COMPARATIVE ASSESSMENT OF THE STRENGTHS OF SOLID AND GLUED LAMINATED TIMBER

BY

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Declaration

I declare that the work in the thesis COMPARATIVE ASSESSMENT OF THE STRENGTHS OF SOLID AND GLUED LAMINATED TIMBERhas been performed by me in the Department of Building under the supervision of Dr. H.T.Kimeng and Prof. O.G**.** Okoli. The information derived from the literature has been duly acknowledged in the text and a list of reference provided. No part of this thesis was previously presented for another degree or diploma at any University.

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Certification

The thesis entitled COMPARATIVE ASSESSMENT OF THE STRENGTHSOF SOLID AND GLUED LAMINATED TIMBER by Ekundayo Olurotimi Olusegun meets the regulations governing the award of the degree of Master of Science (Construction Technology) of Ahmadu Bello University, and is provided for its contribution to knowledge and literary presentation.

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DEDICATION

To God Almighty my Lord and Savior (**Jesus Christ**) from whom all blessings flow, I owe all I am to your Mercy. Tomy parent for their tireless support.

Acknowledgement

I wish to acknowledge everyone that contributed to the success of this work. First and foremost, I am grateful to my parents Rev. (Dr.) J.J Ekundayo and Pst. (Mrs) H.A. Ekundayo for their love, prayersand support.My supervisors in the persons of Dr. H.T. Kimeng and Prof. O. G Okoli for their guidance and contributions. I also want to appreciate Mr Olufemi of the carpentry workshop, Building department. Many thanks to the entire staff of the Department of Building A.B.U, Zaria for their inputs in making this work a success. Thanks also are extended to colleagues and friends for their moral support. All my friends are appreciated for their support especially those that regularly call my attention to this work.I owe very special thanks to my entire family for their kindness and support during thestudy.

Abstract

Timber isa construction material with unparalleledenvironmental credential. Howbeit, limitations of span and crossectional dimension, strength reducing defects and anisotropy limits its engineering application. Mechanical methods of jointing to address the earlier challenge has introduced serious wood fiber failure and increased the embodied energy in timber as a green material. However, developed societies have established in literature the possibility of overcoming these limitations to utilize timber beyond the traditional application in Nigeria being glueable for developing engineered wood products like glued laminated timber (glulam) using their timber species. Conversely, while little or no interest is shown in timber as a structural material in Nigeria, many of the few researches in timber have focused on solid timber elements leaving its limitations unattended. Consequently, its structural capabilities is yet unappreciated. Nevertheless, the fact remains that reconstituting natural timber as glulam is an effective way of optimizing this green material for limitless structural use. Whether these qualities are achievable with local timber is the main thrust of this research. The research therefore conducted laboratory experiments on selected timber species namely; Ire (*Funtumia africana*), Awun (*Alstonia congensis*) and Oriro (*Antiaristoxicaria*) being readily available and widely used species with no information on Oriro and Ire in NCP 2 of 1973. The aim was to assess their strength properties as glulam elements with the view to improving their structural capacity.It also set out to determine their glueability, the effects of temperature variation on compressive strength parallel to grain for glulam short columns by subjecting specimens ofequal dimension for the three species to different temperatures of 0 ^{0}C, 40 ^{0}C, 50 ^{0}C, 70 ^{0}C, 100 ^{0}C and room temperature for 4 hours in an electric oven prior to testing; to compare the mechanical properties of solid and glulam elements. In furtherance, specimens were

prepared and tested for; static bending strength, compression parallel and perpendicular to grain, density and moisture content in line with ASTM D193, EN 408(2003) and EN13183-1(2002). The research established that the species are; structurally glueable, that due to temperature increase compressive strength is lost in glulam columns from control temperature (30 ^{0}C and 27.9^{0}C) to 100 was 41% 14.4% and 21.6% in Ire, Awun and Oriro. Results showed that glulam elements developed 55%, 95% and 143% of clear solid wood bending strength and that bending strength of 65.22N/mm$^{2;}$ 36.44N/mm^2, 26.15N/mm^2; 25N/mm^2 and 14N/mm^2; 20N/mm^2 in solid and glulam in the species are structurally significant.The study has therefore demonstrated that the timber species studied can be engineered to load bearing glued laminated structural elements using polyvinyl acetate glue without severe loss of strength below and above room temperature.

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LIST OF SYMBOLS AND ABBREVIATIONS

AITC	American Institute of Timber Construction
APA	American plywood Association
ASTM	American Society for Testing and Material
BS	British Standard
C-perp	Compression perpendicular to grain
C-para	Compression parallel to grain
$E_{0,}$	Modulus of elasticity in compression parallel to grain
E_{90} ,	Modulus of elasticity in compression perpendicular to grain
f_{ck0}	Compressivestrength parallel to grain
f_{ck90}	Compressive strength perpendicular to grain
$f_{m,k\ stress}$	Characteristic bending strength
g,	grams
Kg/m^3	Kilograms per cubic meter
N	Newton
N/mm^2	Newton per millimeter square
NCP	Nigerian Code of Practice
MC	Moisture Content
MOE	Modulus of elasticity
mm	Millimetre
PVAc	Polyvinyl acetate glue
ρk	Characteristic density
%	Percentage
°C	Degree centigrade

CHAPTER ONE

1.0 INTRODUCTION

1.1Background of the Study

The versatility of timber finds wide application in the construction industry spanning from simple framing in housing projects to large scale public facilities. However because sawnwood hasrestrictionsto spans and cross-sectional dimensions due to size of tree as well as strength reducing features which occur at growth, its value as a structural material for extensive structural applications is limited. Engineered wood products such as glue laminated timber (glulam) were thereforedeveloped to improve the use of natural timber beyond its natural limitations.

Structural glued laminated timber is an engineered structuraltimber glued up from suitably selected and prepared pieces ofstress graded lumber either in a straight or curved form with the grain of all pieces essentially parallel to the longitudinal axis of the member (APA, 1996; Manja *et al.*, 2010). According to the American plywood association (APA, 2013), glulam has remained the most resource-efficient approach to wood building products when it comes to optimizing products from a carefully managed timber resource. Glued laminated wood can be built out of defective wood without losing its strength properties as reported by Regina*et al.*,(2010). The application of glue laminated timber as a construction material would therefore make many species of timber previously regarded as non-merchantable useful for structural purpose. Clearly, this has the potential to revamp the forestry industry making it a massive employer of labor. Glulam can also be manufactured from small diameter fast growing tree, thereby bridging the supply deficit from slow growing trees(Evalina*et al.*,2010). According to the American institute of timber construction

(AITC), structural glued laminated timber refers to an engineered, stress-rated timberproduct comprising assemblies of suitably selected and prepared wood laminations bonded together with adhesives. Glulam is used for beams, arches or columns consisting of several laminates of timber arranged parallel to the longitudinal axis of the member with the individual pieces assembled with their grains approximately parallel and glued together to form a member which functions as a single structural unit. This is often achieved by using different layers or fragments of timber glued or compressed in different directions, creating a new material. In order to obtain larger spans, finger-joints or other equivalent connections are used to bond different timber elements in the same horizontal layer.

In elements of this type, any strength reducing features, such as knots, that exist in the individual laminates are leveled out, unlike a solid timber element from the same piece (Wan *et al.*,,, 2011). Furthermore, glulam offers the possibility of obtaining larger cross- sectional dimensions and longer lengths than solid timber (Manja *et al.,* 2010).

The manufacturing procedures for glulam depend on volume and nature of work. However all stages of the production process must comply with BS EN 386 *Glue laminated timber - Performance requirement and minimum production requirement.* According to Timber Research and Development Association (TRADA, 2003) the manufacturing procedure includes; Material preparation in conformity to BS EN 519:*Requirements for machine strength graded timber and grading machines,* and BS 4978:*Specification for visual strength grading of softwood.* End Jointing to achieve full laminates using finger joints in conformity to BS EN 385 requiring strength of joint to be compatible with strength of grade and species of timber used.

Joint requirements are also covered in BS EN 387:*Glue Laminated Timber - Larger Finger Joints – Performance Requirement and Minimum Production Requirements.*

Bonding of the laminates is to conform to BS EN 301 *Adhesives*- where adhesives must provide sufficient bonding between laminates that is at least as strong as the timber and lastly, finishing to required standards by planning and sanding, preservative application if required and fabrication. Moody and Hernandez (1997) also stated the manufacturing process to be as above.

1.2Statement of Research Problem

Timber has been identified as a construction material with an excellent environmental credential that is unparalleled (Bradford, 2008). However, limitations in cross-sectional dimension and span as well as growth defects have limited its extensive use for structural purpose. However, to address span and dimensional limitations, methods of jointing were developed (Kimeng, 2010).Such methods as mechanical fastener-connectorsinclude; shear plates, split rings, tooth rings, metal frames, framing anchors, and wire nails (Izomoh, 1994). Traditional methods which includes tongue and groove systems were used,metal bolts were also used over the traditional system to offer longer spans of up to 10.5m (Apu, 2003). However, some of the short falls these methodshadincludedsplitting in wood, and loss of strength at elevated temperature, inadequate clear wood strength of15 - 20 % as in the tongue and groove system(Apu, 2003;Jacob and Barragan 2007, Kimeng 2010).In addition, the extensive use of mechanical fasteners detracts from the tenets of the "Greenness" timber construction offers being high embodied - energy splicing components.

Sequel to these was recourse to wood adhesives which proved to be better alternatives than mechanical fasteners Banea and Silver (2009).

Furthermore, it is observed that literature is replete with researches in Europe and the United States of America (USA) showing that their timbers are glueable to take advantage of qualitiessuch as seamlessness of connection, flexibility of design and lightness of structure that glulam offers (Kimeng *et al.,* 2014). The use of temperatetimberwith natural and synthetic wood adhesives has therefore been established. Species like Southern pine (*Pinus*spp.), Douglas fir (*Pseudotsugamenziesii*)–larch (*Larixoccidentalis*), and Norway spruce specieswith naturaland synthetic wood adhesives like Resorcinol – Formaldehyde Resins, melamine - Formaldehyde resins and Epoxy Resins in the production of reconstituted wood elements has been reported(Robert and Roland, 1995; Suhaimi*et al.,* 2004; Wan*et al.,* 2011). Several researches in Nigerian have shown the mechanical properties and performance of some indigenous timber species only in solid timber form, these studies have not focused on the use of Nigerian timber species in the development of glulam for structural purpose toenhance the structural capabilities of local timber species (Suhaimi*et et al.,* 2004; Kimeng *et al.,* 2014). That the properties of timber between and within species is diverse makes it imperative to understand the behavior of local timber species as glued laminated elements.

1.3Justification of the Study

The need to situate the Nigerian construction industry within the context of the "Green" agenda is imperative as the subject of sustainability and environmental friendliness continues to top the agenda among the highest level of policy

makerssuch as the G7 meetings where issues of global concern like climate change is discussed. Therefore setting the trajectory for the industry along the green path is to take advantage of locally available forest resources. Home grown and processed timber,when successfully glued for structural purpose could achieve the benefits of sustainability, environmental friendly construction and construction cost reduction working in tandem (Bradford Forest Inc. 2008;Anthony and Joshua, 2014).

Establishing the glueability of indigenous timber species for structural purpose would demonstrate to designers and engineers that local timber species can perform excellently as structural glulam elements as demonstrated with timber species used for important structures in the United kingdom and the United states of America; that they can compete favorably with other traditional construction material without compromising the tenets of structural safety.

1.4Aim and Objectives

1.4.1Aim

The aim of this study is to assess the strength properties of glue laminated Ire (*Funtumia, Africana)* Oriro*(Antiaristoxicaria)* and Awun (*Alstoniacongensis)* species using polyvinyl acetate (PVA) glue with a view to presenting the capability of glulam elements made from the selected timber species.

1.4.2Objectives

The specific objectives are;

(i) To determine the glueability of Ire (*Funtumia, Africana),*Oriro *(Antiaris Toxicaria)* and Awun (*Alstonia Congensis).*

(ii) To evaluate the effects of varied temperature on strength performance of polyvinyl acetate glue and the mechanical properties of the glue laminated compression members.

(iii) To determine the mechanical properties such as static bending strength, compression parallel and perpendicular to grain of solid wood and glulam beams specimen of the species studied.

(iv) To compare the mechanical properties of solid and glued laminated timber elements.

1.5 Methodology

The methodology adopted for this study included relevant literature review of the subject matter from journals, books, seminar papers, conferences and workshops, where secondary information was sourced.

a) Experimental program; determination and comparison of characteristic values of mechanical properties, moisture content and density, in accordance with EN408 (2003), and BS EN 384 (2004).

b) Manufacture of glue laminated timber: The manufacture of glue laminated elements such as beams and columns is in accordance with, BS 5268: part 2 (2002)

1.6 Analysisof Results

Results were analyzed using descriptive andinferential statistical tools such as measure of central tendency: mean, median and mode and measure of spread; range, variance, mean deviation and standard deviation.Results were thereafterpresented in tables and charts from which comparison was made between strength properties of the species, their glulam elements and solid timber where-upon conclusions were drawn and recommendations made.

1.7Scope and Limitation

The scope of the study was limited to investigating the strength properties of solid wood and glue laminated elements using Ire (*Funtumia, Africana),*Oriro *(Antiaris Toxicaria)* and Awun (*Alstonia Congensis)* readily available in the local timber market in Sabon- gari, Zaria.Ire (*Funtumia, Africana)*and Awun (*Alstonia Congensis)* are softwoods whileOriro *(Antiaris Toxicaria)*is a light hardwood all of which are grown in Ondo state of Nigeria and are widespread across West Africa. Glue laminated elements produced and tested from the species includes beams and compression members laminated using polyvinyl acetate glue (PVA). The loading considered includes compressive loads for solid timber and glulam columns, 3 point load for solid timber and glulam beams. Comparison was made between solid wood and glulam elements of uniform dimensions between species upon which conclusions were drawn. The sizes of the beam elements used in the study is in line with ASTM D193 to ensure a span to depth ratio that allows for failure in flexure alone while the column elements where dimensioned in line with EN 408 where for compression parallel to grain the height prescribedis six times the smallest cross sectional dimension.

1.8 Limitation

1. The clamping devices had no measurement device to measure the clamping force which could have provided additional information on the force applied.
2. The age of the species used in the study was not taken to cognizance as such information are not ready obtainable upon supply.

CHAPTER TWO

2.0Literature review

2.1Structural Glue Laminated Timber

According to the glued laminated timber association (GLTA) of the United Kingdom, glulam beams account for 50% of total glued laminated timber sales for structural application in the United Kingdom making it one of the fastest growing structural materials today; its consumption is reported to have doubled between 1985 and 1995 in Britain alone. Glued laminated timber has gained wide application and demand because of the standard sizes and availability of glued laminated structural elements such as beams and columns. This trend has made architects and specifies to give preference to glulam over other materials for a wide range of structural application in building.

Structural glued laminated timber is obtained by gluing up suitably selected and prepared pieces of stress graded wood in straight or curved form with the grain of all pieces running parallel to the longitudinal axis of the member (APA, 1996; Moody and Hernandez 1997). This technology allows the flexibility in the formation of structural elements with a wide variety of sizes, profiles, and lengths having superior strength, serviceability, and appearance to sawn timber. Structural elements such as beams, columns, floor joist and purlins can be produced as glulam elements. Glued laminated timber beams are manufactured with the strongest laminations on the bottom and top of the beam, where greatest tension and compression stresses occur so as to optimize the use of the material (Wan, 2011).

Depending on the intended use, glued laminated timber members can be manufactured using single or multiple grade of timber, similarly any specie can be used for glulam timber, provided its mechanical and physical properties are compatible and the specie glueable (APA, 1996; Zhiyong & Robert, 2007).

2.2Glued Laminated Timber Appearance Grade

The grading of glued laminated elements by appearance refers only to its appearance and not strength (American laminators, 2005). Hence appearance classifications bear no structural relevance to design values for glued laminated timber. APA-EWS Form No. EWS Y110 has identified four basic appearance classifications for glulam elements (i.e. beams, columns, purlins and floor joist) which are also defined in ANSI A190.1 (2012). These classes includes: Framing, Industrial, Architectural, and Premium. The GLTA similarly identifiesthree appearance classifications, Premium, Architectural, and Industrial and Industrial Special. Premium and Architectural beams are finished for higher appearance and surfaced for a smooth, beautiful finish. Industrial appearance beams are applicable where appearance is not important while industrial Special appearance beams are used for headers. The framing classification is provided to match standard dimension lumber widths such as 3 1/2" and 5 1/2" widths. In the framing grade, glued laminated members are planned in a manner not paying much attention to details. Low laminations, glue smear, end joint offsets and glue line squeeze out are permitted. Splits and wane is also permitted with knot holes left unfilled.

2.3Timber Species for Glued Laminated Timber Production

Literature is replete with temperate timber species which have been researched and thus typically used for glulam production; these includes several softwood species, such as Douglas Fir- Larch and Southern Pine, Hem-Fir, Spruce-Pine-Fir, Western Woods, Alaska Cedar, and California Redwood. In addition, several hardwood

species, including Red Oak, Red Maple, and Yellow Poplar, are also used (APA, 1996 moody and Hernandez in Wan 2011).

However, while studies have shown that forest reserves occupy about 10 million hectares in Nigeria, representing 10% of a land area of approximately 96.2 million hectares (NPC, 2006; Alamu and Agbeja, 2011 in Abubakar and Nabade,2013)it is reported that the exact quantity of wood and non-wood forest products in Nigeria cannot be easily estimated (Alamu and Agbeja, 2011; Abubakar and Nabade,2013). This report clearly shows the abundance of forest resources in Nigeria. However, in spite of the vast forest resources and numerous species of timber available locally not much research effort has been channeled towards ascertaining the suitability of local timber for glulam production.

BS EN 386 gives a list of timbers which can be selected for the production of glued laminated timber. However, clear, bright appearance, limited knot sizes, suitable grades and excellent bonding properties are properties which makes species suitable for this purpose.

Generally timber researches in Nigeria have concentrated on sawn timber. For example, while the existence of glulam technology predates the production of NCP 2 (1973) as it was first patented in 1900 in Germany, the code of practice has reported mechanical properties for54 species of timber only as sawn wood elements with no local code to offer guidance on production and use of glulam. A tour of local timber market in Sabon gari Zaria during this study however revealed more timber species than profiled in NCP2. That this may be the case in timber retail outlets nationwide may not be farfetched (Babatola & Malami, 2011). The fact established nevertheless

is that the mechanical properties described in NCP2 are for an inconclusive specie list of sawn wood in basic stresses for green and seasoned timber. The need therefore arises to both identify more merchantable untested species, to ascertain their suitability for glulam production as well as their performance as structural glulam since not all species can be glued. With the global trend towards green construction material such as engineered wood products likeglulam, the need for an instructive local code of practice to guide and regulate the use of glulam has become necessary. However, the miniscule amount of studies on this subject may preclude such attempts. Several advantages are derivable from glued laminated timber such as exceptionally low mass, high strength and considerable stiffness, reduction in foundation loads, easeof delivery and erection (GLTA, 2010).The need to profile more local species and verify their structural suitable as glulam elements could impact on the cost of building production. While about 50% cut in cost of producing a frame structure using sawn timberinstead of concrete is possible as reported by Anthony and Joshua(2014), it is expected that similar cost reduction may be elicited using glulam although the necessary processing of sawn timber to glulammay make the reported figure lesser .

Glued laminated timber like other construction material is prone to deterioration and structural failures. Deterioration can occur either due to biological attack and weathering or adhesive degradation due to chemical, physical alterations, or temperature variation leading to loss of strength and or delamination, (Florindo *et al.*, 2013). The application of soft wood species such as: Southern pine (*Pinus* spp.), Douglas fir (*Pseudotsuga menziesii*)–larch (*Larix occidentalis*), Hemlock (*Tsuga heterophylla*)-Douglas fir andspruce (*Picea* spp.)-Pine-fir, and Red maple (*Acer* spp.)

have been verified with various adhesives in the production of glulam (Wan. *et al.*, 2011), timber research in Nigeria for structural purpose is yet to verify and establish the use of various types of adhesives especially polyvinyl acetate glue which is readily available on local timber; how the properties of glulam elements manufactured with this adhesive defer from those of solid wood and to ascertain whether polyvinyl acetate glue provides sufficient bond and strength, as compared to solid wood (Suhaimi *et al.,* 2004), as well as the extent of deterioration of locally fabricated glulam.

2.4Adhesives

According to the Glue Laminated timber Association (GLTA, 2010) adhesives must provide bonds of such strength and durability that their integrity is maintained in the assigned Service class throughout the expected life of the structure applicable both for bonding the laminations and for making the finger joints. Ambient temperature and relative humidity affect the timber's moisture content, whilst fluctuations in load and changes in the environment surrounding the structure also influence the long-term performance. For glued laminated elements the effects of the aforementioned parameters need also to be investigated on the behavior of polyvinyl acetate glue used with local timber so as to verify its service class.

Type I specification (BS EN 301) which may be used in all Service classes.

Type II specification (BS EN 301) which shall only be used in Service classes 1 or 2 and not under prolonged exposure to temperatures in excess of 50°C.

2.5Challenges of Timber Utilization in Nigeria

Timber has remained an important building material since ancient times. Being a forest product, its minimum intrinsic energy makes it an inexpensive material. It is also known to exhibit greenhouse gas balance and far less energy than other building materials is required in processing to finished product (Regina *et al.,* 2010; Dorina *et al.,* 2012).

In spite the advancement made in engineered wood products (EWP) and the existence of the technology, the use of timber in Nigeria is still juvenile. Some of the challenges to timber utilization are discussed below:

2.5.1Research

The organic and adaptive nature of timber and the existence of diverse species render it a complex building material. The properties of wood are known to vary with species, age, site and environmental condition. This therefore calls for in depth researching of its behavior under various circumstances. Yomi *et al*., (2005) have identified the extent of timber utilization to inadequate emphasis on timber in the research carried out by academic and research institutions, better funding of directed research and proper dissemination of these research findings are also pivotal to societal interest in timber structures. Zziwa *et al.,* (2006) has identified insufficiency of test data on both wood and wood composites as factors that affect the reliability of test result in research findings. Research primarily addresses the inherent problems associated with the use of timber through series of test to improve its reliability and develop composite products of interest to the public. Timber can be used to sustain a house from floor to roof. This fact is corroborated in"The concept of tall wood buildings" which according to Chiu(2013) is not new giving a 2012 survey

conducted revealing that there are 125 post and beam buildings in Greater Toronto Area with at least 37 buildings5-8 storeys built between 1872 – 1933 while most of it between 1910-1920. Therefore timber houses can be framed on a system of columns and beams which will consist of timber walls, timber window frames and shutters, timber doors, timber ceiling boards on timber trusses. In furtherance, the limit to timber structure being non- existent in Norway and the United Kingdom gives credence to its versatility and reliability. Where restrictions exist to height of timber structures they are in the order of 3 storeys in Russia, 4 storeys in Finland and Canada, 18m in Germany and 6 storeys in Switzerland (Chui, 2013). These antecedents therefore show that timber as a material has the potential to ameliorate the astronomical cost of housing in Nigeria being a locally sourced building material abundant in the country. However lack of sufficient research efforts in timber in the direction of treatment against weathering, termite infestation and fire resistance (which are some of the critical apprehension held to the use of timber) has precluded the use of a material capable of making housing accessible and affordable to a majority of Nigerians,(Ayedun and Oluwatobi,2011).

2.5.2Technological Capability

According to Yomi *et al.,* (2002), technological capabilities are the capabilities needed to acquire, assimilate, use, adapt, change or create technology. The building of technological capability, therefore, requires considerable indigenous effort, allocation of resources, commitment, in-house tailor-made training in that particular sector, and the creation of an environment, which has a local demand for innovation. Technological capability is tied to, research and development, nature of research and development, re-orientation of the research Institutes and research funding.

According to Omoluabi (1994), the saw mill industry is characterized by small scale operatives who constitute more than 90% of the entrepreneurs in the sector, a subsector characterized by plummeting performance due to obsolete equipment. The capacity utilization in the saw mill industry is averaged at 37% and the lumber recovery rate 40-60% respectively. Technological improvement in this industry will impact significantly on log to plank conversion efficiency.

2.5.3Mode of Strength Assessment

The mode of wood strength assessment has significant effect on the reliability of timber. It has become clear over the years that the visual assessment and the destructive method of testing is inadequate in capturing the wide degree of variability exhibited by timber due to its complex internal multicomponent structure. This method has the shortfall of only being able to test limited number of samples from which generalization is made for the entire population. Visual method of grading timber at sales outlets and destructive methods of testing deployed in the limited researches under taken still plague the use of timber in Nigeria. Countries such as Australia with strict quality control measures have shifted from the prohibitively expensive and time- consuming destructive approaches to the use of faster and cheaper NDE and modeling techniques (Mackenzie *et al.,* 2005; Green *et al.,*2006 in Zziwa *et al.,* 2009).

2.5.4Lack of Quality Control

The lack of quality control measures like the (non-destructive methods of testing to guarantee that timber for construction purpose meet satisfactory performance in use and the enabling laws to enforce it has blighted the reliability of timber as a

construction material. It has remained difficult or even impossible for the various sectors in the timber industry to enforce quality control standards that will ensure that the material supplied meets the standards for its use. The widespread sale of unseasoned or poorly seasoned timber in the market is a ready example of this, Yomi *et al.*,(2005). Lack of large modern factories for production of timber components contributes to this lack of standards.

2.5.5 Acceptability

Part of the challenges that precludes the extensive use of timber in Nigeria is that it is perceived as a material for temporary structures and low cost housing alternative, which many would consider demeaning(Yomi *et al.*, 2005). It is commonly used for the erection of overcrowded, temporary poorly built accommodation for the absorption of rural dwellers in shanty towns closely situated to high braw urban centres. Timber has been viewed with the same social stigma attributed to the unsettled section of the population such as internally displaced persons (IDP) camp. It is generally considered to be less durable than other materials. Similarly the introduction of new species without any selection criteria undermines the integrity of timber structures and consequently the acceptance(Nsikak, *et al.*,2013).

2.5.6Skewed dependence on a few species

Concentration of academic research on a few tree species assessed based on small clear specimens according to Zziwa *et al.*, (2006)misrepresents the nature of structural timber obtainable from a wide variety of timber species. However due to

dependence on a few selected timber species for the vast application of timber by timber users the depletion of such species has necessitated the harvest of low quality timber with little or no technical information on their mechanical properties to guide users.The shortage of domestic supply of round wood is a constraint to producing high quality final products that are competitive in international markets. According to Arowosoge, (2010), 97% of log production are of the lesser used wood species. A number of lesser used wood species are now widely available in plank markets in various parts of the country. Lesser used wood species are met with poor patronage (Jayanelti; 1998; Eastin *et al*, 2003; Barany *et al.*,2003). Coleman, 1998 and Barany *et al* 2003 have indicated that lack of information on lesser known wood species, natural durability, physical properties, working qualities, and use range important to manufacturers has precluded increased utilization of lesser known species. This also may have led to misplaced utilization leading to inferior products(Arowosoge, 2010). This trend can however be reversed by well documented, readily available and reliable information possible when researchers extend the coverage of research to lesser known timber species.

2.5.7Jointing Systems

Joints are usually zones for incipient failure in timber structures. The traditional tongue and groove systems are known to develop only 15- 20 % strength of clear wood, which is inadequate, the use of mechanical fasteners such as metal bolts over the traditional system was introduced to offer longer spans of up to 10.5m (Apu, 2003).However, the use of mechanical fasteners has become obtrusive for modern architecture. Hence glue laminated timber is one of the ways to improve the use of timber to meet the present demands in modern architecture. This method of jointing

which maintains the seamlessness of solid wood makes glulam element desirable for a wide range of structural application in construction. Similarly joints made of structural adhesives are known to develop up to 95% clear wood strength.

2.5.8Lack of Comprehensive Standards

Adogbo and Kolo(2008) identified the absence of comprehensive standards for building materials in Nigeria, as one of the factors that hinders the extensive use of timber in Nigeria for structural purpose. British Standards (BS) and the American Society for the Testing of Materials (ASTM) standards are commonly used. The standards that exist has been those for modern building materials such as cement, concrete products, processed timber composites etc. NCP 2 of 1975 which was adopted from foreign standards remains the only standard for timber use in Nigeria, however those standards from which it was adopted have being reviewed while it yet remains outdated. In view of the current trends in timber utilization NCP 2 may not offer comprehensive guidance for the use of timber, this further precludes the extensive use of timber by engineers. Similarly dependence on foreign standards may not be reliable for local (tropical) timber as those were used to calibrate temperate timber (Zziwa *et al.,* 2009). One of the disadvantages of lack of standards is that it can lead to very high production cost making indigenous materials non-competitive with import-based materials.

2.6 Mechanical Properties of Wood and Wood Composites

2.6.1**Elastic Properties**

Material selection, design and specification of EWPs is established by elastic and strength properties. An elastic property refers to recoverable deformations produced by stress values below the limit of proportionality. According to David *et al.,* (1999) Twelve constants of which nine are independent are needed to describe the elastic behavior of wood, this includes; three moduli of elasticity *E*, three moduli of rigidity *G*, and six Poisson's ratios.

2.6.2 **Modulus of Elasticity**

Elastic properties are characterized by values of modulus of elasticity (MOE) in bending and compression. MOE is the measure of resistance to bending deflection relative to stiffness, the procedure to determine MOE for glulam products is fully described in ASTM D 7341,BS EN 338:2004 from small clear specimen and EN 408:2003 for structural and glue laminated timber. MOE is determined along the longitudinal, radial and tangential axis.

2.6.3 **Modulus of Rigidity**

The shear modulus indicates the resistance to deflection of a member due to shear stresses. The three moduli of rigidity denoted by G_{LR}, G_{LT}, and G_{RT} are the elastic constants in the three reference planes that is the longitudinal, tangential and radial planes LR, *LT*, and *RT* respectively. This property is moisture content, and specific gravity dependent.

2.6.4 **Poisson Ratio**

The proportionality of deformation perpendicular and parallel to the direction of the load due to axial loading is computed as the ratio of the transverse to axial strain

which is the Poisson's ratio. The Poisson's ratios are denoted by μ_{LR}, μ_{RL}, μ_{LT}, μ_{TL}, μ_{RT}, and μ_{TR}. The direction of applied stress is denoted by the first letter of the subscript and the second letter to direction of lateral deformation. This property varies between and within species and is moisture content and specific gravity dependent.

2.6.5**Strength Properties**

Strength is a measure of the maximum stress that can be developed in a member due to applied actions prior to failure. Modulus of rupture in bending, maximum stress in compression parallel to grain, compressive stress perpendicular to grain, and shear strength parallel to grain are some mechanical properties commonly measured and represented as strength properties for design. Strength tests on specimens are ascertained at moisture equilibrium under prescribed conditions. ASTM D 1037, ASTM D 3044, ASTM D 5456, ASTM D 3737, and ASTM D 7031, BS EN 384, AND BS EN 408 describe the procedures to determine the strength of wood and engineered wood products which includes glue laminated elements. According to (Cai, 2006), the mechanical properties of most EWPs might not be as high as those of solid wood, consistency and uniformity of performance however can be their salient feature.

2.6.6**Bending Strength**

The four point and three point bending strength tests as specified by EN 408 (2003) and ASTM D193 (2000) are used to carry out tests on the mechanical properties of

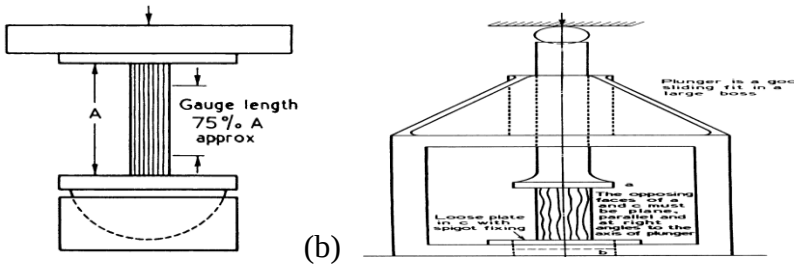
timber specimen. Specimens are tested using universal testing machine (UTM) until failure occurs. The failure load for the element in respect of the species is then recorded. The three point bending test produces maximum bending stress at the mid-point of the specimen with reduced stress elsewhere. This stress localization is ideal for testing specific isolation of stress on a component or material. While the four point bending test produces peak stresses along an extended region of the specimen (Abubakar & Nabade 2013).

2.6.7 **Compressive strength**

The resistance to compression is determined both parallel to the longitudinal grain, and perpendicular to the longitudinal grain.

a)Compression parallel to grain.

The form and dimensions of the test pieces are as given in Figure 1.



(a) (b)

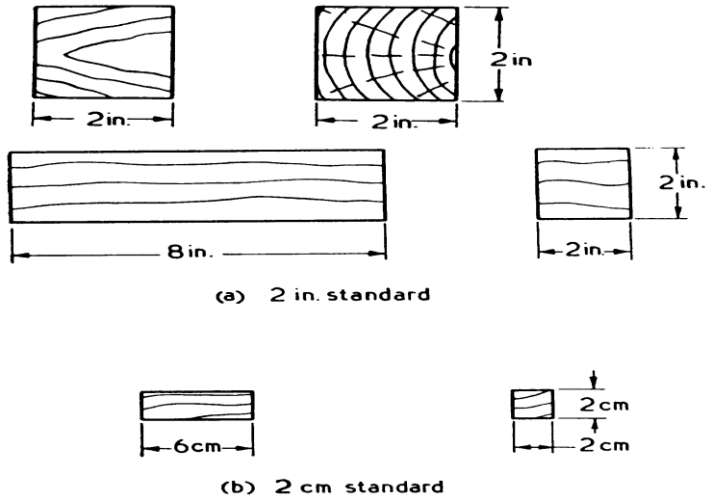
Fig 1: Forms of test pieces for compression parallel to grain

The methods by which the tests on both the 2 in. standard and the 2 cm standard test pieces are made are shown diagrammatically in Figure 1a and Figure 1b. The load is applied to both types of test piece in such a way that the loading plates approach each other at a rate of 0.025 in. /min.

2.6.8**Compression Perpendicular to Grain.**

The test piece is a cube of 2 in. side as shown in Figure 2a. The test is be made by loading between parallel plates. It is made in both the radial and tangential directions. The load is applied to the test piece at a constant head speed of 0.025 in. /min. The load compression curve is then plotted to the point when the compression of the test piece reaches 0.1 in.

At a definite maximum load reached at some lesser value of compressive strain, the maximum load and its associated strain is then recorded.



(a) Compression test parallel to grain (2 in. standard)

(b) Compression parallel to grain (2 cm standard)

Figure 2: Test piece for compression perpendicular to grain

2.7Grading of Timber

The use of timber for structural load bearing application is predicated on the knowledge and control of strength and stiffness properties. However the unpredictable nature of timber precludes the acquisition of precise data to predict and

control such properties. Timber is generally punctuated by a series of strong and weak zones over the three mutually perpendicular directions. In describing the variability phenomenon, Riberholt *et, al.* (1979) proposed a model in which it is assumed that timber is composed of localised weak zones connected by segments of clear wood and that failure is initiated at these weak zones. These weak zones are manifested by knots or groups of knots distributed along the length inconsistently. Hence timber does not lend itself to such influences as is possible with man- made materials like steel and concrete where mechanical properties are predictably enhanced by the use of alloying components and admixtures. Nevertheless quality within desired limits as touching mechanical properties is reasonably achievable through grading. There are principally two grading systems:

(a) Visual strength grading: based on visual inspection by certified personnel to ensure defect free pieces or such as is limited within specified limits in grading rules. In the USA ASTM D245 published in 1927 contains grading guidelines (Madsen. 1992), grading rules were introduced in Europe from the 1930s (Glos, 1995). However deficiencies associated with this grading system is that only visually recognizable characteristics are captured. Key strength indicators like density are poorly assessed. Similarly visual defects that are only superficially situated are misconstrued as deep seated defects.

(b) Machine strength grading: this involves the passage of the pieces through a machine which measures certain parameters none destructively from which strength and stiffness is predicted. This system of grading non-destructively was proposed concurrently in the USA and Australia in the late 1950s (Madsen, 1992) not for a matter of strength only but to facilitate better accuracy in the strength calibrating

process and optimization of the available timber resources. The most widely used machine grading principle is the flat wise bending stiffness. The flat wise bending stiffness/MOE is simple to measure. This uses a three point loading test carried out continuously. Two systems of the flat wise bending involves: a load kept constant and deflection measured and secondly timber forced to a certain pre- measured deflection and the load required to maintaining the deflection is measured.

2.8 Glue Laminated Timber

Glued laminated timber is obtained by bonding together a series of laminations whose grain is essentially parallel (GLTA, 2010). Laminates are stacked together and glued to form the cross-section of any structural element. Alternative lay-ups of species and cross-section is permitted in accordance with BS EN 1995-1-1 for glulam production. It is therefore in principle possible to stack up any species of timber to form glulam provided a suitable adhesive is available, the timbers glueable and their mechanical properties compatible. According to Sven *et al.,* (2003), studying the performance of glulam often involves comparing its performance with solid wood. The two approaches for the comparative study are;

1. Comparing the bending strength of glulam beams with the bending strength of solid timber beams
2. To compare the bending strength of glulam beams with the bending or tensile strength of laminations.

2.8.1 Properties of Glue Laminated Timber

According to the glued laminated timber association (GLTA, 2006), the following are properties associated with glulam elements.

(a) Strength and weight

Depending on specific loading conditions, a structural steel beam may be 20% heavier and a reinforced concrete beam 600% heavier than an equivalent glulam beam of the same load-carrying capacity. It is one of the strongest structural materials per unit weight. Compared with structural steel or concrete it can produce a lighter superstructure with a consequent economy in foundation construction.

(b) Durability

In most structural applications, the life of Glulam can be considered virtually unlimited. The use of modern phenolic synthetic resin adhesives also ensures an indefinite life for the bond between the laminations. The main threat to unlimited service life is a rise in moisture content to more than 22%-25% for prolonged periods. However, sound maintenance procedures and good initial design including the avoidance of moisture traps and the provision of ventilation where it is applicable will prevent the glulam from being affected.

(c) Chemical Resistance

Timber generally has a remarkable resistance to chemical attack in polluted atmospheres and to contact with chemical solutions. Indeed, it has long been used for

vats containing chemicals and for aggressive processes like leather tannin. The synthetic adhesives used in bonding glulam are equally resistant to most chemicals.

However, glulam is not totally immune to Oxidizing agents, Sulphides and Alkalis, for example, will exert a pulping action on the timber and lead to loss of fiber and strength. But these are unusual agents in most service environments to use glulam in such conditions specialist advice is to be sought.

(d)Fire Resistance

Glulam has a high and predictable performance infire because timber chars at a slow and knownrate: 40mm per hour for European white-wood.It retains its structural integrity under fire.The high thermal insulation characteristics of timber, and the charcoal layer that forms on it, both ensure that the interior of a fire-exposed member remains cool and structurally sound over the design Period. A glulam member also behaves as a single unit throughout its exposure to fire because of the high resistance of laminating adhesives to fire temperatures. According to Bednarek(2008),the charring rate of timber depends on a number of factors such as: timber species, timber density, moisture content, chemical composition, timber defects (e.g. fissures), the actual specimen geometry (dimensions, shape and surface quality). For GLT, the possibility of matching these factors to advantage could be responsible for their fire resistance over solid timber.

This reliability of Glulam's performance in fire means that it is possible to predict the inherent fire resistance of a particular component, or to design a component to resist fire for a specified period without the need of expensive testing.

2.8.2 Effects of heat treatment on the mechanical properties of glue laminated timber

The effect of heat treatment on some mechanical properties of timber has been studied with positive results reported. It has been experimentally verified that one effect of heat treatment is dimensional stability, (Altinok *et al.,* 2010). Altinok *et al.,* (2010) applied this treatment to laminated black pine (*Pinus nigra*) where it was shown that mechanical properties including compression strength, bending strength and bonding strength were affected positively with heat treatment, and increase in temperature and duration further increased strength values of the glue laminated wood specimens laminated with polyurethane and polyvinyl acetate glue. Heat treatment is usually applied to the samples at 100-150°C for 4 hours in drying oven. Heat treated samples give better results due to temperature increase, Mustapha*et al.,* (2013). However the above are reports of seasoned laminating stocks at various temperatures prior to gluing. What the effect of varying temperatures is on the integrity of glue on already glue laminated members of local timber could also be investigated.

2.8.3Glueability of Timber

According to Manja, *et al.*,(2010), not all timber is suitable for gluing. The glueability of any timber specie is an essential feature which prequalifies it as applicable for glue lamination. According to Mettem (1986) timbers used as structural glulam in the soft and hard wood class are known to be glueable. Some of these include the European white wood, red wood and Douglas fir. Some Nigerian timbers are also known to be glueable, Jamilu, (2014) verified the glueability of

white Afara (*terminalia superba*) for structural purpose. However the glueability of many Nigerian commercial timbers for structural purpose is yet to be reported.

The gluing characteristic of timber is affected by various properties. Of these properties density is perhaps the most important, hence, the glue-bond quality required for a dense species is greater than for a lighter one. The amount of shrinking and swelling with changes in moisture content is also an important factor, particularly where long term serviceability of glue joints is required. In certain cases, pitch content, oiliness, and the presence of other exudation products and extractives also have some influence on glueability.

Proportions of springwood, sapwood and the manner in which a board is sawn from the log also accounts for some of the variations in glueability and the strength of glue lines. Hence to ensure effective and tolerable variations of glueability, selection of specie must be to strict tolerance for materials which match in sawing orientation, growth character and other aspects. However where this is not possible on economic grounds or for the lack of timber of the latter features, the gluing techniques must be such as permit marginal variations in glueability, (Mettem 1986).

2.8.4Fabrication of glulam

The local availability of various species of timber has allowed every country the adoption of peculiar reference standards for the manufacture of glue laminated timber. The ANSI/AITC A190.1 standard of the American National Standards Institute (ANSI 1992) contains requirements for the production, testing, and certification of structural glulam timber in the United States. Requirements for the

manufacture of structural glulam in Canada are given in CAN/CSA O122 (CSA 1989).

Glulam is manufactured to comply with relevant British and European standards where applicable. The recommended British Standard reference for the manufacture and application of glulam are: BS EN 301 for Synthetic resin adhesives (phenolic and amino plastic) for wood. BS EN 386 which covers manufacture of glued-laminated timber structural members.

BS EN 518 and BS EN 519 for timber grades for structural use. Structural use of timber: Part2. Code of practice for permissible stress design, materials and workmanship. BS 5268: Part 2.1996 Code of practice for the structural use of timber: Part 5. Preservative treatments for constructional timber. BS 5268: Part 5. Manufacture of finger joints of structural softwood. BS EN 385: Tropical hardwoods graded for structural use.

In Japan and Europe glue laminated timber is manufactured in accordance to JAS11, EN 386 and 1194. Depending on the nature of timber to be used standards may further be distinguished on the binary of hard and soft wood. Glulam is a material made from selected and prepared (engineered) pieces of wood of the same or different species provided the mechanical properties are compatible. They may be in straight or curved form, with the grain of all pieces essentially parallel to the longitudinal axis of the member. The maximum laminate thickness is 25mm (1 in.), and the laminations are typically made of standard 25- or50-mm- (nominal 1- or 2-in.-) thick lumber. Some standards, North Americans standards for example require that glulam be manufactured in an approved manufacturing plant and since the

lumber could be end, edge, and or face jointed, the size of glulam is limited only by the capabilities of the manufacturing plant and the transportation system.

According to Moody *et al.,* (1999) the manufacture of glulam timber must be justified by recognized national standards to ratify engineering design values. The structural performance of properly manufactured glulam is characterized by balance between the quality of the wood and the adhesive bonds.

The ANSI A190.1 standard (ANSI 1992) has a two-phase approach to all phases of manufacturing. First is the qualification phase in which all equipment and personnel are examined by a third party agency for qualification. The second phase involves the establishment of a daily quality assurance procedures and criteria targeted to keep each of the critical phases of the process under control. However the manufacturing process can be divided into four major parts:

(a) Drying and grading the lumber

(b) End jointing the lumber

(c) Face bonding and

(d) Finishing and fabrication.

Further Pressure treatment of members with preservative is recommended for high moisture service condition and protection of members during transportation.

2.8.5Production Essentials

The following according to Glue laminated timber association (GLTA, 2010) are production essential requirements stipulated for quality glulam production:

1. Adhesive types and performance.
2. End joints in laminations – tensile and bending strength.
3. Glue-line integrity and strength.
4. For special components - bonded finger joints in complete glulam members.
5. Production conditions and factory premises, staff qualifications and performance.
6. Equipment standards for the actual manufacture and for the quality control operations.
7. Record keeping, inspection and testing measures; responsibilities and documentation.

2.8.6Indigenous Timber Species in Glulam Production

Efficient use of glulam in construction requires an understanding of the structural behavior of numerous species and species groups due to the large inherent material variations. To promote the application of glulam, more data is needed on the glulam manufactured using various indigenous species. Glulam supports the use of wood in construction by optimizing the available local natural resources, (Regina, *et al.,* 2010). The use of indigenous species means locally available forest resource can be optimized, thereby obviating the need for importation while ensuring affordable prices. Wan *et al.*, (2011) conducted preliminary investigation on the bending strength behavior of glulam manufactured from selected Malaysian tropical timber where the results showed that the glulam produced passed the required allowable strength value. It was observed that there was no significant difference in bending

strength of *Resak and Keruing* glulam beams even though they are in different strength groupings. Thus implying that glulam production when done to standard optimizes the use of almost any timber species.

With the revision of the British BS 5268(2002) formally CP112 (1967) design codes (the source of the NCP 2 1973) from permissible stress design to limit state design EN 1995-1-1 (2004), the need to review the Nigerian code of practice, NCP 2 has been has been identified, (Abubakar & Nabade, 2013). Recalibration of mechanical properties of indigenous timber based on existing rules could reveal better mechanical properties for optimum use as structural glulam material.

ASTM D3737 (ASTM 1997b) covers the procedures to establish design values for structural glulam timber. Properties considered include bending, tension, compression parallel to grain, modulus of elasticity, horizontal shear, radial tension, and compression perpendicular to grain.

2.9 Adhesives

The use of Adhesive bonding technology has brought about the advent of the development and growth to timber construction. Structural adhesive joint are required to be able to perform satisfactorily under severe exposure conditions and support design loads under service conditions for the life time of the structure. According to Joao *et al.*, 2009 a number of factors affect the durability of structural adhesive joints. These can be grouped in three categories: environment, materials and stresses, temperature and moisture being major factors that govern environmental conditions. The materials category includes the adhered, the adhesive, and the inter-phase between them both. While longevity and residual strength is affected by

stresses to which the bond is subjected during or after exposure to service environment.

Adhesive bonding according to (Duncan *et al.,* 2005) is a key jointing technology in many industrial sectors. Adhesives are widely used for their ability to join dissimilar materials, with joints which are durable but at the same time unobtrusive and do not detract from the aesthetics of the finished product. The basic definition of an adhesive according to (Owen, 1990) as used by the Adhesive Sealant Council in America is a material used for bonding that exhibits flow at the time of application. For acceptable adhesives and their requirements, reference is made to BS EN 386 and BS EN 301. The four main performance requirements of adhesives include:

Wettability of the surfaces – this demands the displacement of all air and other contaminates that are present as it flows out over the surfaces that are being bonded.

Adherence to the surfaces - That as it flows over the whole surface area it must start to adhere and stay in position.

Strength development - The material must change its structure to become strong or non-tacky but still adherent.

Stability - The material must remain unaffected by age, environmental conditions and other factors as long as the bond is required.

2.9.1Structural Adhesives

These provide a means of achieving structural joints in timber with the advantage of rigidity durability and strength in joints over large or small areas while it obviates the need for visible fasteners. According to the glue laminated timber association (GLTA), the most widely used adhesives includes phenol-resorcinol

formaldehyde(PRF), made out of the resorcinol-formaldehyde, (RF), most resorcinol adhesives used today are PRF. They produce distinctive brown glue lines and are suitable for the most severe conditions.

Adhesives are to be in accordance with BS EN 301: Adhesives, phenolic and amino plastic for load bearing timber structures. Adhesives for structural purpose must meet official standards of glulam manufacture and applied in accordance with regulations and standards and in strict conformity with the adhesive manufacturer's instructions. Adhesives must provide bonds of required strength and durability of such integrity that matches the assigned Service class throughout the expected life of the structure. This applies both for bonding the laminations and for making the finger joints. The relative seamlessness of jointing through this method is of particular interest to the architect. However the application of glues in timber joints demands a skilled workmanship, efficient workshop equipment and effective supervision. To achieve dependable bond strength in timber structure calls for proper preparation of the surfaces, well stored and seasoned timber to attain equilibrium moisture content.

2.9.2Factors That Affect Adhesive Bonding

2.9.2.1 *Types of Structural Adhesives*

Glues can generally be categorized as natural or synthetic. Naturally occurring glues are those whose basic ingredients are sourced from natural materials like by-products of meat processing (for animal and blood glues), or casein, soybean, and starch. Not until nearly the middle of the 20th century this was the principal adhesive bonding agents for wood. Synthetic adhesives are products of chemical synthesis. They only began to appear in the early 1930s and became widespread in the woodwork industry

for their versatility. Synthetic resin were observed to produce joints as strong as clear wood and remained so even when exposed to moisture. The latter advantage was an edge over natural glues which remained strong only in dry conditions.

(a) Synthetic Resin Adhesives

The major advantage of synthetic resin adhesives is their excellent durability which makes it possible to service glued wood products under more severe exposure condition than was possible with the non-synthetic resin glues. Synthetic resin adhesives facilitated the manufacture of many glued wood products. Among these are laminated bridge timbers, and glue laminated members for use under severe service condition.

(b)Types Of Synthetic Resins

According to National Institute of Industrial Research (2002), Synthetic resin are products of chemical polymerization process, which results in the creation of polymers that are more stable and homogeneous than naturally occurring resin. They are known to be more stable and cheaper, than various forms of synthetic resin and are used in a variety of products such as plastics, paints, varnishes, and textiles. Several adhesives have also found application in structural timber construction. There are various kinds of synthetic resins; acetyl resins, amino resins, casein resins, epoxy resins, emulsion polymers, hydrocarbon resins, polyamide resins, polyesters rubber resins etc. epoxy resin stands out as one example of synthetic resin manufactured through polymerization, used as a thermoset polymer for adhesives and composites. It is known to be two times stronger than concrete, seamless and waterproof. Polyamide resin is another example of synthetic resins, a product of polymerization

of an amino acid or the condensation of a diamine with a dicarboxylic acid. They are used for fibers, bristles, bearings, gears, molded objects, coatings, and adhesives. Resins are valued for their chemical properties and associated uses, such as the production of varnishes, adhesives, lacquers, paints, rubber and pharmaceutical uses. The applications of synthetic resins are seen in some important industries like paint industry, adhesive industry, the printing ink industry, the textile industry, the leather industry, the floor polish, paper, agricultural industry etc. There is therefore an enormous scope of application of resins, including structural wood applications.

The most important synthetic-resins for structural applications come under the following general groups - the phenol, resorcinol, urea, melamine, and polyvinyl resin emulsions, hot melts, epoxies, contacts, mastics, and various combinations of specific adhesives.

Polyvinyl resin emulsions simply referred to as polyvinyl resins or PVA's are thermoplastic, softening when the temperature is raised to a particular level and hardening again when cooled. They are prepared by emulsion polymerization of vinyl acetate and other monomers in water under controlled conditions. In the emulsified form, the polyvinyl resins are dispersed in water and have a consistency and non-volatile content generally comparable to the thermosetting resin glues. They are obtainable as milky-white fluids to be used at room temperature in the form supplied by the manufacturer, normally without addition of separate hardeners. Joints produced with some of the newer polyvinyl resins gave unusually high shear strengths, particularly with denser species. In terms of durability, polyvinyl resin emulsion adhesives are considerably less resistant to warm, moist, or humid conditions than the thermosetting resins. The PVA's lack resistance to water and high

relative humidity, and a number tend to soften at temperatures as low as 110° F. Studies have indicated that some polyvinyl resin emulsion glues are promising in assembly joints such as dowel, mortise and tenon, and lock-corner. Their fast setting is of benefit and their elasticity may be an additional advantage where the dimensional changes in the joint are not extensive.

(C) Selection of Adhesive

There are many different adhesives for many different applications. It is reported that a particular timber does not produce glue lines of equal strength given all types of adhesives. Similarly, no single adhesive has ever been formulated, to meet the various requirements of the wide range of applications of adhesives. Hence it is important that proper background scientific information especially in examining how an adhesive works and, in particular, what happens at the molecular level informs the choice of an adhesive best suited for a particular substrate and service application.

Duncan *et al.*, 2005 highlighted certain adhesive attributes which are common for all application under the general-purpose heading of the National Physical Laboratory (NPL) Report DEPC-MPR-020. These include:

• Low cost

• Clean running (absence of stringing or dripping)

• Long pot life (thermal stability – resistance to viscosity change and charring)

• Low temperature application – mainly desirable to reduce worker exposure to fumes and lessen the burn hazard

• Wide temperature application window

• Taint free – food packaging applications

• Generates substrate failure – fibre tear is a universal measure of satisfactory bond performance in the packaging industry.

Deep freeze

• Resists brittle failure under deep freeze conditions.

Heat/creep resistant

• Resists failure under long term applied load in warm climates.

Difficult substrates

• Able to adhere to low surface energy substrates, eg polyethylene coated and UV

Varnished boards.

• Open time and setting time are important characteristics of the adhesive, which need to

be matched to the specific application.

• Universal application – manufacturing companies prefer to use a single adhesive gradefor all applications to simplify housekeeping, minimize inventory levels and to avoidmistakes.

CHAPTER THREE

3.0Experimental Procedure

3.1Preamble

This research set out to determine and compare the strength properties and failure mode of solid wood and glued laminated elements of three timber species in Nigeria, namely; Ire (*Funtumia Africana),* Oriro *(Antiaristoxicaria*) and Awun (*Alstoniacongensis*). The glueability of the said species was investigated using Polyvinyl Acetate glue. Effects of varied temperature on strength properties and failure characteristics of both solid wood and glue laminated element were investigated. Details of materials and methods are as follows.

3.2Materials

The material used for this research includes timber stress graded according to BS 5268. Ire, Oriro and Awun (*Funtumia Africana, Antiaris toxicaria, Alstonia congensis)* and polyvinyl acetate glue, detail of which are as follows:

Ire *(Funtumia Africana)* wood is a white or pale yellowish even textured soft wood. It is used for cheap joinery, furniture and matchstick manufacture. The wood is also reportedly used for carving stools, doors and miscellaneous household requirements. A forest tree composing the second storey in rainforest with geographic distribution across Angola, Cameroon, Cote d'Ivoire, Democratic Republic of Congo, Gabon, Kenya, Liberia, Mozambique, Nigeria, Sierra Leone, Tanzania, Togo, Uganda (WAC).

Awun *(Alstonia Congensis)* is a lightweight wood which occurs from south-western Nigeria to the Central African Republic, eastern and southern DR Congo, and northern Angola. The wood is used for light construction, light carpentry, open boats, molding, furniture, interior joinery, implements, boxes, crates, matches, pencils, sculptures (e.g. masks), and for veneer and plywood (interior). It is locally popular

for the production of household implements because of its good working properties and stability. In trade the wood of Awun (*Alstonia Congensi*s) is not distinguished from that of *Al*sto*nia boonei* De Wild.; it has similar properties. The heartwood is creamy white and indistinctly demarcated from the up to 20 cm wide sapwood. The grain is straight, occasionally wavy, texture moderately coarse. Growth rings indistinct or absent.

Oriro *(Antiaris Toxicaria*) yields a light hardwood. There is little difference between the sap and heartwood; it is yellow-white and soft with moderate shrinkage upon seasoning. The wood has good peeling properties making it a good choice for veneer production. The timber is also used in construction of beer canoes. Wood treatment using boron, chromium, arsenic fluoride treated with 5 and 10% BFCA preservative by hot immersion (1, 2 or 3 h at 60-70 ^{o}C) followed by cold immersion for 24 h is suitable. Rapid conversion and the application of anti-stain chemicals upon felling are essential, as the wood is liable to sap-stain. The wood is easily attacked by termites and the marine-borer (*Limnoriatripunctata)*,(Orwa *et al.*, 2009)

3.3Experimental design

As shown in table 3.0,a total of 60 specimens were dimensioned in line with ASTM D 193to 1500mm x 80mm x 34mm and cut for static bending test, 30 specimens as solid timber beams and 30 specimens as glued laminated timber (four laminas of 20mm each) for edgewise and flatwise bending, while a total of 10 solid wood short columns and 10 glulam short columns per species (5 laminas of 20 mm) of the same dimension (200 x 100 x 34mm) were prepared for compression parallel to grain and (180 x 100 x 34mm) for compression perpendicular to grain of the same quantity in line with EN 408 (2003). Similarly, a set of 24 specimens per species of short glued

laminated columns 200mm x 100mm x 34mm were prepared to investigate the effect of varied temperature on the glue and glulam columns in compression parallel to grain. Temperatures of 0 ^{o} C 30 ^{o}C, 40 ^{o} C, 50^{o}C, 70^{o}C and 100 ^{o}C were administered to the specimens for the experiment.

Table 3.0:*Experimental Design*

Type of Specimen	Number of Samples	Dimension of test piece to ASTM D193 and EN 408 (2003)
Solid beams	30	1500mm × 80mm × 34mm
Glulam beam	30	1500mm x80mm × 34 mm
Short solid columns C- Para	30	180mm× 100 mm x 34mm
Short glulam columns C-Para	30	180mm× 100 mm x 34mm
Short glulam columns C-Perp	30	200mm× 100 mm x 34mm
Short glulam columns C-Perp	30	180mm× 100 mm x 34mm
Short columns for temperature effects C-Perp.	72	200mm× 100 mm x 34mm
Total	252	

Polyvinyl Acetate (PVA):B.S. 4071; 1966 describe polyvinyl acetate (PVA) emulsion adhesives, for wood as a white liquid, transparent when set, which generally does not discolor other material. It is suitable for joints which will not be required to resist high continuous stresses, in particular for bonding or joinery, paper, leather, cloth and similar materials to be used in dry conditions.

3.4 Methods

The physical properties of the selected timber species including moisture content and density were determined in accordance with EN 13183-1 (2002) and EN 408 (2003). Mechanical properties of the timber species such as bending strength, compression parallel and perpendicular to grain were determined based on standards such as ASTM D193 (2000) and EN 408 (2003). Characteristic values of the material properties were determined in accordance with EN 384 (2004). Adjustments of the characteristic values of mechanical properties and density of the selected timber species were made to the equivalent moisture content of 18% applicable to local environmental condition in Nigeria (NCP2, 1973).

3.4.1 Bending strength test

The static bending test was performed by loading third point as shown in plate I, in line with ASTM D193(2000). The specimen was measured and weighed. The center loading point and supports were marked, the orientation of the test species ensured perpendicularity to the direction of loading. The test pieces were stabilized with an initial load, after which the dial gauge was mounted and adjusted to zero to monitor deflection. The test piece was supported at the ends while unrestrained to allow bending action throughout the member and ensure failure due to flexure. The speed of the machine was set to load the test piece and allow adequate monitoring of the dial gauge. Readings on the dial gauge were taking at intervals within the elastic limit before failure.

Material: the materials used for bending test were clear samples of solid and glue laminated timber beam.

Apparatus: the apparatus used in this test includes500KN Capacity Denison universal testing machine which is shown in plate I, dial gauge deflector, steel roller beam supports, metal plate and a steel roller loading device.

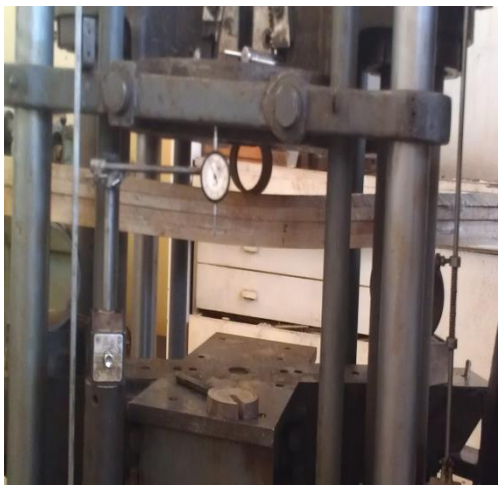


Plate I: *Three point static bending test set up.*

3.4.2 Compressive strength test

Material**:** The material used includes clear samples of solid wood and glue laminated short columns.

Apparatus: The apparatus includes Denison universal testing machine, metal plate, solid cylindrical steel support and a dial gauge**.**

Defect free samples were prepared for each test piece. The test piece was placed in position and metal plate was placed on top to provide even distribution of the concentrated load, as shown in plate 2. Each specimen was tested to different failure load. The dial gauge was mounted and set to zero to measure strain by recording the change in distance between the loading plates at regular load intervals within the elastic limit.



Plate 2: *Compression Parallel and perpendicular to grain*

3.4.3 Compressive strength test and temperature variation

Samples were prepared in line with clause 17.1 of EN 408 (2003). Varying temperatures of 0^{o}C, 30^{o}C, 40^{o}C,50^{o}C, 70^{o}C and 100^{o}C were administered to the specimen placed in an electric oven for 4hrs before the compressive strength test. Those for zero degree were placed in a freezer for 4hrs. Iced blocks were then used to maintain the temperature of the specimen at 0 ^{0}c to the point of testing for compression.

3.4.4 Moisture content and density determination

The moisture content and density were determined in accordance with EN 13183-1 (2002), EN 408 (2003) and BS 373: (1995)

(a) Material: The materials used were clear specimens of Ire (*Funtumia, Africana)* Oriro *(Antiaris Toxicaria)* and Awun (*Alstonia Congensis)* species.

(b) Apparatus: The apparatus used are standard table spring balance, ELE laboratory dry oven machine with 240^{0}C maximum temperature.

(c) Analysis Technique:

Statistical measures from the statistical tool pack in Microsoft Excel appropriate for the analyses of masses of numerical data to summarize the essential features and relationship of the data were applied in the study. These include the following;

I. **Measures of Central Tendency**: to obtain the arithmetic average, median and mode of the mechanical and physical properties studied.

$\bar{x}=\Sigma$ X/n..... (1). In the study, for every physical property that was studied the data for the number of observations were collected summed up and divided by the number of observations to obtain mean values where calculation was not appropriate an inspection of the data obtained was carried out to obtain median and mode values as mean values.

II. **Measures of spread or dispersion**: These were used where averages did not offer sufficient description of the difference in outcome of two observed tests. Measures of spread were employed to contrast the performance of solid and glue laminated timber.These include;

a)**Range**: the range was used to determine the spread of observed values and to identify and eliminateoutlier values from the observation that could introduce errors in the analysis.

b) **Mean deviation** (x):

Expressed as, $x= (X-\bar{x})$……(2)

c)**Variance (σ^2)** expressed as,

$\sigma^2= \Sigma(X- \bar{x})^2$ N……(3)

d) **Standard Deviation**(σ)expressed as$\sigma= \sqrt{\Sigma(X- \bar{x})^2}/ \mathbf{N}$ …… (4)

Where:

$\bar{x}$ is the mean

X- $\bar{x}$ is mean deviation

Σ is the summation

X is the values in the distribution

N is the number of observation

e) **Coefficient of Variation:** The coefficient of variation, COV, was used to determine the magnitude of the deviation from the mean and thus by implication the magnitude of the variability of properties of the specimens.

$$COV = \sigma/\bar{x} \quad \text{..... (5)}$$

σ= standard deviation, $\bar{x}$= mean value of the given sample

III. **Measures of relationship:** Coefficient of Correlation as a Correlation measurewas used to determine the degree of relationship between paired data. The most often and precise coefficient of correlation is the Pearson product –moment coefficient(r). Pearson's correlation coefficient was used to measures the strength of linearrelationships. For example the relationship between compressive strength and temperature. It is denoted by *r* with boundary conditions of $-1 \leq r \leq 1$. A negative correlation between strength and increase in temperature was arrived at using this technique.

$$r = \Sigma(Z_X)(Z_Y)/N \quad \text{..... (6)}$$

f) **Student T- Test:** When small samples are used, the t-test is used to determine statistical significance of the observation in the study (John & James, 1989).

Characteristic values; this are values for which not more than 5% of the test values fall.

$$\rho_{05} = \bar{x} - 1.65\sigma \quad \text{.....(7)}$$

CHAPTER FOUR

4.0 PRESENTATION OF RESULT ANALYSIS AND DISCUSSION

4.1 Preamble

Three strength properties were investigated for the timber species as summarized on tables 4.1 to table 4.9. Solid and glue laminated timber elements were produced from Ire (*Funtumia Africana),*Awun *(Alstonia congensis)* and Oriro *(Antiaris toxicaria).*

The structural elements included solid and glue laminated beams and short columns. Results were analyzed, examined and discussed.

Results 4.2

Table 4.1:Ultimate load inEdge wise bending

Ire (*Funtumia Africana)*							
Solid Timber				Glued laminated timber			
S/N	Weight (g)	Ultimate load (N)	deflection mm	S/N	Weight (g)	Ultimate load (N)	deflection mm
1	1900	13000		1	1800	8500	
2	1880	12000		2	1700	8000	
3	1690	10000		3	1600	10000	
4	1700	12000		4	1700	8000	
5	1750	12500		5	1750	7500	
Awun *(Alstonia congensis)*							
Solid Timber				Glued laminated timber			
1	1700	5400	0.97	1	2000	5200	1.55
2	1600	6410	0.84	2	1800	5000	1.35
3	1800	7350	0.80	3	1800	5200	1.49
4	1800	6950	0.88	4	2000	5100	1.51
5	1800	5960	0.90	5	1800	5000	1.30
Oriro *(Antiaris toxicaria)*							
Solid Timber				Glued laminated timber			
1	2000	4050	2.09	1	1600	4600	1.80
2	1650	3950	2.17	2	1600	5200	1.82
3	1590	5150	1.39	3	1900	4400	1.87
4	1500	3400	1.36	4	1600	4650	2.15
5	1400	6900	0.95	5	1650	3700	2.25

Table 4.2: Ultimate load in flat wise bending

Ire *(Funtumia Africana)*							
Solid Timber				Glued laminated timber			
S/N	Weight (g)	Ultimate load (N)	deflection mm	S/N	Weight (g)	Ultimate load (N)	deflection mm
1	1950	5000		1	1600	6000	
2	1700	5000		2	1700	5000	
3	1750	4000		3	1750	5000	
4	1630	4500		4	1750	5000	
5	1660	3500		5	1800	4000	
Awun *(Alstonia Congensis)*							
Solid Timber				Glued laminated timber			
1	1800	2350	2.01	1	2000	3200	1.42
2	1600	2400	1.83	2	1900	2400	1.79
3	1850	2000	1.55	3	2000	2600	1.84
4	1700	2000	1.50	4	1700	2150	2.01
5	1750	2300	1.62	5	1750	2250	1.88
Oriro *(Antiaris Toxicaria)*							
Solid Timber				Glued laminated timber			
1	1590	1550	1.84	1	2000	1600	2.48
2	1600	2900	1.53	2	1900	1800	2.25
3	1900	2700	1.64	3	2000	2300	1.78
4	1350	2000	1.36	4	1700	1550	2.15
5	1550	2500	2.15	5	1750	2000	2.25

Table 4.2: Shows the ultimate load of both solid and glued laminated beams as lower than those edge wise bendingwhich demonstrated that the orientation of the load has significant effects on the carrying capacity of the beams.

Ire ***(Funtumia Africana)***	

Table: 4.3 Compressive Strength Parallel to Grain

Solid Timber				Glued laminated timber			
S/N	Weight (g)	ult.load (N)	Comp. strength (N/mm^2)	S/N	Weight (g)	Ult load (N)	Comp. strength (N/mm^2)
1	279	80000	23.5	1	333	110000	32.4
2	285	90000	26.5	2	320	100000	29.4
3	298	90000	26.5	3	342	100000	29.4
4	336	60000	17.6	4	332	130000	38.2
5	298	74000	21.8	5	330	115000	33.8
6	302	91000	26.8	6	315	120000	35.3
7	326	90000	26.5	7	331	130000	38.2
8	329	110000	32.4	8	343	120000	35.3
9	313	94000	27.6	9	317	103000	30.3
10	318	105000	30.9	10	334	145000	42.6

Awun *(Alstonia Congensis)*

Solid Timber				Glued laminated timber			
1	249	99500	29.3	1	261	84000	24.71
2	243	110500	32.5	2	254	80000	23.53
3	267	108000	31.76	3	258	103000	30.29
4	262	101500	28.85	4	260	83000	24.41
5	258	102000	30.00	5	265	99000	29.12
6	268	107500	31.62	6	260	108000	31.76
7	249	107000	31.47	7	255	102000	30.00
8	248	109000	32.06	8	266	117500	34.56
9	250	105000	30.88	9	260	106000	31.18
10	248	75000	22.06	10	271	101000	29.71

Oriro *(Antiaris Toxicaria)*

Solid Timber				Glued laminated timber			
1	183	64000	18.80	1	209	59500	17.5
2	216	62500	18.30	2	217	63500	18.68
3	205	68500	20.15	3	215	62000	18.24
4	203	63000	18.53	4	245	57500	16.91
5	187	66000	19.41	5	228	76500	22.5

Ire *(Funtumia Africana)*

Solid Timber				Glued laminated timber			
S/N	Weight (g)	Ult.load (N)	Comp. strength	S/N	Weight (g)	Ultimate load (N)	Comp. strength
10	189	71000	17.80	10	258	82500	18.38
6	183	67000	16.77	6	218	72000	21.18
7	180	74000	21.77	7	208	73000	21.5
8	177	66000	19.41	8	213	78000	22.94
9	213	71000	20.90	9	238	82500	24.27

Table: 4.4 Compressive Strength perpendicular to Grain

			(N/mm^2)				(N/mm^2)
1	277	60000	17.64	1	308	85000	25.00
2	272	94000	27.65	2	305	80000	23.53
3	293	110000	32.35	3	310	85000	25.00
4	288	68000	20.00	4	298	78000	22.94
5	283	110000	32.35	5	275	74000	21.76
6	271	66000	19.41	6	297	59000	17.35
7	284	97000	28.53	7	280	61000	17.94
8	289	75000	22.05	8	314	71500	21.03
9	281	64000	18.82	9	274	61000	17.94
10	286	88000	25.88	10	312	74000	21.76

Awun *(Alstonia Congensis)*

Solid Timber				Glued laminated timber			
1	226	38800	6.34	1	213	40500	6.62
2	210	31000	5.06	2	225	26000	4.25
3	225	32500	5.31	3	256	47500	7.76
4	217	38500	6.29	4	240	34500	5.64
5	239	57000	9.31	5	225	28500	4.66
6	220	35500	5.8	6	212	35000	5.72
7	202	42500	6.94	7	233	35800	5.85
8	232	38500	6.29	8	235	43600	7.12
9	209.5	31500	5.15	9	226	38000	6.21
10	218	48000	7.84	10	244	60000	9.8

Oriro *(Antiaris Toxicaria)*

Solid Timber				Glued laminated timber			
1	165	23500	3.83	1	237	51500	3.42
2	167	24000	3.92	2	214	30500	4.98
3	165	25000	4.09	3	220	20500	3.35
4	162	28000	4.58	4	200	28000	4.58
5	167	24000	3.92	5	244	173000	28.3
6	170	30500	4.98	6	192	21000	3.43
7	168	28500	4.66	7	238	42000	6.87

8	164	22000	3.59	8	242	47000	7.68
9	234	152000	25.84	9	192	16000	2.61
10	165	158500	25.89	10	258	28500	4.66

Table4.5: Density of solid and glued laminated timber species of study

Density (Kg/m^3)								
Ire *(Funtumia Africana)*			**Awun *(Alstonia Congensis)***			**Oriro *(Antiaris Toxicaria)***		
s/no	Solid (Kg/m^3)	Glulam (Kg/m^3)	s/no	Solid (Kg/m^3)	Glulam (Kg/m^3)	s/no	Solid (Kg/m^3)	Glulam (Kg/m^3)
1	464	456	1	345	430	1	419	347
2	461	426	2	346	378	2	341	327
3	415	412	3	371	408	3	308	373
4	417	449	4	378	382	4	308	341
5	429	419	5	379	408	5	301	329
			Density test from flat wise bending					
6	441	434	6	356	463	6	334	338
7	392	412	7	341	388	7	320	316
8	450	426	8	342	409	8	302	384
9	418	415	9	339	330	9	319	358
10	430	452	10	350	376	10	325	343
			Density test from compression parallel to grain					
11	410	489	11	366	384	11	269	307
12	419	471	12	357	374	12	318	319
13	438	503	13	393	379	13	301	316
14	494	488	14	385	382	14	298	360
15	438	485	15	379	389	15	275	335
16	444	463	16	394	382	16	269	320
17	479	487	17	366	375	17	265	306
18	483	504	18	364	391	18	260	313
19	460	466	19	368	382	19	313	350

20	468	491	20	365	398	20	278	379
			Density test from compression perpendicular to grain					
21	407	453	21	332	313	21	243	349
22	400	449	22	308	331	22	246	314
23	431	456	23	331	376	23	243	324
24	424	438	24	319	353	24	238	294
25	416	404	25	351	331	25	246	359
26	399	437	26	323	312	26	250	282
27	418	412	27	297	343	27	247	350
28	425	462	28	341	346	28	241	356
29	413	403	29	307	332	29	344	282
30	421	459	30	321	359	30	325	289

Table 4.5 presents the densities of the solid and glued laminated timber species for all the mechanical properties that were observed in the order of bending strength, compression parallel and perpendicular grain.

Moisture content (%)								
			Edge wise bending					
Ire *(Funtumia Africana)*			Awun *(Alstonia congensis)*			Oriro *(Antiaris toxicaria)*		
s/no	Solid (%)	Glulam (%)	s/no	Solid (%)	Glulam (%)	s/no	Solid (%)	Glulam (%)
1	20	6.5	1	8.51	11.11	1	10.8	6.0
2	15	9.5	2	10.63	9.22	2	10.7	8.90
3	26	8.9	3	12	10.36	3	10.7	8.4
4	17	18	4	10.7	10	4	21	22.5
5	20	16.6	5	10.7	11.11	5	9.6	16.20
			Flat Wise Bending					
6	20.7	13.5	6	10.3	11.1	6	11.21	8.6
7	15.5	16	7	12.9	10.9	7	8.11	11.6

8	29	9	8	9.9	11.1	8	8.23	8.13
9	26	8	9	10	12.0	9	8.00	11.6
10	17	13	10	16	11.5	10	10.34	10.0
				Compression parallel to grain				
11	23.3	10.8	11	12.05	10.34	11	14	9.50
12	20.7	16	12	11.50	10.60	12	12	8.80
13	22.1	16	13	10.90	11.42	13	12.2	9.30
14	20.5	18	14	10.70	12.02	14	11.8	7.30
15	28	10.9	15	12.40	7.92	15	12.8	10.90
16	27	10.2	16	11.57	11.92	16	12.6	11.50
17	20.2	10.8	17	10.44	12.20	17	11.8	10.60
18	12.5	9.04	18	11.30	11.65	18	13.5	11.70
19	17.6	15	19	11.60	11.54	19	12.2	9.20
20	19	6.9	20	12.09	9.96	20	13.8	7.80
				Compression perpendicular to grain				
21	22.70	11.40	21	8.4	10.3	21	10.3	10.5
22	10.29	7.90	22	9.5	11.11	22	11.9	9.8
23	10.90	10.30	23	8.9	11.33	23	12.12	10.45
24	14.29	9.40	24	10.10	10.00	24	11.7	11
25	9.50	20.00	25	10.00	10.70	25	11.4	12.29
26	16.24	11.11	26	10.5	11.32	26	11.8	12.5
27	10.21	9.60	27	11.9	11.16	27	11.9	11.3
28	20.76	9.60	28	10.34	10.64	28	11.6	10.7
29	24.50	9.12	29	8.8	11.95	29	11.11	11.9
30	18.53	24.4	30	10.1	11.06	30	10.9	11.7

Table: 4.6 Moisture Content of specimens for all mechanical properties

4.3 Characteristic Material Properties

Table 4.7 presents the average values of bending strength, compressive strength and density based on the measured moisture content(MC) and specimen test dimensions. The bending strength values in Table 4.8 were those from table 4.7 adjusted to 18% content and further adjusted to a reference depth of 150mm as shown in Table 4.9 using equation (8) in line with EN 384 (2004) where the specimen size to be considered for bending test should have a depth of 150mm. Equivalent 18% MC adjustment of properties in table 4.7 in line with local environmental condition was done as shown in table 4.8 (NCP2, 1973) using equation (9).

Table: 4.7: Characteristic material properties of solid and glulam timber species of study

Characteristic Properites	**IRE**		**AWUN**		**ORIRO**	
Bending Strength $f_{m,k\ stress}$	Solid timber	Glulam timber	Solid timber	Glulam timber	Solid timber	Glulam timber
Edge-wise (N/mm^2)	62.15	43.3	31.9	30.6	15.92	22.44
Density (Kg/m^3)	398	400	336	366	254	313
Flat wise (N/mm^2)	50.12	55.95	27.6	27.7	20.78	19.6
Density (Kg/m^3)	388	401	334	373	300	306
Compression (N/mm^2) $\mathbf{f}_{ck0}$	25.7	27.3	25	23	16.77	15.96
Density (Kg/m^3)	407	461	353	371	249	289
Compression (N/mm^2) $\mathbf{f}_{ck90}$	8.5	9.3	4.25	3.73	3.39	9.78
Density(Kg/m^3)	398	399	296	307	199	267
Modulus of Elasticity in Bending and Compression (N/mm^2)						
Edge wise bending			2301	1215	34714	34714
Flat wise bending			3645	7290	47313	40178

MOE Compression (N/mm^2) E_0	20283	14347	13071	11422
MOE Comp(N/mm^2) E_{90}	1928	1667	583	592

Table 4.8: Adjusted Values of Mechanical Properties to 18% Moisture Content.

CHARACTERISTIC PROPERITES	**IRE**		**AWUN**		**ORIRO**	
Bending Strength $f_{m,k\ stress}$	Solid timber	Glulam timber	Solid timber	Glulam timber	Solid timber	Glulam timber
Edge-wise (N/mm^2)	65.22	36.44	26.15	25	14	20
Flat wise (N/mm^2)	56	48	24	23	16.5	16
Density (Kg/m^3)	430	464	363	386	301	344
Modulus of Elasticity in Bending and Compression (N/mm^2)						
Edge wise bending			2073	1095	32443	32143
Flat wise bending			3344	6688	41869	36525
MOE in Compression E_0 (N/mm^2)			18608	13043	12103	10198
MOE in Comp. (N/mm^2) E_{90}			1753	1515	577	543

Table 4.9: Adjusted characteristic bending strength to 150mm depth

CHARACTERISTIC PROPERITES	**IRE**		**AWUN**		**ORIRO**	
Bending Strength $f_{m,k\ stress}$	Solid timber	Glulam timber	Solid timber	Glulam timber	Solid timber	Glulam timber
Edge-wise (N/mm^2)	115	65	46	44	25	35

Flat wise (N/mm^2)	50	43	22	21	15	14

For the characteristic bending strength, EN 384:2003 specifies that for depths other than 150mm 5 -percentile values of bending strength shall be adjusted to depths and width of 150mm.

$K_h = \{(150/h)^{0.2}\}$ ……(8)

K_h is the depth adjustment factorand h is the depth used for testing that is 80mm. Therefore the adjusted depth becomes 180mm. $K_h$therefore becomes 0.564 by which characteristic bending strength shall be divided (Abubakar and Nabade, 2013).

The adjustment for characteristic values of bending strength from the measured MC to 18% MC in line with local environmental condition (NCP2, 1973) was computed using equation 9:

$f_{mk},18\% = f$ measured / $1+0.0295(18 - U)$…….. (9)

Where $f_{mk,\ 18\%}$ is the characteristic bending strength at 18% moisture content, u is the measured moisture content in (%) and f measured is the characteristic bending strength(N/mm^2) at the test moisture content.

The 18% MC adjustment for characteristic density of timber specie as required by NCP2 (1973) was computed using equation 10 (Abubakar and Nabade, 2013):

$\rho_{k,\ 18\%} = \rho_w [1-(1-0.5)(U-18)/100]$……..(10)

$\rho_w$is the characteristic density at the time of testing
U is the moisture content at the time of test
According to section 3.1 of EN 384 (2004) for MOE, the mean MOE is also a characteristic value. For this reason, mean MOE is equivalent to characteristic MOE

as shown in table 4.8 where the values of MOE were adjusted to 18% moisture content in line with NCP 2 using equation 11.

$E_{m,\ 18\%} = E_{measure} / 1 + 0.0143(18 - U)$ ..... (11)

Where;

$E_{m,\ 18\%}$ is the characteristic bending MOE at 18% MC,

$E_{measure}$ is the characteristic MOE at the measured MC (N/mm^2)

U is the measured MC (%)

Table 5.0: Effects of Temperature Variation on Compressive Strength

Temp 0^o C	Ultimate load N	Compressive strength (N/mm^2)	Moisture content (%)	Density (Kg/m^3)
IRE (*Funtumia africana*)				
0	117000	34.4	5.1	485
30 (control)	140000	41.2	5.7	485
40	133000	39.2	6.8	457
50	127000	37.3	5.3	447
70	93000	27.4	5.6	462
100	83000	24.4	5.5	469
AWUN (*Alstonia congensis*)				
0	69500	20.44	10.54	258
27.5 (control)	59000	17.35	11.25	255
40	58000	17.05	10	266
50	57300	16.85	12.5	287
70	54500	16.03	11.23	259
100	50500	14.85	7.45	364
ORIRO (*Antiaris toxicaria*)				
0	98250	28.89	1.25	359

27.5 (control)	83000	24.11	7.7	338.8
40	82000	24.12	6.8	351
50	69000	20.29	13.5	363
70	68300	20.09	2.1	338.8
100	64500	18.9	7.45	364

The material -variables of concern for glued laminated timber in this study are the timber species and the glue. Wood adhesives are generally affected by the type of wood or adhered, environment and stresses. Temperature as an element of environment was investigated in the three species. Results are as tabulated in table 5.0.

4.4Discussion of Results

4.4.1Static bending test

From Table 4.7, five (5) samples each for solid and glued laminated timber beams were prepared for edge wise bending per specie. From the results of characteristic bending strength in table 4.7 the performance of solid timber and glued laminated timber across the three speciesare comparable. Results from table 4.7 adjusted to 18% MC as shown in table 4.8 showed the influence of moisture content on bending strength values. With the exception of the solid beam in Ire (*Funtumia Africana)*where the MC at test was higher than 18% the adjusted MC resulted in bending strength reduction in the other species as the adjustment was from a lower MC than 18%. Increase in characteristic bending strength was also recorded after applying the depth adjustment factor K_h as shown in table 4.9, thus representing the

bending strength for structural sized beams. From table 4.9 having applied the necessary moisture content adjustments, the comparative performance of solid and glue laminated beams shows that the glue laminated beams developed 55%, 95% and 143 % clear wood strength in edge wise bending (fig.3) and 85%, 95% and 97% clear wood strength in flat wise bending (fig.4) for Ire (*Funtumia African*), Awun (*Alstonia congensis)* and Oriro (*Antiaris toxicaria*) in that order.

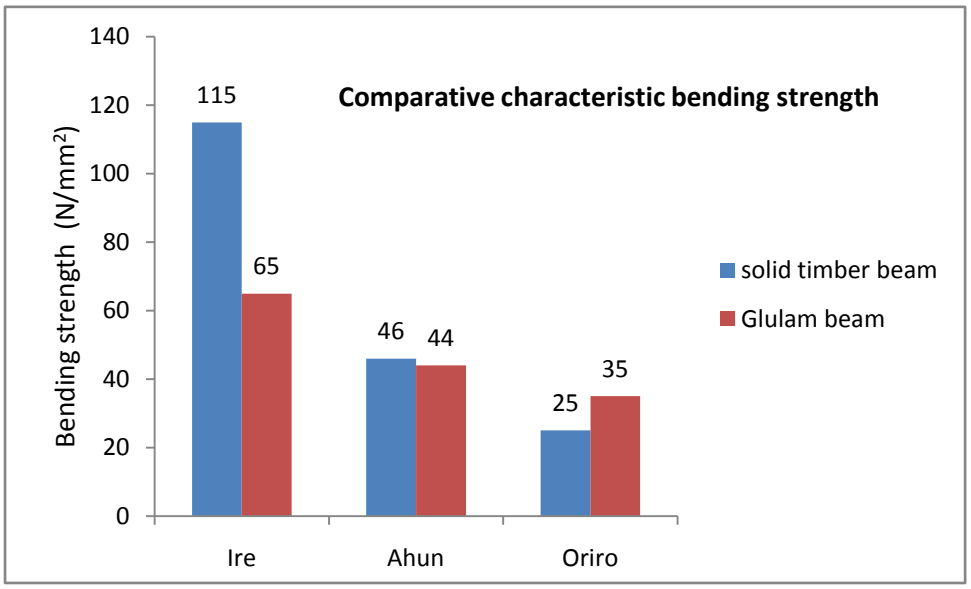


Figure 3: *Comparative bending strength edge wise bending*

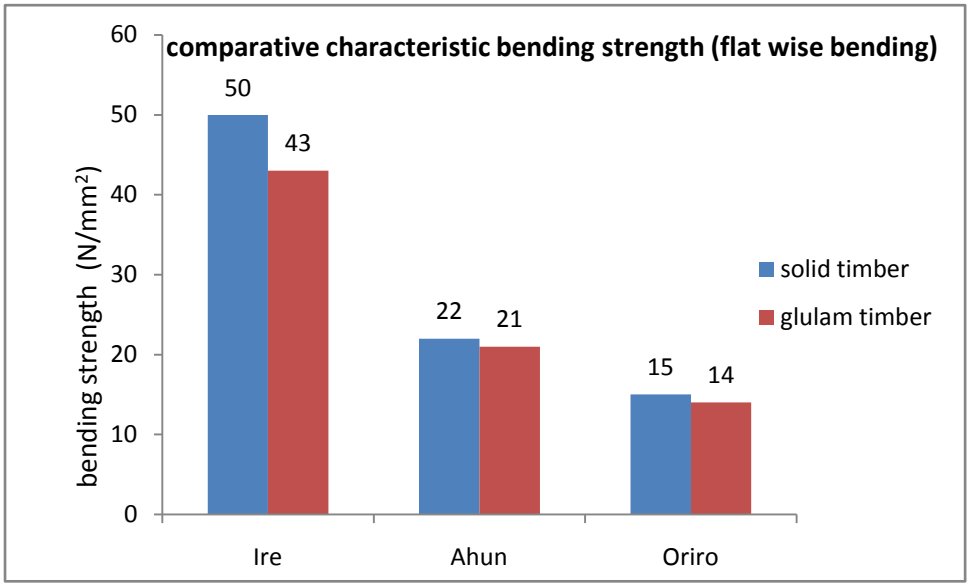


Figure 4: *Comparative bending strength flat wise bending*

4.4.2Variability in density

Density computed from all the mechanical properties tested as shown in table 4.5 were analyzed using descriptive statistics. Density values for each of the mechanical property test were also analyzed using the t- test: Paired Two sample for mean of density, the coefficient of variation was alsocomputed. However table 5.1 shows a summary of characteristic density values obtained for the entire test for the three species.

Table 5.1: Summary of characteristic values of density adjusted to 18% moisture content

Sample	Mean density Kg/m^3	Coefficient of variation	Characteristic density
IRE			
Solid	433	0.06050	390
Glulam	451	0.067229	400
AWUN			
Solid timber	350	0.07357	308
Glulam	373	0.091212	317
ORIRO			
Solid timber	292	0.142778	223
Glulam	332	0.082904	286

These results show that the glue laminated elements had higher densities than solid timber in all three species; this however was not seen to translate into higher strength properties.

4.4.3Compression parallel to grain

From table 4.3 results of compressive strength parallel to grain for short columns are tabulated. Ire (*Funtumia Africana*) sustained a mean ultimate load in compression parallel to grain of 88400N at a mean moisture content of 21.09% while the glue laminated columns offered a mean ultimate load of 117000N at a mean moisture content of 12.4%. However an adjustment of the mean ultimate load of the solid column to 12% moisture content in line with EN 384:2004 would yield an adjusted value of 151164N (44.46N/mm^2) at 12% moisture content so that the glue laminated column developed 77.4% (34.41N/mm^2) of the clear solid wood strength. A

coefficient of variation of 16.3% in ultimate loads of the tested specimen was obtained for the solid columns while 12.6% was obtained for the glue laminated columns.

Awun *(Alstonia congensis)* also offered a mean ultimate load in compression of 102500N at 11.45% mean moisture content while its glue laminated alternative offered an average ultimate load of 98350N at 10.9% moisture content to develop 96% clear solid timber strength. Values of coefficient of variation for the solid and glued laminated columns were 10% and 12% respectively.

Oriro *(Antiaris toxicaria)* sustained a mean ultimate load of 65300N at a mean moisture content of 12.6% while the glue laminated column offered a mean ultimate load of 68700N at a mean moisture content of 9.7%. An adjustment of the later value to 12% moisture content is 63877N so that glue laminated column developed 98% of clear wood strength. The coefficient of variation of the ultimate load for the solid and glued laminated columns was 7.6% and 12.7 % respectively. The coefficient of variation for the glue laminated elements across the three species was observed to be relatively constant as compared to the solid elements.

4.4.4Compression perpendicular to grain

Values of compression perpendicular to grain for the three species are as tabulated on Table 4.4 Mean ultimate load in compression for solid column of Ire (*Funtumia Africana)* was 83200N at mean moisture content of 15.8% while glue laminated column developed a mean ultimate load of 72850N at a mean moisture content of 12.3%, EN 384: 2004 was silent about moisture content adjustment for perpendicular

to grain test. Therefore the glued laminated column developed 87.56% of the solid column strength. The coefficient of variation of the ultimate load in compression perpendicular to grain was 22.9% and 13.3% for solid and glulam columns respectively.

Awun *(Alstonia congensis*) offered a mean ultimate load for compression perpendicular to grain for solid column which was 39380N while glued laminated column offered a mean ultimate load of 38940N at average moisture content of 9.9% and 10.9% respectively. Therefore the glue laminated column developed 98.9% of the solid timber column strength. The coefficient of variation obtained was 20.5% and 25% for solid and glue laminated columns.

Oriro *(Antiaris toxicaria)*: Solid timber column had a mean ultimate load of 51600N (15.17N/mm^2) while the glue laminated column had 45800N (13.47N/mm^2) at an average moisture content of 11.5% and 11.2% respectively. The glued laminated column therefore developed up to 89% clear solid timber column strength. The coefficients of variation in ultimate loads were 11% and 35% for solid and glulam timber columns. The statistical significance of the comparative values was analyzed using t-test: Paired Two -sample for mean of ultimate loads. The one and two tailed t-critical values obtained were 1.83 and 2.26 which showed the statistical significance of the difference of the observations. Table4.7 shows the characteristic compressive strength for the species and the adjusted MOE values to 18% MC in table 4.8.

4.4.5Moisture content

The effect of moisture content on strength properties of timber elements could be far reaching. Hence it is expected to have timber elements for structural purpose within

equilibrium moisture content (EMC), at which point the material becomes stable, resistant to insect attacks and incipient decays prevented. The moisture content in wood can be determined by several methods as defined by the three European standards for moisture content measurement valid for sawn timber and planed or timber machined in other ways. These standards includes: EN 13183-1 *Moisture content of apiece of sawn timber. Part 1: Determinationby oven dry method,* EN 13183-2 *Part 2: Estimation by electrical resistancemethod,* EN 13183-3 *Part 3: Estimation by capacitance method.* Moisture content was determined in this study using the oven dry method. Moisture content for every mechanical test was determined after each test according to BS 373 (1953), results were collated and analyzed for solid and glue laminated timber using the t-test two samples for means of moisture content. However overall analysis of moisture content for 60 specimens per specie collected from every test (*with exception of those for temperature effects*) was also conducted as shown in table 4.6. The mean moisture content at the time of testing was close to equilibrium moisture content. Ire (*Funtumia Africana)* for both solid and glue laminated timber recorded mean moisture content of 19% and 12% , Awun (*Alstonia Congensis)* 11% for both solid and glue laminated timber, Oriro (*Antiaris toxicaria)* had mean moisture content of 12% and 11% respectively.

4.4.6Effects of temperature variation on compressive strength

Timber in many structural applications would be subjected to compressive action both parallel and perpendicular to grain. Similarly, building and civil engineering structures at some points in service life are prone to temperature variations and fire risk depending on the use of the structure. Much research efforts is required to understand the responses of local glue laminated structural elements subjected to the

action of temperature variation with the view to forestall the limit state associated with these temperature effects for safe evacuation of persons and as well the safety of rescue teams (Bednarek,2007). Concrete and steel structures have been extensively investigated in this line. Local timber and composites has however not been extensively profiled along this path.

Table 5.0 shows the performance of the glue laminated members in compression parallel to grain at varied temperatures of 0^oC,30^oC, 40 ^oC, 50 ^oC, 70^oC, and 100 ^oC administered to test samples over a period of four hours for the three species of study.

For Ire (*Funtumia Africana),* the moisture content of the oven treated specimens had a mean value of 5.6% and mean density of 467.5kg/m^3. As the temperature increased from 0^oC to 30^oC, there was an increase in compressive strength after which there was a gradual decrease in strength as the temperature increased to 100^oC as shown in figure 5. A mean compressive strength of 34.4 N/mm^2 was recorded at 0^oC while a rise to 41.2N/mm^2 was recorded for 30 ^oC which was the control at an average room temperature as at the time of testing. However subsequent decreases in mean compressive strength were recorded with increasing temperature from 30^oC to 100^oC. The drop in strength from 30^oC to 100^oC was 40% while the increase in strength from 0^oC to 30^oC was 16.5%. The relationship between compressive strength and temperature also showed similar behavior in Awun (*Alstonia Congensis)* (fig.5) Compressive strength and temperature showed a strong correlation, R^2 =0.895. At an average moisture content of 10.5 % the highest compressive strength of 20.44N/mm^2 was recorded at 0 ^oC while the lowest was 14.85N/mm^2 the strength at control temperature was 17.35N/mm^2. The loss in strength from 0 ^oC to control temperature of 27.5 ^oC was 15.11 % while the strength loss from control temperature to 100 ^oC

was 14.4 % Compressive strength continued to ebb as temperature increased. A similar behavior was observed for Oriro (*Antiaris toxicaria)* compressive strength dropped as temperature increased (fig. 5). The loss of strength from 0 ^{o}C to room temperature (27.5^{o}C) was 15.5% while that from room temperature to 100 ^{0}C was 14.6%. These results agreed with Bednarek, (2007) who reported losses in the compressive strength in Oak and Pine timber specimens with increase in temperature.

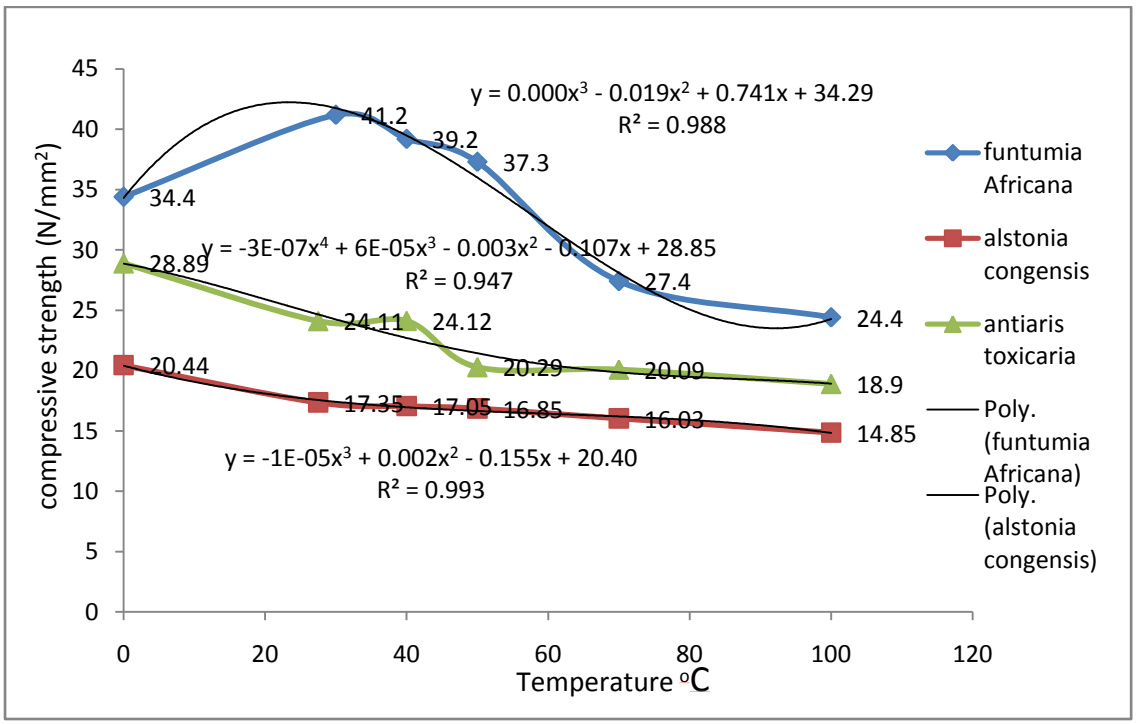


Figure 5:*Effects of temperature variation on compressive strength*

4.4.7 Failure mode

In practice, the understanding of failure Modes in timber structures aids in analyzing potential reliability problems which may occur in service with the aim to forestall such occurrences early in the design process (Kenneth, 2002). Identifying potential failure modes and determining their effect on the performance of structural elements helps to identify strategies for failure mitigation. While anticipating every failure mode is not possible, certain failure modes have been identified through extensive

research as shown in fig.6. Generally, failure occurs when materials start exhibiting inelastic behavior. Brittle and ductile materials exhibit different modes of failures. Mode of failure also depends on loading. Ductile materials exhibit yielding and plastic deformation before failure while brittle materials exhibit no yielding but sudden failure.

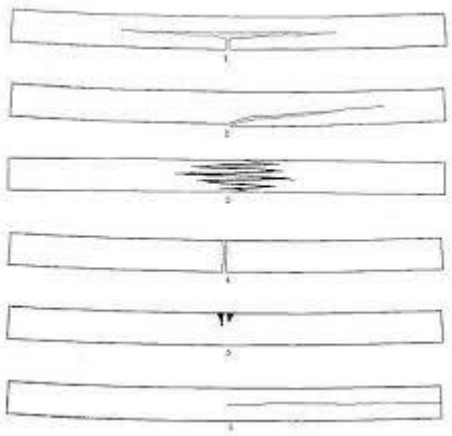


Fig. 6: Failure patterns in beams

The failure modes for different structural elements tested were studied across the species of study.

4.4.8Beam failure mode

A total of sixty solid and glue laminated beams were tested for the three species out of which thirty were tested edge wise and thirty in flat wise bending. The failure modes of the solid timber beams loaded edge wise showed similar failure characteristics in the three species as shown in plate 3. Failure was initiated at the outer bottom fiber which was propagated upwards perpendicular to the grain. Plate 4 shows a typical case of brittle failure in solid beam specimen loaded flat wise. The

mode of failure in flat wise bending was generally that of tension failure as shown also in plate 3 specimen (1) F.W.B



Plate 3: *Wood fiberfailure in solid beamsperpendicular to grain*

Cases of brittle failure were also recorded in flat wise bending as shown on plate 4.



Plate 4: *Brittle failure in solid beam*above *and yielding before failure in the beam below*

4.4.9Glue laminated timber beams

The failure mode in glue laminated beams loaded edge wise was characterized by tension failure with cracks propagated along weak zones off the glue line longitudinal to grain direction as shown in plate 5.

Plate 5 and 6 shows tension failure in beams with cracks propagated longitudinally and diagonally. Generally the failure mode in the glue laminated beams was characterized by wood failure and not de-lamination which meant the strength of the glue exceeded that of the wood.



Plate 5: Wood fiber failure in glulam beams as the fault line avoid the glue line



Plate 6: Tension failure in glulam beam

4.4.10 Compression members

Failure mode in the compression members showed wood crushing in both solid and glue laminated columns while maintaining glue line integrity in the glulam elements.

Compression members perpendicular to grain showed failure with tension cracks on the convex sides of glulam columns which was notably different from that of sawn timber columns as shown in plate 9. The dominance of tension cracks as a failure mode in glulam specimens before reaching the ultimate load was also observed by Damkilde *et al.*, (2011) in comparing structural and glulam timber. This development was however without delamination of the glue line as shown in plate 9.



Plate 7: *Wood fiber crushing in glulam short column loaded parallel to grain*



Plate 8: *Wood fiber crushing in solid timber short column loaded parallel to grain*



Plate 9: *Tension failure in wood fiber in glulam short columns perpendicular to grain loadin*g

The failure mode of compression members subjected to varied temperatures was generally that of wood crushing and delamination. Delamination was the case for extreme temperatures of 0^{o}C and 100^{o}C for the three species. Delamination and crushing of the timber was characterized by a glass like fracture at 0^{o}C as polyvinyl acetate glue is known to harden at low temperatures and soften at higher temperature 100^{o}C.



Plate 10: *Crushing and delamination of glued specimens at 0^{o} C*



Plate 11: *Crushing and Delamination of glue specimen at 100^{o} C*



Plate 12: *Crushing without delamination of glue specimen at 30*c

CHAPTER FIVE

5.0Summary, Conclusion and Recommendation

5.1 Summaryof Research Findings

Laboratory experiments were conducted to determine the physical and mechanical properties of three Nigerian timber species, namely: Ire (*Funtumia african),* Awun *(Alstonia congensis) and* Oriro *(Antiaris toxicaria,)* in accordance with ASTM D193, EN 13183-1 (2002), EN 408 (2003) and EN 384(2004). The mechanical properties were determined using three points loading for bending strength. The characteristic values of the material property were calculated and tabulated on table 4.7: *Characteristic material properties*. The strength properties were adjusted to 18% moisture content relevant to the equilibrium moisture content for structural use of timber in Nigeria as shown on table 4.8: *Adjusted characteristic bending strength to 150mm depth*. The Nigerian standard code of practice (NCP 2:1975) has seven

strength classes ranging from N1- N7 with the highest strength in N1 and the lowest being N7. From the results of laboratory test the following were found:

i. From the results of Characteristic properties it was shown that solid wood had higher strength properties than glue laminated timber with Ire offering the highest bending strength of 62.15 N/mm^2 to 43.3 N/mm^2 followed by Awun with 31.9N/mm^{2}to 30.6N/mm^2 and Oriro offering 15.92N/mm^{2}to 22.44N/mm^2 for solid and glulam beams respectively. This fact is recognized in literature by Zhiyong and Ross, (2006) Thelandersson and Larsen, (2003).

ii. The glulam elements developed significant clear solid wood strength of 55% 95% and 143% in edgewise bendingin Ire, Awun and Oriro respectively which could be improved upon with more efficient pressing techniques.

iii. Failure generally occurred in wood fiber and not along the glue line for the glulam elements as shown in Plates V, VII, IX and XII.

iv. The results of bending strength and compression parallel and perpendicular to grain in the both solid and glulam elements were of structural significance as contained in table 4.7:*Characteristic material properties.*

v. For Compressive strength parallel to grain, at varied temperature, the effects of heat on glulam elements showed a progressive loss of strength with increasing temperature and thus strength and temperature were negatively correlated as shown in Fig.5: *Effects of temperature variation on compressive strength.*

5.2Conclusion

Giving the above, the following conclusions were reached:

i. The said species are glueable using polyvinyl acetate glue

ii. Polyvinyl acetate glued joints performed reasonably well within temperature variation from 0^0C to 100^0C.

iii. The strength of glulam was not always higher than solid wood however the strength of glulam elements was of structural significance with Ire offering the highest bending strength of 62.15 N/mm^2 , 43.3 N/mm^2 followed by Awun with 31.9N/mm^2 and 30.6N/mm^2 and Oriro offering 15.92N/mm^2 , 22.44N/mm^2 for solid and glulam beams respectively.

iv. Solid and glulam beams were more flexible in flat wise bending with higher MOE

v. For classification according to density and strength class of NCP 2 (1973) the species all fall to group $N_{7.}$

vi. Timber classified into the least strength class of N_7 could be used for structural purpose in tandem with those from higher strength classes as wood composite.

5.3 Recommendation

i. Based on the strength developed, the glulam elements of the said species are useful as structural elements using polyvinyl acetate glue.

ii. Giving the extent of strength developed the species show useful potential for structural application as glulam elements with higher strength properties than solid wood over greater depths and span.

iii. The use of polyvinyl acetate glued elements should be restricted to temperatures at and close to room temperature.

iv. Ire *(Funtumia Africana)* and Oriro (*Antiaris Toxicaria)* are timbers harvested and sold in the local timber market without information on their properties. These timbers fall in the same class as Awun (*Alstonia Congensis) and* should be included in reviewed editions of NCP 2.

v. According to NCP 2(1973) all Nigerian timber species are hardwood i.e. harvested from broad leaf trees regarded as deciduous trees on the bases of which the timber species especially AwunandOriro are hard wood while Ire is a softwood.

5.4Recommendation for Further Studies

Further studies could assess;

i. The glueability of other timber species as contained in NCP2 with the view to establish their glueability.

ii. Suitability of other types of synthetic glues on local timber species for structural purpose.

iii. The mechanical properties of structural sized beams and columns of the species used in the study.

iv. The relationship between the quantity of glue and the strength of the glue line as well as the effect of species on the relationship.

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