FRACTURE TOUGHNESS AND RESISTANCE-CURVE BEHAVIOUR OF LAMINATED BAMBOO

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By

Bello Kabirat Omobolanle

40509

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CERTIFICATION

This is to certify that the thesis titled “**FRACTURE TOUGHNESS AND RESISTANCE-CURVE BEHAVIOUR OF LAMINATED BAMBOO”** submitted to the school of postgraduate studies, African University of Science and Technology (AUST), Abuja, Nigeria for the award of the Master’s degree is a record of original research carried out by Bello Kabirat Omobolanle in the Department of Material Science and Engineering.

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By

Bello Kabirat Omobolanle

A THESIS APPROVED BY THE MATERIAL SCIENCE AND

ENGINEERING DEPARTMENT

RECOMMENDED: ______________________________

Supervisor, Prof Wole Soboyejo

____

Co-Supervisor, Prof Abel Olorunnisola

____

Head, Department of Material Science and Engineering, Prof Peter Azikiwe Onwualu

APPROVED: ______________________________

Chief Academic Officer

____

Date

ABSTRACT

In this study, the fracture toughness and resistance curve behaviour of laminated panels, produced from the tropical Nigerian bamboo species *Bambusa vulgaris*, were investigated to assess its potential for use as an alternative construction material. Round bamboo culms were processed into laminated panels. The Mode I fracture toughness K_{IC}, and the resistance-curve (R-curve) behaviour of the laminates in the crack arrester and divider orientations were investigated using ASTM E399 single-end notch bend (SENB) specimens. Results showed that the bamboo laminate had a higher resistance to crack propagation in the arrester orientation than in the divider orientation, with average fracture toughness of 11.24 MPa $\sqrt{m}$ and 8.51 Mpa $\sqrt{m}$ respectively. Modest rising R-curve behaviour was observed in both orientations and the predicted estimates of the toughening levels using the small-scale bridging (SSB) and large-scale bridging (LSB) models showed trends that were consistent with the tests observed in the experimental resistance curves. The implications of these results are discussed, as it affects the use of bamboo laminate as an alternative construction material.

Keywords: laminated bamboo panels, alternative construction material, fracture toughness, resistance-curve behaviour

DEDICATION

To my entire family for their unflinching support and love throughout my academic career.

May Allah (SWT) continue to strengthen us (Amin).

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CHAPTER One INTRODUCTION

1.1 BACKGROUND

The importance of shelter for human existence cannot be overemphasised. Presently, one of the major challenges facing housing delivery in Africa, especially sub-Saharan Africa, is the inability to meet the huge demand for affordable and sustainable housing for the rapidly increasing population (Akeju & Andrew, 2007). Nigeria, according to the World Bank, currently has an estimated population of 180 million and a housing deficit of about 17 million units. This deficit can be attributed mainly to the increased rate of urbanisation, drastic rise in population, and the high cost of land and construction materials, making housing unaffordable for the rural and urban poor (Matawal & Ojo, 2014). These figures imply that huge sums of money will be required to bridge the enormous gap in the Nigerian housing sector and this cost will continue to increase unless concerted efforts are made to support housing development in the country.

Building construction is highly capital intensive with building materials alone constituting almost 70% of the total housing expenditure. The cost varies according to the complexity of the architecture (Ugochukwu & Chioma, 2015). In spite of this, many of the building materials used in Nigerian construction, from roof to flooring, are sourced either completely or partially as finished or raw materials from outside the country (Oladipo & Oni, 2012). This has increased the cost of conventional building materials, posing a serious challenge to the delivery of decent bulk housing in the country. Therefore, the need to meet the large demand for affordable building materials in the Nigerian construction industry requires the design, development and adoption of alternative construction materials (ACM) that are economical, sustainable, ecologically friendly and innovative, while also providing a positive socio-economic impact on the nation.

ACM, according to Anigbogu (1999), are described in three forms: firstly as conventional materials modified with the aim of reducing their cost; secondly, as unconventional materials used entirely without modification, thereby achieving lower cost; and thirdly, as unconventional materials modified with a view to incorporating them into modern day construction. Some materials used as ACMs in any of the three forms mentioned above include, laterite blocks, compressed earth bricks, rice husk ash, raffia palm, papercrete, bamboo and straw. One material that is gaining worldwide acceptance in view of its properties, low cost, availability, environmental friendliness, potential for use in construction and composite board applications, is bamboo.

Bamboo is one of the oldest building materials used by humans; it is a naturally occurring, highly renewable plant with about 1,200 species growing worldwide (Sharma, Gatóo, Bock, & Ramage, 2015). *Bambusa vulgaris*, also known as Common Bamboo, is the naturalised and most dominant species in Nigeria, growing up to 20 m high and is 4-10 cm in diameter (Ogunwusi & Onwualu, 2011). To improve its utilisation, natural round bamboo culms are converted to laminated composites, similar to glue laminated timber products, allowing bamboo to be made into uniform cross-sections, while retaining the inherent strength of the raw material.

1.2 PROBLEM STATEMENT

The application of natural round bamboo in construction is limited by the difficulty in making joints and connections, the lack of standards and the inherent variability in properties from top to bottom within a species and between species. In most cases, bamboo is used only for scaffolding and discarded afterwards.

To harness fully the potential of bamboo as a construction material, bamboo needs to be transformed into laminated sections suitable for construction applications. Research into the detailed engineering properties and behaviour of the laminates needs to be intensified in order to provide data for the effective design of laminated bamboo structures. Few studies on the fracture properties and R-curve behaviour of these laminates are available.

1.3 AIM AND OBJECTIVES

This study investigates the Mode I fracture toughness and R-curve behaviour of laminated bamboo panels produced from the tropical bamboo species *Bambusa vulgaris* to assess its potential for use as an alternative material in the Nigerian construction industry.

The objectives of the study are:

- the processing of raw bamboo into laminates;
- the determination of Mode I fracture toughness and the R-curve of the bamboo laminate; and
- the estimation of toughening due to small-scale bridging (SSB) and large-scale bridging (LSB) models.

CHAPTER Two LITERATURE REVIEW

2.1 BAMBOO AS A RAW MATERIAL

Bamboo is known to be one of the fastest growing plants in the world with a growth rate ranging from 0.3 m to 1 m per day; thus making it a highly attractive renewable natural resource (Paudel, 2008; Nguyen, Shehab, & Nowroozi, 2010). Raw bamboo consists of a hollow culm tapering from the base to the top, with longitudinal fibres aligned within a lignin matrix. The length of the culm is divided by nodes (Sharma et al., 2015), see Figure 2.1. As a functionally graded composite material, its fibre distribution varies within the culm wall, decreasing in density from the exterior to the interior (Ghavami & Rodrigues, 2003). Generally, strengths are highest in sections closer to the ground and also along the outer surfaces decreasing inwards (Tan et al., 2011).

Figure 2.1: Typical Bamboo Plant

Bamboo is commonly found in Africa, Asia, Central and South America, with some species growing successfully in mild temperate zones in Europe and North America. An estimation of the total world bamboo resource shows that bamboo covers a total of 36 million hectares, with Nigeria growing about 26.8 million tonnes of bamboo on 1.59 million hectares, which equals about 14% of the Nigerian total forest area (Lobovikov et al., 2007).

Ogunwusi and Onwalu (2011) carried out an inventory of bamboo distribution in Nigeria. Their study shows that the south and middle belt regions of Nigeria have the highest occurrence of bamboo and the northern region the least. The distribution pattern indicates the adaptability of bamboo to rainforest regions due to their high mean annual rainfall and the length of the rainy season. Despite the wide availability of this resource in Nigeria, it is still underutilised with common applications restricted to scaffolding during construction, providing supports (studs) in decking, fencing, fuel (combustion and cooking), ladders, yam stakes and frames for mud houses in rural areas, especially in the south-east and south-south regions of Nigeria (Ogunwusi, 2014).

The acceptability of bamboo as an environmentally friendly alternative to conventional building material has been on the increase in many countries due to its superior properties, like high strength to weight ratio, high tensile strength, low cost and easy availability (Nguyen et al., 2010; Sharma et al., 2015). It is difficult to generalise the physical and mechanical properties of bamboo as they differ from species to species due to differences in site/soil and climatic conditions, silvicultural treatment, harvesting techniques, age, density, moisture content, position in the culm, nodes or internodes and bio-degradation (Lee, 1998; Paudel, 2008).

Bamboo, like timber, is non-durable in its natural state. It is vulnerable to attack by environmental agents: insects and moulds. The level of natural durability depends on species, age, conservation, treatment and the curing methods used. In order to reduce the nutrition content, bamboo needs to be properly dried to a humidity of less than 15%. Drying methods include air-drying, oven drying or over an open fire (Ghavami, 2008).

2.2 LAMINATED BAMBOO

Although bamboo in its natural form has excellent strength properties and potential to serve as an alternative construction material, its widespread use and acceptability is limited by its circular section which is susceptible to splitting, has an inherent variability within and between species and a lack of standardisation to which builders, engineers and architects can design (Sharma et al., 2015; Rittironk & Elnieiri, 2008). To promote the utilisation of this material, laminated bamboo was developed to overcome the above challenges, while retaining its inherent strength (Sharma et al., 2014). Laminated bamboo, sometimes referred to as engineered bamboo, is formed by the conversion of round bamboo culms into strips. These strips are planed, processed, carefully arranged, laminated and pressed together with a suitable adhesive (Sharma et al., 2015; Verma et al., 2017), see Figure 2.2. As the laminated bamboo is made up of many strips, the product maintains the longitudinal fibres of the natural bamboo and it can be designed to varying geometries. Laminated bamboo composites are of particular interest due to the standardisation of shape and the relatively low variability in material properties (Sharma et al., 2014). Significant research has been carried out globally on processing techniques, and the physical and basic mechanical properties of laminated bamboo (Sharma et al., 2015; Verma & Chariar, 2012; Nguyen, Shehab, & Nowroozi, 2010; Rassiah et al., 2014; Mahdavi, Clouston, & Arwade, 2012.; Mahdavi et al., 2011).

Several techniques for producing laminated bamboo lumber (LBL) have been developed. Nugroho and Ando (2001) investigated a technique to process LBL by crushing moso (*Phyllostachys pubescens*) bamboo culms using roller press crushers to create zephyr strand mats; the zephyr mats were coated with resorcinol-based adhesive and stacked on top of each other, after which they were cold pressed until the adhesive was fully bonded. Rittironk and Elnieiri (2008) produced LBL by splitting bamboo culms into slender strips using a splitter machine, scraping and planning all the surfaces to remove wax and silica, as well as to create rectangular cross sections. Adhesive was applied to the strips, which were arranged next to and on top of each other under pressure to create the final product. Lee et al. (1998) produced LBL by splitting moso bamboo culms in half longitudinally then flattening them at a pressure of 690 kPa for 1-4 minutes. The inner and outer layers were flattened and passed through a planer in order to remove the wax and silica. Resorcinol-based adhesive was applied to the surfaces and carefully stacked on top of one another under a pressure of 1,380 kPa for 12 hours. The properties of the LBL produced from the techniques discussed above did not differ significantly and exhibited properties comparable to wood-based panels. Verma et al. (2014) compared the mechanical properties of laminated bamboo to wood and wood-based composites in order to explore the possibility of its usage as a structural material in place of wood. Results from the study clearly showed that laminated bamboo has comparable strength with wood and wood-based products and that it could be used as a substitute for wood and wood-based products in structural applications.

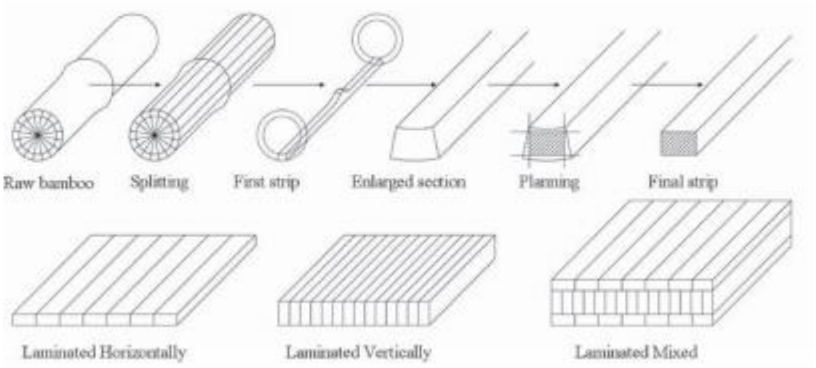


Figure 2.2: Manufacturing Process of Laminated Bamboo (Rittironk & Elnieiri, 2008)

2.3 FUNDAMENTALS OF FRACTURE MECHANICS

Fracture mechanics is a tool used to predict the load-bearing capacity of materials in laboratory-fracture toughness tests. All natural materials contain defects, which normally manifest during processing and fabrication. It is very common for these defects to occur as pre-existing cracks and are virtually impossible to avoid. Hence, in engineering, the study of fracture is important in the design of materials to ensure a low probability of failure in applications (Patton-Mallory & Cramer, 1987).

Fracture occurs when an increase in loading results in an accelerated growth of pre-existing cracks, resulting in the separation of the body into two or more pieces. This can occur in three distinct phases:

- loading without crack growth;
- stable crack growth; and
- unstable crack growth.

In principle, stable crack growth proceeds relatively slowly; this means that it resists any further extension unless there is an increase in the applied stress. On the other hand, unstable crack growth spreads rapidly and will continue spontaneously without an increase in the applied stress (Callister, 2007). It is therefore important to understand the initiation and growth of cracks in materials and its influence on the strength of the material in order to assess its structural reliability.

The mode of separation of the crack surfaces is known as the mode of fracture and can occur in three basic modes, namely:

- Mode I is where the cracked body is loaded with normal stresses causing the crack to open orthogonally to the local fracture surface resulting in tension or compressive stress, see Figure 2.3a.
- Mode II is known as the in-plane sliding mode which causes the cracked surfaces to slide relative to each other, see Figure 2.3b.
- Mode III is the tearing mode caused by out-of-plane shear stress. This results in the crack faces being sheared parallel to the crack front, see Figure 2.3c.

All three loading modes may be experienced separately or simultaneously during the fracture of a structural component (Patton-Mallory & Cramer, 1987; Soboyejo, 2003).

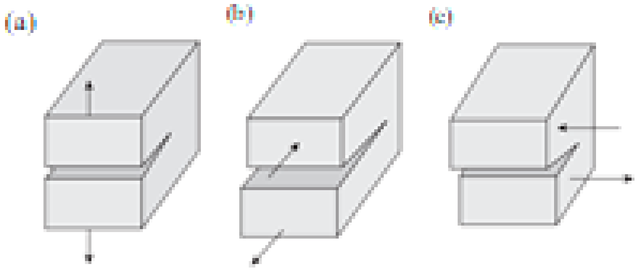


Figure 2.3: Modes of Fracture

2.3.1 Fracture Toughness

Fracture toughness indicates a material's resistance to fracture and is evaluated by loading a pre-cracked specimen using fracture mechanical principles (Landes, 2012). During the application of fracture mechanical principles, an expression, which relates the critical stress (σ_c) during crack propagation to the crack length (a) was developed. The expression is written as Equation (1):

$$K_Q = \sigma\sqrt{\pi a}.f\left(\frac{a}{w}\right)$$

Where K_Q is the crack-driving force or stress-intensity factor or fracture toughness, which usually includes a subscript (I, II, or III) which refers to the 3 different modes of loading a cracked body, σ is the stress, a is the flaw size, and F(a/W) is the geometry factor which depends on the size and geometry of the specimen.

Fracture mechanics specimens containing atomistically sharp pre-cracks are typically used to study the fracture initiation and/or resistance. There are different geometry functions for different fracture mechanics specimens but for the purpose of this study, the single-edge notched bend (SENB) specimen geometry was considered, according to ASTM standard E399-81, Annual Book of ASTM standards, Part 10, 1981.

It is important to note that the material response of a small laboratory specimen may be used to study the material response of a large structure to the same stress intensity. This is due to the concept of similitude, which states that different crack geometries have the same crack driving force when the stress intensity factor at the crack tips are the same. Once plane strain conditions are attained at the crack tip, the K_Q value does not decrease with increasing thickness. Hence, the measured values of K_Q for sufficiently thick specimens correspond to a material property that is independent of thickness (Soboyejo, 2003). Figure 2.4 is an illustration of a loaded SENB specimen.

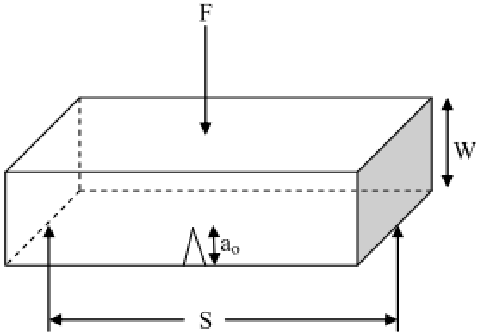


Figure 2.4: Single-edge Notch Bend Specimen

2.3.2 Resistance-Curve

For many materials, fracture is a slow and stable process rather than a fast and unstable event. To promote stable crack growth, fracture specimens are selected and loaded in incremental stages, under displacement or load control, until stable crack growth is observed to initiate. The crack driving force (K) at which crack growth is initiated is known as the initiation toughness. For extremely brittle materials, there is no resistance to crack growth and crack growth continues as long as K = Kc, where Kc is the critical value of stress intensity required to propagate a crack. However, most materials exhibit some R-curve behaviour and would require a higher crack driving force, to grow the crack. Thus, the transition from stable to unstable crack growth can be determined by the analysis of the R-curve. The fracture toughness values, therefore, correspond to points of instability on a rising R-curve (Landes, 2012; Soboyejo, 2003). Rising R-curves are common among materials that exhibit toughening mechanisms (Smith, Landis & Gong, 2003).

2.3.3 Toughening Mechanism

The R-curve behaviour observed in tested materials depends strongly on the underlying toughening mechanisms that give rise to stable crack growth. Such mechanisms, which include crack bridging via ductile or brittle reinforcements, primarily act behind the crack tip and shield the crack locally from the applied driving force. Toughening mechanisms using crack bridging in bamboo structures have been studied (Askarinejad, Kotowski, Youssefian, & Rahbar, 2016; Tan et al., 2011) and show that the bridging models were in agreement with the measurements obtained from fracture mechanics experiments.

Toughening using SSB was modelled using an idealised elastic-plastic spring model, which was first proposed by Budiansky et al. (1988) and used by Mustapha, Annan, Azeko, Zebaze Kana and Soboyejo (2016) and Tan et al. (2011). In this case, the size of the bridging zone is much smaller compared to the crack length (bridge length < 0.5mm) (Budiansky et al., 1988), with the ductile phase toughening expressed in terms of the stress-intensity factor that the material could sustain before failure (Tan et al., 2011). Toughening due to SSB ΔK_{SSB} is given by Equation (2):

$$\Delta K_{SSB} = \alpha V_f \sqrt{\frac{2}{\pi}} \int_0^L \frac{\sigma_y}{\sqrt{x}}\, dx$$

Where α is the constraint/triaxiality factor (in this case taken to be 1) (Tan et al., 2011; Budiansky et al., 1988), V_f is the volume fraction of the ductile phase, L is the bridging length which is equal to the distance from the crack tip to the last unfractured reinforcement (Askarinejad et al., 2016), σ_y is the uniaxial yield stress and x is the distance from the crack tip.

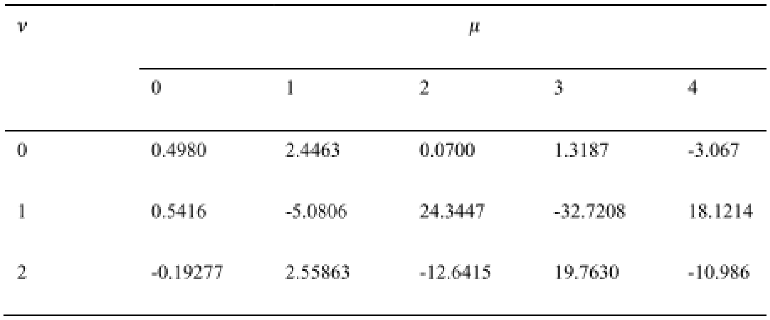
For shielding from LSB, ΔK_{LSB} is given by Equation (3):

$$\Delta K_{LSB} = V_f \int_L \propto \sigma_y h(a,x)\ dx$$

Where $\propto$ is the constraint/triaxiality factor (theoretically between 1 and 3), V_f is the volume fraction of the reinforcement phase, L is the bridging length, σ_y is the uniaxial yield stress, a is the crack length, w is the specimen width and x is the distance from the last unfractured fibre to the crack tip. Also, $h(a,x)$ is the weighting function given by Fett and Munz (1994), shown in Equation (4):

$$h(a,x) = \sqrt{\frac{2}{\pi a}}\frac{1}{\sqrt{1-\frac{x}{a}}}[\,1 + \sum\nolimits_{(v,u]} \frac{A_{v,u}\left(\frac{a}{w}\right)}{\left(1-\frac{a}{\omega}\right)}\left(1 \cdot \frac{x}{a}\right)^{v+1}\ ]$$

The coefficient $A_{v,u}$ is given in Figure 2.5 for the SENB specimen.



v	μ				
	0	1	2	3	4
0	0.4980	2.4463	0.0700	1.3187	-3.067
1	0.5416	-5.0806	24.3447	-32.7208	18.1214
2	-0.19277	2.55863	-12.6415	19.7630	-10.986

Figure 2.5: Summary of Fett and Munz (1994) Parameters for SENB Specimen

2.4 PRIOR WORK ON FRACTURE TOUGHNESS AND RESISTANCE-CURVE BEHAVIOUR OF BAMBOO

The development of bamboo as an environmentally friendly structural material has attracted a lot of interest and significant research has been carried out to understand its mechanical behaviour, such as compressive, tensile and bending properties. However, there are few studies on the fracture properties of the many available species of bamboo. Amada and Untao (2001) studied the fracture toughness of bamboo culms and nodes.

They used two-year old moso bamboo with a notch inserted into the culm and node specimen, using a razor blade. The results showed that the fracture toughness is proportional to the volume fraction of fibres with a higher fracture toughness at the culm surface, which decreases towards the inner surface. Average fracture toughness of bamboo culm and nodes were 56.8 MPa √m and 18.4 MPa √m respectively.

Liou and Lu (2010) investigated the effect of moisture on the fracture toughness of moso bamboo. Dry and water-saturated bamboo culms were tested using the arc-shape bend specimen specified in ASTM E399. The result showed that the fracture toughness of air-dried and water-saturated specimens was 31.2 Pa√m and 19.1 Pa√m respectively, which means that the fracture toughness was reduced by 39% in water-saturated moso bamboo. This is a significant reduction and therefore, the moisture effect should be considered when using bamboo.

A combined experimental, theoretical and computational study of crack growth and toughening mechanisms in moso bamboo was carried out by Tan et al. (2011). The R-curve behaviour was studied using SENB specimens notched along three different orientations: outside surface orthogonal to the fibre orientation, inside surface orthogonal to the fibre orientation and side surface orthogonal to the fibre orientation. Results showed that the inside crack samples exhibited the highest R-curve behaviour, the outside crack samples had the lowest R-curve behaviour and the side crack samples' R-curve behaviour was in between. Also it was observed that high fibre densities resulted in lower overall toughening, while the lower fibre densities in the inside regions resulted in greater overall toughening.

Another study by Xu et al. (2014) investigated the Mode I fracture toughness of moso bamboo with a three-point bending (SENB) specimen. The crack-opening displacement was determined using the COD gauge. Then the load-displacement curve and the value of the load at crack growth initiation P_Q were found by the method of 95% stiffness correction. The results showed that the bamboo has good fracture toughness with an average of 16.05 MPa √m.

Ali et al. (2016) studied the fatigue and fracture properties of composites made of woven layers of the *Gigantochloa scortechinii* (Buluh semantan) species of bamboo prepared using a hand lay-up technique with unsaturated polyester (UP). To investigate the effect of fibre orientation on the fracture toughness, specimens with horizontal and vertical fibre orientations were tested and the results showed that specimens with vertical orientation showed greater resistance to crack propagation with K_{1C} value of 8.33 MPa √m ± 0.05 compared to those with a horizontal orientation with K_{1C} of 4.84 MPa √m ± 0.05.

An experimental study on the structure and toughening mechanisms in moso culm bamboo was carried out by Askarinejad et al. (2016); four-point bend fracture experiments were performed and the R-curves were computed. The fracture and deformation mechanisms of bamboo were studied and it showed that the R-curve behaviour was dependent on the orientation of the fibres and, in cases where the fibres were perpendicular to the crack growth, toughening was observed to occur via crack bridging. Intermediate shielding levels were observed when toughening occurred by crack deflection for crack growth along the fibre orientation.

From the studies reviewed above, considerable efforts have been made to understand the fracture properties of moso bamboo. Although there are discrepancies in the fracture toughness results, which may be due partly to the sample preparation (whole bamboo or bamboo composite) and testing methods used in the study, it is apparent from the studies that the fracture property of bamboo is largely dependent on its functionally graded structure. This must, therefore, be taken into consideration in its application.

CHAPTER Three METHODOLOGY

3.1 INTRODUCTION

The species of bamboo, *Bambusa vulgaris*, was used in this study, as it is the predominant species of bamboo found in Nigeria. The bamboo culms used were approximately 5 years old. The processes involved in the production and testing of the bamboo laminates are described below.

3.2 SAMPLE PREPARATION

3.2.1 Bamboo Sourcing

Bamboo culms were sourced from a local bamboo market within the Federal Capital Territory (FCT), refer to Figure 3.1, where it was transported to the processing location in Dede, Abuja. Selection was done by visual examination of individual culms. The criteria used for selection included the thickness of the culms and absence of major blemishes like deep cuts, discoloration over a large area, splitting and insect bites. Proper selection of bamboo culms is essential as it determines the quality of bamboo strips that can be produced.

Figure 3.1: Bamboo Culms Sourced

3.2.2 Processing of Bamboo Culms into Strips

The bamboo culms were processed into strips at a furniture factory in Dede, Abuja. The processing was broken down into four stages:

- cutting and splitting culms
- four-sided planning of strips
- treatment of bamboo strips
- drying of bamboo strips

3.2.2.1 Cutting and Splitting of Culms

The bamboo culms were cross-cut into segments of about 1.0 m. Only the bottom and the middle sections of the bamboo culms were used as they had sufficient wall thickness for strip production. The segments were split into rectangular strips using a circular saw machine; the bamboo strips produced at this stage retained the natural curve of the plant and thus needed to be further processed to obtain flat strips. Four strips were obtained from each segment, each about 3 cm wide as shown in Figure 3.2.

Figure 3.2: Bamboo Strips

3.2.2.2 Four-sided Planing of Strips

The bamboo strips were planed using a planing machine; the outer edges/sides of the bamboo strips were planed to straighten the edges of the strips. The outer and inner surfaces of the strips were also planed to remove the wax and silica layer, which does not allow adhesive to be retained; leaving the mid-section which is the medium-fibre density region of the bamboo (Tan et al., 2011). The planing process helps to produce flat rectangular bamboo strips, which provide smooth surfaces and edges for gluing during the bamboo laminate production. Only straight strips were utilised for this study.

3.2.2.3 Treatment of Bamboo Strips

According to the National Mission on Bamboo Applications (NMBA) (2006), the natural durability of bamboo is very low and without any protective treatment, its service life is less than 5 years. This is due to the presence of starch, which makes it very attractive to microorganisms causing decay, disintegration and unsightly stains and blotches.

The chemical treatment of the bamboo strips was carried out by spraying the strips with boric acid: borax solution. The strips were then stacked against the wall and sprayed with a 2% boric acid solution: borax, using the spraying machine as shown in Figure 3.3. The treatment procedure was carried out according to the methods specified by the NMBA (2006).

Figure 3.3: Spraying of Bamboo Strips

3.2.2.4 Drying of Bamboo Strips

The bamboo strips were air-dried by stacking the strips on a rack in a dry shady place as shown in Figure 3.4. They were arranged so that there was even movement of air within the stacks. The strips were dried to a moisture content of 10-12%. The moisture content of the bamboo strips was monitored with the aid of a moisture meter. It is generally desirable to dry the bamboo before use, as dry bamboo is stronger and less susceptible to degradation (biological, thermal or chemical) than wet bamboo. In addition, wet bamboo cannot be glued effectively or properly treated with preservatives.

Figure 3.4: Air-drying of Bamboo Strips

3.2.3 Bamboo Laminate Production

The surface of each strip was properly sanded to receive adhesive. Bamboo laminates were produced by clamping bamboo strips together using phenol formaldehyde adhesive to produce thicker and wider sections as shown in Figures 3.5 and 3.6.

Figure 3.5: Glue Application

Figure 3.6: Clamping of Bamboo Strips

3.3 FRACTURE TOUGHNESS EXPERIMENT

The Mode I fracture toughness test, i.e. the critical value of the stress-intensity factor K_{IC}, was measured according to the method specified in ASTM Standard E399-12 for determining fracture toughness under linear-elastic plane-strain condition. SENB specimens of 75 mm x 15 mm x 7.5 mm were cut from fully cured sections of bamboo laminates. Specifications used for the preparation and sizing of the SENB specimens, as stipulated by the standard, include:

1. Specimen ligament size (W-a) was greater than $2.5(\frac{K_{IC}}{\sigma_{ys}})^2$ where

$$K_{IC} = Fracture\ Toughness\ and\ \sigma_{ys}\ \text{is the 0.2\% yield stress of the material}$$

2. Notch length (a) to width (W) ratio used for the SENB samples was between 0.45 – 0.55.
3. Width to thickness ratio (W/B) = 2 and a span of 4W was used

Figure 3.7 shows the test setup and loading condition of the SENB sample.

Figure 3.7: Test Setup and Loading of SENB Samples

In order to facilitate the crack propagation, a notch was made in the middle of the sample using a sharp flexible blade of approximately 0.8mm creating a notch to width ratio (a/w) of 0.5. To explore the fracture and R-curve behaviour of the bamboo laminate along different orientations, the notch was inserted into the samples in two orientations namely: the crack arrester, as illustrated in Figure 3.8(a), and the crack divider orientation, shown in Figure 3.8(b).

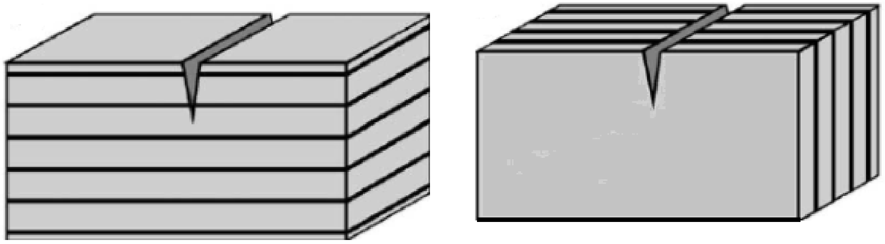


Figure 3.8: (a) Crack Arrester Orientation (b) Crack Divider Orientation

In the crack arrester orientation the initial notch/crack is perpendicular to the layers and moves sequentially through the layers, while in the crack divider orientation the initial notch/crack plane is normal to the plane of layers and passes through all the layers of the laminate simultaneously (Bloyer, Venkateswara Rao, & Ritchie, 1998).

Five replicate SENB samples were produced for each orientation. The experiment was carried out on a 5KN Instron Testing Machine at the Kwara State University (KWASU) mechanical engineering laboratory using a displacement rate of 0.1 mm/s until fracture occurred. The test results and load versus displacement plot were recorded and plotted digitally by the machine. The 95% secant method was used to extract the peak loads (P_Q) from the plot in accordance with the ASTM E-399 criteria. This was done by constructing a secant line through the origin of the test record with a slope equal to 95% of the slope of the initial linear portion of the load-displacement plot. After determining P_Q, the value of fracture toughness K_{IC} was computed using Equation (5):

$$K_{1c} = f\left(\frac{a}{w}\right)\frac{P_Q S}{BW^{\frac{3}{2}}}$$

Where P_Q is the maximum load, S is the loading span, B is the specimen breadth, H is the specimen height, a is the crack length, and f(a/W) is the compliance function, which was obtained from Equation (6):

$$F\left(\frac{a}{w}\right) = \frac{3\left(\frac{a}{w}\right)^{\frac{1}{2}}(1.99 - \left(\frac{a}{w}\right)\left(1-\frac{a}{w}\right)\left(2.15 - 3.93\left(\frac{a}{w}\right) + 2.7\left(\frac{a}{w}\right)^{2}\right)}{2\left(1 + 2\frac{a}{w}\right)(1 - \frac{a}{w})^{\frac{3}{2}}}$$

The function f(a/W) was calculated using a Microsoft Excel spreadsheet for each measured crack length.

3.4 RESISTANCE-CURVE EXPERIMENT

The R-curve measurements were obtained by the direct observation and measurement of crack initiation and extension in the SENB samples loaded in the 3-point bending on a universal testing machine. Samples were loaded in incremental steps until stable crack growth was initiated. The experiment was carried out under load control conditions at a loading rate of 6.67 N/s and snapshots of the crack extension were taken with the optical microscope at every load increment of 50 N. The load at which the notch tip began to extend was recorded as the crack initiating load and the new crack length was measured. Further crack extensions were measured with their corresponding loads. Experimental data of applied loads and crack extensions were recorded for the analysis of the R-curve behaviour of bamboo laminate. The stress-intensity factors for crack initiation and propagation on the R-curve were obtained from Equation (7). The R-curve was measured in terms of stress-intensity factor K as a function of crack extension $\Delta a.$ The resulting R-curve for the crack divider and the crack arrester orientations were discussed.

$$K_c = f\left(\frac{a}{w}\right) \sigma_f \sqrt{\pi a}$$

3.5 TOUGHENING MODELS

Toughening mechanism due to crack bridging was modelled and added to the crack initiation toughness to predict the R-curve behaviour of the composite structure (Mustapha et al., 2016; Soboyejo, 2003). The shielding contribution was estimated using the SSB and LSB models described in Section 2.3.3.

The expression for the estimation of the fracture toughness/R-curve behaviour is given by Equation (8):

$$K_c = K_i + \Delta K_B$$

Where K_c is the composite fracture toughness, K_i is the initiation toughness and ΔK_b is the toughening due to crack bridging where for SSB $\Delta K_B = \Delta K_{SSB}$ and for LSB $\Delta K_B = \Delta K_{LSB}$.

In this study, the fibre properties used in both SSB and LSB models were as follows: α was taken to be 1.0 (Budiansky et al., 1988; Askarinejad et al., 2016; Tan et al., 2011) and, due to the mid-section of the bamboo culm used in the production of the laminates, volume fraction V_f of 0.5 was used. The uniaxial yield stress and Young's modulus used were 97.74 MPa and 6.1 GPa respectively.

CHAPTER Four RESULTS AND DISCUSSION

4.1 CHARACTERISTICS OF BAMBOO LAMINATES PRODUCED

The bamboo laminates were produced from 4-year old bamboo stock. This age of bamboo was selected because research findings have proved that the mechanical properties, including moisture content, of bamboo vary significantly with age but reach optimum values between 2.5 and 4 years (Low et al., 2006). The laminate produced from the study, shown in Figure 4.1, has an average moisture content of 10-12%.

Figure 4.1: Laminated Bamboo

4.2 FRACTURE TOUGHNESS

Images of the SENB specimens after the fracture toughness experiment, for both orientations, is shown in Figures 4.2a and 4.2b respectively. A representative load-displacement plot for the bamboo samples in arrester and divider orientation are also shown in Figures 4.3 and 4.4. In order to determine the peak load P_Q from the plot, a tangent to the initial linear portion of the plot and a secant line equal to 95% of the slope of the tangent line were drawn on the curve; with P_Q being the point where the secant line intersects the curve. The average values of P_Q were 1164.5 N and 881.6 N in the arrester and divider orientation respectively. The peak load P_Q obtained was used to calculate the fracture toughness K_{IC}.

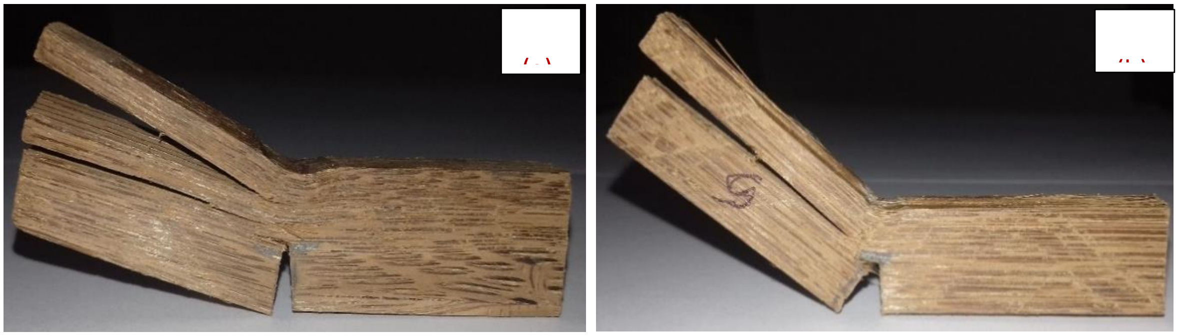


Figure 4.2: SENB samples after fracture toughness experiment (a) Arrester orientation (b) Divider Orientation

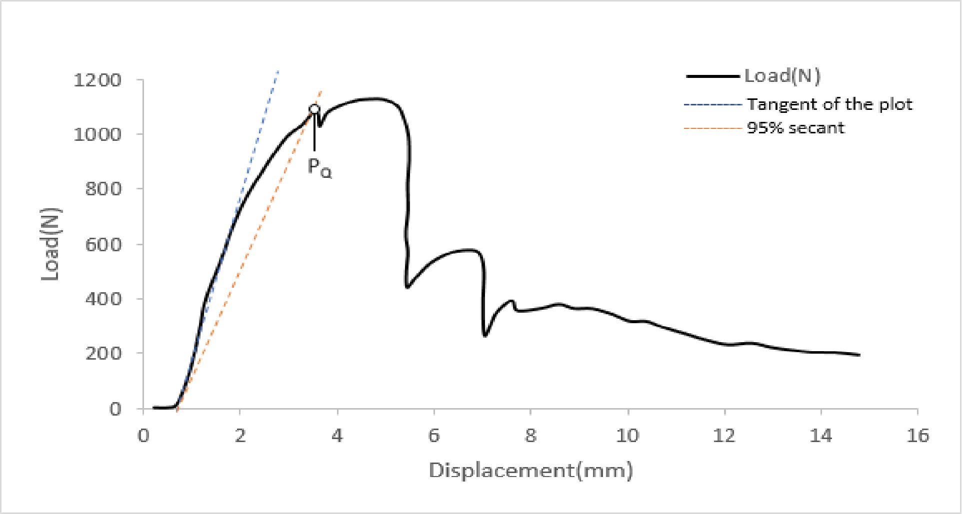


Figure 4.3: Load-Displacement Curve in Arrester Orientation

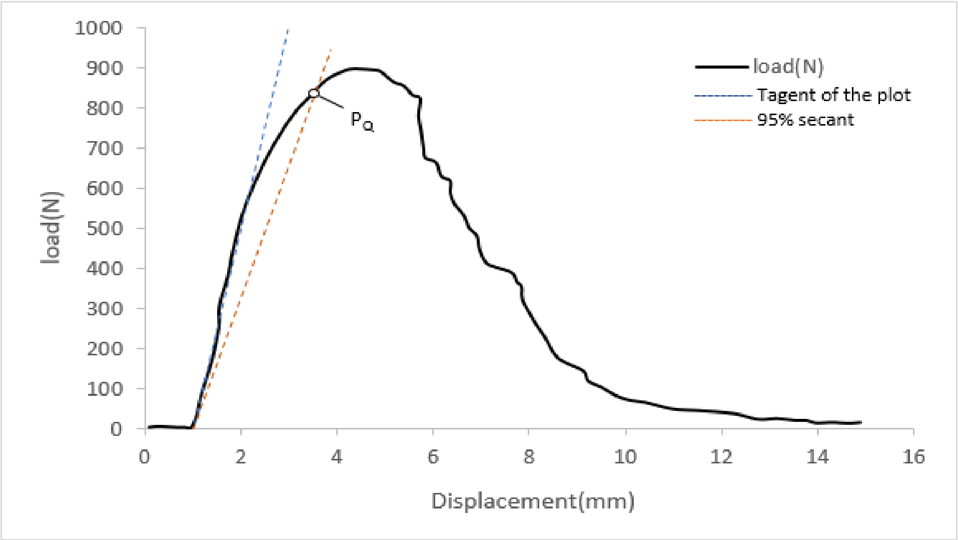


Figure 4.4: Load-Displacement Curve in Divider Orientation

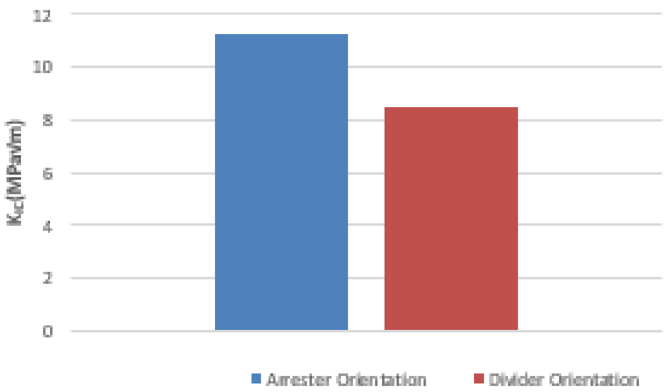


Figure 4.5: Fracture Toughness of Bamboo Laminate

The critical stress-intensity factor K_{IC} was calculated from Equations (5) and (6). The average fracture toughness (K_{IC}) of the bamboo laminate in the arrester and divider orientation was 11.24 MPa √m and 8.51 Mpa √m respectively as presented in Figure 4.5. Looking at this result, it can be concluded that the bamboo laminate had a higher resistance to crack propagation in the arrester orientation than in the divider orientation. This is as a result of the crack propagation mechanism exhibited in each orientation. In the arrester orientation, the entire crack front was trapped in an individual layer of bamboo and the crack propagation was shielded by the bamboo fibre bundles present, which acted as an additional toughening mechanism. However, in the divider orientation, the crack tip was exposed to all layers of bamboo and joints at all times and this was presumed to have contributed to the lower $K_{IC.}$ This was similar to the behaviour of laminates tested by Bloyer et al. (1999); in both orientations the crack propagation was along the fibre direction which is perpendicular to the direction of the original notch. The K_{IC} values obtained in this study were lower than that reported in studies carried out by Amada and Untao (2001) on 2-year old moso bamboo with an average K_{IC} value of 56.8 MPa √m, Liou and Lu (2010) with average K_{IC} of 31.2 Mpa √m for moso bamboo, Xu et al. (2014) with an average K_{IC} value of 17.39 MPa √m for 4-year old moso bamboo. This study's results were, however, comparable to results reported in studies carried out by Low et al. (2006) with average K_{IC} values of 5.5 MPa √m and 8.0 Mpa √m for 1 yr and 5 yr old *Sinocalamus affinis* bamboo respectively, and Ali et al. (2016) with average K_{IC} values of 4.84 MPa √m and 8.33 MPa √m for *Gigantochloa scortechinii* bamboo in the horizontal and vertical orientations respectively. The discrepancies in the results can be attributed to the differences in species, testing methods, sample type and ages of the bamboo used in each study.

4.3 RESISTANCE-CURVE

The resistance of the bamboo laminate to crack growth was determined by plotting the stress-intensity factor against the crack growth length for the two different crack orientations studied. In each case a rising R-curve was observed, which indicated the resistance to increased crack extension with the increasing crack length. Upon initial loading of the sample in incremental stages, the crack tip configuration remained the same, except for a little widening of the crack until a point when crack extension was noticed along the bamboo fibre matrix, this was called the initation toughness K_I. After the crack was initiated, the process continued slowly at first and then rapidly until the material finally failed. The failure of the material was not catatstropic but occurred gradually from stable crack growth up until the point of instability where the material failed. This further confirms the high damage tolerance of bamboo which contributes to its high fracture toughness (Low et al., 2006). The resistance curves for the arrester and divider orientations are shown below in Figures 4.4 and 4.5.

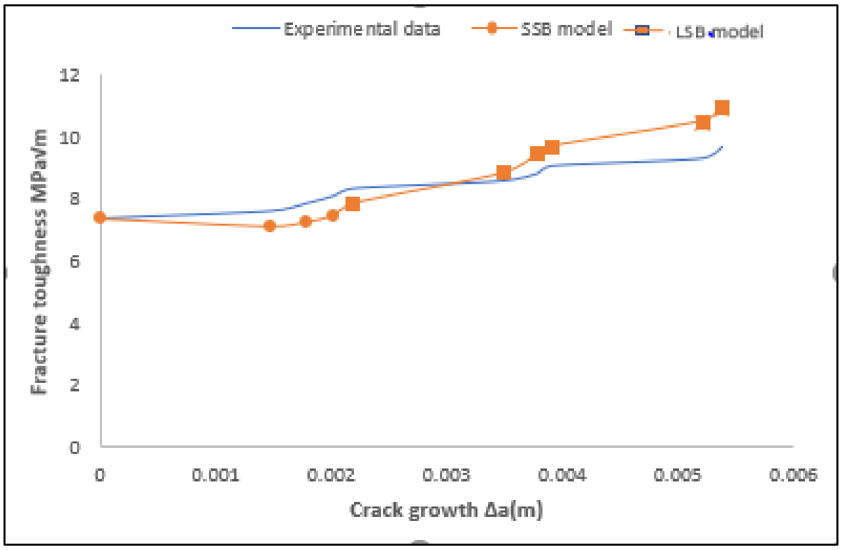


Figure 4.6: Resistance-curve Measurement of Bamboo Laminate in the Arrester Orientation with Calculated Curves from Bridging (SSB & LSB) Models.

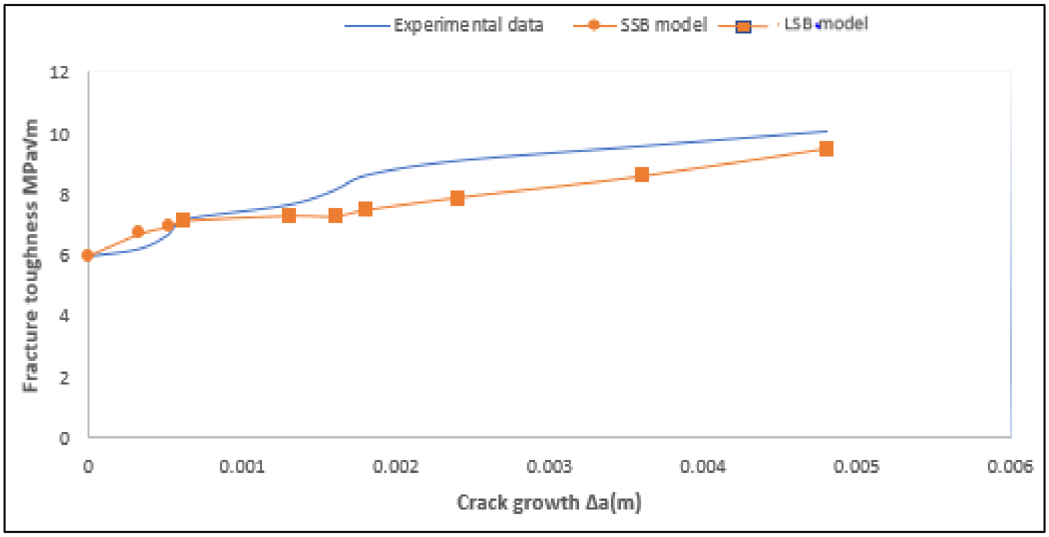


Figure 4.7: Resistance-curve Measurement of Bamboo Laminate in the Divider Orientation with Calculated Curves from Bridging (SSB & LSB) Models.

It was observed that the crack growth in both orientations did not continue in the direction of the initiated crack but perpendicular to it along the fibre direction. Figure 4.3 shows the crack growth in the sample after testing.

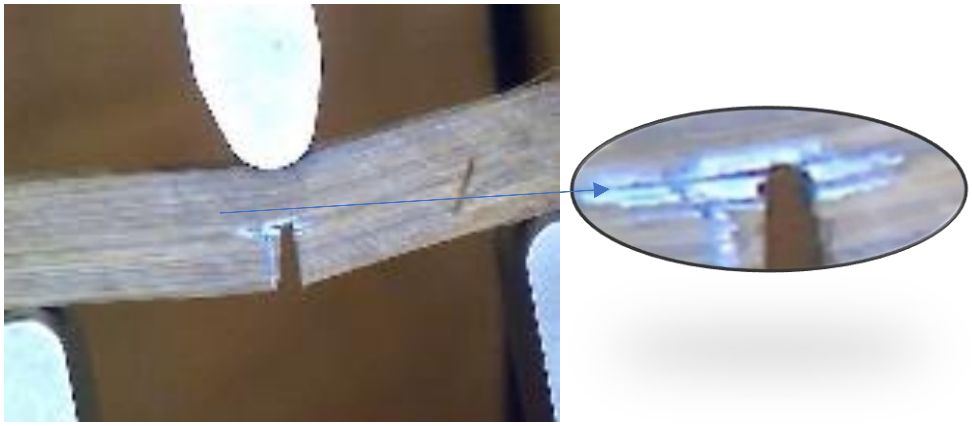


Figure 4.8: Crack Growth in Bamboo Laminate Sample

The major toughening mechanism observed was due to crack bridging and it was modelled using the SSB and LSB models. Other mechanisms observed include interfacial debonding between the bamboo fibres and sliding. The cracks observed in both orientations did not propagate in the bond interface but between the bamboo fibres near the interface. The absence of delamination between bonded layers indicates the excellent bonding between the layers of bamboo strips. The initiation toughness associated with the material’s resistance to fracture was observed to depend on the orientation of the crack. The arrester orientation had a higher initiation toughness of approximately 7.3 MPa √m than the divider orientation with 6.0 MPa √m. Stable crack growth progressed as the load was increased until failure of the material. Predicted estimates using the SSB model for the two orientations are plotted alongside the experimental results in Figures 4.6 and 4.7: the R-curve rises steadily with the increase in load up until the point of instability, which can be regarded as the point of failure of the material. The model showed a trend that was consistent with the experimental results. Both experimental and modelled curves show a trend of improved toughness in the material. Major toughening was associated with the initiation toughness in both orientations. The laminated bamboo flooring facilitated by this study is shown in Figure 4.4.

Figure 4.9: Laminated Bamboo Flooring

CHAPTER Five CONCLUSION

The Mode I fracture toughness and R-curve behaviour of bamboo laminates has been studied within a combined experimental and theoretical framework. The following conclusions have been reached:

- The result of this study adds to the body of research knowledge into the fracture and R-curve behaviour of one of the many species of bamboos existing in abundance in tropical and subtropical parts of the world.
- The fracture toughness of the bamboo laminate in the arrester and divider orientation was 11.24 MPa √m and 8.51 Mpa √m respectively, higher resistance to crack propagation in the arrester orientation than the divider orientation is attributed to the crack propagation mechanism exhibited in each orientation.
- Crack growth in both orientations did not continue in the direction of the initiated crack but perpendicular to it along the fibre direction.
- Modest rising R-curve behaviour was observed in both orientations. The arrester orientation had a higher initiation toughness, approximately 7.3 MPa √m, while the divider orientation had an initiation toughness of 6.0 MPa √m. The predicted estimates of the toughening levels using the SSB and LSB models show trends that are consistent with the trends observed in the experimental resistance curves.
- Although both orientations showed relatively good fracture resistance properties, bamboo laminates had better properties in the crack arrester orientation than in the crack divider orientation and this should be taken into consideration when using bamboo laminates.

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