UNIVERSITY OF NAIROBI

MECHANICAL PROPERTIES OF BAMBOO (*Bambusa vulgaris*)
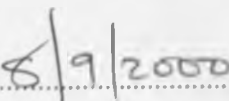
GROWN IN MUGUGA, KENYA

BY

DUNCAN ONYANGO MBUGE

A Thesis Submitted to the University of Nairobi

in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE IN AGRICULTURAL ENGINEERING,

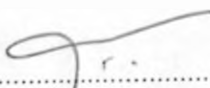Faculty of Engineering,

SEPTEMBER, 2000.

DECLARATION

This thesis is my original work and has not been presented for a degree at any other university.
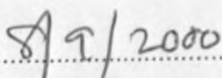
Sign.. Date...8/9/2000

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This thesis has been submitted for examination with my approval as university supervisor.

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DEDICATION

This work is dedicated to:

NICHOLAS AND TERESA MBUGE,

MY BELOVED PARENTS.

ACKNOWLEDGMENTS

ABSTRACT

MECHANICAL PROPERTIES OF BAMBOO (*Bambusa vulgaris*)

GROWN IN MUGUGA, KENYA

By

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This research project investigated the tensile, bending and compressive strength of a species of bamboo called *Bambusa vulgaris*, in an effort to contribute towards the development of a code of design using bamboo. The density of the of B. Vulgaris was found to be 590 kg/m^3 (oven dry). The tensile strength was found to be 94.3 MPa with nodes and 117.9 MPa without nodes. The compressive strength was 49.9 MPa with nodes and 56.7 MPa without nodes, bending strength was 107.0 MPa with nodes and 137.7 MPa without nodes and the modulus of elasticity in tension was 3002.2 MPa with nodes and 3594.0 MPa without nodes. The Modulus of Elasticity in compression was 10,405.3 MPa without nodes and 7,268.1 MPa with nodes. The nodes were found to have a significant effect in lowering the tensile and bending strength of bamboo. The compressive strength was not affected by the presence or absence of nodes.

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LIST OF SYMBOLS

H   - Any value between 0 and 10 derived by dividing the length of the culm into ten   equal parts in which 0 means bottom and 10 means top.

ρ - Density (kg/m^3)

A   - Age (years)

E   - Young's modulus or modulus of elasticity (MPa)

σ - Stress, Ultimate tensile, bending, compressive strength (MPa)

ΔP - Unit force (N)

dP - Unit force (N)

ΔA - Unit area (mm^2)

dA - Unit area (mm^2)

P   - External load (N)

A   - Cross-sectional area (mm^2)

P_x - Mechanical property at a given moisture content (MPa)

P_{12} - Property of bamboo at 12 % moisture content (MPa)

P_g - Property of bamboo in green condition (MPa)

M   - Moisture content at which property is desired (%)

M_p - Moisture content at the inner section of a horizontal line representing the strength of greenwood and an inclined line representing the logarithm strength-moisture content relationship for dry wood (%)

ε - Strain (mm/mm)

l_o - Original length of a member (mm)

l_1 - Final length of a member after straining (mm)

ε_{km} - Cauchy's infinitesimal strain tensor

σ_{ij} - Stress tensor

C_{ijkm} - Stiffness tensor

G   - Modulus of rigidity

υ - Poisson's ratio

σ_n - Normal stress (MPa)

A_0 - Original cross-sectional area (mm^2)

ε^e - Elastic strain

ε^p - Plastic strain

τ	- Shear stress (MPa)
γ	- Shear strain (mm/mm)
W_1	- Mass of sample at test (g)
W_0	- Mass of oven dry sample (g)
F_{max}	- Load at failure (N)
F_t	- Tensile strength (MPa)
Π	- Pi
d_e	- External diameter (mm)
d_i	- Internal diameter (mm)
F_c	- Compressive strength (MPa)
b	- Width of timber (mm)
h	- height of cross-section of timber (mm)
I	- Section moment of area (mm^4)
C	- Maximum height from neutral axis to point of load application (mm)
Z	- Section modulus (mm^3)
F_b	- Bending strength (MPa)
S.D.	- Standard deviation
C.V.	- Coefficient of variation
$\overline{Y}$	- Sample mean
Y_i	- ith observation
n	- Number of observations

ABBREVIATIONS

U.N.   - United Nations
M.C.   - Moisture content
mm.   - Millimeter
m.   - Metre
UON   - University of Nairobi
ILRI   - International Livestock Research Institute
ICRAF   - International Centre for Research in Agroforestry
KEFRI   - Kenya Forestry Research Institute
KBS   - Kenya Bureau of Standards
USDA   - United States Department of Agriculture
BS   - British Standards
KS   - Kenya Standards

CHAPTER 1: INTRODUCTION

1.1 The Need for Sustainable Use of Forests

Wood is only a renewable resource if the annual supply of wood products can keep up with the demand for them. This has not been the case in Kenya because trees are being cut down much faster than they can replace themselves (Ondimu and Gumbe, 1997 and Hankins, 1987).

The forested area in Kenya has, therefore, been on the decline. While this is largely attributable to clearing for agriculture, fuel-wood, and paper manufacture, many trees are cut each year for use in the building and furniture industry. Wood is a commonly used building material in many parts of the world because of its reasonable cost, ease of working, attractive appearance, insulation properties, and adequate life if protected from moisture and insects (Bengtsson and Whitaker, 1988).

Due to these desirable characteristics, it is likely that wood will continue to be exploited for construction. The construction industry has tended to draw timber from just a few species (Ondimu and Gumbe, 1997). The depletion of primary forest by excessive harvesting of useful plants threatens the gene resource (Zhang and Cao, 1995 and Kigomo, 1988).

To reduce pressure upon the forest resources and utilize them rationally, a systematic conservation strategy and more scientific effort are needed urgently (Zhang and Cao, 1995). Hankins (1987) says that the standing stock must be constant to ensure sustainable yield. To ease pressure on forests, Agroforestry must be practiced with greater intensity (Christianty *et al.*, 1997). Secondly, this can be achieved by obtaining timber from many different trees so as not to deplete individual species (Ondimu and Gumbe, 1997). Another course of action may be to encourage the use of timber from early maturing trees.

One source of wood which meets these criteria is bamboo. The fast growth rate of bamboo is

well known and many varieties are available that are suitable for semi-arid and humid conditions (Dhanarajan *et al.*, 1990). It has a short growing period of 6-8 years (Bengtsson and Whitaker, 1988) as compared to most hardwoods and softwoods which take up to 35 years to mature (Kaigarula, 1987 and Brown, 1978).

1.2 General Description of Bamboo

Bamboos are perennial, grass like, woody plants. In botany, they are an order of the *Graminae* class and are subdivided into four families (U.N.,1972). With over 1250 species in 75 genera, this perennial grass grows over a wide range of climates on some 14 million ha. worldwide. 80% of this is in Southern tropical region of Asia and 1.5 million hectares in Africa. The main genera in East Africa are; *Oxytenanthera, Arudinaria, and Oreobambos* (Kigomo, 1988).

Bamboo is versatile, with a short growth cycle. The diversity of bamboo (over 1000 species on earth) makes it adaptable to many environments. It can be harvested every 3-5 years versus 10-20 years for most softwoods. Bamboo tolerates extremes of precipitation from 750mm-6250mm of annual rainfall (Environmental Bamboo Foundation, 1999).

Bambusa vulgaris, the bamboo under study in this project, was originally introduced to Kenya from India as cuttings. It is indicated to be suitable for cultivation in Central Province districts in Kenya with high to medium rainfall, specifically on the Aberdares Range and on Mt. Kenya (Kigomo, 1988 and Dale and Greenway, 1961).

B. Vulgaris is pantropic in cultivation, in two colour forms of culm; plain green and green stripped yellow (U.N., 1972).

1.2.1 Growth Characteristics

Bamboo is the fastest growing plant on earth. It grows one third faster than the fastest growing tree and some species have been reported to grow more than one metre in a single day (Environmental Bamboo Foundation, 1999).
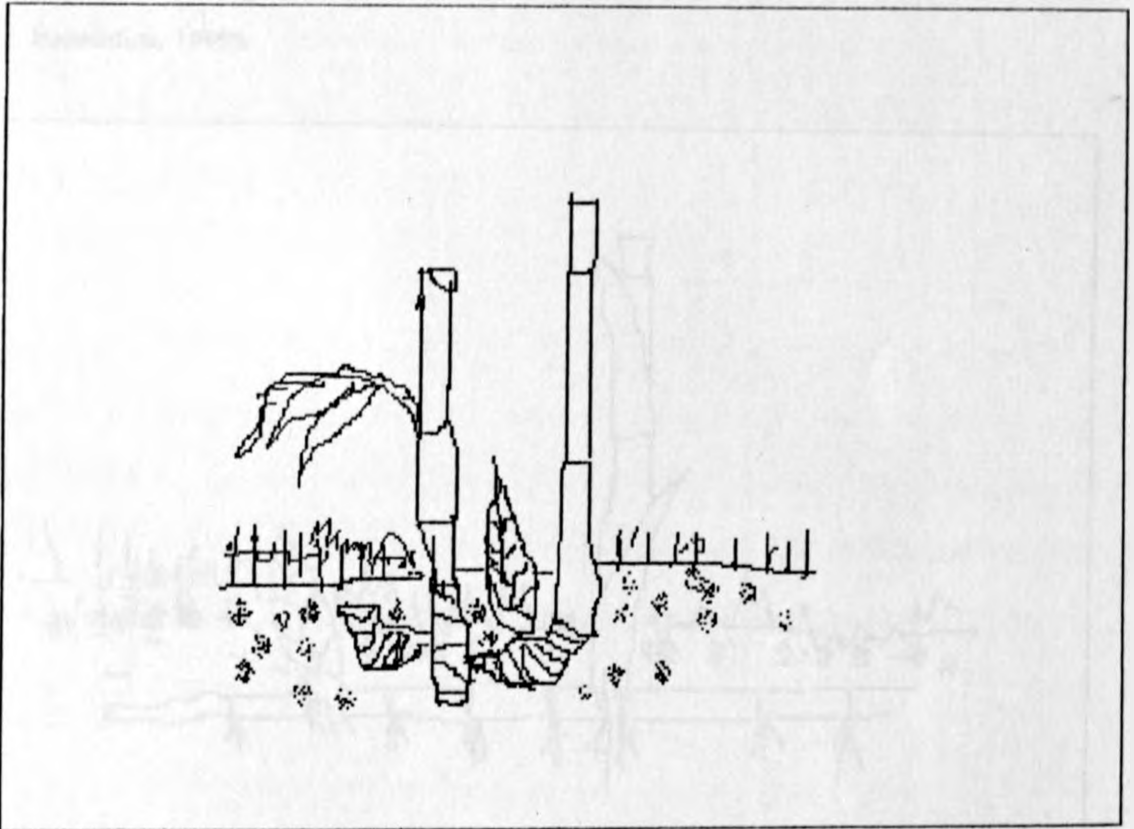
Fig. 1.1: Sympodial Bamboo (Stulz and Mukerji, 1988).

New stalks are formed annually in clumps growing out of spreading roots. The individual bamboo shoots complete their growth within six months in the first growing season. A strengthening process takes place during the subsequent two to three years and the culm reaches maturity after the fifth or sixth year or even later depending on the species. It must be cut before

blooming since it loses its resistance and dies after blooming. Some bamboo grow to 35m. in

height while others are no more than shrubs. Diameters may vary from 10mm. to 300mm. and

walls range from 5mm. to 50mm. thickness. Erect bamboos have as a rule, perfectly straight

stems (Bengtsson and Whitaker, 1988). There are two main types of bamboo:

1. sympodial, or clump forming bamboo, found in the warmer regions and,

2. monopodial or running bamboo, found in the cooler zones (Environmental Bamboo

    Foundation, 1999).
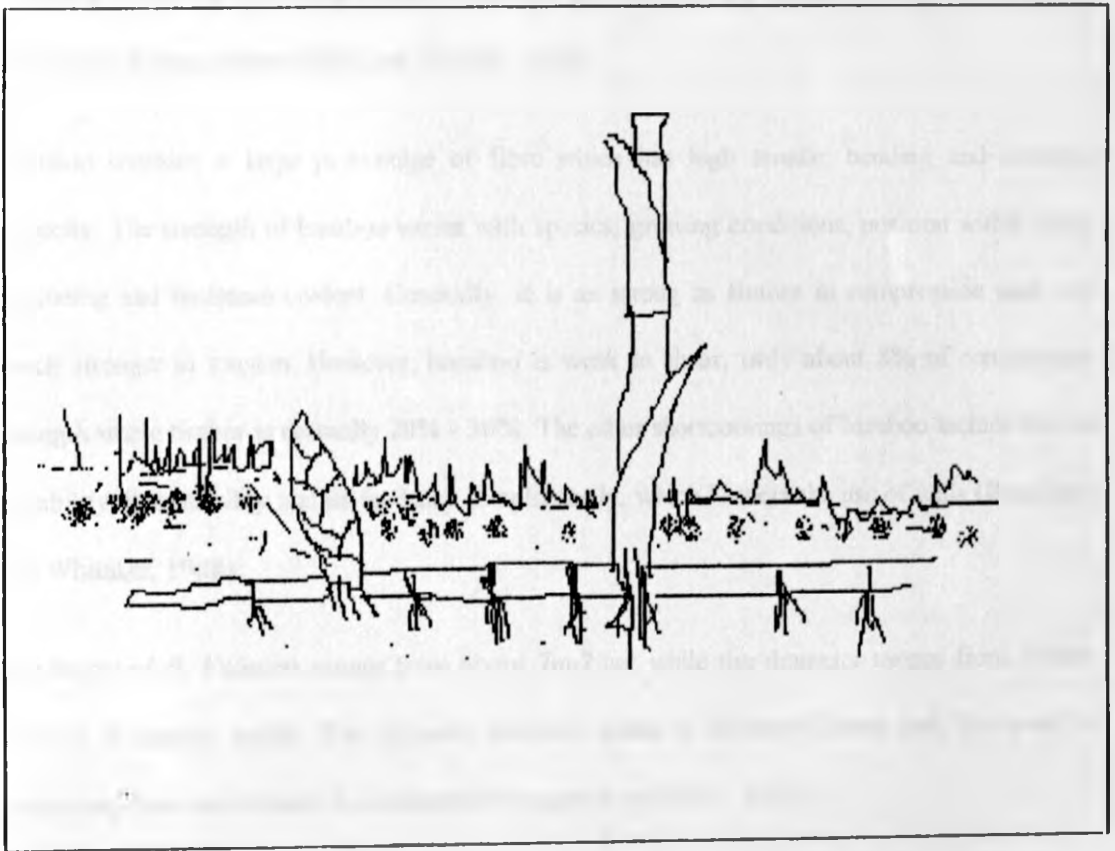
Fig. 1.2: Monopodial Bamboo (Stulz and Mukerji, 1988).

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The roots of bamboo are called rhizomes, which grow sideways below the ground. The rhizomes of sympodial bamboo multiply with short links symmetrically in a circle from which the bamboo shoots grow, forming clumps. Monopodial bamboo sends its rhizomes in all directions covering a wide area with widely spaced clumps (Stulz and Mukerji, 1988).

1.2.2 Physical Characteristics

The hollow, cylindrical bamboo culms comprise a fibrous, woody outer wall, divided at intervals by nodes, which are thin, hard traverse walls that give the plant its strength. Branches and leaves develop from these nodes (Stulz and Mukerji, 1988).

Bamboo contains a large percentage of fibre which has high tensile, bending and straining capacity. The strength of bamboo varies with species, growing conditions, position within culm, seasoning and moisture content. Generally, it is as strong as timber in compression and very much stronger in tension. However, bamboo is weak in shear, only about 8% of compression strength where timber is normally 20% - 30%. The other shortcomings of bamboo include its low durability, flammability and its tendency to split easily, which hinders the use of nails (Bengtsson and Whitaker, 1988).

The height of *B. Vulgaris* ranges from about 7m-23m; while the diameter ranges from 50mm-100mm in mature culms. The distance between nodes is 200mm-450mm and the wood is moderately thick and strong. It is indicated for general use (U.N., 1972).

1.3 Uses of Bamboo

Bamboo has a very wide application in many areas. A summary of these uses is given here below. However, a more comprehensive list of uses is given in Appendix 1 and a set of pictures of further applications is also given in Appendix 2..

1.3.1 House Construction

Bamboo is used for the following structural elements; Posts, joists, studdings, laths, rafters, purlins, posts, door and window frames, shutters and cave troughs, shingles, floor and ceiling panels, woven walls and flattened boards (Brown, 1978 and Bengtsson and Whitaker, 1988).

1.3.2 Hydraulic Applications

Arundinaria Alpina has been used to supply 100,000 people scattered in 28 villages with water through a network of 150 km. of bamboo pipelines by 1985 in Tanzania and as gutters for rain water harvesting (Lipangile, 1987). Singh (1979) has reported and discussed an indigenous method of drip irrigation, made out of split bamboo and practiced in Meghalaya State in India since a long time. The method is simple and of valuable scientific importance and is extensively used on high slopes of up to 10%.

1.3.3 General Construction

Bamboo aids during construction in the following ways; Scaffolding and staging, centering for masonry culverts and arches, shade frames for nursery beds and flag pole and for reinforcing concrete (Brown, 1978 and Bengtsson and Whitaker, 1988). The main geo-technical application of bamboo is in reinforcing soil structures such as in slopes, highway / road embankments, and vertical retaining walls (Janssen *et al.*, 1991).

1.3.4 Land Transportation and Navigation

Bamboo is used to make components such as; Yokes, vehicle shafts and rollers for moving heavy objects used in land transportation. Masts and spurs for boats, or shafts, boat poles, seats and false bottoms, and ribs for boat awnings are examples of bamboo products used in navigation (Brown, 1978).

1.3.5 Furniture and Household Equipment

Bamboo is used for Benches, Chairs, tables, beds and bookshelves may be made of bamboo (Brown, 1978 and Dransfield and Wiidjaja, 1995).

1.3.6 Soil Conditioning

In parts of India and China, bamboo is being used for rehabilitating degraded and mined lands. Bamboo binds the soil preventing erosion and is very versatile, growing on a variety of soils, which are poor in mineral and nutrient content (Christianty *et al.*, 1997).

The overriding advantage of bamboo over other sources of timber sources is its use in agroforestry. Christianty *et al.* (1997) found that due to the slow decomposition of its silica - rich litter, and extremely high biomass of its fine roots, bamboo increased nutrient levels when planted with other crops. They concluded that without bamboo, 'the land dies.'

1.3.7 Other Uses of Bamboo

Because of the high yield of cellulose, much bamboo is used for paper pulp in the paper industry. Bamboo grains and young shoots are eaten in Tanzania and Uganda. Roots are used as medicine, and bamboo beer is brewed (Kigomo, 1988).

Bamboo, therefore, is a truly multipurpose (grass) species and well justifies the sentiment that at least a third of humanity uses bamboo in one form or another during their lifetime (Dhanarajan, *et al.*, 1990).

1.4 Statement of the Problem

This section first highlights problems that are associated with bamboo design and then details what research activities need to be carried out to solve these problems.

1.4.1 Problems Associated With Bamboo Design

The applications of bamboo are many and varied. A number of textbooks and handbooks have been written which explain how bamboo may be used. However, as Darrow and Pam (1978) warn; design is not so much 'how to build' as 'how to choose techniques and materials appropriate to a given situation'. To select a material for use, it is vital to know the exact forces the material is able to withstand. It turns out that the mechanical properties have not been adequately measured and properly documented for main bamboo species in East Africa.

Yet, if design in bamboo were codified, engineers would be able to use it with the same confidence that they display in the use of recognised engineering materials such as steel and timber (Boughton, 1988). This provides a case to conduct research in this area with the aim of determining the mechanical characteristics of bamboo, particularly of those species in East Africa.

These properties include tensile, compressive, shear and bending strength, the capacity of bamboo walls to withstand the pressure of fluids flowing in it, cracking and fracture modes. It is also important to determine the moduli of elasticity, rigidity, resilience and toughness for bamboo.

Due to limitation of time and equipment, not all these parameters were determined by this research project. There are over 1200 species of bamboo. Hence it was necessary to limit this research effort to one of the main species in East Africa viz; *B. vulgaris*, which was readily available and is reported to be grown even as an ornamental plant (Kigomo, 1988).

1.4.2 The Need to Research on Mechanical Properties of Bamboo

From the introduction above, it is clear that one mode of ensuring sustainable use of forest is by encouraging the use of fast-growing, early maturing trees for constructions as opposed to the traditional sources of timber which take long to mature. Also, the highest priority (in ensuring

sustainable use of forests) has to be to increase production and this means a shift of emphasis from naturally gathered resources to one of harvested crops. As the focus is changing in this way, it becomes a high priority to target a limited number of species out of the hundreds available and scores previously worked on (Williams and Rao, 1994).

Bamboo has been identified as one such source of building material. Its properties and uses lend credence to the suitability of bamboo for this application. The role of *A.Alpina* in supplying water to the rural people of Tanzania (Lipangile, 1987) in (Kigomo, 1988) serves as a good example of the socio - economic role of bamboo in rural development.

The properties of bamboo vary with species and there are over 1200 species of bamboo. This is what may have inspired the U.N. (1972) in a chapter entitled 'Recommendations for further Research' to sound the clarion call that research is needed to select the species for cultivation that will be used in building construction. Kigomo (1988) calls for well thought out research options and strategies to address this issue and so do Zhang and Cao (1995). This project is a response to these pleas.

The hindrance to the use of bamboo in design in East Africa has been the fact that its mechanical properties have not been adequately measured and documented for the species here. While these properties have been determined elsewhere for other species, these values are not useful in East Africa where the main species are different from those used in the earlier research work. Without accurate values of such properties as tensile, compressive and bending strength, designers are faced with the problem of either over designing (which is costly) or under designing (a safety risk).

While Design Engineers will be able to decide on the safety factor needed to calculate the maximum design stress, they rely on the researcher for the value of yield stress, published in handbooks. Boughton (1988) points out the following three benefits to be accrued by

publishing an internationally recognized bamboo design code:

1. Engineering recognition - This is bound to ensure safe and cost effective designs, bring about broad based experience useful for a designer working in isolation, and provide a checklist to ensure that all possible combination of loads and failure modes have been checked.

2. Contractual advantages - Codification enables building regulations and code of practice to be specified in a contract without the uncertainty as to the safety or effectiveness of the finished product.

3. Trade advantages - When design is codified, quality control on bamboo products is easier.

It is for this reason that this research exercise sought to determine as accurately as possible the properties that are important for design using *B.vulgaris*. It is hoped that when these properties are published, designers will have at least one more properly defined and codified construction material from which to choose, which also meets the objective of sustainable use of forest resources.

Further to this, there is a growing concern at the rate at which the cost of conventional building material has continued to rise. In response to this there has arisen a movement of designers and planners developing 'no cost' housing that stresses available local materials such as Mud/earth bricks and bamboo, and restores to people the ability to shape their environment and that of stored crops and animals (Darrow and Pam, 1978). In socio-economic terms, bamboo forests contribute enormously to the national and individual wealth. The plant is said to house tens of millions in Bangladesh, India, Burma, Thailand, Philippines and Indonesia. Hence, bamboo has been described as "the poor man's timber," "the miracle grass," and "a cradle to coffin timber" (Dhanarajan, 1990). The use of *B.vulgaris* in this undertaking is advantageous since it grows in many parts of Sub-Saharan Africa (Kigomo, 1988) and the research findings may be used over a wide area. This species of bamboo is listed among the major priority species noted to be

important but little information is available on their potential (Williams and Rao, 1994).

Zhang and Cao (1995) suggest that to reduce pressure upon the forests, plantations should be set up for fuelwood and diverse agroforestry systems and multi-species should be introduced and developed. Bamboo is one of the species recommended for plantation in India (Taylor and Dicken, 1991) to ease pressure from forests. Bamboo is by nature, thin, unlike other sources of timber which have to be split into smaller sections. This may be seen as an energy saving (Environmental Bamboo Foundation, 1999).

1.4.3 Objectives

The broad objective of this study was to determine the mechanical properties of bamboo *(B.vulgaris)*. The specific objectives were;

1. To determine the following properties of *B.vulgaris:*

   (i)   Density.

   (ii) Tensile strength.

   (iii) Compressive Strength.

   (iv) Bending strength.

   (v)   Modulus of elasticity.

2. To compare the values of the above parameters with those of other bamboo species.

3. To evaluate the effect of nodes on tensile, compressive and bending strength.

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CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Physical and mechanical properties of bamboo have been investigated by several researchers. The properties that have been investigated include; growth and anatomy, thermal expansion, moisture content, density, chemistry, compressive strength, dynamic visco-elasticity, bending strength, shear strength, and tensile strength. The relationship between these properties has also been investigated (Janssen, 1991).

This chapter is dedicated to the analysis of the work that has been done on the properties mentioned above with a view to pointing out where this project fits amidst the past research work and highlight the contribution this project will make to research on bamboo.

2.2 Moisture Content

The moisture content in green culms of bamboo is believed to be influenced by position on the culm from which the test piece was cut, maturity (age), and the species being investigated (Talukdar and Sattar, 1982). Fangchum (1981) for example, investigated the effect of position on the moisture content and developed the following regression formula:

$$M.C. = 94.5 - 12.7H + 1.6H^2 - 0.088H^3 \qquad \ldots (2.1)$$

Where: H = Any value between 0 and 10 derived by dividing the length of the culm into
          ten equal parts in which 0 means bottom and 10 means top.

          M.C. = Moisture content.

The moisture content for *B. vulgaris* in green condition is reported by Talukdar and Sattar (1980) to be between 48.7-52.8% and 85.7-94.5% for mature and immature culms respectively. Hence, moisture content can be said to decline as bamboo matures. This can be explained by the fact that

as bamboo matures, the wood material replaces moisture.

2.3 Density

Density, like moisture content is a function of the age of the culm and the position on the stem. Below are examples of regression formulae that may be used to predict the density of a piece of bamboo, with knowledge of the age or position along the culm for *A. alpina*, grown in China at an altitude of 1500m. (Fangchun, 1981).

$$\rho = 596 + 15H + 0.4H^2 \qquad \dots (2.2)$$

$$\rho = 435 + 11A - 0.155A^2 \qquad \dots (2.3)$$

Where: ρ = density (kg/m³)

           A = age (years)

           H = any value between 0 and 10 derived by dividing the length of the culm into

               ten equal parts in which 0 means bottom and 10 means top.

It is necessary to determine the volume of a bamboo test piece during the measurement of density. It is recommended to use a 2.5mm test piece (Talukdar and Sattar, 1980). However the only regular dimension is the length along the culm, and the presence of nodes, the changing internal and external diameters make it difficult to use regular methods to determine the volume of the test piece.

Chiang (1973) has measured volume by immersion in water and the density of the bamboo substance has been determined after grinding with a pycnometer. The former method fails to take into account the absorption of water into bamboo tissues and as a result of this the volume determined is likely to be inaccurate.

In this research project, volume has been determined by the use of fine sand rather than water in

recognition of this problem.

2.4 Tensile Strength

Apart from the determination of the tensile strength of the various bamboo species, many researchers have considered the influence of several factors on tensile strength such as moisture content, density, age, position along the culm and seasoning. Tensile strength ranged from 100 - 287 MPa (Janssen, 1991).

2.4.1 Methods and Procedures

There seems to be no existing standard shape and size for the specimens used in tensile strength of bamboo test. For example, Mc Laughlin (1979) working on Jamaican *B. Vulgaris* used specimens of 300mm. length with a cross-sectional area of between 30 mm^2-300mm^2. In the same experiment, he also used dumbbell-shaped specimens with a cross-section of 0.004mm^2- 0.025mm^2 in the narrow part, which he used to determine the tensile strength of fibres.

On the other hand, Xiu-xin *et al.* (1985) used a total length of 250mm, both ends in the form of a spoon, width 10mm, and in the centre a length of 120mm, width 1.5mm. The thickness of the specimen was equal to the culm wall thickness. Loading speeds ranged from 0.0007mm/mm/sec (Cox and Geymayer, 1969) to 0.12 mm/mm/sec (McLaughlin, 1979).

In the absence of any standard bamboo sizes, this research project borrowed heavily from timber standards, which provide suitable length/width ratios.

2.4.2 Factors Affecting Tensile Strength

1. Mass Per Volume

McLaughlin (1979) developed the following two regression equations that may be used estimate the tensile strength of the Jamaican Bamboo using the density and Young's Modulus. The

Young's Modulus was determined using three-point bending tests.

For large samples (10-100mm^2 cross-sectional area),

$$\sigma = 0.76\rho + 2.25 \times 10^{-3} E - 131 \qquad \ldots (2.4)$$

For small samples or fibres (0.004-0.025mm^2 cross-sectional area),

$$\sigma = 0.25\rho + 2.14 \times 10^{-3} E - 443 \qquad \ldots (2.5)$$

Where:

σ = ultimate tensile strength (MPa)

ρ = mass per volume of the bamboo (kg/m^3)

E = Young's modulus (MPa)

A more direct equation was developed by Fangchun (1981) working on bamboo from different Chinese regions;

$$\sigma = 0.307\rho \qquad \ldots (2.6)$$

Where: σ = ultimate tensile strength (MPa)

ρ = mass per volume (kg/m^3)

2. Age

There are wide differences in the ages recommended by various authors at which bamboo will have the highest tensile strength. Performing tests on bamboo from four different regions of China, Xiu-xin *et al*. (1985) developed regression formulae which they used to estimate the age at which bamboo has the highest tensile strength to be 4.5 years.

However, Fangchun (1981) working on bamboo from four different regions of China, estimated

that the age at which bamboo has the highest tensile strength is 6.5 years.

These differences may indicate the need for more research but may also represent the differences that occur when bamboos from different regions are considered.

3. Position

As early as 1941, Duff had investigated the variation of the ultimate strength of bamboo across the thickness of the culm wall. He showed that the tensile strength is greater on the outer surface than on the inner surface.

Experiments of Atrops (1969) confirmed these results. He found that the ultimate tensile stress for the outer layer of the culm-wall was 287 MPa and 151 MPa in the inner layer. The mean tensile strength obtained from specimens as thick as the culm-wall yielded an average value of 210 MPa.

4. Nodes

Working on whole culms of *Arundinaria tecta*, fixed with Chinese pullers, at a loading speed of $0.12N/mm^2/s$, Cox and Geymeyer (1969) found that there was no significant difference between the stress at the internode and at the node. This is despite the fact that 14 out of 18 specimens or 76.5% failed at the nodes.

The fact that 76.5% of the specimens failed at the nodes indicates that the nodes may have some influence on tensile strength. The reason why Cox and Geymayer (1969) did not find a significant difference between specimens with nodes and without nodes, may be that the number of specimens used (18) were too few. This research project has doubled the number of specimens to 36, (18 with nodes and 18 without nodes) so as to determine whether this larger sample size will yield a significant difference.

2.5 Compression Strength

Apart from the determination of the compressive strength of the various bamboo species, many researchers have considered the influence of several factors on compressive strength such as moisture content, density, age, position along the culm and seasoning.

2.5.1 Methods and Procedures

The values of compression strength for the various bamboos presented in Janssen (1991) range from 30 - 90 MPa. This wide variation can be explained by the fact that different species of bamboo may exhibit different characteristics.

The differences in values of compressive strength may also be attributed to the wide range of methods and procedures used by different researchers. For example, Yunlien and Yehzen (1983) used 90 culms collected from 21 fields. All culms had a diameter of 100mm or more and a length of 15cm. Tests were done on specimens from the lowest 6m. Compression test specimens were 20mm to 20mm selected from 7 year old culms.

Limaye (1962) on the other hand, used 200 culms, with diameters between 25mm and 62 mm, and with length ranging from 5.4 - 7.8m. The ages of culms used ranged from 1 - 2.5 years. Such wide variations in materials and methods used may contribute significantly to the variations recorded in values of compressive strength.

2.5.2 Factors Affecting Compressive Strength

1. Moisture Content

According to research conducted by Fangchun (1981) into the effect of moisture content on compressive strength, compressive strength is highest at a moisture content of about 5%. The compressive strength reduces rapidly until a moisture content of 20% is attained. Above 20%

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moisture content, the compressive strength is constant.

Yunlien and Yehzen (1983) developed the following formula relating ultimate compression stress (σ) and moisture content (M.C.)

$$\sigma = 56.56 + \frac{130}{M.C.} \qquad \ldots (2.7)$$

2. Density

Sekhar *et al.* (1962) developed ratios between the mass per unit volume and ultimate compressive strength in *Bambusa nutans*.

For green condition,

$$\sigma = 0.003\rho^{1.5} \qquad \ldots (2.8)$$

For dry condition,

$$\sigma = 0.0089\rho^{1.33} \qquad \ldots (2.9)$$

The ratio developed by Fangchun (1981) varies slightly and was developed from work conducted on Chinese bamboo;

$$\sigma = 0.107\rho \qquad \ldots (2.10)$$

Where: σ = Ultimate Compressive strength (MPa)

ρ = Density (kg/m³)

3. Age

Xiu-xin *et al.* (1985) working to determine the influence of age at the time of cutting on

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compressive strength deduced from the polynomials they developed in their research project that the age at which the Chinese bamboo they investigated has the highest compressive strength is about 5.5 years.

However, Fangchun (1981) studying bamboo from different provinces and species found the age with the highest compressive strength to be 7.2 years. This is the solution to the following regression equation he developed:

$$\sigma = 44.4 + 13.1A + 1.83A^2 \qquad \qquad \ldots (2.11)$$

Fangchun (1981) also revealed that the cutting season has an influence on the compressive strength of bamboo.

4. Position

An unexpected outcome was found by Fangchun (1981) that the compressive strength increases towards the top of a bamboo culm. This is not expected because the top of the culm is expected to contain the newly formed, unstrengthened tissues, which are expected to be weak in any test.

5. Nodes

The compressive strength varies along the internode and decreases towards the nodes (Ota, 1953). A study conducted by Atrops (1969) on the ultimate compressive stress for specimens without a node, with one node and with two nodes, revealed that the specimens with one node were the strongest in compression tests when loaded axially. They had a compressive strength of 43.4 MPa.

2.6 Bending Strength

Apart from the determination of the bending strength of the various bamboo species, many researchers have considered the influence of several factors on bending strength such as

moisture content, density, age, position along the culm and seasoning

2.6.1 Methods and Procedures

There are two methods of performing bending tests, which yield different results. Static bending involves the application of a continuos force in constant contact with the specimen, at a specified rate until the specimen yields. In impact bending, a weight is dropped on to the surface of the specimen from a given distance. The weight dropped is increased until the specimen fails. The impact bending strength is calculated from the weight that causes yielding (USDA, 1987). The span used in the bending strength test varied greatly among different researchers; 240mm (Fangchun, 1981), 200mm (Xiu-xin et al, 1985), 700mm (Limaye, 1952 and Sekhar, 1962).

2.6.2 Factors Affecting Bending Strength

1. Density

Fangchun (1981) developed the ratios below to describe the relationship between the mass per volume and compressive strength for Chinese bamboo.

For tangential bending,

$$\sigma = 0.220\rho \qquad \qquad \ldots (2.12)$$

For radial bending,

$$\sigma = 0.206\rho \qquad \qquad \ldots (2.13)$$

2. Age

Xiu-xin et al. (1985) found that the age at which the bamboo they investigated has the highest strength was about 5 years. Fangchun (1981) on the other hand calculated the best age for

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bending strength to be about 7 years.

2.7 Modulus of Elasticity

The modulus of elasticity is usually determined from the other properties such as tensile, compressive and bending strength . Some of the methods used are presented in this section.

2.7.1 Methods and Procedures

The Young's Modulus for the various bamboos presented in Janssen (1991) range from 7,000 - 25,000 MPa. This wide variation is attributable to the fact that the values of Modulus of Elasticity may be obtained from compression, and tensile tests in which deformations are different. Hence, it is always necessary to mention the test from which the Modulus of Elasticity is calculated. For example, in this project both the tensile and compression tests were used.

2.7.2 Factors Affecting the Modulus of Elasticity

1. Density

Sekhar and Gulati (1973) found that the Young's Modulus increases with an increase in the density. This relationship was described by the equation below.

$$E = -17800 + 45\rho \qquad \qquad \dots (2.14)$$

Where: E = Young's Modulus (Mpa) and ρ = Density (kg/m^3)

2. Moisture Content

The Modulus of Elasticity decreases with an increase in the moisture content (Godbole and Lakkad, 1986). They developed the following regression formula.

$$E = 22786 - 223M.C. + 1.19M.C^2 \qquad \qquad \dots (2.15)$$

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2.8 Conclusion

Two inferences may be drawn from the review presented above. It stands out very prominently that most of the research published was performed in Japan, China and other countries in the Asian continent. This is hardly surprising considering the vast populations of bamboo in these areas and the scarcity of other hardwoods here as Brown (1978) notes.

Secondly, the variations in strength between species are greater than the variations within individual species and that the strength varies with species age and growth conditions, moisture content, disposition of nodes and position along culms. U.N. (1972) warns that for design purposes, the age, moisture content and above all the species should be known. For example, the modulus of elasticity of mature air-dried culms ranges from 125 MPa - 195 MPa, the modulus of rapture varies from 900 Pa - 1700 Pa. and compressive strength varies from 315 Pa - 725 Pa. for different species. These wide variations among the species suggest that each bamboo must be treated in isolation.

Results and studies on physical, mechanical and chemical properties of over 70 species have been also been presented by Hsiung (1986). According to research carried out and presented in these proceedings, the moisture content in air dry condition is 15% - 18%, fibre saturation point is 30% - 35%, volume to weight ratio is 0.60 - 0.77, radial shrinkage is 4% - 5%, tangential shrinkage is 3% - 4%, and longitudinal shrinkage is 0.3 - 0.5%, fibre content is 40% - 60% and the combustion value is 4550 Cal/g - 4680 Cal/g. These wide variations in properties found in Hsiung (1986) further suggest the need for species specific research.

Most of the equations presented in this section tend to relate only two properties at a time. For example, equation 2.1 relates moisture and height alone. One weakness with this equation is that moisture content does not depend on height alone, but also on other factors such as climate, species, altitude and age. The same applies for equations 2.2 and 2.3 which relate density with

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height and age respectively. The remedy to this problem would be to combine these equations into one representative equation containing all the parameters affecting the property being measured. Whenever such combination is not possible all the important parameters should be mentioned so as to make such experimental results reproducible.

The research projects cited above concentrated on such as genera as *Arundinaria, Cephalostachyum, Phyllostachys*, and *Schizostachyum*, all found in the Eastern Hemisphere. It is vital to conduct research on *B.vulgaris*, one of the main species found in Africa from Ethiopia to Angola and Ghana since its properties may be very different from those other species. In most of the past research work cited in this project, the 5th percentile was used. Since it is often necessary to compare research work done by different researchers, it was found necessary to use the 5th percentile in this research too. This would ensure an easy comparison of this work with earlier research work.

It then becomes clear that the existence of very many species bamboo (over 2000) is the reason why more research must be done on this perennial grass, since as Aggarwal and Dawal (1996) recommend, the species grown should be tailored to the local market.

CHAPTER 3: THEORETICAL CONSIDERATIONS

3.1 Stress

Stress is the basic parameter from which strength is determined. This section constitutes a derivation of stress from first principles and shows how it relates to strength.

3.1.1 Stress at a point

Consider the small cube below to be a point on which stress acts in all directions, idealized in the rectangular cartesian coordinate system in three dimensions (Chung, 1988):
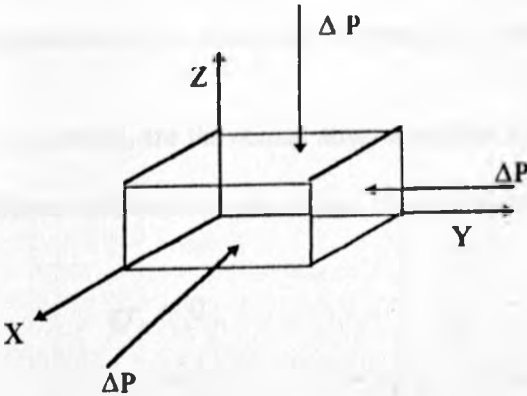
Fig. 3.1 - Stress in All Directions.

If a small area ΔA is taken in a plane and a force ΔP is the internal force acting on it activated from the load P, then the unit stress acting at this point is defined as (Chung, 1988)

$$\sigma = \lim_{\Delta A \to 0} \frac{\Delta P}{\Delta A} = \frac{dP}{dA} \qquad \ldots (3.1)$$

The unit stress is decomposed into two components:

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1. Normal stress - Normal to the plane of reference.

2. Shear stress - Parallel to the plane of reference.

To completely specify the stresses at point, it is necessary to specify the stresses at the point on 3 mutually perpendicular planes passing through the point. For each plane it is possible to specify one normal stress and two shear stresses. This yields a total of nine stresses at a point. If the three mutually perpendicular planes are perpendicular to the x, y and z coordinate axes, then the complete specification of the stress at a point is σ_{ij} (Timoshenko and Goodier, 1983). Where:

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \qquad \qquad \ldots (3.2)$$

The first subscript denotes the normal to the plane under consideration and the second subscript designates the direction of the stress. Thus σ_{12} denotes a shearing stress acting on the plane perpendicular to the x-axis and the stress acts in the y-axis.

σ_{11}, σ_{22} and σ_{33} are the normal stresses and the rest are shear stresses. Hence, the necessary and sufficient condition for state of pure shear exists when:

$$\sigma_{ii} = 0 \qquad \qquad \ldots (3.3)$$

3.1.2 Plane State Of Stress

If there are no stresses (or negligible stress) acting in Z direction, but there are stresses acting in X and Y directions, the state of stress is called plane stress. Hence,

$$\sigma_{13} = \sigma_{23} = \sigma_{33} = 0 \qquad \qquad \ldots (3.4)$$
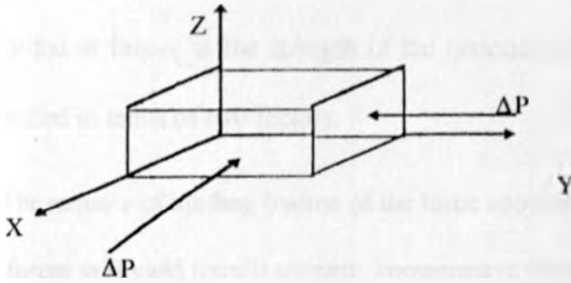
Fig. 3.2 - Plane Stress.

Then (Mase, 1970):

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & 0 \\ \sigma_{22} & \sigma_{22} & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad \qquad \ldots (3.5)$$

3.1.3 Unidirectional Stress

Here, stress acts in one direction only, say X - direction. Hence (Mase, 1970):

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} = \sigma_{11} = \frac{P}{A} \qquad \ldots (3.6)$$

This is the stress determined in this project since the testing machines for stress (strength) determination only give values of stress in one direction (unidirectional) at a time. Hence to give all the nine parameters required to fully define the state of stress in all directions, the orientation of the material must be changed on the machine to suit the various directions.

3.1.4 Material Strength

Mechanical properties of wood are measures of its resistance to exterior forces which tend to deform its mass. If the unidirectional force applied to the specimen causes yielding, the stress recorded at failure is the strength of the material (USDA, 1987). The strength of a material is specified in terms of two factors;

1. The manner of loading (nature of the force applied) - Tensile, Compressive, and Bending forces will yield tensile strength, compressive strength and bending strength respectively.

2. The orientation of the material when the force is applied. In wood, for example, it is necessary to specify whether the force applied is parallel to the grain or across the grain since the properties in the two cases are different. Therefore, the statement: 'Tensile strength of bamboo parallel to the grain' is exhaustive (Tsoumis, 1991).

The focus of this research project was on the determination of the strength properties of bamboo namely: tensile strength, compressive strength and bending strength. This was necessary because the strength parameters are constant for a particular material and can be reproduced and verified under similar conditions. There are two different methods of analyzing strength and failure of timber (Dinwoodie, 1994).

1. Engineering Approach to Strength of Materials

Here, the emphasis is on fracture mechanics. It is based on an argument that all materials contain certain defects, and that their performance is determined by the nature of these imperfections. Hence the performance of wood is determined by the propagation of cracks arising from these defects.

2. Classical Strength of Materials Approach

This is the approach employed in this research project. It involves analysing material strength of timber in terms of the arrangement of molecules, fibrils and the cells and thinking in

terms of a theoretical strength and attempting to identify reasons why the theory is never satisfied. It is therefore always necessary to specify the orientation of the grains in this approach. Materials are classified as follows according to orientation of grains:

(a) Homogenous Materials

These materials have uniform properties throughout. Hence, the properties are not functions of positions in the body (Gumbe, 1993).

(b) Inhomogenous Materials

If a material has non-uniform properties over the body and the properties are functions of positions in the body, then it is said to be inhomogenous.

(c) Isotropic Materials

These are bodies with properties that are the same in every direction at a point within the body. Therefore, the properties are not functions of orientation at a point in the body (Gumbe, 1993).

(d) Anisotropic Materials

Anisotropic materials have properties that are different in three mutually perpendicular directions at a point in the body and also have three mutually perpendicular planes of material symmetry. Unlike isotropic materials, properties are functions of orientation at all points (Gumbe, 1993).

(e) Orthotropic Materials

These are materials with properties that are different in all directions at a point. There are no planes of symmetry and the properties are functions of orientation at a point in the body.

3.1.5 Orthotropic Nature of Wood
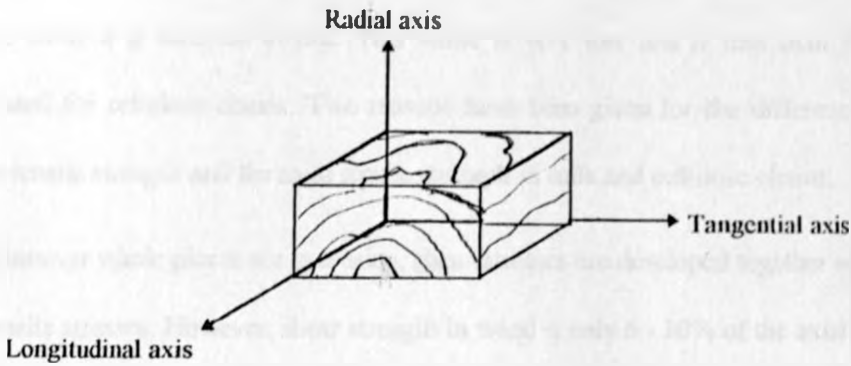
Fig. 3.3 - Orthotropic Nature of Wood.

Wood may be described as an orthotropic material since it has unique and independent mechanical properties in the directions of three mutually perpendicular axes (Gumbe, 1993). In wood these axes are; longitudinal axis (parallel to the fibre), radial axis (normal to the growth rings) and tangential axis (perpendicular to the grain but tangent to the growth rings) (USDA, 1987).

3.1.6 Tensile Strength of Wood Parallel to the Grain

Tensile stress is induced in a body when the forces acting tend to increase its length. When these forces are applied parallel to the grain, they are called axial forces and the strength obtained is called axial tensile strength. Forces applied across the grain are transverse forces. Axial strength may be 50 times more than transverse strength in wood (Tsoumis, 1991).

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The axial tensile strength of single cells in wood may go up to 1300 MPa. The strength of cellulose chains is theoretically estimated at 7500 MPa (Tsoumis, 1991)

U.N. (1972) observed that the ultimate axial tensile strength of bamboo varies from 140 -280 MPa, when it is stressed *in-situ*. This value is very low and is less than 10% of the value indicated for cellulose chains. Two reasons have been given for the difference between *in-situ* axial tensile strength and the axial tensile strength in cells and cellulose chains;

1. Whenever whole pieces are in tension, shear stresses are developed together with the axial tensile stresses. However, shear strength in wood is only 6 - 10% of the axial tensile strength. Hence, wood in tension is likely to fail by shear first. This means that the high tensile strength of wood is rarely utilized (Toumis, 1991 and Dinwoodie, 1994).

2. Tsoumis (1991) adds that axial strength is greatly reduced by the presence of knots, spiral grains or other growth abnormalities. In bamboo, nodes may be considered to be one such defect. Hence for each test, a comparison was made of the strength with and without nodes.

3.1.7 Compression Strength of Wood Parallel to the Grain

Compression failure is a slow yielding process in which there is a progressive development of structural change (Dinwoodie, 1994). This failure is caused by the rapture of intercellular layers, cleavage or shearing, buckling or folding of cells and rapture of cell walls (Tsoumis, 1991).

Axial compression strength for bamboo varies from 40 - 70 MPa and transverse strength from 1 - 20 MPa. The average strains associated with compression in wood are of the order 0.33% (Tsoumis, 1991).

3.1.8 Bending Strength of Wood

During bending the upper part of timber is subjected to compression stresses and the lower part to tensile stresses. Since compression is only one third of tension, failure will occur on the

compression side first during bending. Failure in bending therefore takes place progressively from the top to the bottom and fracture occurs when stress on the tensile surface reaches the ultimate strength in bending (Dinwoodie, 1994).

The modulus of rapture ranges from 50 - 160 MPa (Janssen, 1991). According to Tsoumis (1991) these values are similar to those obtained in axial tensile test and may be used interchangeably in the absence of one set of data.

3.1.9 Factors Affecting Mechanical Properties of Wood

During tests to determine mechanical properties of timber the following factors are recorded together with the strength parameters. This is important so as to make such experiments reproducible.

1. Moisture

When moisture decreases below the fibre saturation point, it begins to affect the mechanical properties of wood. Decrease in moisture content increases the strength of wood since the cell walls become more compact. Cell walls are compacted because, with loss of moisture, the mass of wood substance contained in a certain volume increases (Tsoumis, 1991).

Given any mechanical property at standard values of moisture content, it is possible to predict the values of that property at any moisture content using the Equation 3.7 (USDA, 1987)

$$P_X = P_{12} \left(\frac{P_{12}}{P_g} \right) Exp. \left(\frac{12-M}{M_p-12} \right) \qquad \qquad \dots (3.7)$$

Where: P_x = mechanical property at a given moisture content, for example, tensile strength

at 8% m.c.

P_{12} = property at 12% m.c.

P_g = Property value in green condition

M = m.c. at which property is desired

M_p = Moisture content at the inter section of a horizontal line representing the strength of greenwood and an inclined line representing the logarithm of strength-m.c. relationship for dry wood. It is usually taken to be 25% m.c.

Because of the effect of moisture, mechanical properties are determined in green condition (above fibre saturation) or in air - dry conditions (12% m.c.). In this way, it is possible to have comparable results. There are correction factors used to adjust moisture content to these two standard values (Tsoumis, 1991).

2. Density

Bamboos are grass like, woody plants. Density is a measure of the wood substance contained in a given volume (Tsoumis, 1991). The substance of which wood is composed has a specific gravity of about 1.5. Yet wood floats on water. This implies that there are numerous cell cavities and pores in wood. Since the strength of timber is a function of wood material present, density is a good indicator of strength (USDA, 1987).

3. Temperature

The influence of temperature can be analysed at two levels:

(1) Reversible Effects

In general, the mechanical properties of wood decrease when heated and increase when cooled. At constant m.c. and below 150°C, mechanical properties are approximately linearly related to temperature. At temperatures below 100°C, the immediate effect is essentially reversible; that is, the property will return to the value at the original temperature, if the change is rapid.

(2) Irreversible effects

This occurs at elevated temperatures. This permanent effect is one of degradation of wood substance, which results in loss of weight and strength. However, wood will often not reach the daily extremes in temperature of the air around it in ordinary construction; thus, long term effects should be based on the accumulated temperature experience of critical structural parts (USDA, 1994).

4. Time Under Load

Static strength tests are typically conducted at a rate of loading to attain maximum load in about 5 minutes. Higher values of strength are obtained for wood loaded at more rapid rates and lower values are obtained at slower rates. For example, the load required to produce failure in a wood member in 1 sec. is approximately 10% higher than that obtained in a standard strength test.

3.2 Strain

When an elemental body is deformed, the unit elongation or strain at a point on the element is U_{ij} in the X direction and V_{ij} and W_{ij} in the Y and Z directions respectively.

The shearing stresses are: $1/2(V_{i,j} + U_{i,j})$, $1/2(V_{i,j} + W_{i,j})$, and $1/2(U_{i,j} + W_{i,j})$.

Hence the complete specification of strain at a point is ε_{ij} (Timoshenko, 1983). Where:

$$\varepsilon_{ij} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{22} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix} \qquad \dots (3.8)$$

The first subscript (i) denotes the normal to the plane under consideration and the second subscript (j) designates the direction of the strain. Thus ε_{12} denotes a shearing strain acting on the plane perpendicular to the x-axis and the strain acts in the y-axis.

Equation (3.5) can be reduced in the same manner to obtain unidirectional strain. Thus:

$$\varepsilon_y = \varepsilon_x = \frac{(l_1 - l_0)}{l_0} \qquad \qquad \ldots (3.9)$$

in the x - direction. This is the strain determined in this research project for bamboo in tension.

3.3 Hooke's Law

Hooke's law applies when stress is linearly proportional to the strain. The generalized Hooke's law for small strain in linear elasticity is (Chung, 1988):

$$\sigma_{ij} = C_{ijkm} \varepsilon_{km} \qquad \qquad \ldots (3.10)$$

Where: ε_{km} = Cauchy's infinitesimal strain tensor,

σ_{ij} = the stress tensor

C_{ijkm} = the stiffness tensor and it describes the elastic moduli of materials.

For an anisotropic body with material properties that are different in all directions at a point, with no planes of symmetry and whose properties are functions of orientation at a point in the body (Gumbe 1993) C_{ijkm} has a total of 81 constants. That is $d^n = 3^4 = 81$, with d = number of dimensions, n = orders of tensor. Hence for anisotropic materials (Chung, 1988),

$$C_{ijkm} = \begin{bmatrix} C_{1111} & C_{1122} & C_{1133} & C_{1112} & C_{1123} & C_{1113} \\ & C_{2222} & C_{2233} & C_{2212} & C_{2223} & C_{2213} \\ & & C_{3333} & C_{3312} & C_{3323} & C_{3313} \\ & & & C_{1212} & C_{1223} & C_{1213} \\ & & & & C_{2323} & C_{2313} \\ & \text{symm.} & & & & C_{3113} \end{bmatrix} \qquad \ldots (3.11)$$

For orthotropic materials (materials symmetric with respect to two planes such as wood, there are only 9 non-zero components out of the 81 constants in the stiffness tensor. Hence, for orthotropic

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materials (Chung, 1988),

$$
C_{ijkm} = \begin{bmatrix}
C_{1111} & C_{1122} & C_{1133} & 0 & 0 & 0 \\
& C_{2222} & C_{2233} & 0 & 0 & 0 \\
& & C_{3333} & 0 & 0 & 0 \\
& & & C_{1212} & 0 & 0 \\
& & & & C_{2323} & 0 \\
& \text{symm.} & & & & C_{3113}
\end{bmatrix}
\qquad \ldots (3.12)
$$

Twelve constants (nine are independent) are needed to describe the elastic behaviour of wood. Three moduli of elasticity, (E), three unit moduli of rigidity, (G), and six poisson's ratios, (υ) (USDA, 1987). Hence for wood (Chung, 1988),

$$
\begin{bmatrix}
\gamma_{11} \\
\gamma_{22} \\
\gamma_{33} \\
\gamma_{12} \\
\gamma_{23} \\
\gamma_{31}
\end{bmatrix}
= \frac{1}{C_{ijkm}}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{23} \\
\sigma_{31}
\end{bmatrix}
=
\begin{bmatrix}
1 & -\upsilon & -\upsilon & 0 & 0 & 0 \\
-\upsilon & 1 & -\upsilon & 0 & 0 & 0 \\
-\upsilon & -\upsilon & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & E & 0 & 0 \\
0 & 0 & 0 & 0 & E & 0 \\
0 & 0 & 0 & 0 & 0 & E
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{23} \\
\sigma_{31}
\end{bmatrix}
\qquad \ldots (3.13)
$$

The moduli of elasticity and poisson's ratios are related by the expression of the form (USDA,1987).

$$
\frac{\upsilon_{ij}}{E_i} = \frac{\upsilon_{ij}}{E_j}, i \neq j, i, j = L, R, T
\qquad \ldots (3.14)
$$

3.3.1 Modulus of Elasticity

The three moduli of elasticity denoted by E_L, E_R and E_T are, respectively moduli along longitudinal, radial and tangential axes of wood (USDA,1987).

3.3.2 Modulus of Rigidity

The three moduli of rigidity are denoted by G_{LR}, G_{LT}, G_{RT} are the elastic constants in the LR, LT and RT planes, respectively. For example G_{LR} is the modulus of rigidity based on shear strain in the LR plane, and shear stresses in the LT and RT planes (USDA,1987).

3.3.3 Poisson's Ratio

The six poisson's ratios are denoted by υ_{LR}, υ_{RL}, υ_{LT}, υ_{TL}, υ_{RT}, υ_{TR}. The first letter of the subscript refers to the direction of the applied stress and the second letter refers to the direction of the lateral deformation. For example, υ_{LR} is the Poisson's ratio for deformation along the radial axis caused by stress along the longitudinal axis (USDA,1987).

3.4 Tensile Test

When a cylindrical rod is subjected to tensile loads on both ends its length increases and a conventional stress-strain curve such as the one below may be plotted.
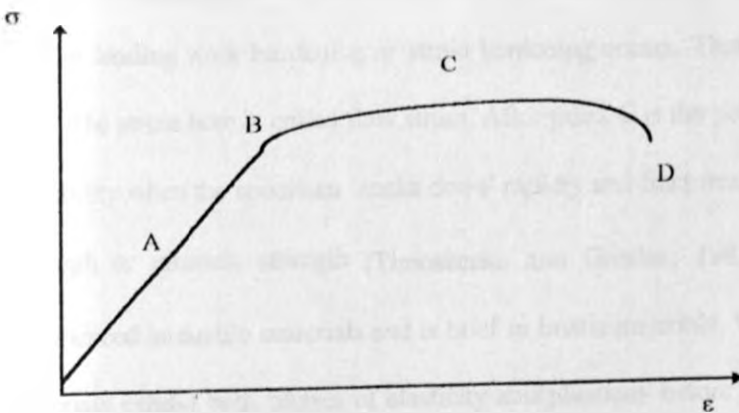
Fig. 3.4 - Conventional Stress - Strain Curve.

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Normal stress (σ_n) is obtained by dividing the load by the original cross-sectional area (A_0) or (Timoshenko and Goodier, 1983)

$$\sigma_n = \frac{P}{A_0} \qquad \ldots (3.15)$$

Conventional or engineering strain (e) is ratio of the increase in length $(L - L_0)$ to the original length (L_0) that is (Timoshenko and Goodier, 1983),

$$\varepsilon = \frac{(L - L_0)}{L_0} \qquad \ldots (3.16)$$

When normal stress is plotted against conventional strain such as in fig 6, the relation is initially linear until point A - the proportional limit. Hooke's law is valid up to this point. Between A and B (the elastic limit or yield point) elasticity is maintained although the relationship is not linear. Usually A and B are assumed to be at the same point. The stress at B is called proof strength or offset yield strength (Timoshenko and Goodier, 1983).

Beyond the elastic limit all deformation is permanent and is referred to as plastic deformation. On further loading work hardening or strain hardening occurs. That is, strain increases at a greater rate. The stress here is called flow stress. After point C is the point of maximum load or point of instability when the specimen 'necks down' rapidly and fractures. The stress here is called tensile strength or ultimate strength (Timoshenko and Goodier, 1983). This sequence of events is pronounced in ductile materials and is brief in brittle materials. Whether it is observed or not, all materials exhibit both phases of elasticity and plasticity before the ultimate strength is reached. The total strain (ε) can therefore be considered as being made up of two parts, the elastic component (ε^e) and the plastic component (ε^p) (Timoshenko and Goodier, 1983).

CHAPTER 4: MATERIALS AND METHODS

4.1 Material Selection and Sampling

The material used in this research project was bamboo of the species *Bambusa Vulgaris*. The particular culms used were obtained from the bamboo plantation at the Kenya Forestry Research Institute (KEFRI) arboretum in Muguga (off the road to the Kenya Agricultural Research Institute - KARI) in March, 1999. The clumps of *B. Vulgaris* at KEFRI had been introduced in Kenya from India and propagated as offsets in 1988. Muguga has a latitude of about 1.5°S, a longitude of 37°E and an altitude of about 1700 m. above sea level. The annual rainfall is about 1500 mm. per annum. On the basis of agricultural climatic zones, Muguga falls in Zone 3, being of a relatively high altitude and of high potential for agriculture (Kigomo,1988).

The plantation had 110 clumps (bushes) of bamboo. From each clump, two mature culms were identified and selected with the assistance of an experienced forester as follows: being sympodial bamboo, which spreads from the centre outwards, the mature culms were likely to be at the centre of the bush. The mature culms were less bright in colour than young plants, were relatively taller, had shed their lower leaves or the lower leaves were dry and had relatively new shoots growing around them. Since only mature culms were selected, their age can be estimated to have been ten years. This is because the plantation had been established in 1988 and bamboo poles had not been harvested from it since that time.

The number of samples required was 120 (40 for each of the three strength parameters under study). Hence each of the identified stalks was numbered from No. 1 - No. 220. Random numbers were then generated from a calculator to select the required 120 stalks. From the selected 120 culms, 24 culms were randomly selected for the abstraction of samples for determination of density and moisture content. After cutting off specimens for moisture content determination, the

selected culms were put back among the rest for use in the determination of strength properties.

The 120 stalks were then divided into three groups by randomly assigning the numbers 1,2,3 to each sample. The forty samples obtained in each group were used in the determination of tensile, compressive and bending strength respectively.

The diameter of the bamboo stalks used ranged from 4 cms. to 6 cms. The actual diameters were used to obtain the areas used to calculate the strength parameters specified in the tables in Appendix 3. The heights from which the samples were obtained were limited to 6m from the bottom of the stalk.

4.2 Material Drying

The bamboos were then air dried (naturally dried) for six weeks when they attained a moisture content of 10.8%. Subsequent measurements of moisture content in the next two weeks gave similar values to those obtained earlier, indicating that the stalks had reached equilibrium with the atmospheric conditions. Since ambient temperature and relative humidity were in the range of $17^{O}C$ to $23\ ^{O}C$ and 63% to 67 % respectively, the mode of moisture reduction was in agreement with BS 373: 1979 for control of moisture content.

4.3 Experiments

Several experiments were carried out to determine the various mechanical properties of *B. Vulgaris*. The properties investigated included density, tensile strength, compressive strength and bending strength.

4.3.1 Density determination

A length of 2.5 cms along the grain is recommended by KS 02 – 982: Part 2: (1990) for the determination of density. These dimensions were measured using vernier calipers and cut with an accurate electric saw. The mass was determined before oven drying using an electronic balance and recorded as m_0. The specimens were then oven dried and the mass attained after drying at 105°C. recorded as m_1.

Then, the volume was determined as follows: A test piece was put in a large measuring cylinder which was then filled with very fine sand (passing through 0.02mm. sieve). The volume of the sand in the cylinder together with the specimen, V_0, was recorded. The specimen was then retrieved from the cylinder and volume V_1 recorded and the decrease in volume ($V_0 - V_1$) calculated. This was taken as the volume of the specimen. Mass before drying was then divided by volume to obtain density.

4.3.2 Tensile Strength

The test materials had the dimensions shown in Fig. 4.1.
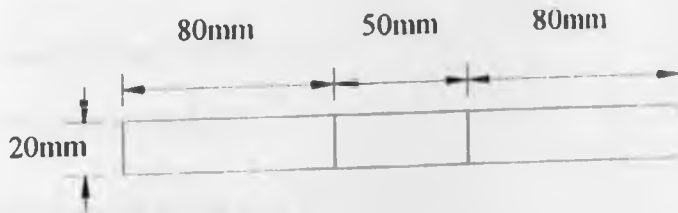
Fig. 4.1 - Tensile Strength Test Specimen.

These dimensions were arrived at following the KS 02-982: Part 5: 1990 recommendation that for the tensile strength test, the gauge length along the grain should be 50mm -100mm and the length of the cross-section should be 10mm - 20mm.

Forty specimens were used: 20 having nodes at the centre and the rest without nodes. The thickness of the test pieces were determined and used to calculate the cross-sectional areas. KS (1990) recommends a minimum of 24 specimens for this test.

After recording the ambient temperature and the relative humidity, the specimen was mounted on the tester. A tensile load was applied uniformly at 1.27mm/min (BS 373,1957) which caused failure within 420s (BS 5820, 1979). The load at failure was recorded and used to calculate the tensile strength using the formulas 4.1 and 4.2.

$$A = 20X \qquad \qquad \dots (4.1)$$

$$F_t = \frac{F_{max}}{A} \qquad \qquad \dots (4.2)$$

Where: F_t = tension strength (MPa) 3 sf.

F_{max} = maximum load (N)

A = cross-sectional area (mm^2)

4.3.3 Compression strength

The 40 pieces of test materials used had the dimensions in Fig. 4.2.

80mm
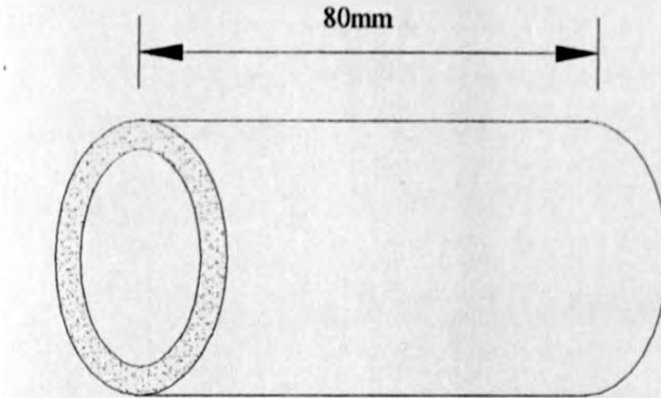
Fig. 4.2 - Compression Strength Test Specimen

20 pieces had nodes while the other 20 pieces did not have nodes. Due to the danger of failure by buckling rather than pure compression the appropriate height/ diameter ratio should be in the range 0.7-1.5 (Mburu, 1992). Hence a length of 80 mm. was chosen, which agrees with the KS 02-982: Part3 (1990) standard of length along the grain.

The ambient temperature, relative humidity and internal and external diameters of the specimens were determined before each compression test.

The specimens were then loaded at a continuos rate of 0.625 mm/min (BS 373,1957) and failed within 420s. (BS 5820, 1979). The mode of failure was recorded together with the load at failure (f_{max}). The compressive strength (f_c) was then calculated using the formulas 4.3 and 4.4.

$$A = \Pi \left[\left(\frac{d_e}{2}\right)^2 - \left(\frac{d_i}{2}\right)^2 \right] \qquad \ldots (4.3)$$

$$F_c = \frac{F_{max}}{A} \qquad \qquad \dots (4.4)$$

Where: d_e = external diameter (mm)

d_i = internal diameter (mm)

A = cross sectional area (mm^2)

F_c = compressive strength (N/mm^2)

F_{max} = maximum load (N)

4.3.4 Bending Strength

Forty test pieces (20 with nodes and 20 without nodes) were used which had the dimensions in the 3-point set up in Fig 4.3:

100mm   100mm

100mm
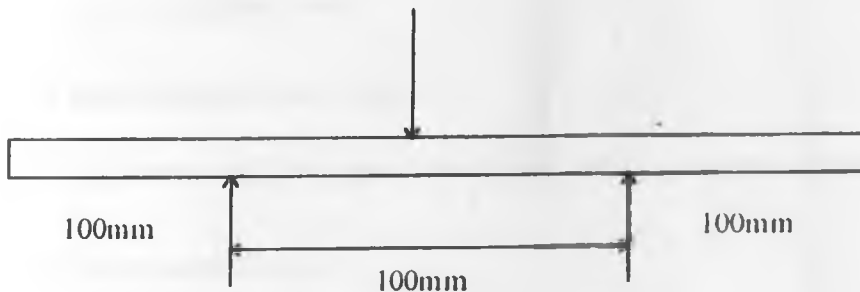
Fig. 4.3: Bending Strength Test Specimen

The width was a constant 15mm. The above dimensions are below the 18:1 Length/Depth ratio, (BS 5820, 1979) standard and 4:1 Depth/Width ratio. The specimen thickness, h, ambient temperature and relative humidity were recorded.

The test materials were then loaded uniformly to cause failure within 420 seconds. (BS 5820,

1979). The load at failure (f_{max}) was recorded. The second moment of area (I), section modulus (z) and bending strength (fb) were calculated using the formulas 4.5, 4 6 and 4 7

$$I = \frac{bh^3}{12} \qquad \qquad \ldots (4.5)$$

$$Z = \frac{I}{C} \qquad \qquad \ldots (4.6)$$

$$f_b = \frac{F_{max} I}{2Z} \qquad \qquad \ldots (4.7)$$

Where:　　b = width of the timber (mm)

h = height of cross section of timber (mm)

l = length of specimen (mm)

I = section moment of area (mm^4)

C = maximum height from neutral axis to point of load application = h/2 (mm)

Z = section modulus (mm^3)

F_{max} = maximum load at failure (N)

f_b = bending strength (MPa)

The Torsee Universal Tensile Machine type AMU - 5 - DE, shown in Fig. 4.4 was used in the determination of the tensile, compressive and bending strength.
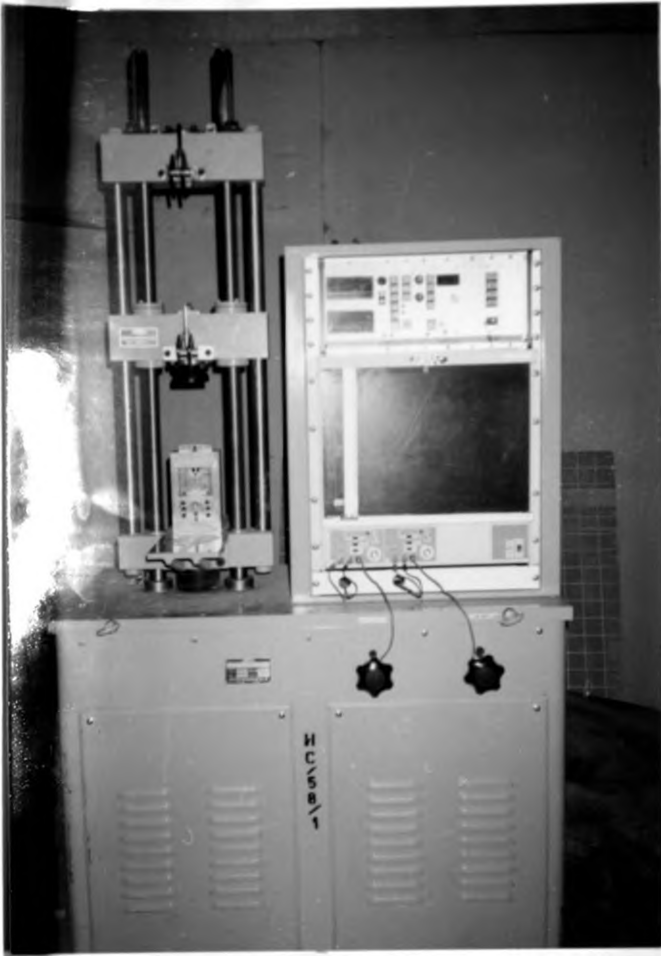
Fig. 4.4 - Universal Testing Machine

4.4 Statistical Design

Nodes are known to increase or reduce the strength of bamboo (Janssen, 1991).Hence for each test a comparison was made of the values from the specimens with nodes and those without nodes. The test criterion used for each test was a completely randomised design of the analysis of variance. For each test, the mean, standard deviation and standard error of means were calculated. The statistical calculations are in Appendix 3.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Introduction

This research project aimed at determining the following mechanical properties of *B. vulgaris*: Density, tensile strength, compressive strength, bending strength and modulus of elasticity. Table 5.1 is a summary of the results obtained. The table gives the results of the various tests performed in the project, in terms of mean, standard deviation (S.D.) and coefficient of variation (C.V.). The rest of this chapter is a discussion of the results obtained. Detailed results are presented in Appendix 3 and the frequency diagrams are drawn from the tables in Appendix 4.

Table 5.1: Summary of all results

PROPERTY		MEAN	S.D.	C.V. (%)
Moisture content	Dry basis	10.76 (%)	1.35	12.55
Density	Oven dry	590 kg/m³	0.10	16.95
Compressive strength	With nodes	49.89 MPa	8.93	17.89
	Without nodes	51.68 MPa	7.95	15.38
Tensile strength	With nodes	94.3 MPa	19.10	20.20
	Without nodes	117.9 MPa	9.70	8.20
Bending strength	With nodes	107.0 MPa	21.50	20.10
	Without nodes	137.7 MPa	15.30	11.10
MOE* (tensile strength)	With nodes	3002.2 Mpa	567.30	18.90
	Without nodes	3594.0 MPa	649.80	18.00
MOE* (comp. strength)	With nodes	7268.1 MPa	2889.20	39.80
	Without nodes	10405.3 MPa	3525.5	33.90

*MOE is modulus of elasticity

5.2 Density

Before the commencement of tests to determine the various strength parameters, it was necessary to determine the moisture content of the air dried bamboo. It was found that the M.C. was 10.76

(%). This particular experiment confirmed that the bamboo culms to be used in the determination of strength properties were below 12% moisture content as stipulated by the standards. These values are useful in correcting the strength values obtained in this particular research project to the required strength at 12% moisture content. This conversion is done using Equation 3.7.

The determination of the density of the bamboo culms used was also performed before the start of the experiments to determine strength properties. It was found that the density was 590 kg/ m³. It was necessary to find out the density of the particular bamboos used in this project in recognition of the fact that density has a great influence on mechanical properties of wood

In the research papers presented in Janssen (1991) the values of density range from 500-700 kg/m³. The values of density obtained for *B. Vulgaris* in this project falls within this range. From this result alone, it is possible to deduce that, holding all other factors the same, the strength parameters obtained in this research project will be similar to those of other bamboo species on the strength of the fact that density has a major influence on strength. This is because the density of bamboo is a property of the wood material in it.

5.3 Compressive Strength

Figure 5.1 is the frequency diagram of results obtained in the compressive strength test. The frequency curve was drawn using the data contained in Figure A3.1. Janssen (1991) and U.N. (1972) report that the values of compressive strength from past research work on bamboo in general falls within the range of 30 - 90 MPa. The results obtained in this project, that is, 49.89MPa and 51.68MPa for nodes and internodes respectively, fall within this range. Statistical analysis in Appendix 2 reveals that there is no significant difference between the compressive strength of specimens with nodes and those without nodes. Hence, the presence or the absence of nodes was found not to have any effect on the compressive strength as per this experiment. This is supported by the frequency curves in Figure 5.1 in which the peaks of the node and the

47

internode are on the same vertical line, indicating similar values of compressive strength

This phenomenon may be explained by the fact that the internode of bamboo is composed of fibres running through a woody matrix. The node, on the other hand, is composed of the matrix only. The fibres are strong in bending and tensile strength, while their effect in compression is insignificant. Therefore, during compression, only the matrix exerts any resistance to external force and the fact that the internode has fibres in the matrix does not make it stronger than the node which only has the matrix. The Figures 5.2 and 5.3 compare whole specimens with specimens which have not yielded.
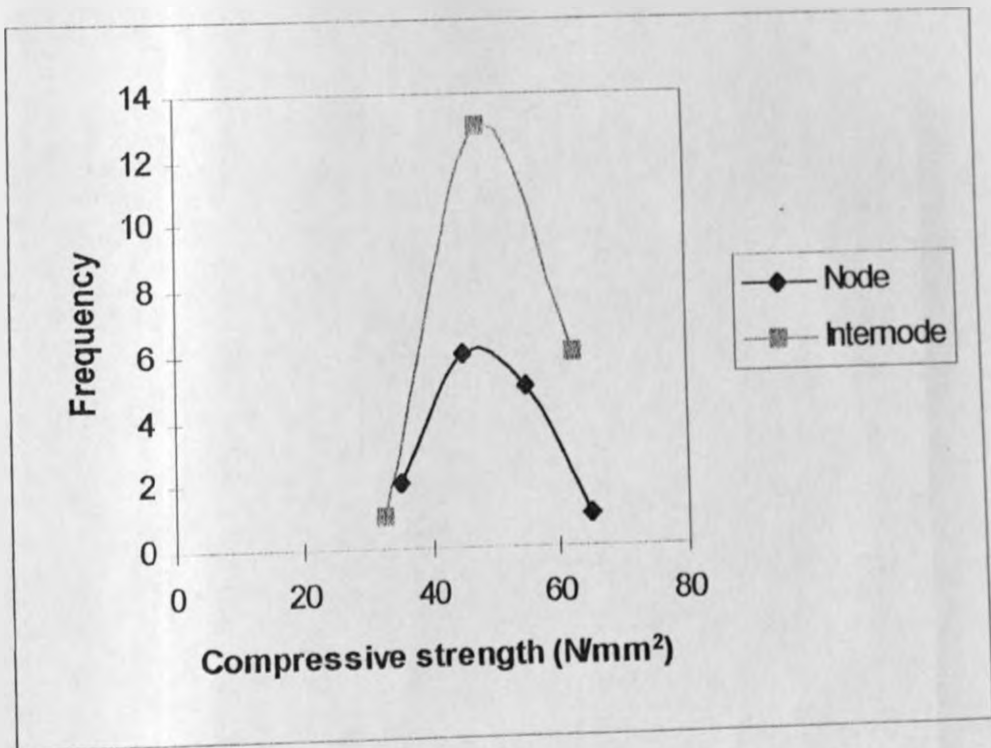
Fig. 5.1: Frequency Curves for Compressive Strength Test.
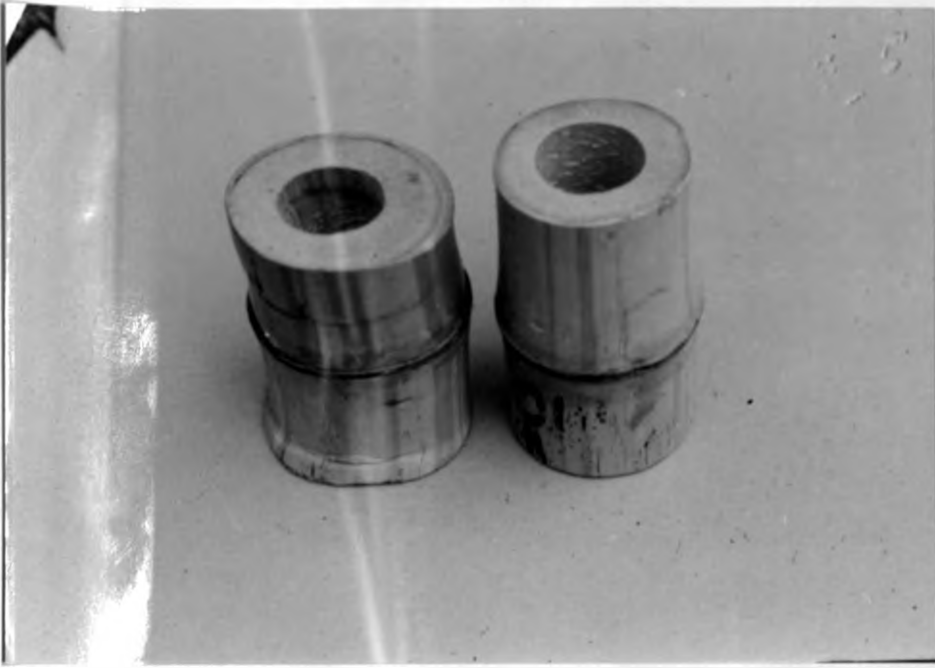
Fig 5.2: Failure in Compression (With Nodes)

Fig. 5.3: Failure in Compression (Without Nodes)

The practical application of these results is that, during compression, the loads may be applied at any point as long as they do not exceed the values indicated for the nodes and the appropriate slenderness ratios. The most common application of compression members is in columns. It is possible to use bamboo for this application as long as the area and slenderness ratios are adequate. Since, the node does not affect compressive strength, this means that the multiplicity of nodes (more than one node) along the culm will not affect the overall strength of a bamboo member in compression.

5.4 Tensile Strength

The following results were obtained in the tensile strength test: 94.30MPa with nodes and 117.90MPa without nodes as presented in Table 5.1.
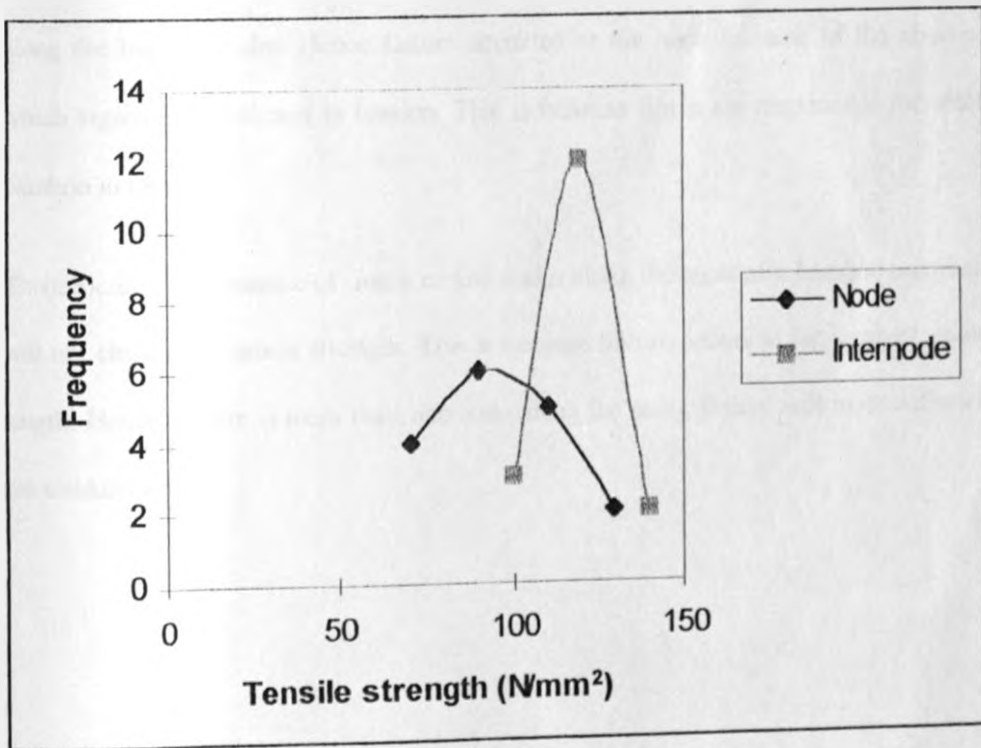
Fig. 5.4: Frequency Curves for Tensile Strength.

The values obtained for tensile strength at the node obtained in this project were slightly lower than those obtained in the earlier experiments presented in Janssen (1991) which range from 100-200 MPa. However, the value of tensile strength for specimens without nodes still falls within this range. This difference may be explained in the context of different ages, growth conditions and species of bamboo used.

The statistical analysis presented in Appendix 2 revealed that there was a significant difference in strength between specimens with node and those without the nodes. This means that that the internode of bamboo culms is stronger in tension than the node. This can be supported by the fact that in the experiments, all the specimens with nodes failed at the node in tension. The fact that the peak of the tensile strength frequency curve (Fig 5.4) of the node is to the left of the tensile strength frequency curve of the internode also shows that bamboo is stronger in the internode.

Again, the statistical result obtained in Appendix 2 can be attributed to the distribution of fibres along the bamboo culm. Hence failure occurred at the node because of the absence of fibres which signifies a weakness in tension. This is because fibres are responsible for reinforcing the bamboo in tension.

Theoretically, the presence of more or less nodes along the stem of a bamboo member in tension will not change the tensile strength. This is because failure occurs at the weakest point along the length. Hence if there is more than one node along the stem, failure will most definitely occur at the weakest node.
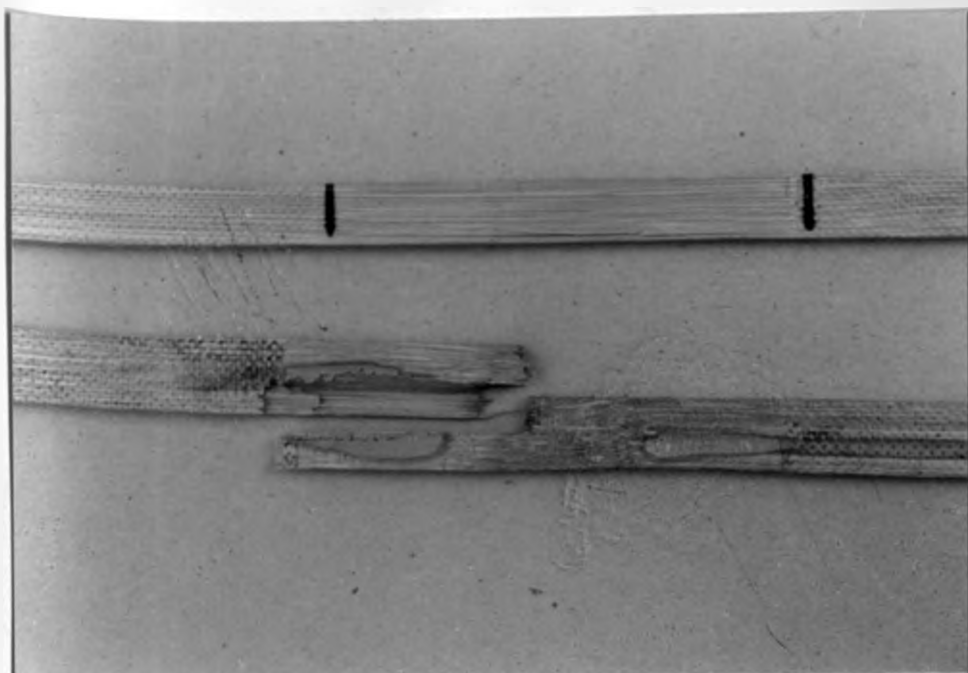
Fig. 5.5: Failure in tension

5.5 Bending Strength

The frequency table in Figure 5.6 obtained from Table A3.3 in Appendix 3.
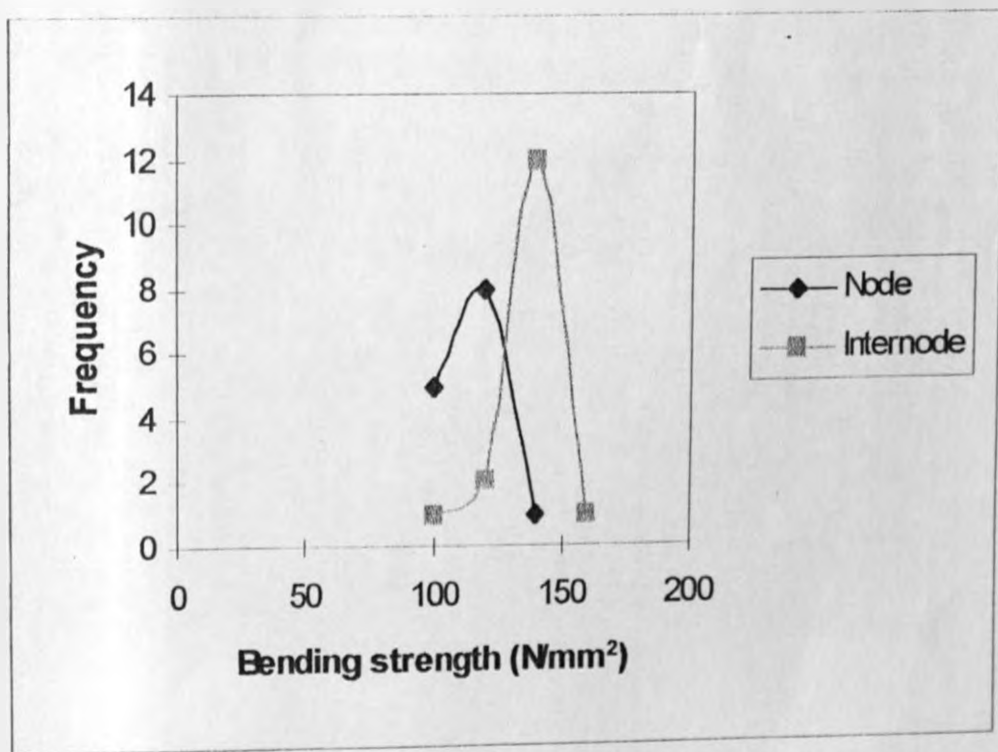
Fig. 5.6: Frequency Curves for Bending Strength Test

These values of bending strength obtained in the bending strength test, that is, 107.00 MPa and 137.70 MPa with and without nodes respectively, tally with those obtained for the other bamboo species used in past research and presented in Janssen (1991) where the range is between 90 - 150 MPa.

The nodes were shown in the statistical analysis (Appendix 2) to have a significant effect on the bending strength of bamboo. In the actual bending strength test, all the specimens with nodes failed at the node, which indicates an obvious weakness at the node. This failure at the node can be explained by the absence of fibres at the node, which would have resisted bending.
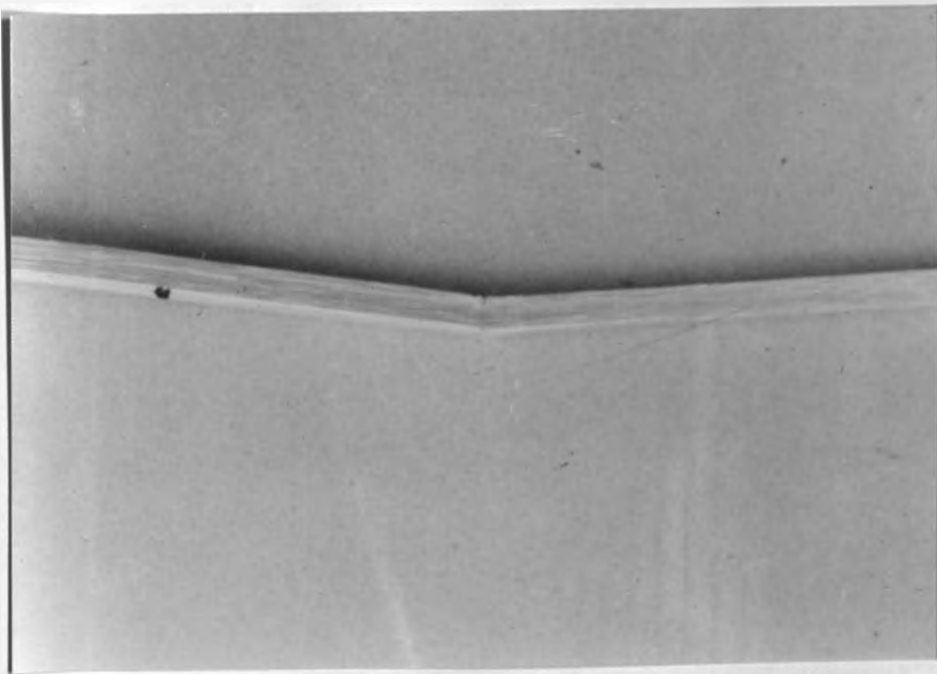
Fig. 5.7: Failure in Bending

When there is more than one node, failure will most likely occur at the nodes closest to the

loading. As such, the loading with bending forces (of beams) must be designed to avoid the node. It would be helpful for designers using bamboo beams to use more than one bamboo pole and have nodes on different poles featuring at different positions along the poles.

5.6 Modulus of Elasticity

The Modulus of Elasticity was determined in both the tensile and compressive tests. The values of Modulus of Elasticity obtained from the compressive strength test (10,405.3 MPa and 7,268.1 Mpa) are much higher than those obtained from the tensile strength (3002.2 MPa and 3594.0 MPa). The values from the tensile strength test are much lower than the values expected for the Modulus of Elasticity of Bamboo.

This may be explained by the fact that when subjected to tensile forces, wood tends to fail by shearing. Hence, the elongation is much longer than expected and this decreases the value of the Young's Modulus. Therefore the values obtained from the compressive test can be considered to be more accurate than those obtained from the tensile strength test.

5.7 Summary

The practical application of these findings would constitute a note to designers to load bamboo during construction with forces not exceeding those indicated for the nodes, particularly during tension and bending. For bending in particular, the application of loads at the node must be avoided.

The values of the strength parameters indicated above for *B. vulgaris* do not differ significantly from those obtained for other bamboo species recommended for construction. Hence, *B. Vulgaris* can be said to be suitable as a construction material and may be applied for all the functions for which the other bamboos are used as outlined in the appendix.

This research project, however, can be said to have confirmed the third obstacle to the use of

bamboo as a construction material: that the node on the bamboo stem weakens rather than strengthens bamboo. The other two obstacles are:

1. Bamboo cracks easily on nailing.

2. The construction industry uses solid members with a rectangular cross-section of known dimensions. Yet bamboo is circular, hollow, and with dimensions tapering towards the end and varying from culm to culm.

These adverse factors lead to the conclusion that for bamboo to play a greater role in construction it must be processed to make it more conventional and useful in construction. This will enable greater use of this cheap, and environment friendly source of timber. Below are two examples of processes that may be employed to make bamboo more conventional:

1. Crushing several bamboo poles traversely to flatten out the hollow sections. The result of the crushing will be long fibres of bamboo. These fibres can be joined together using glue and allowed to dry. The resulting composite can be machined by regular wood working machines into desirable shapes and sizes of timber. The crushing and joining using glue will make bamboo solid and capable of being machined into regular shapes and sizes. The use of glue will also give bamboo a new matrix which will not crack during nailing. Since nodes are arranged differently on different culms, the nodes will not feature at the same point along the new material. This will cancel the effect of the weak nodes.

2. Grinding the bamboo into particles and using it to make chipboards and plywood.

CHAPTER 6: CONCLUSIONS

a) The following strength parameters were obtained from the study

   1. The mass per volume of bamboo was found to be 590 kg/m³

   2. Tensile strength of bamboo at the node was found to be 94.30 MPa while the internode was found to have a strength of 117.90 MPa.

   3. Compressive strength of bamboo at the node was obtained as 49.89 MPa and 51.68 MPa at the internode.

   4. The bending strength test yielded 107.00 MPa at the node and 137.70 MPa at the internode.

   5. The Modulus of Elasticity as calculated from the compressive strength test was 10,405.3 MPa at the internode and 7,268.1 MPa at the node.

b) The mechanical properties of *Bambusa vulgaris* compares very well with those of other species of bamboo.

c) The effect of nodes has been shown in this research project to be significant in tension and in bending, but has no influence over the compressive strength. Hence the node is the weakest point in this bamboo during tension and bending.

CHAPTER 7: SUGGESTIONS FOR FUTURE WORK

1. The determination of shear strength and time related strength characteristics (creep and relaxation) of *Bambusa vulgaris*.

2. An investigation into the ability to of *Bambusa vulgaris* to withstand pressure from fluids flowing in it so as to establish the optimal pressure at which water and other fluids may flow through bamboo stems without the risk of bursting.

3. The identification of species of bamboo which can withstand cracking and methods of fastening bamboo to avoid cracking.

4. Identification of methods that may be used to process or machine bamboo to make its dimensions comparable to those of timber, while maintaining its strength.

5. Comparison of the strength of *Bambusa vulgaris* grown in Muguga with the strength culms of the same species grown in other Agroclimates.

6. Investigating the effect of more than one node on the overall strength of a bamboo pole.

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APPENDICES

Appendix 1: Uses of Bamboo

Source : Environmental Bamboo Foundation (1999).

A

A-frame houses, activated charcoal, acupuncture needles, airplane wing members and stress skin for fuselage, alarms, alcohol, antenna supports, aphrodisiac, arbors, arrows and arrow tips, ashtrays, awnings.

B

Baby carriages, bagpipes, barrels, baskets, beads, beanpoles, beds, beehives, beer, bicycles, bilge pumps, blinds, blowguns and darts, boards, boat hoods, boats, bolts, bookcases, books, brooms, bottles, bowls, bows (archery), boxes, bracelets, bridges, brooms, brushes, brush pots, buckets, buttons.

C

Cables, cages, candlesticks, canes, canteens, carts, castanets catalyst (tabasheer), caulking, chairs, charcoal, chisels, chopsticks, churches, cigarette holders, clothes, clothes racks, clubs, colanders, combs, cooking vessels, chicken coops, couches, cow bells, cradles, crates, cribs, crosses, crutches, cultures for bacteria, cups, curtains.

D

Dams, defensive fortifications, deodorizers, desks, diesel fuel, dikes, dirigible, dolls, domes, dowel pins, dredge (finishing), drouges, dustpans.

E

Eggcups.

F

Fans, farming uses, fences, fenders, fertilizer, fiesta assistant, fifes, firearms, fire starters, firewood, fireworks, fishnets, fish poles, flagpoles, flails, floats, flooring, flowerpots, flutes, flying art, food, forage, forms, frames, fruit pickers, fuel, furniture.

G

Gabions, games, garments, gates, grain, grain storage, graters, greenhouses, guns, gutters, gypsy vans.

H

Hairpins, hampers, handles, hats, hawsers, hay and forage, hedges, helmets, hen houses, hinges, hoops, hookahs, house plants, houses, humidors, hummers.

I

Iceless coolers, incense sticks, insect cages, irrigation waterwheels and pipes.

J

Jackets, jars, jewelry, joss sticks, junks.

K

Kiosk, kites.

L

Laquerware, ladders, ladles, lamps, lampshades, landing docks, landscaping, lanterns, lathing, laundry poles, levees, light bulb filament, lofts, looms.

M

Marimbas, markers, masts, mattangs, matting, mattresses, medicines, mills, mobiles, mushroom culture, musical instruments, mahjong tiles.

N

Nails, napkin rings, net floats, nets, needles, netsuke.

O

Organs, ornaments, outriggers, ox cart beds, ox goads, oyster cultivation.

R

Racks, rafts, raincoats, rainspouts, rakes, rattles, rayon, record needles, reeds, reinforcement for concrete and adobe, rings, ritual objects, roofing, ropes, rug poles, rulers.

S

Sail covers, sails, sailstays, sake, salt well drilling, sandals, scaffolding, scales, scarecrows, scoops, scratchers, screens, scrubbers, sedan chairs, shades, shakuhachis, shavings, sheaths, shields, shingles, ship designs, shoe horns, shoe soles, shoots for food, shovels, shuttles for weaving, sieves, silk industry, skewers for cooking, ski poles, slide rules, sluices, snow fences, spears, splints, spouts, spray guns, springs, stakes, staves, sticks, stilts, stools, string, sugar, sunning floors, swimming pools.

T

Tabasheer, tables, tallies, tea houses, tea strainers, tea whisks, tents, temporary structures, tiles, tortures, towers, toys, trailers, transport, traps.

U

Umbrellas.

V

Valiha (musical instrument).

W

Wagons, walking sticks, walls, war, water jugs, water pistols, water storage, waterwheels, waxes, weapons, weaving shuttles and looms, weirs, well sweeps, wheelbarrow, whetstones, whips, whistles, wicks, wind breaks, wind mills, wine storage, winnowing machines, writing brushes and pens.

X

Xylophones.

Y

Yurts.

Z

Zithers.

Appendix 2: Uses of Bamboo (Pictures)

Fig. A2.1: Bamboo Grain Store
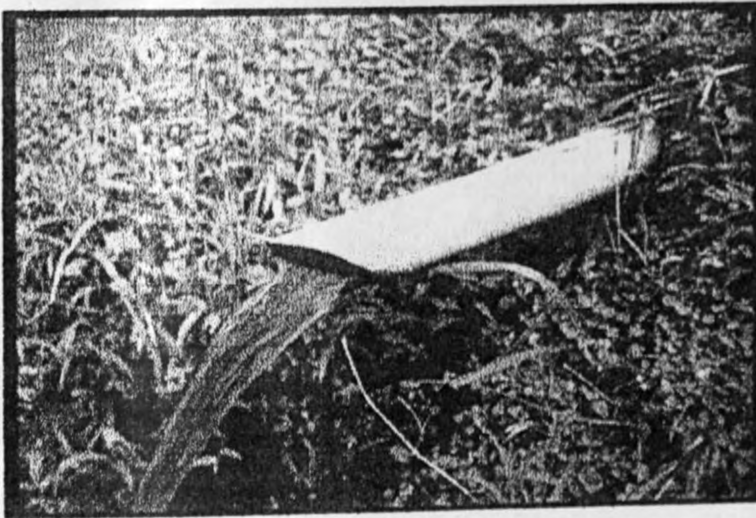
Fig. A2.2: Bamboo Water Pipe
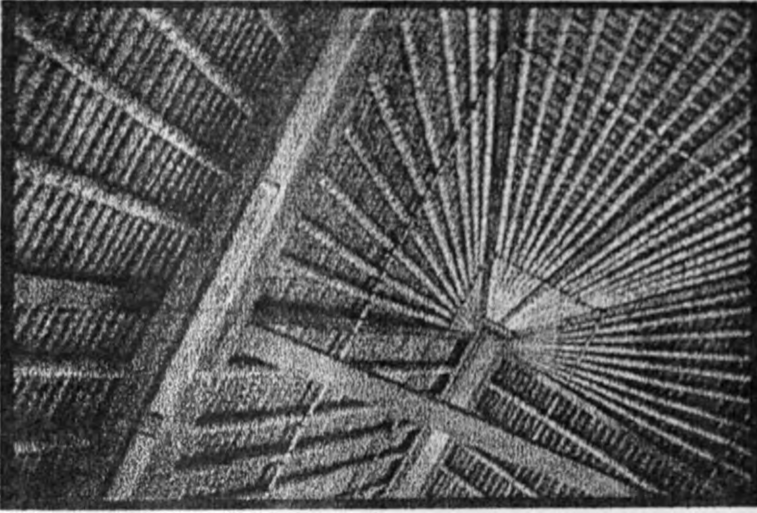
Fig. A2.3: Bamboo Roof
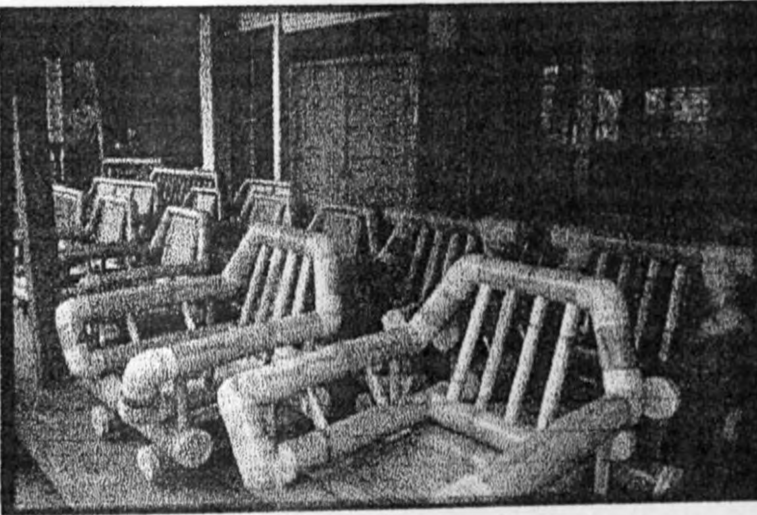
Fig. A2.4: Bamboo Furniture
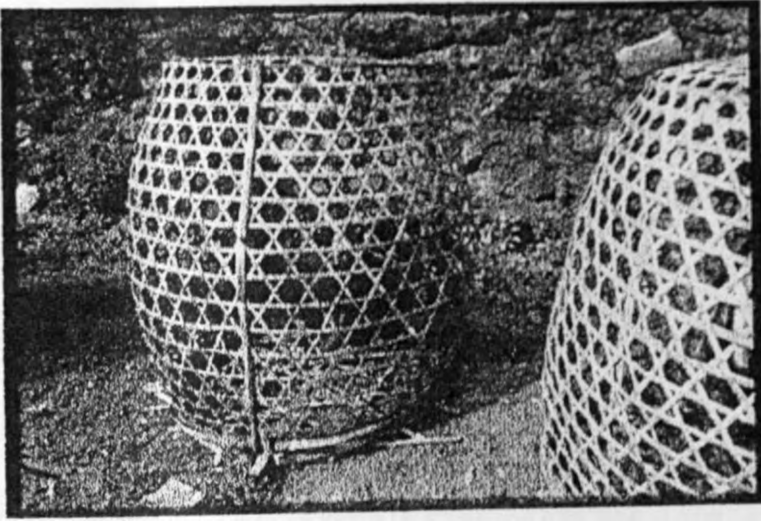
Fig. A2.5: Bamboo Baskets

Fig. A2.6: Bamboo Tray and Cups

Fig. A2.7: Bamboo Xylophone

Appendix 3: Statistical Analysis

The following operations were carried out on the data collected.

1. For each experiment, the sample mean, $\overline{Y}$ of the values of strength obtained was calculated, so as to give a measure of central tendency. The following formula was used. (Steel and Torrie, 1980)

$$\overline{Y} = \frac{\sum_{i=1}^{n} Yi}{n} \qquad \qquad \dots (A3.1)$$

Where: $\overline{Y}$ = Sample mean

$Yi = i^{th}$ observation

n = Number of observations

*For each test, mean M.C., mean Temperature and mean R.H. were calculated.

2. The sample standard deviation, SD, of the values in each experiment was then determined. The sample standard deviation, being a measure of spread or variation was deemed to be an important complement to the sample mean in summarizing data. To obtain sample standard deviation, the formula below was used, (Steel and Torrie, 1980).

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(Yi - \overline{Y})}{n-1}} \qquad \qquad \dots (A3.2)$$

3. To facilitate comparison with other experiments of a similar nature, the coefficient of variation, CV, was determined for each experiment, (Steel and Torrie, 1980)

$$CV = \frac{100SD}{\overline{Y}} \qquad \qquad \dots (A3.3)$$

4. In this research project three strength parameters were evaluated, namely; compressive

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strength, tensile strength and bending strength. For each strength parameter, two experiments were done.

(i) for samples having nodes

(ii) for samples without nodes

To test the significance of the effect of the absence or presence of nodes on the strength of bamboo, an analysis of variance (ANOVA) was performed using the completely randomised design. There were two treatments (the absence or presence of a node) and at least 18 replications per treatment.

The following considerations were made for each analysis:

-MODEL: Fixed Effect Model (Model 1)

$$Y_{ij} = \mu + \tau + \varepsilon_{ij} \qquad \qquad \dots (A3.4)$$

Where: Y_{ij} = Strength in N/mm^2 from the jth specimen under the ith treatment (presence or absence of nodes)

i = 1,2

j = 1-19

μ = Mean strength

τ_i = Net effect of the ith node status

-PARAMETERS: μ, τ_1, τ_2, σ

-HYPOTHESES: Ho: Both μ_i are equal

Hi: One μ_i is different from the other.

-LEVEL OF SIGNIFICANCE: 1%

-FORMULAE:

The following formulae were used in the analysis:

$$C = \frac{Y^2_{..}}{r_1 + r_2} \qquad \qquad \dots (A3.5)$$

$$TotalSS = \sum_{ij} Y^2{}_{ij} - C \qquad\qquad \dots \text{(A3.6)}$$

$$TreatSS = \left(\frac{Y^2{}_{1.}}{r_1} + \frac{Y^2{}_{2.}}{r_2} \right) - C \qquad\qquad \dots \text{(A3.7)}$$

Where:

C = Correction factor

$Y_{..}$ = Total sum of readings with or without nodes

Y_{ij} = Individual readings

$Y_{1.}$ = Total sum of readings without nodes

$Y_{2.}$ = Total sum of readings with nodes

r_1 = Number of replications for tests without nodes

r_2 = Number of replications for tests with nodes

Table A3.1: Compressive Strength Test

REPLICATIONS	TREATMENT		TOTAL
	WITHOUT NODES (MPa)	WITH NODES (MPa)	
1	46.07	31.62	77.69
2	55.33	59.52	114.85
3	57.91	43.75	101.64
4	28.83	57.53	86.36
5	45.66	61.42	107.08
6	54.86	49.27	104.13
7	46.88	47.45	94.33
8	57.93	38.00	95.93
9	49.57	58.95	108.51
10	54.37	45.02	99.39
11	43.23	43.66	86.89
12	48.21	49.43	97.64
13	65.20	55.41	120.61
14	52.09	57.47	109.56
15	54.58		54.58
16	48.86		48.86
17	54.75		54.75
18	55.51		55.51
19	61.99		61.99
TOTAL	981.83	689.47	1680.30
SAMPLE MEAN	51.68	49.89	
SAMPLE S.D. (S)	7.95	8.93	
C.V.(%)	15.38	17.89	

Table A3.2: Anova Table

SOURCE	df	SS	MSS	Fcalc.	Ftab(1,31) 0.01
TREATMENTS	1	25.670	25.670	0.37	7.54
ERROR	31	2175.094	70.164		
TOTAL	32	2200.764			

CALCULATIONS FOR COMPRESSIVE STRENGTH

$$C = \frac{1680.3^2}{33} = 85557.821$$

$$TotalSS = 8775855 - 85557.821 = 2200.764$$

$$TreatSS = \left(\frac{981.83^2}{19} + \frac{698.47^2}{14} \right) - 85557.821 = 25.670$$

CONCLUSIONS

Fcal (0.37) < Ftab(7.54)

$\Rightarrow$ Fail to reject Ho

$\Rightarrow$ The means are similar

Hence there is insufficient evidence to conclude that the presence or absence of nodes affects the compressive strength of bamboo.

Table A3.3: Tensile Strength Test

	TREATMENT		
REPLICATIONS	WITHOUT NODES (MPa)	WITH NODES (MPa)	TOTAL
1	116.9	100.8	217.7
2	117.9	71.5	189.1
3	104.7	102.8	207.5
4	118.7	74.0	192.7
5	121.4	87.1	208.5
6	106.1	64.5	170.6
7	127.9	84.0	211.9
8	134.9	92.9	227.8
9	136.6	102.7	239.3
10	120.4	122.7	243.1
11	123.8	95.5	219.3
12	112.0	119.9	231.9
13	113.5	126.9	240.4
14	107.6	83.6	191.2
15	114.9	94.1	209.0
16	127.6	112.6	240.2
17	113.7	68.1	181.8
18	103.3		103.3
TOTAL	2121.6	1603.7	3725.3
SAMPLE MEAN (Y)	117.9	94.3	
SAMPLE S.D. (S)	9.7	19.1	
C.V. (%)	8.2	20.2	

Table A3.4: Anova Table

SOURCE	df	SS	MSS	Fcalc	Ftab(1,33)0.01
TREATMENTS	1	4841.14	4841.14	21.51	7.50
ERROR	33	7428.22	225.10		
TOTAL	34	12,269.36			

CALCULATIONS FOR TENSILE STRENGTH

$$C = \frac{3725.3^2}{18+17} = 396510.29$$

$$TreatSS = \left(\frac{2121.6^2}{18} + \frac{1603.7^2}{17} \right) - 396510.29 = 4841.14$$

$$TotalSS = 408779.65 - 396510.29 = 12269.36$$

CONCLUSION

Fcalc(21.51) > Ftab(7.50)

$\Rightarrow$Reject Ho

$\Rightarrow$The two means are significantly different.

Hence, there is sufficient evidence to conclude that the presence or absence of nodes affects the tensile strength of bamboo.

Table A3.5: Bending Strength Test

REPLICATIONS	TREATMENTS WITHOUT NODES (MPa)	WITH NODES (MPa)	TOTAL
1	147.5	120.9	268.4
2	158.6	97.1	255.7
3	132.5	122.1	254.6
4	150.4	121.4	271.8
5	92.1	105.5	197.6
6	150.0	112.8	262.8
7	142.6	90.4	233.0
8	144.9	134.7	279.6
9	146.6	119.5	266.1
10	132.1	95.5	227.5
11	120.5	116.9	237.4
12	143.1	124.4	267.5
13	131.1	113.0	244.3
14	127.8	116.4	244.4
15	150.0	57.7	207.7
16	136.9	63.9	200.8
17	134.7		134.7
TOTAL	2341.6	1712.1	4053.7
SAMPLE MEAN	137.7	107.0	
SAMPLE S.D. (S)	15.3	21.5	
CV(%)	11.1	20.1	

25 41-6
17 12-1
4053 7

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Table A3.6: Anova Table

SOURCE	df	SS	MSS	Fcalc	Ftab(1,31)0.01
TREATMENTS	1	7786.09	7786.09	22.61	7.54
ERROR	31	10672.49	344.27		
TOTAL	32	18458.58			

CALCULATION FOR BENDING STRENGTH

$$C = \frac{4053.7^2}{17 + 16} = 497954.05$$

$$TotalSS = 516412.63 - 497954.05 = 18458.58$$

$$TreatSS = \left(\frac{2341.6^2}{17} + \frac{1712.1^2}{16} \right) - 497954.05 = 7786.09$$

CONCLUSION

Fcal (26.61) > Ftab (7.54)

$\Rightarrow$ Reject Ho

$\Rightarrow$ The two means are significantly different

Hence there is adequate evidence to conclude that the presence (or absence) of nodes definitely

affects the bending strength of bamboo.

Appendix 4: Results

Table A4.1: Moisture Content And Density Determination Before Testing

S.N.	V_0 (cm^3)	V_1 (cm^3)	W_0 (g)	W_1 (g)	V (cm^3)	ρ_{oven} (g/cm^3)	ρ_{air} (g/cm^3)	M.C. db(%)	M.C. wb(%)
1	115	99	12.76	11.52	16	0.72	0.80	10.76	9.72
2	115	82	19.05	17.23	33	0.52	0.58	10.56	9.55
3	115	75	22.98	20.53	40	0.51	0.57	11.93	10.66
4	115	76	23.54	21.21	39	0.54	0.60	10.99	9.90
5	115	88	19.53	17.71	27	0.66	0.72	10.28	9.31
6	115	100	11.18	10.10	15	0.67	0.74	10.69	9.66
7	115	92	13.90	12.63	23	0.55	0.60	10.05	9.14
8	115	76	20.50	18.54	39	0.48	0.53	10.57	9.56
9	115	89	15.81	14.37	26	0.55	0.60	10.02	9.11
10	115	95	12.65	11.42	20	0.57	0.63	10.77	9.72
11	115	81	17.53	15.88	34	0.47	0.52	10.39	9.41
12	115	90	16.23	14.75	25	0.59	0.65	10.03	9.12
13	115	97	13.16	11.97	18	0.67	0.73	9.94	9.04
14	115	73	24.85	21.38	42	0.51	0.59	16.23	13.96
15	115	95	12.27	11.13	20	0.56	0.61	10.24	9.29
16	115	99	12.16	11.04	16	0.69	0.76	10.14	9.21
17	115	91	15.77	14.32	24	0.59	0.66	10.12	9.19
18	115	97	17.51	15.88	18	0.88	0.97	10.26	9.31
19	115	80	20.72	18.62	35	0.53	0.59	11.28	10.14
20	115	86	19.23	17.43	29	0.60	0.67	10.84	9.78
21	115	98	9.17	8.34	17	0.49	0.53	9.95	9.05

Table A4.2: Strength Parameters Obtained in Compressive Strength Test (With Nodes)

S.N	M.C. wb (%)	Fmax (kN)	Fc (MPa)	ε_c (mm^2)	E_c (MPa)
1	10.28	50.36	31.62	0.013	2529.6
2	9.81	45.78	59.52	0.005	11906.0
3	10.05	47.74	43.73	0.008	5830.7
4	9.77	45.78	57.53	0.006	9204.8
5	9.92	48.40	61.42	0.005	12284.0
6	9.95	47.74	49.27	0.015	3284.7
7	9.89	45.12	47.45	0.013	3796.0
8	-	49.05	38.00	0.005	7600.0
9	9.81	48.40	58.94	0.008	7858.7
10	9.95	47.09	45.02	0.006	7203.2
11	10.10	49.05	43.66	0.008	5821.3
12	10.05	45.78	49.43	0.006	7908.8
13	9.93	49.05	55.41	0.006	8865.6
14	9.81	45.78	57.47	0.008	7662.7
MEAN	9.95		49.89		7268.1
MEAN TEMPERATURE					25 °C
MEAN RELATIVE HUMIDITY					46%

Table A4.3: Strength Parameters obtained in Compressive Strength Test (Without Nodes)

S.N.	M.C. wb(%)	Fmax (kN)	Fc (MPa)	ε_c (mm/mm)	E_c (MPa)
1	9.94	44.47	46.07	0.005	9214.0
2	9.90	41.86	55.33	0.005	11066.0
3	9.84	45.13	57.91	0.005	11580.0
4	10.47	47.74	28.83	0.008	3844.0
5	9.76	45.13	45.66	0.005	9132.0
6	9.87	44.47	54.86	0.005	10972.0
7	10.28	44.47	46.88	0.008	6250.7
8	10.11	45.13	57.93	0.005	11586.0
9	10.13	49.05	49.57	0.005	9914.0
10	10.00	46.43	54.37	0.006	8699.2
11	10.28	45.78	43.23	0.006	6916.8
12	9.76	43.82	48.21	0.003	19284.0
13	9.72	41.20	65.20	0.004	17386.7
14	9.84	39.89	52.09	0.005	10418.0
15	9.97	45.78	54.58	0.005	10916.0
16	9.99	43.16	48.86	0.005	9772.0
17	9.86	45.78	54.75	0.005	10950.0
18	10.01	47.74	55.51	0.008	7401.3
19	9.75	44.47	61.99	0.005	12398.0
MEAN	9.97		51.68		10405.3
MEAN TEMPERATURE					24°C
MEAN RELATIVE HUMIDITY					48%

Table A4.4: Strength Parameters Obtained in Tensile Strength Test (With Nodes)

S.N.	M.C. wb(%)	Fmax (kN)	Ft (MPa)	ε_t (mm/mm)	E_t (MPa)
1	10.43	8.50	100.8	0.026	3894.5
2	10.33	6.10	71.5	0.019	3798.4
3	10.42	8.39	102.8	0.031	3360.7
4	10.57	7.85	74.0	0.031	2419.2
5	10.34	11.34	87.1	0.038	2259.2
6	10.74	5.45	64.5	0.021	3099.6
7	10.40	7.63	84.0	0.027	3169.1
8	10.50	7.63	92.9	0.031	2980.0
9	10.29	10.14	102.7	0.035	2971.0
10	10.20	14.39	122.7	0.037	3286.6
11	10.32	9.70	95.5	0.030	3183.3
12	10.21	11.34	119.9	0.033	3689.2
13	10.41	12.43	126.9	0.039	3251.8
14	10.49	7.63	83.6	0.033	2508.0
15	10.44	9.27	94.1	0.036	2603.4
16	10.13	10.57	112.6	0.040	2815.0
17	10.40	8.18	68.1	0.039	1747.9
MEAN	10.39		94.3		3002.2
Mean Temperature					23 °C
Mean Relative Humidity					53%

Table A4.5: Strength Parameters Obtained in Tensile Strength Test (without nodes)

S.N.	M.C wb(%)	Fmax (kN)	Ft (MPa)	ε_t (mm/mm)	Et (MPa)
1	10.63	8.07	116.9	0.031	3799.3
2	10.62	8.94	117.6	0.027	4448.0
3	10.49	8.28	104.7	0.028	3729.9
4	10.56	10.36	118.7	0.029	4080.3
5	10.53	12.21	121.4	0.033	3642.0
6	10.64	10.46	106.1	0.047	2254.6
7	10.12	8.72	127.9	0.036	3517.3
8	9.99	11.99	134.9	0.040	3372.5
9	10.16	11.34	136.6	0.036	3779.3
10	10.38	8.94	120.4	0.036	3331.1
11	10.23	8.28	123.8	0.031	4023.5
12	10.42	9.81	112.0	0.035	3240.0
13	10.25	8.18	113.5	0.031	3663.0
14	10.27	7.96	107.6	0.026	4196.4
15	10.23	11.12	114.9	0.038	3025.7
16	10.29	8.39	127.6	0.025	4976.4
17	10.05	7.85	113.7	0.038	2956.2
18	10.08	7.85	103.3	0.039	2656.3
MEAN	10.33		117.9		3594.0
MEAN TEMPERATURE					23 °C
MEAN RELATIVE HUMIDITY					54%

Table A4.6: Strength Parameters Obtained in Bending Strength Test(With Nodes)

S.N.	M.C. wb(%)	I (mm⁴)	C (mm)	Z (mm³)	I (mm)	Fmax (N)	Fb (MPa)
1	-	278.24	3.29	84.57	296	-	-
2	10.27	218.47	3.03	72.10	301	348.8	120.9
3	10.37	-	3.21	-	297	-	-
4	10.11	115.43	2.57	44.91	295	174.4	97.1
5	10.07	284.41	3.44	82.68	300	403.8	122.1
6	9.84	392.92	3.61	108.84	299	528.7	121.4
7	10.08	375.01	3.54	105.93	296	446.9	105.5
8	9.71	236.29	3.26	72.48	298	327.0	112.8
9	10.41	293.85	3.36	87.46	299	316.1	90.4
10	9.88	287.29	3.38	85.00	297	457.8	134.7
11	10.11	238.49	3.17	75.23	299	359.7	119.5
12	9.93	146.88	2.78	52.83	300	201.7	95.4
13	9.88	161.22	2.61	61.77	300	288.9	116.9
14	10.01	369.90	3.63	101.90	300	506.9	124.4
15	9.85	124.95	2.59	48.24	296	218.0	112.0
16	10.11	666.88	4.13	161.47	300	752.1	116.4
17	10.07	710.96	4.30	165.33	299	381.5	57.7
18	9.73	397.91	3.59	110.83	298	283.4	63.9
	9.76						107.0
MEAN TEMPERATURE							24°C
MEAN R.H.							48%

Table A4.7: Strength Parameters Obtained In Bending Strength Test (Without Nodes)

S.N.	M.C. wb(%)	I (mm⁴)	C (mm)	Z (mm³)	l (mm)	Fmax (N)	Fb (MPa)
1	9.92	-	2.66	-	302	-	-
2	9.80	161.5	2.82	57.26	291	337.9	147.5
3	9.87	121.6	2.36	51.54	293	327.0	158.6
4	9.84	170.6	2.72	62.74	281	332.5	132.5
5	9.84	113.8	2.37	48.01	295	288.9	150.4
6	9.60	213.7	2.89	73.94	304	272.5	92.1
7	9.72	179.8	3.00	59.94	287	359.7	150.0
8	9.80	153.0	2.67	57.32	304	327.0	142.6
9	9.42	149.2	2.69	55.48	303	321.6	144.9
10	9.66	105.2	2.46	42.76	290	250.7	146.6
11	9.84	275.8	3.22	85.64	300	452.4	132.1
12	9.71	296.6	3.45	85.96	298	414.2	120.5
13	-	321.4	3.59	89.53	297	512.3	143.1
14	9.84	195.2	2.94	66.39	299	348.8	131.3
15	9.76	145.8	2.58	56.52	300	288.9	127.8
16	9.66	255.2	3.23	79.01	297	474.2	150.0
17	9.80	248.4	3.20	77.62	296	425.1	136.9
18	9.84	182.3	2.86	63.74	298	343.4	134.7
	10.02						137.7
Mean Temperature							26 (°C)
Mean Relative Humidity							46%

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