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Preliminary Evaluation of Kenaf as a Structural Material

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ABSTRACT

Kenaf (Hibiscus cannabinus L.) is an annual fiber plant that is kin to cotton and okra and native to east-central Africa, though it is currently grown in numerous locations around the globe. The plant’s apparent high strength and light weight along with its environmental and sustainability advantages makes it a good candidate for use in structural materials. The goal of this study was to design a kenaf product that resembled parallel strand lumber and required minimal processing of the kenaf. The mechanical properties of the two main components of kenaf, the bast fibers and the core, were evaluated using experimental techniques. To supplement components testing, nine 1.2 in. x 2.3 in. x 12 in. kenaf beams were fabricated using strands of Whitten kenaf and a urea formaldehyde resin. The beams were loaded to failure in 3-point bending to characterize strength and stiffness. The kenaf beams had an average bending strength and average horizontal shear strength that were 26.3% and 6.8% respectively of the same properties of southern yellow pine lumber. The average elastic modulus was 7.8% of that of southern yellow pine. A limiting factor of the beams was the fact that the adhesive formed cracks throughout the beams while curing. A linear-elastic analytical model was produced in the form of a calculations spreadsheet to describe the initial load-displacement behavior of the kenaf beams. This model validated the experimental observation that the adhesive did not carry flexural stresses. It also showed that the lower bound strength values found in the component testing correlated with the properties of the materials in the beam. This preliminary study laid the groundwork for future development of whole-stalk kenaf as a
structural material. Suggestions for future investigation are discussed at the conclusion of this thesis.
DEDICATION

I dedicate this thesis first and foremost to my Lord and Savior Jesus Christ for redeeming me and providing for every need; all I have and all I have done has come from Him. I also dedicate it to my loving parents, Phil and Robin Sheldon, for leading, teaching, and encouraging me to get me to this point in my life. I also dedicate this thesis to my soon-to-be wife Danielle. She has faithfully and lovingly stood by my side, supporting me and pushing me to achieve this milestone.
I would like to thank Dr. Brandon Ross for his exceptional work and leadership as my thesis advisor. His wise counsel, insightful criticism, patient encouragement, and lighthearted spirit have made this experience very educational and enjoyable.

Special thanks goes to Gerald Feaster and Paul Roberts at KenafUSA for generously donating a large supply of kenaf. Gerald and Paul were also a valuable resource of knowledge about the agriculture, processing, and applications of kenaf.

I also want to thank Sarah Dellinger for the preliminary work she performed in gathering resources, testing materials, and giving a prototype from which I could base my design.

I am grateful to Dr. Bryant Nielson and Dr. Weichang Pang for serving on my committee and giving me valuable feedback.
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1 INTRODUCTION

Sustainable construction products and practices are increasingly being demanded by the public. One way these demands are being met is by employing natural fibers in existing products as well as using them to create new construction materials. This thesis considers the latter approach by exploring the possibility of using whole-stalk kenaf as a construction material.

Kenaf (*Hibiscus cannabinus*) is an annual fiber plant related to cotton and okra, but it is often compared to bamboo because it grows as a lightweight stalk with high tensile strength. Though it has been in existence for thousands of years, it has gained attention recently because of its environmental advantages, agricultural flexibility, mechanical properties, and a range of potential applications.

The goal of this study was to evaluate whole-stalk kenaf as a structural material similar in design to parallel strand lumber. This goal was achieved in four phases: reviewing the current literature on kenaf; testing the mechanical properties of the materials that were to be used; testing of kenaf beams made by splitting and compressing kenaf stalks and gluing the resulting strands together to form a beam; and modeling the linear-elastic stiffness of the kenaf beams. The work presented in this paper can be used as the groundwork for further development of this application of kenaf.
2 BACKGROUND AND REVIEW OF LITERATURE

2.1 Agriculture

Kenaf (*Hibiscus cannabinus* L.) is an annual fiber plant native to east-central Africa that grows rapidly in tropical climates. It is a member of the Malvaceae family along with cotton and okra. Many cultivars of kenaf exist, varying in flower color, leaf shape, seed shape, and several other botanical characteristics (Crane and Acuna 1945). Figure 1 shows kenaf being harvested from a field.

![Harvesting of kenaf](image)

**Figure 1: Harvesting of kenaf (Nance 2013)**

Kenaf stalk is made up of two main components: the bast fibers and the core fibers. The bast fibers form the outside layer of the stalk and account for about 30-40% of the dry weight of the plant (Akil et al. 2011). These fibers are the main attraction of the plant, since they have a very high strength to weight ratio. The bast fibers are held to each other and to the core by pectin, a natural binding material found in bast plants. The core
is similar in appearance and texture to a very lightweight wood. Though the core fibers are not as strong as the bast fibers, they provide the stalk some rigidity in bending. A small area in the center of the core is either hollow or filled with a pithy material that has a similar appearance and texture as that of polystyrene. Figure 2 shows these components in the cross-section of a typical stalk.

![Cross-section of kenaf stalk](image)

**Figure 2: Cross-section of kenaf stalk**

Kenaf is often categorized as a bast plant along with hemp, jute, and flax. Tahir et al. (2011) concluded that kenaf was the premier bast plant because of its low production costs, agricultural flexibility, and high annual yield. Dempsey (1975) claimed that kenaf is the most adaptable commercially grown plant in regards to soil and climate. This characteristic permits the growth of kenaf in a variety of geographical regions providing for accessibility around the globe.

Because of its rapid growth and short growing season, kenaf is a very sustainable material. The stalks can grow as much as four inches per day. Though the exact yield varies according to climate, soil, and weather, the stalks can reach 12 to 18 feet and
produce 5 to 10 tons/acre in only 150 days. Some regions have recorded as high as 15 tons/acre yield and 20-foot stalks. Kenaf yields in the southeastern United States are three to five times greater than that of southern pine (LeMahieu, Oplinger, and Putnam 1991).

Kenaf has inherent characteristics that make it an environmentally favorable material. The plant has a very high absorption rate of carbon dioxide, the most prevalent greenhouse gas. About 1.5 tons of carbon dioxide are absorbed in the production of one ton of dry kenaf, giving kenaf the highest CO$_2$ absorption rate of any known plant (Mohanty, Misra, and Drzal 2005). Kenaf also absorbs high amounts of nitrogen and phosphorus from the soil. This attribute means kenaf can prevent water pollution when it is planted near bodies of water. On average kenaf absorbs 0.81 g/m$^2$/day of nitrogen and 0.11 g/m$^2$/day of phosphorus, which is a much higher rate than that of most trees (Baillie 2005). Additionally, only minimal fertilizers and pesticides are necessary for proper growth since the plant is naturally resistant to insects simply due to its fibrous composition (Zaveri 2004).

Kenaf is quickly becoming a globally desired material. In 2006, India, China, and Thailand combined to produce about 80% of the world’s raw kenaf (Mossello et al. 2010). It was first introduced in the United States in 1940s, and now it is cultivated in several warm-climate states, such as Georgia, Florida, Mississippi, Texas, and New Mexico (Rymsza 2000). Several universities are currently conducting research on the agriculture and application of kenaf (Rymsza 2000). The Malaysian government has recognized the potential value of kenaf and in recent years has invested in research and development of kenaf cultivation (Mossello et al. 2010).
2.2 **Applications**

Cultivation of kenaf began in northern Africa. Over the years, people have found numerous applications for the various components of kenaf. The most ancient uses include rope, twine, and sackcloth made from the bast fibers (Webber III, Bledsoe, and Bledsoe 2002). More recently, the bast fibers have been used in the production of textiles (woven and non-woven), industrial socks to absorb oil, and fiber reinforcement in thermoplastics and composite materials. The core has been utilized as animal bedding, summer forage, soilless potting mixtures, and an absorbent for oil and other liquids (Akil et al. 2011; Panoutsou 2012; Elsaid et al. 2011). Some countries have even found uses for the seeds and leaves including them in their diet. The leaves are comprised of about 34% protein, and the seeds contain a large amount of omega polyunsaturated fatty acids, which help prevent diseases and enhance general health (Holzworth 2010).

Research reported by Tahir et al. (2011) has shown that kenaf can be effectively implemented as an alternative to wood in pulp and paper production. Kenaf paper has several advantages over normal wood paper. One of these advantages is the lower amount of chemicals needed for the pulping process, reducing impact on the environment. Another advantage is the quality of the product. As compared to traditional wood paper, kenaf paper is whiter, stronger, more durable, more resistant to yellowing, and has better ink adherence (Tahir et al. 2011).

Much research has been carried out exploring the role of kenaf in building materials. The primary application of kenaf in materials is in fiber-reinforced composites.
Wambua, Ivens, and Verpoest (2003) and Sanadi et al. (1995) showed that natural fiber reinforced composites, including kenaf-reinforced polypropylene, have mechanical properties similar to or better than current fiberglass-reinforced polypropylene plastics. Along with reducing the weight of materials, using kenaf in place of glass for the reinforcement of composites provides economic advantages as well as a reduced impact on the environment since fiberglass requires a large amount of energy to produce. Ford Motor Company has recently exploited these advantages by composing door bolsters out of a 50-50 kenaf/polypropylene material, particularly in the 2013 model of the Escape (Sramcik 2012). Experiments have been performed to develop particleboard and medium density fiberboard. The tests showed that the engineered kenaf materials compare well to wood fiberboard varieties (Tahir et al. 2011).

Elsaid et al. (2011) investigated the effectiveness of using kenaf in fiber reinforced concrete. Their testing showed that though kenaf fiber reinforced concrete (KFRC) has a somewhat lower compressive strength than normal concrete, it behaves with more ductility, absorbs more energy, and better distributes cracking. The compressive strength decreased as fiber content increased because the higher fiber content mixes required a cement rich mixture. The authors concluded that KFRC could be a low-cost solution to increase durability and sustainability in certain applications.

A potential application that is very relevant to the study of this thesis is the use of the kenaf core in the formation of adhesive. Juhaida et al. (2010) used liquefied kenaf core to chemically synthesize a polyurethane adhesive. Though the resulting adhesive obtained a lower shear strength than the control adhesive used, the research established
the potential of kenaf in adhesives. The study also establishes a baseline for designing improved kenaf adhesives.

Similarly, Ando and Sato (2009) explored the possibility of creating adhesive-free plywood using powdered kenaf core as the binder. This self-bonding phenomenon has successfully been achieved through hot pressing plywood boards with miniscule fragments of lignocellulosic materials, such as kenaf core, causing a chemical activation in the board materials. Ando and Sato concluded that kenaf core powder is a feasible solution to producing binderless plywood, but the lack of water-resistance must be addressed before the plywood could be sold commercially. Additionally, through the use of steam-injection pressing, Xu et al (2004) successfully produced a binderless particleboard that implemented fine particles of kenaf core to act in place of adhesive.

2.3 Mechanical Properties

In the past few decades, much research has been carried out to determine the mechanics properties kenaf fibers and the processing methods associated with optimal properties. Zimmerman and Losure (2014) reported the density of the bast fibers to be 1.293 ± 0.006 g/cm³. Aziz and Ansell (2004) found the bulk density of the fibers, which is a more accurate measurement of the density of the fibers as they exist on the stalk, to be 1.1926 g/cm³. In the process of finding the effects of various methods of fiber extraction, Amel et al. (2013) found nearly identical values of about 1.19 g/cm³ for the density of the fibers with minimal variation caused by the extraction method. Xu et al
(2004) reported a value of 0.15 g/cm$^3$ for the density of kenaf core, while Elsaid et al. (2011) reported this value to be 0.09 – 0.11 g/cm$^3$.

Another property of interest in recent studies is the tensile strength of the bast fibers. This property has a very wide range reported in the literature. Ochi (2008) reported that a single fiber has a tensile strength ranging from 200 to 650 MPa (39 – 94 ksi). The study demonstrated that both the height of the stalk and the location of the fiber on the stalk influence the strength of the fiber. Those taken from the bottom of a stalk tested stronger than those from the top of the stalk. Similarly, fibers from relatively tall stalks tested stronger than those from short stalks. Symington et al. (2009) reported a tensile strength of 223 MPa (32 ksi) for the bast fibers according to the existing literature. Their study, which involved testing the fibers at various moisture contents ranging from 65% to soaked, produced a tensile strength ranging from 275 to 495 MPa (20 – 72 ksi). Amel et al. (2013) showed that the extraction method has a significant influence on this property. The resulting tensile strength ranged from 171.2 to 393 MPa (24.8 – 63.3 ksi). Edeerozey et al. (2007) investigated the effects of chemical treatment on the fibers using various concentrations NaOH. A hot bath of a 6% concentration of NaOH proved to be the ideal conditions for alkalization, increasing the tensile strength by about 13%.

Ochi (2008) also reported that the elastic modulus of a single bast fiber ranges from 15 to 38 GPa (2000 – 5500 ksi). Symington et al. (2009) declared that the literature value for the elastic modulus was 14.5 GPa (2100 ksi) while their studies produced results ranging from 24 to 38 GPa (3480 – 5511 ksi).
The literature values for the mechanical properties discussed are summarized in Figure 3.

![Graphs showing mechanical properties](image)

**Figure 3:** Values for kenaf mechanical properties as reported in the literature

### 2.4 Harvesting and Processing

Much investigation has been carried out on the methods used for harvesting and processing kenaf. Tahir et al. (2011) compiled information on how processing affects the quality of fibers. They reported that the highest quality fibers come from stalks harvested during the beginning of the flowering period. Harvesting the fibers after the flowering
period yields much lower quality fibers. The timing of this growth period varies depending on the climate, but it occurs approximately 4 – 6 months after planting or, according to Dempsey (1975), when the daylight time goes below 12.5 hrs. Depending on the equipment used, the kenaf can be harvested in whole-stalk form or crushed and baled (Webber III, Bledsoe, and Bledsoe 2002).

As with most bast plants, the bast fibers of kenaf are often extracted from the core so that each component can be used separately. This segregation is often accomplished via retting, which is the process of separating the bast fibers from the core and from each other by soaking the plant in water or chemicals to break down and remove the non-cellulosic materials (bark and pectin). Several types of retting are practiced in bast fiber processing, but the main two categories are water retting and chemical retting. Water retting is the simplest but slowest method, requiring the stalks to be soaked in slow-moving water, stagnant water, or the dew in the field for at least 7 – 14 days depending on the conditions (Tahir et al. 2011). A study completed by Amel et al. (2013) showed that this method produces the highest quality fibers. Chemical retting is a much shorter process, needing approximately one hour, but the fibers produced have a lower tensile strength (Tahir et al. 2011). The study of Amel et al. (2013) supported this claim, showing a 7 – 32% decrease in tensile strength for chemical-retted fibers as compared to water-retted fibers, depending on the chemicals used.

Extraction methods taking the least amount of time are ribboning and decorticating. Ribboning is the process of manually or mechanically peeling the bast off of the core, whereas decorticating is the process of mechanically crushing or beating the
stalk so that the core crumbles and can be sifted out from the fibers. The research of Amel et al. (2013) demonstrated that decorticated fibers are about 7% weaker than water retted fibers, while manually peeled fibers are approximately 60% weaker.

2.5 Summary

Kenaf is a natural material with numerous environmental and agricultural advantages. The reported mechanical properties give encouragement for further exploration of kenaf as a structural material. Though the material is currently being developed for a variety of applications, a design for a construction material with a whole-stalk approach has not yet been formulated. This study seeks to lay the groundwork for the development of such a design.
3 TESTING OF INDIVIDUAL COMPONENTS

Before a beam design could be developed and tested, the materials to be used needed to be tested for their mechanical properties. The first phase of testing focused on the individual components of which later kenaf beam samples would be composed: bast, core, and adhesive. Each component was analyzed for the basic mechanical properties using a Tinius Olsen 10000 universal testing machine (UTM). Testing was conducted in the structural mechanics lab located in Lowry Hall at Clemson University.

Kenaf specimens were donated by KenafUSA and were grown in Micanopy, FL. The cultivar of kenaf used for these experiments was the Whitten variety as that was the type of kenaf that was readily available. The adhesive was a urea-formaldehyde resin with a powdered catalyst for hardening. The adhesive was purchased from National Casein.

3.1 Kenaf Bast Fibers

The bast fibers were tested for tensile strength and elastic modulus using a UTM. The fibers used were either manually peeled (i.e. ribboned) or mechanically decorticated to remove them from the core. The parent stalk for the fibers was approximately 10 feet tall, and fiber specimens were taken throughout the stalk elevation. The test specimens ranged from .0014 in\(^2\) to 0.016 in\(^2\) in cross-sectional area and from 1.8 in. to 10.6 in. in length, and consisted of multiple fibers. Cardboard tabs were glued to each specimen end to protect the portion gripped by the test machine. Binder clips were used to apply
pressure to the cardboard clamps while the adhesive was setting. Equipment for specimen preparation is shown in Figure 4. A total of 20 bast specimens were tested.

![Figure 4: Bast fiber specimen preparation](image)

The cross-sectional area was measured using calipers at several points along a given specimen (Figure 5). The average area was used in calculating the strength and elastic modulus of specimens. The cross-sectional area of a given specimen varied up to 20% along its length. The effective length of the specimen was measured as the distance between the edges of the two cardboard tabs.
Figure 5: Measuring cross-sectional area of bast fiber specimens

Test set-up is shown in Figure 6. The cardboard tabs were inserted into the clamp attachments that were tightened down, ensuring that the entire tab was within the clamp so that the tab-to-tab length could be used as the effective length. The UTM was initially adjusted so that the specimen was taut, after which it was loaded to failure at a displacement rate of 0.05 in./min. During the test, the loads were recorded at given crosshead displacements to form the load-displacement plots, which yield the elastic modulus value via Equation 1:

\[ E = \frac{kL}{A} \quad Equation 1 \]

where \( E \) is the elastic modulus, \( k \) is the slope of the load-displacement plot, \( L \) is the effective length of the specimen, and \( A \) is the average cross-sectional area. The load and
displacement values used in Equation 1 occurred within the linear-elastic range of the material. The ultimate strength in tension was calculated from the data with Equation 2:

$$\sigma_{ult} = \frac{P_{max}}{A} \quad \text{Equation 2}$$

where $\sigma_{ult}$ is the ultimate strength and $P_{max}$ is the maximum load recorded.

The fiber specimens often failed near the interface between the bare fibers and the tab. This was due to stress concentrations and clamping stress occurring at that location. Oftentimes some fibers failed at one end while others failed at the other. Because of the failure location and failure mode, the experimental strength values are considered lower-bound values. Figure 7 shows specimens after testing, including specimens failing near the tabs.

**Figure 6: Bast fiber specimen in UTM**

The fiber specimens often failed near the interface between the bare fibers and the tab. This was due to stress concentrations and clamping stress occurring at that location. Oftentimes some fibers failed at one end while others failed at the other. Because of the failure location and failure mode, the experimental strength values are considered lower-bound values. Figure 7 shows specimens after testing, including specimens failing near the tabs.
Figure 7: Bast specimens after failure

The bast fibers were also measured for specific gravity. To find this property, the mass of each sample was found using a mass balance. The total length of each bundle was measured and multiplied by the average cross-sectional area to find the total volume. Equation 3 and Equation 4 were used to find the specific gravity of each fiber specimen:

\[ \rho = \frac{m}{V} \]  \hspace{1cm} \text{Equation 3}

\[ G_s = \frac{\rho}{\rho_w} \]  \hspace{1cm} \text{Equation 4}

where \( \rho \) is the density of the fibers, \( m \) is the mass of the fiber sample, \( V \) is the volume of the sample, \( G_s \) is the specific gravity, and \( \rho_w \) is the density of water (1 g/cm\(^3\)).

Measurements of cross-sectional area from the calipers were verified using Equation 5, which is derived from Equation 3:

\[ A = \frac{m}{\rho L} \]  \hspace{1cm} \text{Equation 5}
where $A$ is the cross-sectional area, $\rho$ is the literature value for bulk density ($1.19 \text{ g/cm}^3$), and $L$ is the total length of the specimens. Values produced using Equation 5, were typically within 4 – 5% of the average areas determined using calipers.

### 3.2 Kenaf Core

To find the properties of the core, six one-foot samples were prepared by peeling bast fibers from the core. The diameter of each core sample was measured at several points along its length to find the average cross-sectional area. The average diameter of the core samples ranged from 0.33 to 1.15 in. Although the center region of the core was typically either hollow or filled with pith, the cross-section was taken as uniform. This simplifying assumption was of small consequence because the opening was typically less than 10% of the cross-sectional area and because the opening occurs at the neutral axis during the flexural testing discussed below.

The cores were weighed to find their specific gravity. Specific gravity was calculated in a similar manner to the bast fibers, using mass, length and average area of each specimen. To account for the center region, which was either hollow or filled with lightweight pith, the diameter of the center region was measured and the area of the center region was subtracted from the gross cross-sectional area for the calculation of the specific gravity.

A three-point bending test was performed on each core sample using the UTM. Each sample was simply supported and a point load was applied at the center of the span.
The displacement was recorded at consistent force intervals to find the elastic stiffness of the material. The core test set-up is shown in Figure 8 and examples of cores after testing are shown in Figure 9. The ultimate strength and elastic modulus of the cores were calculated using Equation 6 and Equation 7:

$$\sigma_{ul} = \frac{M_{max} y}{I} \quad \text{Equation 6}$$

$$E = \frac{kL^3}{48I} \quad \text{Equation 7}$$

where $M_{max}$ is the moment produced by the maximum point load, $y$ is the distance from the bottom of the core to the neutral axis (assumed to be half of the diameter), and $I$ is the moment of inertia about the neutral axis.
Figure 8: Testing of core samples

Figure 9: Core specimens after failure
Since the cores were to be compressed with a vise in the process of fabricating a kenaf beam (as will be discussed later in the paper), the properties of the core after compression were also of interest. Seven samples of compressed core were tested using a tensile test similar to that carried out on the bast fibers. Cross-sectional areas of the compressed core samples were measured with calipers after they had been compressed. The samples were directly clamped into the UTM and were pulled in tension until failure. The applied force was recorded at given displacement intervals to construct a load-displacement plot, which could be used to find the elastic modulus. Equation 1 and Equation 2 were used to find the elastic modulus and tensile strength of the compressed core specimens.

3.3 Adhesive

A large variety of adhesives are commercially available. A category of adhesives that work well in structural applications is thermosetting polymers. Frihart and Hunt (1999) list several examples of thermosetting polymers including urea-formaldehyde, melamine-formaldehyde, phenol-formaldehyde, isocyanate, and epoxy adhesives. Catalysts are often used along with these polymers to speed up the curing process of an adhesive. These catalysts are chemicals that accelerate the reaction of the polymer but do not become part of the polymeric compound (Frihart and Hunt 1999).

The adhesive used throughout this study was a urea-formaldehyde resin with a powdered catalyst for hardening. The adhesive was purchased from National Casein, and its product name is 750. It is designed for applications involving wood, such as
fabrication of plywood, edge bonding, and veneering. Frihart and Hunt (1999) recommend urea-formaldehyde resins for interior structural applications where high moisture exposure is limited. The resin was a white liquid with a viscosity of 550 cps at room temperature and a specific gravity of 1.29 g/cm$^3$ according to the technical data sheet provided by the manufacturer. The catalyst is a fine, light brown powder. According to the documentation provided with the resin, the two components are to be mixed at a catalyst to resin ratio of 15:100 by weight. The resulting adhesive was brown in color.

To find the mechanical properties of the adhesive, five adhesive samples were formed by rolling a cylindrical rod of wet adhesive in wax paper, sealing the ends, and allowing them to set while standing vertically. The diameter of each sample was taken at several points along the length to calculate an average cross-sectional area. After the adhesive cured, wax paper was removed and the samples were subjected to a three-point bending test, similar to the one performed on the uncompressed cores, to find the elastic modulus and ultimate strength. Adhesive specimens and adhesive testing are shown in Figure 10. Equation 6 and Equation 7 were used to calculate the strength and elastic modulus of the adhesive.
Each component was tested to find its specific gravity, ultimate strength, and elastic modulus. The results are presented in Table 1 below. For comparison, typical properties for southern yellow pine are also shown in the table. These results suggest that the kenaf bast used in this study has about 75% of the strength of southern yellow pine and kenaf core in its natural state has about 49% of the strength of southern yellow pine.
The experimentally determined elastic modulus of the bast and core were only about 37% and 26% of the elastic modulus of southern yellow pine, respectively.

Table 1: Test results for the mechanical properties of individual components

<table>
<thead>
<tr>
<th></th>
<th>Average Specific Gravity</th>
<th>Ultimate Strength (ksi)</th>
<th>Elastic Modulus (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>Average</td>
</tr>
<tr>
<td>Bast</td>
<td>1.3</td>
<td>2.970</td>
<td>9.430</td>
</tr>
<tr>
<td>Core, uncompressed</td>
<td>0.22</td>
<td>4.073</td>
<td>6.201</td>
</tr>
<tr>
<td>Core, compressed</td>
<td>0.25</td>
<td>0.582</td>
<td>0.952</td>
</tr>
<tr>
<td>Adhesive</td>
<td>1.27</td>
<td>1.635</td>
<td>2.002</td>
</tr>
<tr>
<td>Southern Yellow Pine*</td>
<td>0.52</td>
<td></td>
<td>12.67</td>
</tr>
</tbody>
</table>

*Properties of southern yellow pine derived from values reported in “Mechanical Properties of Wood” (Green, Winandy, and Kretschmann 1999)

The average values listed in Table 1 were used to describe the properties of the materials in subsequent analyses. The literature reported values for the strength of the bast fibers were up to 10 times higher than the strength measured in this study. This discrepancy is likely due to the fact that the previous studies have examined a single fiber, whereas the research presented in this paper analyzed specimens consisting of multiple fibers. The smaller values in this study are attributed to the increased likelihood of weak locations in the multi-fiber specimens. Once the strength of a weak section was exceeded, load was spread to the remaining fibers. Popping sounds during testing
indicated that the weak sections were breaking and the load was spreading. This transfer of load was repeated until the remaining section was unable to carry the load.

Another possible cause for the low strength values produced by these tests is that the quality of the bast fibers used may have been uncharacteristically low. As with any organic material, several factors can cause damage or improper development of the fibers. The variety of kenaf used, harvest time, and fiber extraction methods are a few of the factors that could have influenced the outcome. The literature suggested that these variables affect the strength of the fibers. These aspects may have compounded to alter the properties of the kenaf samples.
Three series of kenaf beams were fabricated and tested. Tests were intended to serve as a proof-of-concept for using minimally processed bast and core in structural members. Beams from all three series were approximately 1.2 in. x 2.3 in. x 12 in. and were loaded to failure in 3-point bending. This chapter discusses the fabrication and testing methodologies. Results of testing are also discussed.

4.1 Approach

The goal of this study was to produce whole-stalk kenaf beams that have structural properties comparable to wood and that require minimal processing. Though many techniques have been developed to separate the bast fibers from the core, these processes take much time and effort. In an attempt to avoid this limitation, the author sought to create a structural kenaf product that kept the bast fibers intact with the core. Several test specimens were fabricated to test the structural properties of kenaf beams that met these criteria.

4.2 Specimen Series and Labels

Each kenaf beam was given a unique two-digit label. The first digit (1, 2, or 3) signifies the series while the second digit provides the kenaf beam identification within the series. For example, specimen “1-2” was the second specimen tested in the first series. Specimen “3-1” was the first specimen tested in the third series.
For each series, the beam specimens were fabricated as a single unit from which each kenaf beam specimen was cut, as is shown in Figure 11. Throughout this thesis, this single unit will be referred to as the parent kenaf beam of a series. The series 1 and 2 parent kenaf beams were fabricated using kenaf harvested in late winter and were each divided into two separate beam specimens. The series 3 parent beam was fabricated using kenaf harvested in early winter and was split into five kenaf beams. In general the same fabrication and testing procedures were used for all three series. Any differences are explicitly noted in the section below.

![Figure 11: Series 2 parent kenaf beam](image)

### 4.3 Specimen Fabrication

Kenaf beam specimens were comprised of kenaf stalks and an adhesive and were approximately 1.2 in. tall, 2.3 in. wide, and 12 in. long. Specimens from series 2 are shown in Figure 12. This section presents the details of kenaf beam fabrication.
To assemble the parent beams, the kenaf stalks were cut into approximately 12-inch segments. Using an axe, these samples were split length-wise into quarters (Figure 13). The step of quartering the stalks was used because the use of full stalks did not perform well in previous prototypes (Dellinger 2013). The quartered stalks were then compressed using a vise (Figure 14). This process gave the strands a flatter shape, allowing each piece to fit more closely together.

Figure 12: Kenaf beam specimens
Once the stalks were quartered and compressed, they were placed in a wood form used to shape the parent beam. The form consisted of two short wood boards laid flat on a plywood sheet (Figure 15). The wood boards were about 4.25 inches apart for series 1. A sheet of wax paper was placed in this form to prevent the form from adhering to the
specimen. A layer of kenaf strands was set into the form and a thin layer of adhesive was poured over the kenaf. A plastic fork was used to spread the adhesive uniformly over the kenaf. This layering was repeated until the height of the parent beam was approximately 2 inches. A final layer of adhesive was poured on top to allow a flat surface to form. The wax paper sheet was folded over the top of the kenaf. With the wood boards screwed down into the plywood, a concrete block was positioned on top of the parent beam to compact the strands and squeeze out any excess adhesive (Figure 16). For series 1 the concrete block weighed 74 lbs. Distributing this weight over the area of the face of the parent beam resulted in approximately 1.4 psi of pressure.
Figure 15: Parent kenaf beam in form

Figure 16: Concrete block applying pressure to parent kenaf beam while adhesive cures
Adhesive used in the specimens was a urea-formaldehyde resin from National Casein. The adhesive was prepared with a catalyst per the manufacturer’s instructions for all but series 1. For this series, an amount of water with a weight of 12% of the weight of the adhesive was added to the adhesive to lower its viscosity and allow the adhesive to flow more readily. This modification was made to test the effect of lower viscosity of the fabrication process and specimen mechanical properties.

The parent beams were left under compression for 1 week. The adhesive manufacturer recommended 7 hours for pressing, much less than the time provided. The manufacturer stated that the adhesive’s maximum bond strength is reached in about 7 days. After 1 week the parent beam was removed from the form, and the ends were sawn off to remove the extra adhesive and give the kenaf beams flat edges. For series 1, the 4.25 in. wide parent beam was sawn in half to yield two kenaf beam test samples.

Series 2 kenaf beams were assembled with a similar process to those in series 1, but with a few modifications. First, some of the pithy center of the stalks, which adds no strength to the material, was removed in the splitting and crushing procedure, allowing the strands to be slightly flatter. Second, no water was added to the adhesive. The water appeared to deteriorate the properties of the adhesive. This deterioration was noticed first in the cracking of the adhesive throughout the kenaf beams, but also in the process of forming adhesive test samples as discussed in the previous chapter. The rods made from the watered-down adhesive crumbled shortly after curing. Third, since the adhesive had a much thicker consistency, it would not flow when poured. Therefore, each strand was coated with the adhesive individually using a plastic fork to scoop and spread the glue.
The coated strands were then placed into the form. Finally, additional concrete beams were placed on top of the parent beam while the adhesive was setting to increase the applied pressure. For series 2, these concrete beams weighed a total of 260 lbs. Distributing this weight over the area of the surface of the parent beam yields an applied pressure of 4.8 psi. The series 2 parent beam was approximately 24% kenaf and 76% adhesive by weight.

The series 3 parent beam was 12 in. wide and was fabricated with a process similar to that used to produce the series 2 parent beam. Thirteen-inch kenaf strands were laid in the form parallel to each other one layer at a time until a height of about 2 inches was reached. The strands in the bottom layer were coated in the same manner as those used for the fabrication of the series 2 kenaf beams. For the remaining layers, the strands were placed on top of the previous layer and then brushed with a coat of adhesive using a paintbrush. This change in procedure prevented the application of excessive adhesive. For series 3, concrete beams weighing a total of 520 lbs were positioned on top of the parent beam while the adhesive set. This dead weight applied a pressure of 3.3 psi to the top surface of the specimen.

The series 3 panel was approximately 30% kenaf and 70% adhesive by weight. Relative to series 2, the application method reduced the proportion of adhesive in the beams. Spreading the adhesive with a paintbrush allowed the adhesive to be applied in thinner layers while ensuring that all of the kenaf was covered.

The 12-inch parent beam for series 3 was cut into five equal widths to produce five kenaf beams for testing. The two kenaf beams that were cut from the outermost
sections of the parent kenaf board were planed on their outside edge to give a flatter, more consistent surface.

The series 3 parent beam did not compress while setting as much as the series 2 board did. This difference is due to the smaller applied pressure from the concrete beams as well as the better distribution of the adhesive. Trimming the beams was necessary to maintain consistency in dimensions from one specimen to the next. The top of each of the five kenaf beams was planed to make them approximately 1.2 inches in height. Figure 17 shows a kenaf beam from series 3.

![Figure 17: (a) Top and (b) bottom of series 3 kenaf beam](image)

4.4 **Test Procedure**

Each kenaf beam specimen was tested in a three-point bending test using the UTM. The specimens were simply supported with a span length of 11 inches. Roller supports were placed at each end and at the load point (Figure 18). A point load was
applied at the middle of the kenaf beam and load measurements were taken at given displacement intervals. Load was applied at a displacement rate of 0.05 in/min. Each specimen was tested until failure, which was determined by a reduction in the applied force greater than 10% of the previous maximum.

![Figure 18: Kenaf beam test setup](image)

Each of the three components in the kenaf beams possessed different mechanical properties. Therefore, to describe the behavior of the kenaf beams as a whole, the term “apparent” will be used in regards to the mechanical properties of the kenaf beams. The apparent mechanical properties were determined from test results, and assumed that the cross-section was homogenous. This assumption is not correct, but provides a means for calculating the overall performance of the specimens and for comparing the results to lumber products.
The apparent bending stress and the apparent shear stress were found using Equation 8 and Equation 9:

\[ \sigma_{app} = \frac{My}{I_g} \]  \hspace{1cm}  \text{Equation 8}  \\
\[ \tau_{app} = \frac{VA'y'}{I_gb} \]  \hspace{1cm}  \text{Equation 9}

where \( \sigma_{app} \) is the apparent bending stress, \( M \) is the moment produced by the point load, \( y \) is the distance from the bottom edge of the kenaf beam to the centroid, \( I_g \) is the gross moment of inertia (assuming a homogeneous cross-section), \( V \) is the shear force generated by the point load, \( A' \) is the cross-sectional area from the horizontal plane of interest to the outer edge of the beam, \( y' \) is the distance from the centroid of \( A' \) to the neutral axis, and \( b \) is the width of the beam. The neutral axis was estimated to be at mid-height of the beam, and the area \( A' \) was taken as half of the gross cross-sectional area since the shear is maximum at the centroid. The apparent modulus of elasticity was found using Equation 10:

\[ E_{app} = \frac{(k_{exp})L^3}{48I} \]  \hspace{1cm}  \text{Equation 10}

where \( E_{app} \) is the apparent modulus of elasticity, \( k_{exp} \) is the experimental stiffness (taken from the slope of the load-displacement plot), and \( L \) is the span length. The load and displacement used to calculate the elastic modulus were within the linear-elastic range as determined by a review of the load-displacement data.

The cross-sectional area of the kenaf beams ranged from 2.22 in\(^2\) to 2.78 in\(^2\). To facilitate a comparison of specimens having different dimensions, the load-displacement
plots were normalized by dividing the applied loads for each specimen by that specimen’s moment of inertia.

Local crushing of the kenaf beam was observed at the point of the applied load (Figure 19). This local displacement was typically less than 1% of the overall displacement and was therefore disregarded in the calculations.

![Figure 19: Local crushing of kenaf beam at the applied load](image)

The specific gravity of each specimen was determined using the measured dimensions and mass along with Equation 3 and Equation 4 from the previous section.

4.5 Results

The original and normalized load-displacement behaviors of each kenaf beam are shown in Figure 20 and Figure 21, respectively. Each specimen had an observable linear elastic region. The average normalized stiffness in this region was 4.665 k/in$^5$ with a 12.7% coefficient of variation. This data shows that, in spite of subtle difference in
fabrication, the kenaf beams had a consistent linear-elastic behavior from one specimen to the next.

A consistent crackling noise was observed throughout the testing of the kenaf beams. This observation suggests that individual fibers were breaking and redistributing the load to other fibers. A popping noise often accompanied a reduction in load, signifying the rupture of part of the cross-section. In the inelastic region, the kenaf beams would often hold a fairly constant load (varying less than ±5%) for a relatively large change in displacement (up to 0.3 in.).
Figure 20: Load-displacement behavior of kenaf beams

Figure 21: Normalized load-displacement behavior of kenaf beams
The kenaf beams experienced two types of failure. About half of the kenaf beams failed in tension of fibers near the location of maximum moment. The other kenaf beams experienced horizontal shear failure, where the shear capacity of the adhesive, or in some cases the kenaf’s pectin, was the limiting factor. Figure 22 and Figure 23 show examples of these failure modes.

Figure 22: Tensile failure of kenaf beams

Figure 23: Horizontal shear failure of kenaf beams

The adhesive in the kenaf beams was already cracked prior to testing (Figure 24). Based on this key observation it was believed that the adhesive did not carry flexural stress, though it did contribute indirectly to the stiffness by allowing the other components to transfer horizontal shear and act compositely. This concept is explored
analytically in the next chapter. In conventional applications, this adhesive is applied in very thin layers. Therefore, the thickness of the adhesive layers may have been the cause for the cracking. To avoid this limitation, either a more suitable adhesive should be used in future designs, or a design that allows for thin adhesive layers should be developed.

Figure 24: Cracking in adhesive prior to testing

For each beam, the apparent bending and shear stresses at failure, along with the elastic modulus, are shown in Table 2. These results were relatively consistent between specimens, varying by less than 13% each. The specific gravity of each beam is also presented in the table. The 17.5% coefficient of variation can be accounted for in the variation of the distribution of the components. This relatively small variation shows consistent composition throughout the test specimens.

Performance of the kenaf beams was lower than what was expected based on the literature reports of the mechanical properties of kenaf. The results are compared to the reported properties of southern yellow pine in Table 3. A key factor that affected this comparison is the fact that the adhesive added a large amount of weight, but did not contribute to the strength because of its cracking. The low experimental values for the
elastic modulus of the kenaf beams align with the results produced in the component testing, which were much lower than what was reported in the literature.
### Table 2: Experimental results of kenaf beams

<table>
<thead>
<tr>
<th></th>
<th>Specific Gravity</th>
<th>Apparent bending stress at failure (ksi)</th>
<th>Apparent shear stress at failure (psi)</th>
<th>Apparent Elastic Modulus (ksi)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1-1</td>
<td>0.530</td>
<td>3.14</td>
<td>76.07</td>
<td>117.33</td>
<td>Tensile</td>
</tr>
<tr>
<td>Beam 1-2</td>
<td>0.521</td>
<td>3.32</td>
<td>80.46</td>
<td>114.64</td>
<td>Horizontal Shear (pectin)</td>
</tr>
<tr>
<td>Beam 2-1</td>
<td>0.686</td>
<td>4.07</td>
<td>102.91</td>
<td>117.65</td>
<td>Tensile</td>
</tr>
<tr>
<td>Beam 2-2</td>
<td>0.727</td>
<td>3.91</td>
<td>100.63</td>
<td>114.03</td>
<td>Tensile</td>
</tr>
<tr>
<td>Beam 3-1</td>
<td>0.476</td>
<td>3.55</td>
<td>94.83</td>
<td>157.08</td>
<td>Tensile</td>
</tr>
<tr>
<td>Beam 3-2</td>
<td>0.496</td>
<td>2.82</td>
<td>76.70</td>
<td>117.95</td>
<td>Horizontal Shear (adhesive)</td>
</tr>
<tr>
<td>Beam 3-3</td>
<td>0.479</td>
<td>3.13</td>
<td>84.18</td>
<td>147.86</td>
<td>Horizontal Shear (adhesive)</td>
</tr>
<tr>
<td>Beam 3-4</td>
<td>0.491</td>
<td>2.93</td>
<td>79.38</td>
<td>137.48</td>
<td>Horizontal Shear (adhesive)</td>
</tr>
<tr>
<td>Beam 3-5</td>
<td>0.480</td>
<td>3.16</td>
<td>85.80</td>
<td>140.17</td>
<td>Horizontal Shear (adhesive)</td>
</tr>
<tr>
<td>Average</td>
<td>0.543</td>
<td>3.34</td>
<td>86.77</td>
<td>129.35</td>
<td></td>
</tr>
<tr>
<td>COV</td>
<td>0.175</td>
<td>0.128</td>
<td>0.118</td>
<td>0.127</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3: Comparison of kenaf beams to southern yellow pine

<table>
<thead>
<tr>
<th></th>
<th>Specific Gravity</th>
<th>Ultimate Bending Stress (ksi)</th>
<th>Ultimate Shear Stress (ksi)</th>
<th>Elastic Modulus (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Yellow Pine (Green, Winandy, and Kretschmann 1999)</td>
<td>0.52</td>
<td>12.67</td>
<td>1.28</td>
<td>1651.82</td>
</tr>
<tr>
<td>Kenaf Beams</td>
<td>0.543</td>
<td>3.336 (apparent)</td>
<td>0.087 (apparent)</td>
<td>129.354 (apparent)</td>
</tr>
<tr>
<td>Percentage of Southern Yellow Pine value</td>
<td>104.39%</td>
<td>26.34%</td>
<td>6.76%</td>
<td>7.83%</td>
</tr>
</tbody>
</table>
5 MODELING/VALIDATION

A linear-elastic analytical model was built using a spreadsheet to describe the load-displacement response of the specimens. The fiber section technique was used for modeling the kenaf beams. This method has been used by researchers in other applications, including El-Tawil et al. (2001) who used the method to model reinforced concrete beams. The model was built using the cross-sectional geometry and properties of kenaf beam 2-1. A picture of the cross-section of kenaf beam 2-1 (Figure 25) was imported into AutoCAD for mapping of the cross-section. The cross-section was divided into ten equally distributed layers along its height. The outline of each cross-sectional portion of the bast and core were traced to find the area, centroid, and local moment of inertia of each component in each layer (Figure 26).
For the first round of modeling, the average values of the elastic modulus of the bast fibers and the compressed core, as found in the material testing (Table 1), were used for the calculations. Since the adhesive was cracked prior to testing, as was mentioned in the previous section, it carried no flexural stress. Therefore its elastic modulus was assumed to be zero. To account for the variance in elastic modulus for the components, the transformed area method for composite structures was implemented. This method mathematically converts each component to the same material by using the modular ratio, $n$, as defined in Equation 11:
\[ n_i = \frac{E_i}{E_0} \quad \text{Equation 11} \]

where \( E_i \) is the elastic modulus of the material being transformed and \( E_0 \) is the elastic modulus of the material to which all materials are being transformed. In this case, the elastic modulus of the core was used as the basis for the transformation.

The centroid and transformed moment of inertia were calculated. The transformed moment of inertia was calculated as:

\[ I_{\text{trans}} = I_{\text{core}} + n_{\text{bast}} I_{\text{bast}} + n_{\text{adhesive}} I_{\text{adhesive}} \quad \text{Equation 12} \]

Calculations considered the local moment of inertia for each segment, as well as the moment of inertia about the centroid calculated using the parallel axis theorem. Because the elastic modulus of the adhesive was assumed to be zero due to cracking throughout the kenaf beams, the moment of inertia of the adhesive had no effect on this calculation since the adhesive’s modular ratio was also zero. A theoretical stiffness was calculated using Equation 13, which is taken from the equation for flexural stiffness of a simply supported beam with a center point load:

\[ k = \frac{48E_0 I_{\text{trans}}}{L^3} \quad \text{Equation 13} \]

where \( I_{\text{trans}} \) is the transformed moment of inertia and \( L \) is the 11-in. span used in the testing of kenaf beam 2-1. To refine the model, the calculations were repeated using the lower bound experimental values (Table 1) for the elastic modulus of the bast and the compressed core.
Figure 27 compares the experimental stiffness of the kenaf beams to the theoretical stiffness calculated using Equation 13 with both average and lower bound experimental elastic moduli. In making this comparison it is assumed that the distribution of fibers, core, and adhesive in the cross-section of kenaf beam 2-1, which was used to build the model, is representative of all kenaf beams. This assumption is considered reasonable based on visual comparison of each cross section (Figure 28) and the relative unit weights of each specimen. Because the specimens had slightly different cross-sectional dimensions, normalized values are given in Figure 29 to give a better comparison between experimental and theoretical results.
Figure 27: Comparison of the theoretical and experimental stiffnesses using raw data

Figure 28: Samples of kenaf beam cross-sections
As seen in Figure 29, the theoretical stiffness using the average elastic moduli was two times greater than the average experimental stiffness. The theoretical stiffness using the lower bound values was 8% less than the average experimental stiffness. Using the lower bound moduli, the model is within the experimental scatter and is considered to be a reasonable representation of the physical system. The agreement suggests that the modeling assumption to neglect adhesive is reasonable for the current test program and that the lower bound values better represented the behavior of the materials as they functioned in the kenaf beams.
This study was undertaken to develop a flexural member composed of kenaf that requires minimal processing and, in particular, does not require the separation of the bast fibers from the core.

The two main components of kenaf, the bast fibers and the core, were tested to find their mechanical properties. Three series of 12-in. long kenaf beams were fabricated and tested. These beams were composed of kenaf strands that were produced by splitting the stalks into quarters length-wise. These strands were compressed with a vise before being coated with adhesive and layered on top of each other in a parallel orientation. Once the adhesive had cured, the kenaf beams were cut to the proper dimensions and tested in a three-point bending test. An analytical model was developed to describe the initial linear-elastic response off the specimens.

A few key conclusions can be drawn from the results of this study:

- The component testing resulted in tensile capacities of the bast fibers that were only 10% of the values reported in the literature and were 75% of the flexural strength of southern yellow pine lumber. These low values were most likely due to the fact that most previous studies had tested a single bast fiber, but this study tested the fibers in bundles. Also, the quality of the kenaf used may have been damaged or inadequate.

- The average apparent modulus of rupture and elastic modulus of the kenaf beams were found to be 3.3 ksi and 129 ksi respectively. These values are
26% and 8% of the corresponding properties of southern yellow pine lumber.

- The adhesive was a limiting factor on the structural performance of the kenaf beams. Because the adhesive was cracked throughout the beams prior to loading, it did not carry any bending stresses, though it did provide horizontal shear transfer and allowed the other components to behave compositely.

- By using the stiffness values found in the component testing and assuming that cracking prevented the adhesive from carrying flexural stress, the model predicted properties that bounded the experimental results.

- The performance of the kenaf beams may be able to be improved by using higher quality kenaf and a more appropriate adhesive for this application.
7  FUTURE STUDY

The research reported in this paper was the first step in developing a building material from whole-stalk kenaf. Several areas ought to be explored further to build upon the mixed preliminary results. If these obstacles can be overcome, the material has the potential to be structurally viable in the construction materials industry.

A major improvement that must be studied is the optimization of the adhesive. First, a method to reduce the amount of adhesive contained in the beam must be developed. Because of the natural circular shape of kenaf cross-section, arranging the strands in a rectangular beam creates voids, which are filled by the glue. As was noted previously, the majority of the weight in the test specimens came from the adhesive. Since most adhesives are expensive and caustic to the environment, using large amounts of glue not only makes the beam heavier but also negates the economic and environmental advantages of kenaf. Additionally, the thick layers of the adhesive may have been the cause for the cracks that formed in the adhesive prior to loading. One suggested solution to reducing the amount of adhesive may be to place the kenaf beams under large compressive stress during curing. The CLT Handbook recommends pressures ranging from 40 to 80 psi when using vertical pressing in the manufacturing of cross-laminated timber (Yeh, Kretschmann, and Wang 2013). The compressive stress of 1.4 – 4.8 psi used in the current test program was only a fraction of these recommended pressures that are used by industry in similar applications.

Second, as there are a wide variety of adhesives, the specific type of adhesive should be explored. The adhesive in this study limited the performance of the kenaf
beams. Improving the application process and selecting a more appropriate adhesive are important next steps in the development of kenaf beams. Utilizing ground kenaf core as a binding material may provide a means by which the amount of adhesive could be minimized, if not eliminated. Research performed by Xu et al (2004), Ando and Sato (2009), and Okuda and Sato (2004) showed the effectiveness this application of kenaf core in engineered wood materials. This process requires curing at high pressures (5.3 MPa) and temperature (180° C) (Okuda and Sato 2004).

Another detail for future study is the splicing of strands to make longer beams. The beams fabricated in this current study were composed of strands that spanned the entire length of the beam. The interaction between strands and the behavior of strands not spanning the length of the beam must be investigated to characterize beam behavior.

Because of the highly absorbent nature of kenaf, particularly the core, a method for water-proofing of the beams ought to be developed. Many wood treatment options are readily available. These products would be a practical starting point for exploring the appropriate treatment options for kenaf. It is also possible that the selected adhesive could double as a protective treatment.

The study presented in this thesis had limitations in that the vertical shear, bearing, and creep behavior were not analyzed. These failure modes should be tested as a part of the technology development. Also, since there are numerous varieties of kenaf, a study comparing a sampling of these varieties in a similar application would be advantageous.
The interaction of kenaf beams with fasteners is another area of future exploration. Connections are of critical importance in any structure. Appropriate designs for connecting kenaf beams using standard types of fasteners must be developed.
REFERENCES


