Jurnal Kejuruteraan 34(1) 2022: 131-137
https://doi.org/10.17576/jkukm-2022-34(1)-12

Assessment of Bending Strength of Afara Glued Laminated Timber using Polyurethane (PUR) Adhesive

Pamilerin Sanni[a*] & Oluwarotimi Ekundayo[b]

[a]*Faculty of Engineering, Akwa Ibom State University, Uyo Nigeria*
[b]*School of Environmental Technology, Federal University of Technology, Akure Nigeria*

**Corresponding author: sannibdg148528@futa.edu.ng*

Received 8 February 2021, Received in revised form 2 July 2021
Accepted 2 August 2021, Available online 30 January 2022

ABSTRACT

Timber has long been a popular building material, with benefits such as low energy consumption and the ability to create an in-built atmosphere that helps to mitigate the effects of global warming. Afara (Terminalia Superba) is a well-known timber species with high demand in Nigeria. The objective of this paper is to assess the physical and mechanical properties of Afara (Terminalia Superba) wood, as well as the flexural strength in flatwise bending of its glued laminated timber beam using polyurethane (PUR) adhesive, to determine its viability for structural construction. The research specimens were made using MS758:2001, EN408, and ASTM D198:2013 standards for the physical and mechanical properties tests. By MS758:2001, a shear test for glue line integrity was conducted to assess the bond performance of the glulam. In the laboratory, bending tests were performed on five glulam beams and five solid beams. Glulam beams were glued together with polyurethane (PUR) adhesive. The bending strength of solid wood was higher than that of glue-laminated wood. Solid Afara (Terminalia Superba) beams have a bending strength of 40.09 N/mm^2, whereas glued laminated timber has a bending strength of 19.18 N/mm2. The preliminary investigation of the timber under BS 5268 (structural use of timber) revealed that glue-laminated beams can be used as structural members in a flatwise orientation, despite their strength being lesser than that of solid beams. Also, the polyurethane adhesive strength has an inverse relationship with the moisture content of the specimens at room temperature.

Keywords: Afara wood; Glulam beam; Polyurethane Adhesive; Bending Strength

INTRODUCTION

Humans have used and adapted timber as a prominent building material in buildings and constructions. With its availability, abundance, and capacity for renewal, wood is an important resource for humans (Fuwape, 2000). It has progressed from a readily available natural material to a modern engineering material with the unique ability to contribute to human life as a building material and as a forest component (Youngs, 2001). Wood has many advantages, including low embodied energy, low carbon footprint, and long-term viability (Falk, 2018). The construction industry consumes a lot of energy and releases a of carbon dioxide (CO_2) into the atmosphere. Building with wood-based materials has been shown to use less energy and emit less CO_2 than other materials like concrete and steel, according to an increasing body of research (Sathre, 2006). The improvement in glueing technologies coupled with renewed interest in sustainable construction led to the development of engineered wood products like glued-laminated timber. Glulam is mainly used as a structural material, with the most significant properties being strength, stiffness, and longevity (Gross, 2013). Nonetheless, because of its perceived unreliability, wood has been underutilized as a construction material. Glulam is made up of two or three layers of dimensional lumber that are glued together to form parts that are far larger than the individual pieces that make up the structure. Laminations, or layers of dimensional lumber, are glued together with the grain running parallel to the thickness. As compared to sawn timber, the lumber used in the section assembly is stress graded, allowing for more precise control of individual lamination properties and more predictable configurations (Lacroix, 2014). Although previous research has focused on the mechanical efficiency of some indigenous timber species in solid wood form, little attention has been given to the use of Nigerian timber species in glulam production for structural purposes (Olusegun, 2015).

Glulam consists of two or more layers of dimensional lumber joined together with glue to produce sections that are much greater than that of the pieces forming it. The dimensional lumber in each layer, referred to as laminations, are glued together with the grain parallel to the length. The lumber used in the assembly of the section are stress rated, thereby allowing for tighter control on the individual laminations properties to achieve configurations with more predictable characteristics compared to those achieved in sawn timber. Glulam consists of two or more layers of dimensional lumber joined together with glue to produce sections that are much greater than that of the pieces forming it. The dimensional lumber in each layer, referred to as laminations, are glued together with the grain parallel to the length. The lumber used in the assembly of the section are stress rated, thereby allowing for tighter control on the individual laminations properties to achieve configurations with more predictable characteristics compared to those achieved in sawn timber.

Afara (Terminalia uperba) wood is a common local timber species found in Nigeria's southwestern region. It is a valuable species with a yellow-brown heartwood similar to oak, and it is valued for light construction, door and window frames, joinery, fine carpentry furniture, veneer, and plywood. (Buildam, 2019). Polyurethane, or PUR, is a synthetic material made up of several organic units linked by urethane ties that are commonly used as an adhesive in the production of glulam. PUR adhesive is a great option for woodworking and other building projects because of its excellent performance. The assembly of wood products also removes the need for screws and nails (Melt, 2018). In this context, the objective of this paper is to evaluate the preliminary investigation of physical and mechanical properties of Afara (Terminalia Superba) wood, as well as the flexural strength in flatwise bending of its glued laminated timber beam using polyurethane (PUR) adhesive, to determine its viability for structural construction.

METHODOLOGY

PREPARATION OF TEST SPECIMENS

The test specimens were made from Afara (Terminalia Superba) wood, which is a Combretaceae tree species. It is one of Africa's most commonly used wood species, especially in Nigeria. It's also the most readily available material in Akure, Ondo, where this research was conducted. EN 408 (2003) was used to assess the physical properties of the species, including moisture content and density, as shown in Table 1 and Table 2. Mechanical properties of the timber, such as static bending, shear stress, compression, and tensile strength parallel to the grain, as well as flexural strength, were also calculated using ASTM D193 (2000) and EN 408 standards (2003). Characteristics values of the properties of the materials were determined according to EN 384 (2004).

TABLE 1. Preliminary investigation using small clear specimens

S/N	Type of Test	Type of Specimen	Dimension	No. of Specimen
1	Moisture content, Density			
	Small clear specimen	20mm x 20mm x 60mm	5	
2	Compressive strength	Small clear specimen	20mm x 20mm x 60mm	5
3	Tensile strength	Small clear specimen		
	100mm x 20mm	5		
3	Static Bending	Small clear specimen	20mm x 20mm x 300mm	5

TABLE 2. Afara (*Terminalia Superba*) with polyurethane adhesive

S/N	Type of Test	Type of Specimen	Dimension	No. of Specimen
1	4 point bending	Solid Beams (Control)	1440mm x 150mm x 20mm	5
2	4 point bending	Glulam Beams	1440mm x 150mm x 120mm	5
3	Shear strength	Shear Block	140mm x 110mm x 30mm	5

PRODUCTION OF THE SMALL CLEAR TEST SPECIMEN AND SHEAR BLOCKS

The wood specimens were cut and processed into various sizes according to MS758:2001. The lumber was conditioned to a target moisture content of 12% before being machined to the final specimen measurements (oven-dry basis). The air-dried wood was machined into small clear test specimens. Colour-coded growth rings, stain, decay, and insect holes were all carefully avoided during specimen preparation. Furthermore, all specimens in this study were first obtained in large blocks. The Terminalia Superba (Afara) beam was measured at 140mm x 110mm x 30mm on the shear block specimens, as shown in Figure 1. To ensure accuracy, the cutting was performed with a band saw machine; strong locking edges often help in the proper fitting of large timber blocks during the cutting process without causing any disruption. Since the lamella thickness was greater than 25mm, the loaded surfaces were cut parallel to each other and perpendicular to the grain direction, respectively. The loaded block-level was glued at both sides of the two blocks in the centre, with a clear space of 30 mm height. Polyurethane (PUR) adhesives were used to apply the shear surface area with precision. By the use of the clamp apparatus, a uniform mechanical pressure was applied to the shear areas. After a 24-hours curing time, the pressure was released.

Figure 1. Shear block specimens

PRODUCTION OF GLUED LAMINATED TIMBER BEAM

Thirty (30) laminations with a cross-section of 25 x 180 mm and length of 1450 mm were obtained from the central planks, which were later dried until reaching the moisture content of 12 %. The faces were also planned to reach their final dimensions (20 x 150 x 1440 mm) to facilitate lamination, improve wood-adhesive bonding, and minimize raised grain. The specimen was fabricated in compliance with the British and European standards where applicable. The recommended British Standard reference for the manufacture and application of glulam is BS EN301 for synthetic resin adhesives (phenolic and amino plastic) for wood and BS EN 386, which covers the manufacture of glued-laminated timber structural members (Olusegun, 2015). The fabrication process was done manually. Proper clamping with guards was established to ensure even distribution of exerted force on the wet prepared glulam beam for setting and drying. Six (6) laminates were sorted at a time to produce one glulam beam at a time. The glueing procedure was carried out on each laminate in ascending order. With the help of clamping jigs, U-clamps, gauge, screws and bolts, polyurethane adhesive is spread on each laminate face with an adhesive extruder, then the laminates are assembled into a prescribed lay-up pattern and transported to the clamping portion. The wet prepared glulam was also strategically imported to the prepared clamping segment before being removed from the clamping devices after twenty-four (24) hours. The wet beams were conditioned in a climate environment with a temperature of 22 ± 2°C with relative humidity of 65 ± 5% until reaching the moisture content of 12 %. To evaluate the density, glued laminated beam specimens extracted at both the strong and weak zones, five specimens at each zone measuring at 100 x 100 x 150 mm (length, width, and thickness) were drawn parallel to the fibre's been placed inside an air oven at an adequate temperature for 24 hours after measuring.

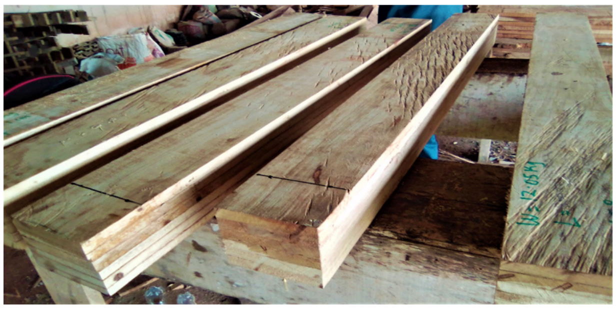

Figure 2. Glued laminated beams

EXPERIMENTAL TESTS

Moisture content was determined under EN 408 (2003) and BS 373: (1957). Each specimen was first weighed, and their respective weights were recorded as Mwet, placed inside the drying oven for 24 hours. The samples of each specimen are brought out and are reweighed to obtain their respective weights as M_{dry}, using Equation 1.

$$\textit{Moisture content (\%)} = \frac{Mwet.- Mdry}{Mdry} \times 100 \qquad (1)$$

In the tensile strength test, the test pieces were prepared concerning the shape and size are given in BS 373- 1957. The result obtained using Equation 2, placed in such a way that the annual ring's direction is perpendicular to the greater cross-sectional dimension. The load is applied at the ends of the sample by the toothed plate grips designed to give axial load, as shown in Figure 3. The sample splits at the thin section, and the maximum load was recorded.

$$\text{Tensile strength } \left(\frac{N}{mm^2}\right) = \frac{\text{Maximum Load } (N)}{\text{Smallest Cross Sectional Area } (mm^2)} \quad (2)$$

In the compression parallel to the grain test, the load was applied to both ends of the test piece so that the loading plates of the universal testing machine (UTM) approached each other at a rate of 0.635 mm/min. The test was stopped when a deformation on the specimen was observed, and the result was obtained using Equation 3.

$$\text{Compressive strength } \left(\frac{N}{mm^2}\right) = \frac{\text{Failure Load } (N)}{\text{Cross Sectional Area } (mm^2)} \quad (3)$$

Three-point loadings performed the static bending test under ASTM D193 (2000). The centre loading point and supports were marked; the orientation of the test species was ensured perpendicular to the loading direction. 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 unrestrained at the ends and assisted at the ends to enable bending motion within the member and ensure failure due to flexure. The machine's speed was set to load the test piece and allow for adequate dial gauge monitoring. Before the failure, readings on the dial gauge were taken at intervals within the elastic limit.

The Moisture Content Values of the samples were adjusted to 12% and 18%. According to Bello & Jimoh (2018), all strength values were adjusted to their 12% equivalent moisture content, and the results were further converted to their equivalent moisture content of 18%, which is the acceptable moisture content of timber to be used in Nigeria using Equation 4 and Equation 5;

Converting to 12% Moisture content;

$$F_{12}=F_w\,(1+\alpha\,(W-12)) \quad (4)$$

Converting to 18% Moisture content;

$$F_{18}=Fw\,(1+\alpha\,(W-18)) \quad (5)$$

Where α is the correction factor for moisture content, W is moisture content at the test time, F_w is the strength value at the time of test, F_{12} is the strength value at 12% moisture content, F_{18} is the strength value at 18% moisture content.

TABLE 3. Showing correction factor (α) for moisture content

State of stress	α-values	Reference
Modulus of Elasticity (MOE)	0.02	Zziwa et al. (2010)
Tensile	0.05	Zziwa et al. (2010)
Modulus of Rupture (MOR)	0.04	Aguwa (2016
Compression	0.05	Aguwa (2016)

SHEAR BLOCK STRENGTH TEST

Following BS EN 392-1995, requirements for a shear test device relating to adhesive bond quality assessment. The specimens were kept in the laboratory environment for acclimatization to have equilibrium moisture content in a range of 10% -14%. The lapped block shear test method was used to deduce the adhesive quality on the bonded wood precisely (Jihan et al., 2019). The specimens were placed in the shear test apparatus with the glue line oriented parallel to the loading direction. The test was performed using the compression testing machine in denoting the maximum failure load that leads to wood failure and delamination. The sheared area and the maximum loads were recorded, and the shear strength was computed for each specimen using Equation 6.

$$\text{Shear strength } \left(\frac{N}{mm^2}\right) = \frac{\text{Maximum Failure Load } (N)}{2\,x\,\text{Shear Surface Area } (mm^2)} \quad (6)$$

Figure 3. (a) Prepared shear block for the test; (b) Failure and delamination of adhesive on the specimen

FLEXURAL STRENGTH TEST ON GLUED LAMINATED BEAM

According to Harte (2018), bending properties are usually calculated by symmetrically loading a specimen at the third point of an 18-times-the-depth-of-the-sample span. A four-point bending test aims to establish a constant moment zone with no shear in the most highly stressed mid-third of the beam under test. By ASTM D193 (2000), the flexural strength test was conducted using four-point loadings, as shown in Figure 4, for Modulus of Rupture (MOR) and Modulus of Elasticity (MOE). At flatwise orientation, compression load was applied to the specimen running parallel to the length of the timber piece. Special bearing plates are mounted on the measuring system to ensure a consistent stress distribution around the specimen's cross-section. Readings were taken from the universal testing machine's dial gauge at various loading levels as the load was applied. As the beam sags or reaches its modulus of rupture, the deflection is determined. By dividing the maximum compressive load (which was off when the dial started returning to the zero position) by the specimen's cross-sectional rupture area, the maximum flexural strength parallel to the grain was determined.

Figure 4. Four-point loading set-up for bending

At the region of flexural cracks on the beams, the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) was computed for each specimen using Equation 7 and Equation 8, where FS is the flexural strength or MOR, ME is the Modulus of Elasticity (N/mm²), p is the maximum load applied, a is the distance between the load and the nearest support (mm), b is the width of cross-section (mm), d is the depth of cross-section (mm), l is the overall length of the beam (mm), and D is deflection distance (mm).

$$Flexural\ strength; \boldsymbol{F}_{S=\frac{3pa}{bd^2}} \tag{7}$$

$$Modulus\ of\ Elasticity; \boldsymbol{M}_{E=\frac{pa(3l^2-4a^2)}{4bd^2D}} \tag{8}$$

RESULT AND DISCUSSION

PRELIMINARY INVESTIGATION TEST

The mean moisture content values at the test were 14.7% for tensile strength, 14.06% for compression parallel to the grain, 13.22% for static bending, and 12.49% for flexural strength consistent with the equilibrium moisture of the wood after the drying process, being close to 12 %. These results showed that the moisture content values fall below the fibre saturation point (FSP). The FSP is usually between 25-30% moisture content (Nabade, 2012). The mean density value at the test was 318.89 kg/m3 for tensile strength, 338.33 kg/m³ for compression parallel to the grain, and 298.17 kg/m³ for static bending. The glued laminated beams mean density was 278.02 kg/m³ for shear strength and 482.64 kg/m³ for bending strength. The overall mean density for all tests was 343.21 kg/m³. As stated in BS 5268 (structural use of timber), the density ranging from 340 kg/m³ to 350kg/m³ belongs to the strength class of C22–C27 (softwood). This shows that Afara (Terminalia Superba) timber is softwood. The mean tensile strength value at the test was 21.53 N/mm², which shows the wood's ability to expand and quantify the resistance to splitting when undergoing strain at both ends. The mean compression strength parallel to grain value at test was 25.75 N/mm³, which shows the ability of a material to withstand an imposed load without twisting and comparing the value of the compressive strength with values of other species, allows classifying the Afara (Terminalia Superba) wood in the group of species with mechanical quality and can be compatible with many kinds of wood traditionally applied in civil construction and the furniture industry. The mean static bending value at the test was 52.23 N/mm² for MOR and 7.2 N/mm² for MOE. As stated in BS 5268 (structural use of timber), the strength class shows that Afara (Terminalia Superba) timber is softwood. The result for adjustment of moisture content values of the samples to their 12% and 18% equivalents is shown in Table 4.

TABLE 4. Strength tests of Afara (Terminalia Superba) on small clear specimens at 12% and 18% moisture content

Mechanical property	Tensile stress (N/mm²)	Compression stress (N/mm²)	Static bending of MOR (N/mm²)	Static bending of MOE (N/mm²)
Strength at 12% moisture content	24.71	29.46	54.74	7.37
Strength at 18% moisture content	18.27	20.68	42.20	6.51

SHEAR STRENGTH TEST AT ROOM TEMPERATURE

The shear strength of the wood is directly proportional to its density but depends mainly on the direction in which the stress is applied with the growth rings (Massayuki et al., 2014), which the mean shear strength value at the test was 1.5 N/mm². Most of the specimens that fail in wood achieved shear strength limit, indicating that the adhesive bond excellently performed against shear loading, allowing the load to cause the wood failure at its shear strength limit. On the other hand, specimens fail in wood while they did not achieve their shear strength limit, which could be due to the undistributed loading from the shear block test or the moisture percentage contain in the specimen. Timbers tend to have higher strengths when the water content is low, while lower strengths when the water content is high (Jihan et al., 2019).

FLEXURAL STRENGTH TEST

The mean flexural strength value obtained for the glued laminated beam at flatwise orientation was 19.18 N/mm² where elastic deformation occurred in the specimens during the initial stage of loading as shown in Table 5. As the load increased, plastic deformation occurred in the specimens. At this stage, many small compression wrinkles appeared in the specimens. The bending rigidity of the specimen decreased marginally, and the deformations increased significantly. Finally, the bottom laminates reached their ultimate tensile stresses (Ying Gao et al, 2015), which led to the specimen's brittle failure (Gao et al., 2015). According to Faria (2019), the failure in glulam beams generally starts with the crack from the bottom piece and spreading on the cross-section height, with the concomitant crushing of the compressed fibres (top) of the beam. According to EN 1995-1-1, the strength class of glued laminated timber can be classified within GL 24 –36. This value obtained from the test does not meet up to the strength class range. It can be recommended that the design depth of the glulam beam should increase, i.e., more laminates exceeding six (6) in number been provided, to meet the glulam strength class range.

TABLE 5. Four points bending test result of Afara (Terminalia superba) glued laminated timber beams

Specimen no	Mass (g)	Failure load (N)	Deflection (mm)	Bending strength (N/mm2)
1	12400	26200	40	19.83
2	12450	25600	36	19.38
3	12550	25000	35	18.92
4	12600	24500	39	18.55
5	12550	25400	35	19.23
Mean Value	12510	25340	44	19.18

Figure 5. Cracks due to failure of glulam under flexural testing

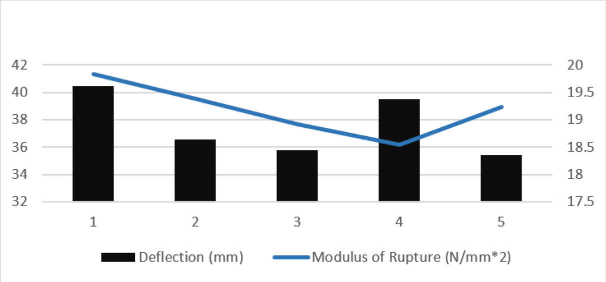

Figure 5. Cracks due to failure of glulam under flexural testing

CONCLUSION

This study proposed an innovative approach to produce Afara (Terminalia Superba) glued laminated timber beams using a polyurethane adhesive. The quality of glueing the pieces to produce the glulam beams is directly related to the chemical composition and the preservative treatments performed in the wood. Polyurethane adhesive tends to work well in contributing enough adhesion strength, ensuring that failure occurs at the weak zones in the timber and not in the glue line. The duration for which the shear blocks fail shows that the amount of moisture content existing in the glued laminated beam undoubtedly influence the shear strength. I.e., the lower the moisture content, the higher the shear strength. To conclude this paper, the following remarks are noted;

a. Afara (Terminalia Superba) solid timber beam has higher bending strength properties compared to glued laminated timber beam.
b. At flatwise orientation bending strength of Afara (Terminalia Superba) glue-laminated timber beam, the modulus of rapture value tends to fall below the glulam class according to ASTM D19.
c. The shear strength at room temperature values has an inverse relationship with moisture content in the specimen.
d. The use of polyurethane adhesive to produce glued laminated timber beam contributes positively towards the strength development.
e. According to the findings, timber is adequate in tension and compression, and therefore should be considered a building material substitute.

ACKNOWLEDGEMENT

The authors are highly thankful to Akwa Ibom State University and the Federal University of Technology for their excellent help and support to conduct this research.

DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Aguwa, J.I. 2016. *The Nigerian Timber Structures.* Ahmadu Bello University Press Limited, P.M.B. 1094 Samaru, Zaria, Nigeria.

ASTM D193. 2000. *Standard Method of Testing Small Clear Specimens of Timber.* American Society for Testing and Materials, USA.

Bello A & Jimoh A. 2018. Some physical and mechanical properties of African birch (Anogeissus Leiocarpus) timber. *Journal of Applied Science and Environmental Management* 22(1): 79-84.

British Standard Institution. 1995. BS EN 392. London: British Standards Institution.

BS 373. 1957. *Methods of testing small clear specimens of timber.* British Standard Institute, BIS London.

BS 5268. 2002. *Structural Use of Timber Part 2 (2002). Code of Practice for Permissible Stress Design Material and Workmanship.* British Standard Institute, BIS London.

Buildam. http://www.buildam.com (accessed 5 February 2019).

EN 408. 2003. *Timber structures –Structural timber and Glued-laminated Timber: Determination of some Physical and Mechanical Properties.* European Committee for Standardization, CEN, Brussels, Belgium.

Faria, D. 2019. Performance of glulam beams produced with free-formaldehyde adhesive and underexploited rubber wood treated with preservatives solutions of chromated copper borate and pyrethroids. *Journal of Adhesion Science and Technology* 18: 1145-1162.

Gross, H. 2013. *Glulam Handbook Volume 1.* Sweden: The Swedish Forest Industries Federation.

Harte, A. 2018. *Introduction to timber as an engineering material.* Galway, Ireland: ICE Manual of Construction Materials, 2009 Institution of Civil Engineers.

Lacroix, D.N. 2014. Flexural response of glued laminated (glulam) beams subjected to blast loads. *World Conference on Timber Engineering:* 9.