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MATRIX-BASED ANALYSIS AND SIMULATION OF A GLUBAM SPACE TRUSS WITH CARBON FIBER- REINFORCED COMPOSITE JOINT

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ABSTRACT: Trusses are commonly used as a roofing system and in other infrastructure. Traditionally, steel is used for truss members and connectors, but its negative environmental impact from iron mining makes it an unsustainable material. This study explores the potential of using glue-laminated bamboo (glubam) made from Bambusa blumeana, a common bamboo species in the Philippines, as a space truss member, and carbon-fiber reinforced composite as member connectors using matrix-based analysis and computer simulation. The researcher analyzed the behavior of the space truss in terms of nodal displacements, internal strain, and internal stresses. Physical and mechanical properties of glubam were determined using ASTM D143-19. The obtained mechanical properties, such as compressive and tensile strengths, were used for matrix analysis of the space truss. The stiffness equation of the truss was determined by matrix analysis, and the maximum load that the truss could carry was calculated, taking into account the proportional limit. The results of Fusion 360 simulation indicated that the connectors will behave elastically before the glubam reaches the proportional limit stress of 59 MPa. Furthermore, the study found that the strength-to-unit weight ratios of glubam and the FRP connector are 0.0318 and 0.0115, respectively, making them more efficient than steel, which has a ratio of 0.0052. These findings highlight the excellent potential of glubam and fiber-reinforced composite as truss component materials.

Keywords: Four or five keywords (The first characters of each key are in capital/uppercase letters), Italic

1. INTRODUCTION

Framed structures are prevalent in the construction industry, used in the creation of buildings, towers, bridges, and other structures. These structures act as the framework or skeleton, providing crucial structural integrity. One common type of framed structure is the truss, which consists of straight members connected by flexible joints. These members form triangular panels that result in a rigid and stable configuration.[1] The replication of truss-like space structures in nature highlights the desire to minimize stress while maximizing strength. This approach capitalizes on the load capacity of each truss member. [2]

Steel is a common material used in truss construction. Typically, structural steel is made of plain carbon steel, designated as ASTM 36 or A36. This material has a yield stress of 249 MPa and a tensile strength ranging from 400 MPa to 550 MPa. Engineers are particularly interested in this type of structural steel due to its ability to undergo significant deformation before fracturing, commonly referred to as ductility. [3] The persistent utilization of steel in construction has a significant environmental impact due to the negative consequences of steel mining. Steel is an unsustainable material that is weighty and produces high carbon emissions during fabrication. To address this issue, timber has become a popular alternative material for the fabrication of trusses. In the Philippines, timber species are classified based on their strength, ranging from moderately low strength, such as Almaciga wood with a tensile strength parallel to the grain of 7.35 MPa, to high strength species like Yakal wood with a tensile strength parallel to the grain of 15.30 MPa. [4]

Bamboo is recognized as a highly sustainable material due to its fast growth rate and natural production. It has found a wide range of applications in construction, and its physical properties make it a promising economic alternative to steel. [5] Its tensile strength, for instance, can compare to that of steel, making it a suitable replacement in various structural applications. With its abundance and renewability, bamboo presents a viable and sustainable solution for reducing the environmental impact of construction activities while simultaneously providing economic benefits.[6]–[8]

The primary objective of this research is to evaluate the performance of a glue-laminated (glubam) space truss constructed from *Bambusa blumeana* with fiber-reinforced composite connectors or joints, utilizing structural matrix analysis and Autodesk Fusion 360 simulation. The study's focus includes analyzing the behavior of the truss, including the determination of maximum stresses, deformations, and strains within both the truss members and joints. Through this investigation, the researchers aim to provide insights into the potential advantages and drawbacks of using such materials in the construction of space trusses.

2. RESEARCH METHODOLOGY

The flow of the research is presented in Figure 1. The researcher designed the methodology to achieve the research objective, beginning with material selection and culminating in the determination of the behavior of the truss prototype.

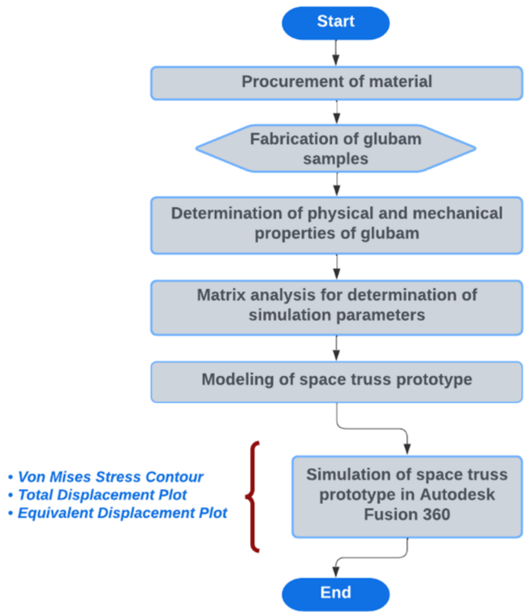


Fig. 1 Research Flow

2.2 Procurement Of Materials

The present paper utilizes Bambusa blumeana or Kawayang Tinik, which is widely recognized as the most commonly used bamboo species in the Philippines. [9] Figure 2 shows the procedure on how the glubam was formed from selection of bamboo culms. The culms utilized in the study were procured from the Sampaloc region of Manila and ranged in diameter from 50 mm to 80 mm with a thickness of 5 to 8 mm.

Bamboo culms were cut into strips having a width of 18 ± 2 mm and a thickness of 6 ± 2 mm. The bamboo strips were immersed in a 6% boric salt solution to eliminate possible fungi infestation.

Fig. 2 Procedure of Fabricating Glubam

The researcher formed the dried bamboo strips into a configuration as illustrated in figure 3 and used wood glue on every adjacent face of the strips. The first layer was glued and clamped until it was dry, followed by the second and third layers which were made in the same manner until the desired cross-section was achieved. The resulting configuration of the glubam cross-section was consistent with the design developed by Wu, which involved arranging groups of bamboo strips in alternate directions. [10]

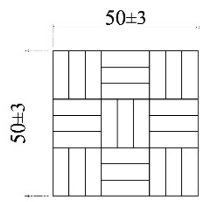


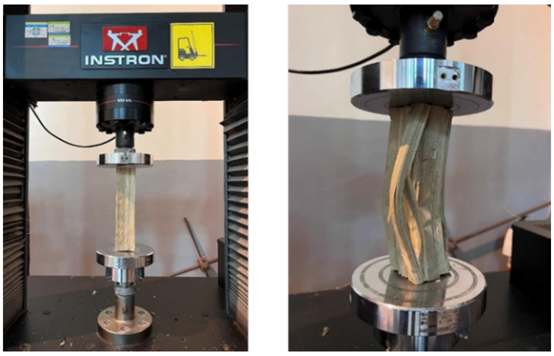
Fig. 3. Glubam Cross-Section Geometry and Configuration with Dimensions in mm

2.3 Determination of Physical and Mechanical Properties of Glubam

The researchers determined the necessary physical and mechanical properties of glubam according to ASTM D143-19 Standards (Standard Test Methods for Small Clear Specimens of Timber).

For the determination of compressive strength, the researcher performed compression-parallel-to-grain tests on 50 by 50 by 200 mm primary method specimens as depicted in figure 4 and researcher measured the actual cross-sectional dimensions and length. A universal testing machine was used equipped with a spherical bearing to ensure uniformity of load distribution over the end of the specimen. The load was applied continuously at a rate of motion of a movable crosshead at 0.003 mm/mm. The Load-compression readings were continued until the proportional limit was well passed.

Fig. 4 Compressive Strength Test of Glubam Sample



The researcher used a dog-bone-shaped specimen, as described in ASTM D143-19 to determine the tensile strength. The specimen had a cross-section of approximately 9.5 mm x 4.8 mm in the middle portion and larger ends with a cross-section of approximately 25 mm x 25 mm. The researcher rated the load at 1 mm/min to determine the tensile strength using the universal testing machine as depicted in figure 5.

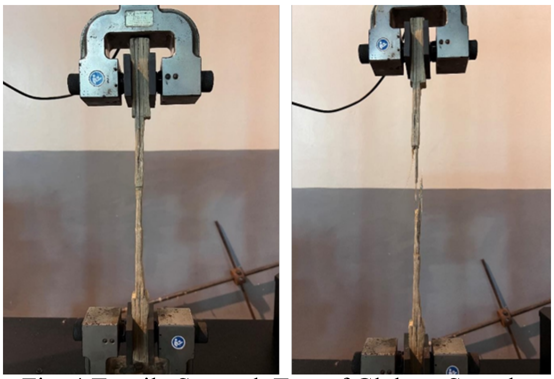


Fig. 4 Tensile Strength Test of Glubam Sample

The determination of the shear strength of glubam was made by the researcher by fabricating a sample having a dimension of 50 mm x 50 mm x 63 mm also following the procedure specified in ASTM D143-19. The sample was loaded in the universal testing machine at a load rate equal to 0.6 mm/min.

The specific gravity was determined by having a sample of 50 mm x 50 mm x 50 mm cube trimmed from the fabricated glubam. The sample was weighed using a digital weighing scale having an accuracy of 0.0001 grams. The weight of the sample was recorded, and the unit weight was determined using equation 1.

$$\gamma_{glubam} = \frac{W_{glubam}}{V_{glubam}} \quad (1)$$

The specific gravity was determined by using equation 2:

$$sp.gr._{glubam} = \frac{\gamma_{glubam}}{\gamma_{water}} \quad (2)$$

2.4 Matrix Structural Analysis of Glubam Space Truss

The researcher established a configuration of glubam space truss prototype as presented in figure 5. Each glubam truss member has a length of 1.3 meters forming a tetrahedral space truss structure.

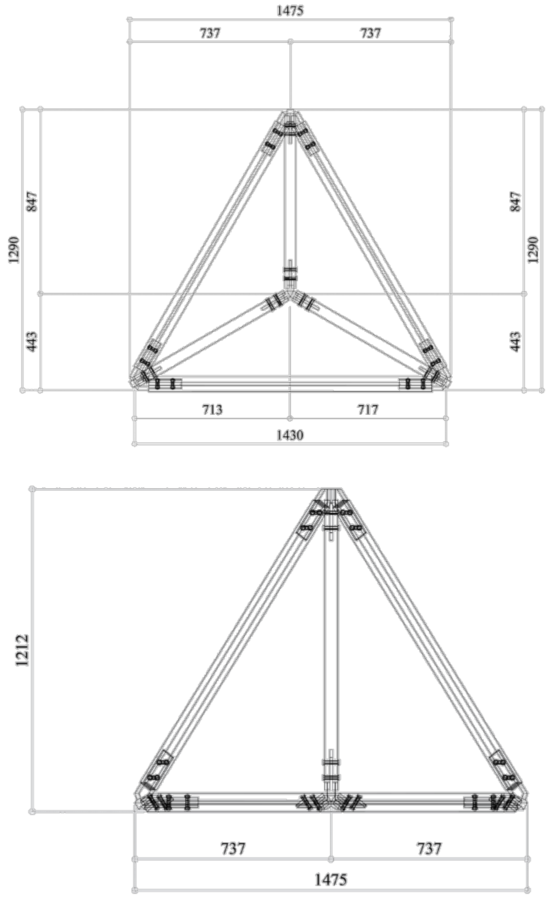


Fig. 5 Configuration of Glubam Space Truss with Dimensions in mm

The stiffness equation of each member of the tetrahedral gkubam space truss structure was solved using equation 3.

$$\begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} = \frac{AE}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} \quad (3)$$

Many truss members are obliquely oriented, or the local axis of the member is not parallel to the global axis. In that case, the stiffness of the member must be modified relative to the global axis. To modify the stiffness equation of the truss member a rotation matrix as shown in equation 4 will be used. This rotation matrix allows the determination of stiffness of truss members that are obliquely oriented both for two-dimensional or space truss.

$$[\gamma]=\begin{bmatrix} l_{x'} & m_{x'} & n_{x'} \\ l_{y'} & m_{y'} & n_{y'} \\ l_{z'} & m_{z'} & n_{z'} \end{bmatrix} \tag{4}$$

The stiffness of the whole truss structure was determined by assembling the stiffness of each of the members. Once the stiffness of the truss is established, it will follow the form of equation 5. [11]

$$\begin{Bmatrix} F_f \\ \cdots \\ F_s \end{Bmatrix}=\begin{bmatrix} K_{ff} & \vdots & K_{fs} \\ \cdots & \vdots & \cdots \\ K_{sf} & \vdots & K_{ss} \end{bmatrix}\begin{Bmatrix} u_f \\ \cdots \\ u_s \end{Bmatrix} \tag{5}$$

The maximum load that the structure can carry was determined from the stiffness equation of the whole space truss. The load is a downward concentrated load at node A. By setting initial values of load, the stresses on each member were checked. The load value that produces an internal axial stress on the members equal to the proportional limit was identified as the load that will be used for the computer simulation of the space truss.

2.5 Computer Simulation for the Analysis of Behavior of Glubam Space Truss

Using AutoCAD software, the researcher constructed a 3D model of the fiber-reinforced (FRC) composite connector. The shape and dimensions of the connector, which take into account its mechanical properties, are illustrated in figure 6. The connector has two holes on each leg that align with corresponding holes in the glulam truss member.

It is also AutoCAD which was used by the researcher to create a 3D model of the six glubam truss members, and 24 bolts connecting the member and the FRC connector, as shown in figure 29. These components were then combined to form the space truss that will be analyzed in Fusion 360.

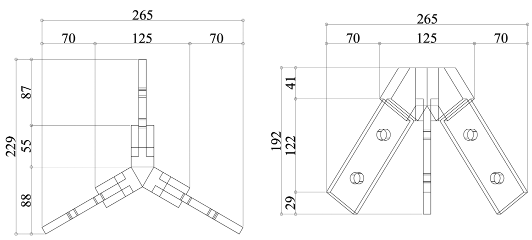


Fig. 6 Design of Fiber-Reinforced Composite Connector with Dimensions in mm

The 3D model of the glubam space truss is presented in figure 7. The .dwg file was uploaded in Fusion 360 for analysis. The environment was converted from a direct modeling environment to a parametric environment (timeline enabled). All bodies were converted to components.

Fig. 7 Glubam Space Truss Model in AutoCAD 3D Space

The components were jointed such that the FRP connector, the glubam truss member, and the bolts are in a "revolute" joint. This jointing configuration allows rotation along the local z-axis of the glubam truss. The joint motion limits are not identified to allow free rotation as presented in figure 30. This procedure was done to all connections.

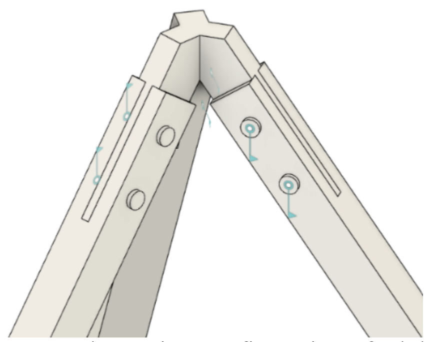


Fig. 8 Revolute Joint Configuration of Glubam Space Truss

The materials of each component were defined in the software. The structural constraints were set limiting displacements on nodes B, C, and D while allowing a complete degree of freedom on node A along global x, y, and z axes. A load was placed vertically downward at node A.

The load was set at different values – 98.10 N, 196.20 N, 294.30 N, 393.40 N, and 490.50 N. The researcher checked if there were interfering components to the model before checking of results. The Von Mises stress, total displacement, and equivalent strain plot were generated by the researcher and checked for maximum and minimum values of stress, strain, and deformation.

3. RESULTS

3.1 Physical and Mechanical Properties of Glubam

The mechanical properties glubam truss member is determined in accordance with ASTM D143-19. Similar test was also performed by Kariuki on 2014 for the determination of compressive strength of glubam made from *Yushania alpina*. [12] The result of the compressive strength showed that the glubam has a total compressive strength of 25.39 MPa. The stress-strain diagram for the compressive strength test is shown in figure 9. It can be seen from the curve that the maximum strain at failure is 0.055. The specimen has a modulus of elasticity for compression that is equal to 1,862 MPa; this was determined from the initial slope of the curve. The proportional limit is at 17.70 MPa stress and 0.017 strain.

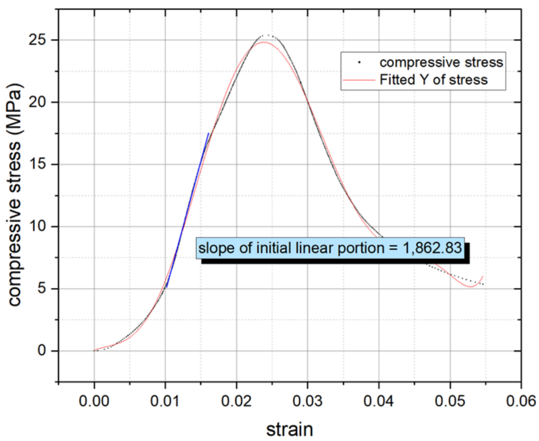


Fig. 9 Compressive Stress-Strain Diagram of Glubam

The stress-strain diagram for the tensile strength test is shown in figure 10. The tensile strength test is performed using ASTM D143-19 (Standard Test Methods for Small Clear Specimens of Timber,. United States, 2009). It can be seen from the curve that the maximum strain at failure is 0.0066. The tensile strength of the glubam was determined to be equal to 209.86 MPa. The specimen has a modulus of elasticity for tension of to 37,391 MPa; this was determined from the initial slope of the curve. The proportional limit is at 59 MPa stress and 0.0024 strain.

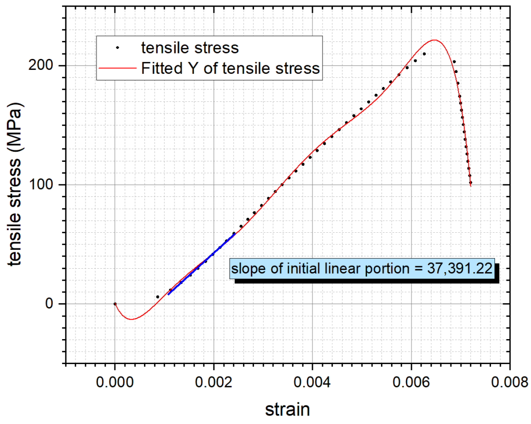


Fig. 10 Tensile Stress-Strain Diagram of Glubam

The shearing stress–strain test is presented in figure 34. From the figure, the shearing strength of the glubam truss member was found to be equal to 16.95 MPa. This test was conducted was conducted in accordance to ASTM D143-19.

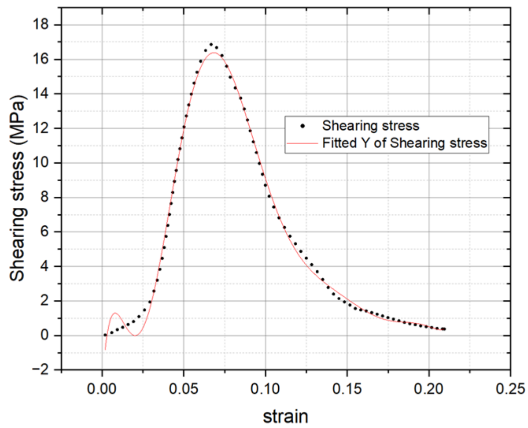


Fig. 11 Shearing Stress-Strain Diagram of Glubam

Physical properties like unit weight and moisture content are determined by performing laboratory experimentation. The volume of the glubam sample is measured and weighed. It was found that the unit weight of glubam is 9,547 N/m3 having a specific gravity equal to 0.67. The moisture content values of glubam is presented in table 12. The average value of moisture content is 8.29% having a coefficient of variability of 0.69%.

Table 1 Moisture Content of Glubam

Sample ID	Moisture Content	Mean	Standard Deviation	COV
MC1	8.36%	**8.29%**	0.0006	**0.69%**
MC2	8.29%			
MC3	8.22%			

The stiffness equation of the glubam space truss is presented in figure 12. From the stiffness equation, the vertical load to be applied at node A for the computer simulation was found to be equal to 490.50 N.

$$
\begin{Bmatrix} F_{Ax} \\ F_{Ay} \\ F_{Az} \\ F_{Bx} \\ F_{By} \\ F_{Bz} \\ F_{Cx} \\ F_{Cy} \\ F_{Cz} \\ F_{Dx} \\ F_{Dy} \\ F_{Dz} \end{Bmatrix} =
\begin{bmatrix}
7{,}749 & 0 & 0 & -23 & 0 & 0 & -3{,}863 & -6{,}271 & 2{,}217 & -3{,}863 & 6{,}271 & -2{,}217 \\
0 & 30{,}792 & 0 & 0 & -10{,}624 & -7{,}242 & -6{,}271 & -10{,}264 & 3{,}621 & 6{,}271 & -10{,}264 & 3{,}621 \\
0 & 0 & 7{,}749 & 0 & -7{,}242 & -5{,}143 & 2{,}217 & 3{,}621 & -1{,}303 & -2{,}217 & 3{,}621 & -1{,}303 \\
-23 & 0 & 0 & 7{,}749 & 0 & 0 & -3{,}863 & 0 & 6{,}652 & -3{,}863 & 0 & -6{,}652 \\
0 & -10{,}264 & -7{,}242 & 0 & 10{,}310 & 7{,}242 & 0 & -23 & 0 & 0 & -23 & 0 \\
0 & -7{,}242 & -5{,}143 & 0 & 7{,}242 & 28{,}232 & 6{,}652 & 0 & -11{,}544 & -6{,}652 & 0 & -11{,}544 \\
-3{,}863 & -6{,}271 & 2{,}217 & -3{,}863 & 0 & 6{,}652 & 23{,}111 & 6{,}271 & -8{,}869 & -15{,}385 & 0 & 0 \\
-6{,}271 & -10{,}264 & 3{,}621 & 0 & -23 & 0 & 6{,}271 & 10{,}310 & -3{,}621 & 0 & -23 & 0 \\
2{,}217 & 3{,}621 & -1{,}303 & 6{,}652 & 0 & -11{,}544 & -8{,}869 & -3{,}621 & 12{,}870 & 0 & 0 & -23 \\
-3{,}863 & 6{,}271 & -2{,}217 & -3{,}863 & 0 & -6{,}652 & -15{,}385 & 0 & 0 & 23{,}111 & -6{,}271 & 8{,}869 \\
6{,}271 & -10{,}264 & 3{,}621 & 0 & -23 & 0 & 0 & -23 & 0 & -6{,}271 & 10{,}310 & -3{,}621 \\
-2{,}217 & 3{,}621 & -1{,}303 & -6{,}652 & 0 & -11{,}544 & 0 & 0 & -23 & 8{,}869 & -3{,}621 & 12{,}870
\end{bmatrix}
\begin{Bmatrix} u_A \\ v_A \\ w_A \\ u_B \\ v_B \\ w_B \\ u_C \\ v_C \\ w_C \\ u_D \\ v_D \\ w_D \end{Bmatrix}
$$

Fig. 12 Stiffness Equation of Glubam Space Truss

3.2 Behavior of Glubam Space Truss from Fusion 360 Simulation

The researcher generates the Von Mises stress and total displacement contours of the FRC truss member connectors for a 490.50 N downward concentrated load at node A. It was found that from all the FRP connectors, joint A exhibited the maximum stress of 0.7836 MPa, while joints B, C, and D can be seen to have to zero stress at the ends of their legs.

A more focused analysis of joint A is presented in figures 12, 13, and 14. The figure shows the Von Mises stress, equivalent strain, and total displacement contours of joint A. This procedure was similar to the research done by Albermani on the analysis of stress on PVC bamboo truss prototype.[13] The maximum stress was located at the upper face of the base of the legs having a value of 0.7836 MPa. This is also the most stressed portion among all the portions of all the connectors in the system. The connector has a maximum strain of 0.0004 and a maximum displacement of 0.017 mm.

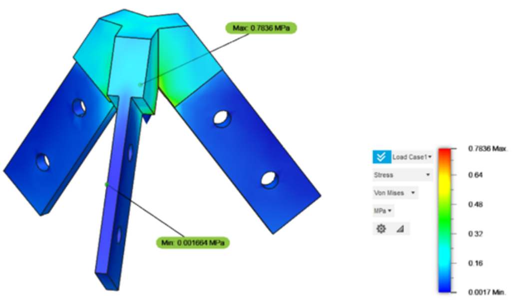


Fig. 12 Von Mises Stress Contour of FRC Connectors

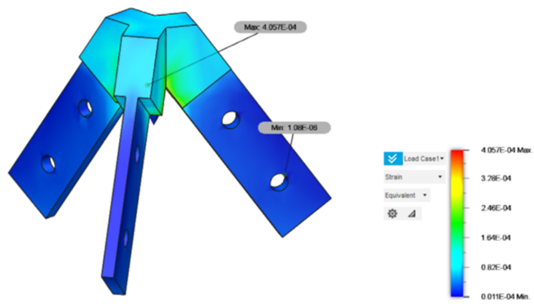


Fig. 13 Equivalent Strain Plot of FRC Connectors

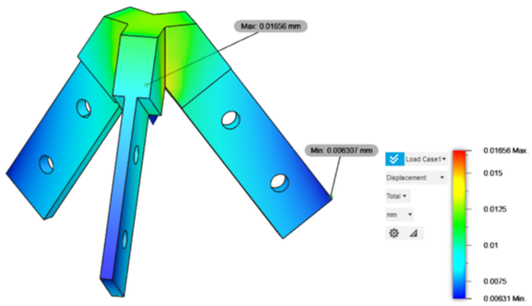


Fig. 14 Total Displacement Plot of FRC Connectors

The Von Mises stress contour of the members is presented in figure 41. The researcher inspected some portions of the members to check for different values of stress. From among the members, Members AB, AC, and AD exhibited the highest stress located at the ends of members at A. The most elevated stress is equal to 0.8051 MPa. The minimum stress, however, was observed at members CB, CD, and BD near the connectors having a very small value than can be taken as equal to zero.

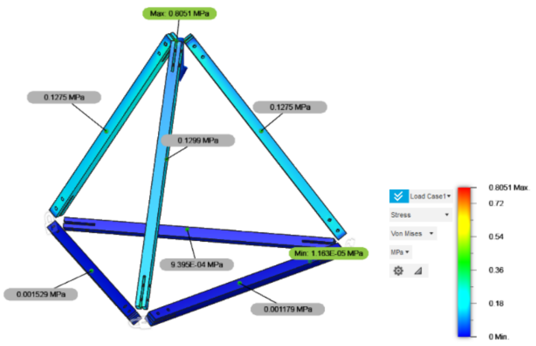


Fig. 15 Von Mises Stress Contour of Glubam Truss Members

The researcher also developed the stress-strain diagram on the most stressed portion of the glubam truss as presented in figure 44. The plotted values of internal stress and the corresponding strain was fitted with a linear regression and the result showed that the curve has a Pearson correlation value equal to 1.00. This high strength of linearity indicates an elastic behavior of the member.

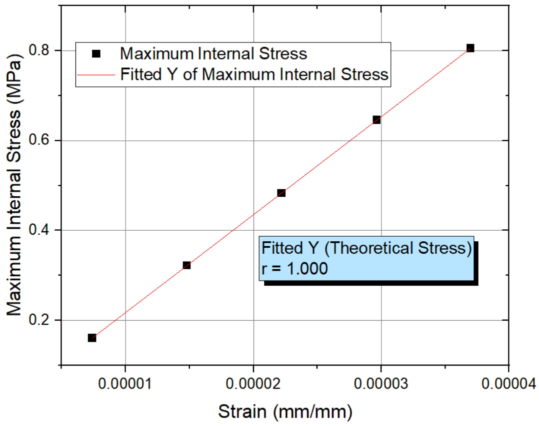


Fig. 16 Internal Stress-Displacement Curve of Glubam from Fusion 360 Simulation

4. CONCLUSIONS

The research findings dislcosed that glue-laminated bamboo (glubam) made from Bambusa blumeana can be a viable alternative to steel as a truss member, owing to its high mechanical properties. Despite having a tensile strength almost 50% lower than ASTM 36 steel, glubam's lightweight nature makes it an attractive option. In addition, the fiber-reinforced polymer (FRP) composite developed as a truss member connector in this study is much lighter than ASTM 36 steel by 629%, yet can exhibit 35% of steel's tensile strength. Furthermore, the strength-to-unit weight ratios of glubam and the FRP connector are 0.0318 and 0.0115, respectively, making them more efficient than steel, which has a ratio of 0.0052.

It can be concluded that the connectors will behave elastically before the glubam reached the proportional limit stress of 59 MPa. This highlighted the excellent potential of glubam and FRP as truss component materials.

5. RECOMMENDATIONS

After conducting the fabrication and actual experimentations, the researchers identified several areas for exploration. Firstly, the glubam cross-section configuration resulted in some unfilled voids due to the use of wood glue. To increase the strength of glubam, the researchers recommend implementing a pressing procedure for the bamboo strips to minimize the occurrence of voids. Secondly, an actual experimentation on the behavior of the glubam truss must be made to compare actual behavior to theoretical results obtained from computer simulation. Finally, . Finally, the behavior of the glubam truss with FRP joint connector beyond the proportional limit up to failure needs to be investigated, and the long-term slippage of connections must be checked.

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