC7	14.69		OPM7	18.42
IC8	11.87		OPM8	18.42
IC9	11.93		OPM9	20.19
IC10	12.13		OPM10	18.66
Average	**12.14**		OPM11	21.64
			Average	**19.04**

SHEAR TEST RESULTS FOR SMALL CLEAR SPECIMEN

Table A. 23: SHEAR TEST RESULTS - 1

TABLE A22-1:				
CENTRAL PART BEAMS				
PERPENDICULAR TO STRIPS			**PARALLEL TO STRIPS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
M1	4.61		M5	6.32
M2	5		M6	2.45
M3	4.71		M7	4
M4	4.9		M8	4.8
Average	**4.81**		**Average**	**4.39**
END 1 BEAMS				
PERPENDICULAR TO STRIPS			**PARALLEL TO STRIPS**	
Specimen	**Max Load**		**Specimen**	**Max Load**

B1	2.86		B5	2.62
B2	2.86		B6	3.01
B3	2.84		B7	2.6
B4	2.87		B8	3.1
Average	**2.86**		**Average**	**2.83**
END 2 BEAMS				
PERPENDICULAR TO STRIPS			**PARALLEL TO STRIPS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
T1	3.86		T5	4.81
T2	4.02		T6	4.7
T3	3.6		T7	5.2
T4	3.94		T8	4.34
Average	**3.86**		**Average**	**4.76**
ORIENTATION 2 BEAMS				
PERPENDICULAR TO STRIPS			**PARALLEL TO STRIPS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
SST1	3.91		SST7	2.94
SST2	2.62		SST8	2.81
SST3	2.65		SST9	3.45
SST4	3.3		**Average**	**3.07**
SST5	3.19			
SST6	3.46			
Average	**3.19**			
ORIENTATION 1 BEAMS				
PERPENDICULAR TO STRIPS			**PARALLEL TO STRIPS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
OO1	3.36		OO11	3.62
OO2	3.86		OO12	2.83
OO3	3.16		OO13	3.35
OO4	2.49		OO14	3.85
OO5	3.95		OO15	3.2
OO6	3.79		OO16	3.24
OO7	4.29		OO17	3.56
OO8	3.75		OO18	3.95
OO9	3.34		OO19	2.57
OO10	4		OO20	2.09
Average	**3.60**		**Average**	**3.23**
GLUE TYPE 1 BEAMS				
PERPENDICULAR TO STRIPS			**PARALLEL TO STRIPS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
OP1	3.8		OP7	3.4
OP2	3.4		OP8	2.37

OP3	3.8		OP9	2.85
OP4	3.71		OP10	2.98
OP5	3.22		OP11	2.26
OP6	3.61		OP12	2.02
Average	**3.59**		**Average**	**2.65**
INNER LAYERS BEAMS				
PERPENDICULAR TO STRIPS			**PARALLEL TO STRIPS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
IC1	2.45		IC7	3.48
IC2	1.96		IC8	3.38
IC3	1.5		IC9	3.6
IC4	1.8		IC10	3.56
IC5	1.44		IC11	3.37
Average	**1.83**		**Average**	**3.48**
GLUE TYPE 2 BEAMS				
PERPENDICULAR TO STRIPS			**PARALLEL TO STRIPS**	
Specimen	**Max Load**		**Specimen**	**Max Load**
OPM1	3.42		OPM6	2.29
OPM2	3.13		OPM7	2.57
OPM3	3.42		OPM8	1.92
OPM4	3.18		OPM9	2.91
OPM5	3.97		OPM10	1.7
Average	**3.42**		**Average**	**2.28**

Table A. 24: BENDING TEST RESULTS FOR CYPRESS FULL SCALE BEAMS

CYPRESS BEAM 1			CYPRESS BEAM 2			CYPRESS BEAM 3		
Deflection (Ʋ)	**Load (Ʋ)**	**Strain (Ʋ)**	**Deflection (Ʋ)**	**Load (Ʋ)**	**Strain (Ʋ)**	**Deflection (Ʋ)**	**Load (Ʋ)**	**Strain (Ʋ)**
			1185	95	2930	**0**	0	0
1	1	0	1177	98	3022	945	8	126
218	4	1	1178	101	3115	1451	25	369
1759	8	215	1174	107	3300	1539	36	531
1759	14	384	1170	119	3670	1539	48	708
1824	26	719	1177	124	3824	1537	61	900
1722	38	1081	1238	131	4040	1510	85	1255
1725	48	1399	1404	142	4379	1634	92	1358
1724	56	1653	1488	148	4564	1812	102	1506
1786	71	2108	1552	154	4749	1989	112	1654
1975	83	2503	1625	156	4811	2025	114	1683
2073	95	2922	1764	166	5119	2167	122	1801
2288	107	3370	1857	170	5243	2380	134	1979
2401	119	3852	1971	173	5335	2469	139	2052
2558	131	4379	1972	177	5459	2575	145	2141
2836	147	5037	1972	181	5582	2789	157	2318
3320	16	40222	1977	183	5644	2895	163	2407
			1979	187	5767	3091	174	2569
			2007	187	5767	3304	186	2747

Table A. 25: BENDING TEST RESULTS FOR BEAMS WITH OUTER LAYERS ON EXTREME FIBRES AND INNER LAYERS AT THE CENTRE

Beam 1	**Deflection (U)**	1	1	25	32	34	34	34	38	42	44	47	49	53	55
Max Load 50.495	**Load (U)**	0	1	91	116	124	124	124	138	153	160	171	179	193	201
Beam2	**Deflection (U)**	34	53	58	58	59	62	63	64	64	65	64	65	66	66
Max Load 33.695	**Load (U)**	0	153	212	219	250	289	298	304	306	330	340	349	373	379
Beam3	**Deflection (U)**	89	90	94	95	97	102	106	107	110	112	114	118	119	120
Max Load 40.531	**Load (U)**	5	100	141	202	277	338	371	444	466	510	593	633	659	697

Beam 1	**Deflection (U)**	59	62	65	68	72	75	77	81	88	91	94	98	100	103
Max Load 50.495	**Load (U)**	215	226	237	248	263	274	281	296	321	332	343	358	365	376
Beam2	**Deflection (U)**	67	69	70	77	78	80	81	82	83	85	86	87	90	91
Max Load 33.695	**Load (U)**	388	446	468	574	583	595	598	603	614	654	670	712	787	811
Beam3	**Deflection (U)**	121	123	125	126	128	129	130	130	132	133	134	137	138	142
Max Load 40.531	**Load (U)**	761	779	802	834	875	908	948	951	996	1030	1183	1244	1345	1411

Beam 1	**Deflection (U)**	107	110	107	111	116	119	122	125	128	130	132	134	136
Max Load 50.495	**Load (U)**	391	402	391	405	424	434	445	456	467	475	482	489	497
Beam2	**Deflection (U)**	92	94	95	96	98	99	101	105	107	108	109	111	112
Max Load 33.695	**Load (U)**	829	869	902	935	955	979	1022	1116	1158	1171	1193	1223	1257
Beam3	**Deflection (U)**	151	233	246	241	237	235	234	233	229	227	281	274	268
Max Load 40.531	**Load (U)**	1440	1450	1453	1454	1454	1455	1455	1455	1456	1463	1463	1463	1463

Beam 1	**Deflection (U)**	139	141	142	142	143	144	144	144	143	157	194	300	384
	Load (U)	508	515	519	519	522	526	526	526	522	573	709	1096	1403
Beam2	**Deflection (U)**	113	114	115	116	117	118	119	121	124	125	127	129	125
	Load (U)	1290	1305	1308	1315	1348	1375	1399	1411	1469	1522	1527	1527	1527
Beam3	**Deflection (U)**	264	262	259	257	280	287	293	298	306	312	315	323	326
	Load (U)	1463	1463	1463	1463	1463	1463	1463	1463	1463	1463	1463	1463	1463

Beam 1	**Deflection (U)**	377	373	370	367	365	363	361	359	357	354	354	353	350
	Load (U)	1378	1363	1352	1341	1334	1326	1319	1312	1304	1293	1293	1290	1279
Beam2	**Deflection (U)**	132	137	140	142	143	143	143	144	145	147	147	147	148
	Load (U)	1527	1527	1527	1527	1527	1527	1527	1527	1527	1527	1527	1527	1527
Beam3	**Deflection (U)**	337												
	Load (U)	1463												

Beam 1	**Deflection (U)**	349	349	347	346	28								
	Load (U)	1275	1275	1268	1264	102								
Beam2	**Deflection (U)**	149	150	150	151	186	210	281	274	268	264	262	259	257
	Load (U)	1527	1527	1527	1527	1527	1527	1527	1527	1527	1527	1527	1527	1527
Beam3	**Deflection (U)**													
	Load (U)	349	349	347	346	28								

Table A. 26: BENDING TEST RESULTS FOR FULL SCALE BEAMS DATA LOGGER

BEAM 1	**Deflection (U)**	4	1040	1289	1532	1700	1822	1830	2053	2095	2284	2289	2365	2740	2780
	Load (U)	0	39	52	69	79	90	91	104	116	125	128	139	159	163
	Strain (U)	13	495	678	937	1079	1255	1267	1463	1643	1803	1842	2058	2616	2766
BEAM 2	**Deflection (U)**	21	1034	1225	1286	1455	1515	1527	1609	1702	1735	1774	1878	2074	2245
	Load (U)	1	32	45	50	61	65	66	74	80	84	88	97	111	121
	Strain (U)	4	384	577	653	825	906	926	1059	1163	1229	1309	1476	1739	1940
BEAM 3	**Deflection (U)**	1705	1705	1025	1052	1280	1430	1603	1720	2046	2086	2265	2384	2542	2850
	Load (U)	1	0	30	39	52	62	74	87	100	112	124	135	147	171
	Strain (U)	184	184	510	617	768	922	1093	1259	1458	1614	1781	1965	2163	2601

BEAM 1	**Deflection (U)**	2780	3011	3052	3225	3229	3350	3498	3370	3230	3230	3042	3050	3042	
	Load (U)	163	174	185	189	196	199	209	206	197	197	186	188	187	
	Strain (U)	2766	3087	3544	3946	4327	4483	5080	5205	5142	5169	5208	5229	5264	
BEAM 2	**Deflection (U)**	2245	2279	2362	2530	2568	2733	2880	3024	3049	3231	3411	3492	3492	3493
	Load (U)	121	127	136	147	150	158	168	179	181	191	202	209	213	224
	Strain (U)	1940	2038	2236	2495	2549	2752	2986	3272	3311	3577	3858	4064	4183	4591
BEAM 3	**Deflection (U)**	2850	3057	3286	3492	3492	3498	3508	3510	3540					
	Load (U)	171	183	195	208	231	233	235	238	240					
	Strain (U)	2601	2939	3240	3668	4651	5257	5502	5324	5360					

Table A. 27: TRUSS MODEL TEST RESULTS

Truss 1	**Load (U)**	0	0	1	1	2	4	4	5	5	7	8	8	9	9	12	13
	Deflection (U)	6	7	65	65	137	518	657	824	1058	1518	1729	1956	2170	2380	3009	3515
MEMBERS STRAINS (U)	**STG1**	0	0	9	9	12	39	43	47	52	69	80	97	121	173	125	126
	STG2	25	25	28	28	29	30	29	29	28	27	26	26	27	35	15	8
	STG3	2	2	37	37	58	116	126	133	143	137	120	96	65	87	187	214
	STG4	0	1	6	6	9	15	19	25	32	53	64	79	98	82	58	58
	STG5	3	4	11	11	15	13	13	13	10	5	14	28	48	47	5	4

Truss 1	**Load (U)**	16	19	20	23	23	19	23	26	28	34	36	37	37	39	41
	Deflection (U)	4396	176	580	1498	1029	1441	2736	3473	4290	6954	7222	7518	8130	8449	9138
MEMBERS STRAINS (U)	**STG1**	146	169	185	202	219	384	478	524	571	461	480	490	515	536	551
	STG2	4	13	15	21	27	34	36	37	38	91	97	101	109	117	119
	STG3	262	303	324	454	454	139	154	172	187						
	STG4	50	32	26	7	7	87	88	94	95	54	57	56	58	66	61
	STG5	49	181	303	487	638	739	887	1003	1111						

Truss 1	**Load (U)**	42	43	38	36	30	34	36	37	36	35	32	32	33	31	33
	Deflection (U)	9924	10402	664	664	666	666	666	667	667	666	667	667	666	667	667
MEMBERS STRAINS (U)	**STG1**	586	578	551	552	544	574	598	613	636	624	622	650	667	658	714
	STG2	117	62	5	21	29	29	28	28	28	30	34	36	38	40	44
	STG3															
	STG4	48	15	73	87	92	108	115	119	122	128	131	144	152	153	167
	STG5	49	181	303	487	638	739	887	1003	1111						

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Truss 2	Load (U)	12	27	33	39	44	46	49	53	62	73	75	77	79
	Deflection (U)	1896	2400	2625	2852	3071	3187	3347	3555	4236	5359	5612	6052	6324
MEMBERS STRAINS (U)	STG1	272	538	652	759	853	890	942	1004	1169	1369	1411	1373	1482
	STG2	43	51	87	118	113	82	85	72	31	111	176	186	189
	STG3	104	218	268	317	369	404	429	458	531	682	728	713	780
	STG4	79	217	290	359	418	428	452	477	516	520	503	492	505
	STG5	12	4	36	69	124	223	250	277	360	649	739	764	814

Truss 2	Load (U)	90	88	94	97	100	102	105	110	112	111	112	113	113
	Deflection (U)	7323	7353	7794	8040	8308	8554	8870	9350	9605	9857	10081	10344	10509
MEMBERS STRAINS (U)	STG1	1703	1656	1749	1810	1871	1925	2004	2058	2078	2101	2124	2150	2149
	STG2	318	333	377	366	409	449	496	566	633	706	772	854	958
	STG3	965	948	1019	1043	1114	1211	1302	1394	1476	1564	1631	1716	1819
	STG4	465	484	496	519	539	529	510	481	463	450	469	468	469
	STG5	1069	1080	1185	1215	1359	1450	1513	1609	1709	1830	1889	2025	2152

Truss 2	Load (U)	111	65	69	71	74	76	72	102	105	110	112	111	112
	Deflection (U)	10514	2354	2353	2353	2353	2354	2354	8554	8870	9350	9605	9857	10081
MEMBERS STRAINS (U)	STG1	2103	1666	1736	1807	1852	1916	1888	1925	2004	2058	2078	2101	2124
	STG2	1192	1931	2052	2147	2208	2411	2509	449	496	566	633	706	772
	STG3	1993	1882	1977	2050	2108	2268	2445	1211	1302	1394	1476	1564	1631
	STG4	491	287	290	348	401	607	590	529	510	481	463	450	469
	STG5	1069	1080	1185	1215	1359	1450	1513	1609	1709	1830	1889	2025	2152

TABLE: A24

Truss 3	Load (U)	1	3	4	7	7	10	11	14	12	16	16	17	18
	Deflection (U)	40	174	611	1154	1366	2031	2378	2724	2750	3389	3586	3772	3923
MEMBERS STRAINS (U)	STG1	0	5	9	11	13	41	46	47	52	68	81	97	119
	STG2	15	23	25	28	29	33	29	28	28	27	26	26	27
	STG3	1	2	37	39	58	116	127	133	143	137	120	96	65
	STG4	0	1	6	7	9	15	19	25	32	53	64	79	98
	STG5	3	4	9	11	15	14	13	13	10	5	14	28	48

Truss 3	Load (U)	19	19	20	21	21	22	23	24	24	27	28	30	30
	Deflection (U)	4100	4275	4453	4696	4950	5223	5756	6449	7245	7525	7826	8179	8506
MEMBERS STRAINS (U)	STG1	167	128	116	151	163	184	202	219	380	478	523	571	652
	STG2	35	15	8	4	13	15	21	27	34	36	37	38	87
	STG3	87	187	214	262	303	324	454	454	139	154	172	187	268
	STG4	82	58	58	50	32	26	7	7	87	88	94	95	290
	STG5	47	5	4	49	181	303	487	638	739	887	1003	1111	36

Truss 3	Load (U)	31	32	32	34	31	33	37	39					
	Deflection (U)	8823	9113	9416	9711	10016	2141	2141	2141					
MEMBERS STRAINS (U)	STG1	759	863	890	845	1004	1179	1369						
	STG2	118	113	82	85	72	31	111						
	STG3	317	369	404	429	458	531	682						
	STG4	359	418	428	452	477	516	520						
	STG5	69	124	223	250	277	360	649						