© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

A Literature Review On the Use of Bamboo as A Truss Member and Fiber-Reinforced Polymer as A Truss Jointing Material

Joe Robert Paul G. Lucena[1,2], Orlean G. Dela Cruz[2*]

[1]Infrastructure Development Office,
Technological University of the Philippines Taguig, Western Bicutan, Taguig City 1630, PHILIPPINES

[2]Graduate School,
Polytechnic University of the Philippines, Manila 1016, PHILIPPINES

*Corresponding Author

DOI: https://doi.org/10.30880/ijie.2023.15.02.017
Received 23 February 2023; Accepted 17 May 2023; Available online 31 July 2023

Abstract: A truss is a structure that has a rigid configuration formed by an assembly of straight members connected by pins. Many roofing systems use trusses, but the wide variety of truss configurations in architecture is an advantage to creating vast arrays of aesthetics in buildings. Steel, mainly plain carbon steel designated A36, is the most used material for truss members and joint connectors. However, these members are both heavy and non-sustainable, so several kinds of literature recommend studying the potential of using lightweight and sustainable alternatives. This review focuses on using bamboo in truss and the potential of fiber-reinforced composite as a truss joint connector. Bamboo culms and glued-laminated bamboo (glubam) are the two types of bamboo commonly used in truss fabrication based on the review. Bamboo culms from Dendrocalamus asper exhibit a tensile strength of 340 MPa, while the glubam made of Yushania alpina has 364 MPa. Other mechanical properties of bamboo necessary for the truss analysis are not yet clearly defined, although studies used ASTM D143-09 to determine several mechanical properties of bamboo or glubam. Fiber-reinforced composite can exhibit an enormous array of varieties and still demonstrate a strength close to or even higher than steel. It is lightweight and can reach a tensile strength of 700 MPa. The researcher recommends synthesizing bamboo or glubam as truss members and fiber-reinforced composite as truss joint connectors.

Keywords: Glubam, bamboo, fiber-reinforced polymer, truss jointing material, truss member

1. Introduction

Framed structures, including bridges, buildings, and many other structures, are used in construction. They are the framework or skeleton that keeps the structure's structural integrity. Besides, a truss is a frame structure formed by an assembly of straight members connected by flexible joints. Moreover, the connected joints include triangular panels, making the truss develop a rigid configuration [1]. Structures like space trusses are copied in nature, causing them to seek an efficient way to minimize stress while maximizing strength, just like how natural systems behave. In addition, the configuration takes advantage of the load capacity of each truss member [2].

The use of steel is conventional as a truss material. Structural steel usually comes as plain carbon steel designated ASTM 36 or A36 with a yield stress of 249 MPa and tensile strength ranging from 400 MPa to 550 MPa. Structural steel of this kind captures the interest of engineers because of its property to undergo considerable deformation before exhibiting fracture or what is commonly termed malleable [3].

*Corresponding author: ogdelacruz@pup.edu.ph
2023 UTHM Publisher. All rights reserved.

The continuous use of steel in construction affects the environment because of the negative impact of steel mining. In addition, steel is not a sustainable material; it is heavy and produces high carbon footprint emissions during fabrication. A common alternative material used in the fabrication of trusses is timber. However, when improperly managed, continuous wood logging would lead to deforestation, so there is a need for sustainable materials other than steel and wood. In addition, the search for alternative materials other than steel is in continuous progress. Several studies strive to assess the performance of trusses made of bamboo. Bamboo is a sustainable material that is heavily abundant in nature. There are various types of bamboo in the Philippines; it even became the sixth-largest exporter of bamboo in 2015 [4]. This review focuses on the potential of bamboo as an alternative truss member and fiber-reinforced polymer (FRP) as an alternative truss member connector to steel materials. The study aims to determine the physical and mechanical properties of bamboo used in the fabrication of trusses and the potential of fiber-reinforced polymer (FRP) as a jointing material for bamboo trusses.

2. Review Methodology

The review was conducted systematically following the concept of The Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020). The authors used this method to address the poor reporting of systematic reviews, PRISMA[5]. Observational study results indicate using PRISMA statements with more thorough systematic review reporting. The benefits of using PRISMA in literature review include good demonstration quality and assessing strengths and weakness [6]–[9]. The creators envision PRISMA 2020 as a tool for studies with or without synthesis. After being cited in over 60,000 papers, the PRISMA flow diagram established a standard for academic rigor in publishing systematic reviews and meta-analyses [10].

The researchers started the review by selecting an online database – Scopus. It supports Boolean syntax, a type of search that allows users to mix terms with operators such as AND. NOT and OR are used to obtain more accurate results. [11]. Moreover, it tracks citation data for other journals and provides access to the system's databases for its journal impact measures (SNIP and SJR) [12]. Next, the authors presented the conduct of the evaluation in the diagram depicted in Fig. 1. Keywords like "Bamboo as a replacement to steel," "Glubam," and "Fiber-Reinforced Polymer" were inputted into the database search engine using Boolean syntax and operators. The search showed 220 results and was screened based on the literature title—removal of duplicate entry before the eligibility screening. The methodology flow is depicted in Fig. 1 to conduct the eligibility screening.

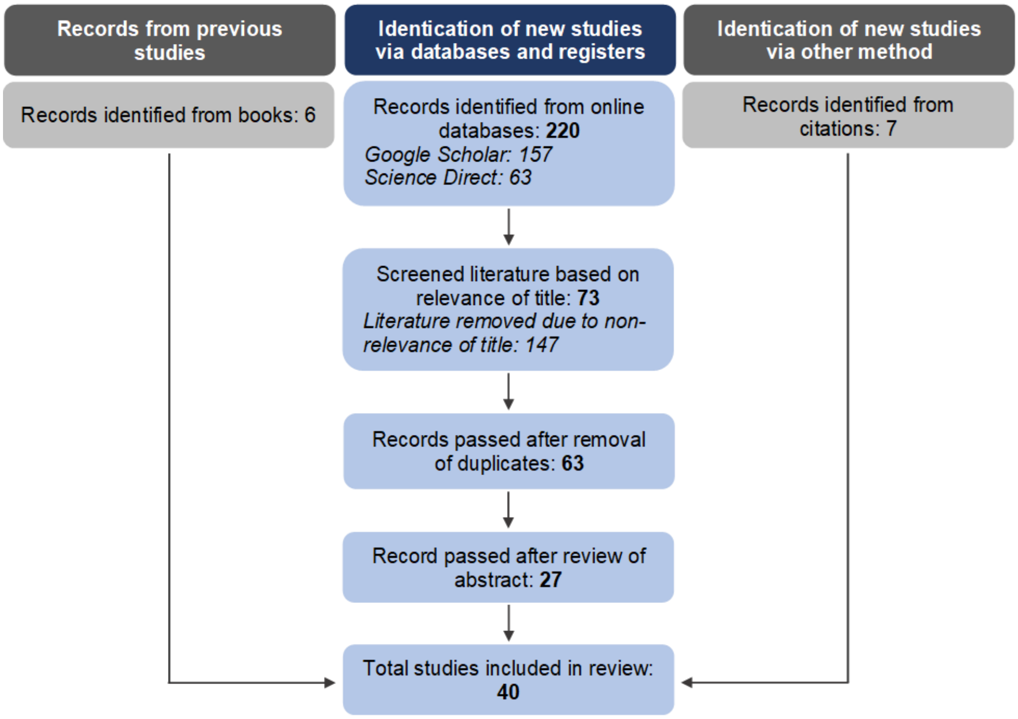

Fig. 1 - Systematic review flow chart

The screening of the eligibility of literature starts with evaluating the abstract. Screening the literature's abstract has allowed the researcher to gain an overview of the paper. The researcher could check the paper's relevance in his conduct of the review. Following the evaluation of the abstract is the assessment of the paper's Conclusions and Recommendations. This portion of the literature allows the researcher to look for the interpretation of the study's results. Conclusions are drawn from this portion by the paper's author. Findings and recommendations such as research opportunities, gaps, and challenges allow for the extraction of ideas. The review of Results and Discussions follows; this portion of the study justifies the conclusions and recommendations of the author. The last item on the eligibility screening is the review of the study's methodology. A review of methods allows the researcher to gain an overview of how the author has undertaken the research. The process can serve as a reference for future research, especially those similar to the investigation. At the end of the review, the researcher should be able to answer the following questions:

- What are the physical and mechanical properties of various bamboo used as alternatives to steel?
- What are the mechanical properties of glue-laminated bamboo (glubam) used in fabricating trusses?
- What mechanical properties of fiber-reinforced composites make them suitable substitutes for steel?
- What are the theoretical and actual test setups in evaluating the performance of a truss made from glubam?

3. Bamboo as Alternative Truss Material

Bamboo is an excellent sustainable, quickly developing, and naturally produced material with many applications in construction. Its physical property makes it a good potential as an economical alternative to steel [13]. Many construction activities involve bamboo; one application replaces steel reinforcement for concrete, and some bamboo species can exhibit a tensile strength equivalent to mild steel. Using bamboo in this manner concludes that it could be a good alternative for low-cost green structures and yields a cheaper construction cost of about three times than steel [14]-[16].

Numerous studies mention the use of bamboo as a component in the construction of truss constructions. The mechanical properties of bamboo are determined to check the potential of bamboo in buildings, particularly as truss members. Table 1 shows various studies of trusses made of bamboo. Studies using bamboo as an alternative to steel are either a culm material or a glubam material.

Table 1 - Different studies that use bamboo as truss material

Title	Material	Description	Reference
Steel and Glubam Hybrid Space Truss	Glue-Laminated Bamboo (Glubam)	The researcher used glued bamboo strips, forming a solid laminated member.	[17], [18]
Lightweight Bamboo Double Layer Grid System	*Phyllostachys bambusoides* and *Phyllostachys pubescen*	The researcher used bamboo culms with 50 mm to 65 mm diameters.	[19]
Investigation on Mechanical Properties and Suitability of Highland Bamboo (*Yushania alpina*) for Use in Structural Truss Members	*Yushania alpina*	The researcher used bamboo culms and determined their mechanical properties like compressive, tensile, and bending strength.	[20]
Performance of Glue Laminated Bamboo Beams And Trusses	*Yushania alpina*	Bamboo cut to strip and glued to form a solid laminated member	[21]

3.1 Physical and Mechanical Properties of Truss Member Made of Bamboo

The physical and mechanical properties of truss members are vital in evaluating the performance of a truss structure. Truss members are assumed only to carry axial load, either compressive or tensile. Bamboo's compressive and tensile strengths must also be determined to compare resilience against stress. Properties like the cross-sectional area, length, and elastic modulus must be necessary to determine the natural stresses and strains that develop in truss members.

Wu [18] created a hybrid space truss in 2018. Glubam and steel members comprise the truss prototype. Glubam members compose the truss' upper and compressive chords while using steel for the other members. Shown in Fig. 2 is the cross-section of the glubam.

Fabricating glubam members involves layering three bamboo strips with a width of 18-19 mm and pressing, forming a small square cross-section of approximately 18.6 mm x 18.6 mm. Gluing the small cross-sections creates a more extensive square cross-section with a 55-56 mm side. The glubam cross-section is a configuration of nine square modules of glued bamboo strips. The physical and mechanical properties of glubam were tested under Chinese Standards [22], [23], and tabulated in Table 2 are the physical properties.

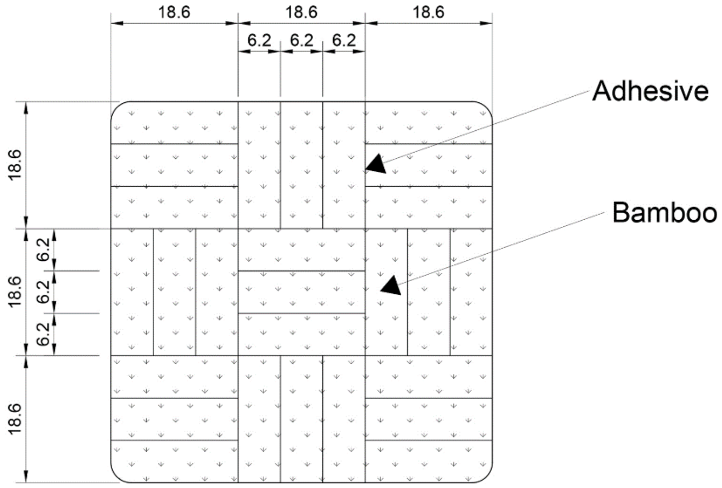

Fig. 2 - Cross-section of glubam truss member [18]

Table 2 - Physical and mechanical properties of glubam [18]

Properties	No. of specimen	Mean value	SD	COV	Accuracy index ($\alpha = 0.95$)	5th percentile
Air-dry density (kg/m^3) [24]	33	736.9	52.3	7.1%	0.02%	680.1
Oven-dry density (kg/m^3) [24]	33	695.6	49.5	7.1%	0.02%	641.6
Compressive strength (MPa) [25]	33	71.2	4.5	6.3%	2.1%	62.9
Tensile strength (MPa) [25]	69	106.7	20.3	19.0%	4.5%	65.3
Shearing Strength (MPa) [25]	24	7.1	1.0	14.5%	5.8%	5.6
Bending Strength (MPa) [25]	61	112.6	15.2	13.5%	3.4%	84.3

Glubam made from *Yushania alpina* was also fabricated in the study of Kariuki in 2014 [21]. The researcher harvested bamboo culms which are three and a half years old. The bamboo culms are from the region of Kamae, Kenya. Selected culms for making the bamboo strips have diameters greater than 80 mm and thicknesses greater than or equal to 10 mm. The fabrication of glubam started by gluing bamboo strips adjacent to each other, forming the first layer, considering that the inner (or outer) layer of bamboo strips is on the same side as the first. Fabricating the second layer is similar to making the first layer. It was then placed atop the first layer and then glued. The glubam member is finished by gluing succeeding layers to attain the desired dimension. Assembled layer comes in different configurations, as shown in Fig. 2.

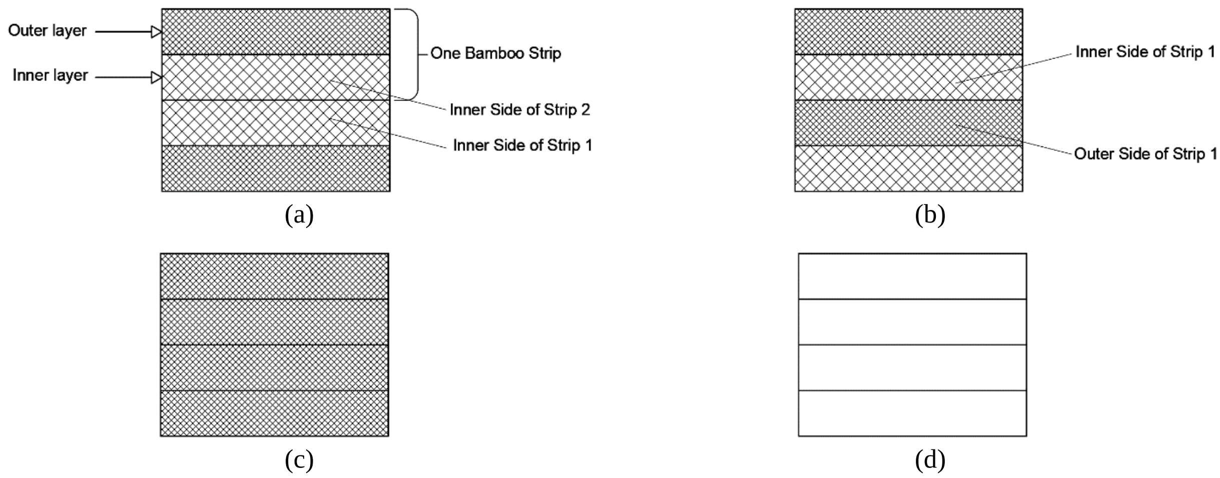

Fig. 3 - Different configurations of layered bamboo strips [21]

From Fig. 4, configuration (a) glued two layers of bamboo, having both inner and outer layers, where the inner side of the first layer of the bamboo strip is in contact with the inner side of the second layer. Configuration (b) shows the assembly where the bamboo strip's first layer's outer side faces the second layer's inner side. While configuration (c), only the outer layers of the culm compose the strips using glue. Moreover, in configuration (d), only the inner layers of the culm contain the strips using glue [21].

A study by Kariuki determined the mechanical properties of glubam with different configurations. Presented in Table 3 are the mechanical properties of glubam made from *Yushania alpina*. [21].

Table 3 - Mechanical properties of glubam made from *Yushania alpina* [21]

Configuration	Modulus of elasticity (MPa)		Tensile strength (MPa)	Compressive strength parallel to the grain (MPa)	Shearing strength (MPa)	
	Load applied at the face.	Load applied at the edge.			Perpendicular to strip	Parallel to strip
a	12,656.25	15,820.31	363.89 ± 0.52	57.03 MPa	9.0	8.1
b	17,015.63	14,062.50		52.91	8.0	7.7
c	10,125.00	15,820.31	N/A	46.91	9.0	6.6
d	8,437.50	10,125.00	253.06 ± 0.87	30.34	8.7	4.6

Several studies used bamboo culm as truss materials. Using bamboo culm as a truss member eliminates the tedious process of fabricating, making bamboo strips, and gluing. Researchers determine the different mechanical properties of bamboo culms, as presented in Table 4.

Table 4 - Mechanical properties of different bamboo species

Material	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of Elasticity (MPa)	Shearing strength (MPa)	Bending strength (MPa)
Yushania alpina from Gurage, Ethiopia [20]	58.28	136.13	N/A	N/A	57.56
Phyllostachys bambusoides [19]	41.80	N/A	10,052	N/A	N/A
Phyllostachys pubescen [19]	49.50	N/A	10,173	N/A	N/A
Guada angustifolia [26]	N/A	N/A	8,787	N/A	N/A
Dendrocalamus asper	73.65 [27]	340 [28] 232 [27]	23,890 [28]	N/A	N/A
Bambusa vulgaris [27]	78.74	232	20,000	N/A	N/A
Gigantochloa scortechinii [27]	68.62	187	N/A	N/A	N/A
Schizostachyum grande [27]	40.03	149	N/A	N/A	N/A
Gigantochloa atroviolacea [29]	48.77	2.70	N/A	7.52	N/A

3.2 Bamboo Selection and Treatment Process

Different studies have different methods of selecting portions of bamboo culms used for truss member fabrication. However, some glubam materials do not specify the amount of bamboo culm used in making bamboo strips. Therefore, the researchers standardize the procedures for selecting bamboo culms by setting parameters like dimensions, thickness, and location of the culm from its entirety. Table 5 shows the different species of bamboo and the size of the culm used for fabricating truss members.

Bamboo is a non-prismatic member due to the presence of nodes that divides the culms. According to a study on the effects of node, internode, and height position of culms extracted from *Gigantochloa atroviolacea* bamboo, samples have almost identical mechanical properties, such as shear and compressive strength, except for the tensile stress that runs parallel to the grain [29].

Treatment of bamboo for use as a truss member follows ISO 22157:2019. To meet the standard, one must prepare, keep, and test the bamboo specimen within an ambient temperature range of 23 ± 3 degrees Celsius. The relative humidity is only 65 ± 5% [30]. In studies using *Guada angustifolia* to determine the mechanical properties of bamboo, the culms were stored upright before treatment to drain the moisture. The natural fermentation process coincided with the conversion of starch and sugar. The culms were treated by immersing them in a 6% boric salt solution for five days and then dried in the open air for 20 days. The culms were furtherly dried using hot air for 2 hours at 12 intervals continuously for 45 days [26], [31]. Other studies do not undergo the same tedious treatment. In determining the mechanical properties of P*hyllostachys bambusoides* and *Phyllostachys pubescens* bamboo culms, the procedure keeps the moisture contents ranging from 5% to 30% [19].

Glubam material also involves the treatment of bamboo using the bleaching process. The process boiled the bamboo in a solution containing 0.5% Hydrogen peroxide (80%), 0.8% Borax oxide, and 0.2% Boric acid, 5 liters, 8 kilograms, and 2 kilograms, respectively, when added to 1,000 liters of water. After bleaching, the strips undergo air-drying to achieve a moisture content lower than 12% [21]. Another treatment, like carbonation, is also used to bleach bamboo strips. The bleached bamboo strips will form the glubam material with glue as the binding agent [18].

Table 5 - Species, size, culm location, and bamboo age used for truss

Bamboo	Size of Culm	Location of Culm	Age of Bamboo
Yushania alpina [21]	External diameter greater than 80 mm and wall thickness greater than or equal to 10mm	Lower section	3.5 years old
Phyllostachy bambusoides and *Phyllostachy pubescens*[19]	External diameters from 50 to 65 mm and wall thickness of 6mm	N/A	3 to 6 years old

3.3 Test Methods for Determination of Mechanical Properties of Bamboo

A variety of standards assess bamboo's mechanical properties like ASTM D143-09 Standard Test Methods for Small Clear Specimens of Timber, ISO 22157:2019 Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods, BS 373:1957 Methods of testing small transparent specimens of timber, and other national standards.

Test for determination of compressive strength of glubam truss material involves making a sample of 30 mm x 20 mm x 20 mm with an aspect ratio of length to a width equal to 1.5, 2, 3, and 4. The specimen test has a carrying load rate of 2mm/min. This procedure includes the attachment of a data-gathering tool that generates stress-strain. The data-gathering tool will plot the stress-strain curve of the specimen from the time of the load's application up to the specimen's failure [18]. ASTM D143-09 stipulates using a 50 mm x 50 mm x 200 mm to determine the compressive strength parallel to the grain. Besides, the load shall be applied continuously during the test with a 0.003 mm/mm rate. In addition, one should read deformations at 0.002 mm [25].

Determination of the tensile strength of bamboo uses a dog-bone-shaped specimen, as depicted in Fig. 4. The sample has a narrow cross-section equal to 15 mm x 4 mm in the middle, while the ends have larger cross-sections having a dimension of 15 mm x 20 mm.

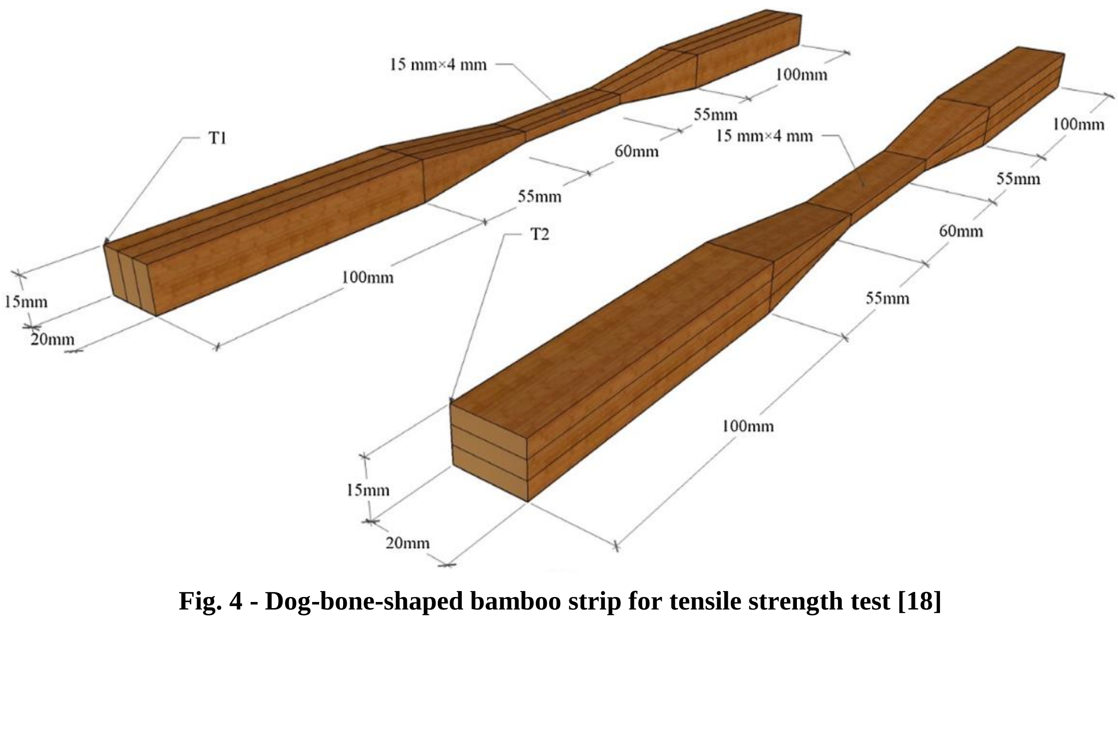

Fig. 4 - Dog-bone-shaped bamboo strip for tensile strength test [18]

ASTM D143-09 requires the exact geometry of the sample for the test. The cross-section of the middle portion of the specimen has a size of approximately 9.5 mm x 4.8 mm, while the ends of the sample are more significant, having a cross-section roughly equal to 25 mm x 25 mm. Therefore, the test will apply a load on the sample at a rate of motion of 1 mm/min [25].

Some truss joints, such as bolted connections, rely on the shear capacity of truss members; hence it is necessary to ascertain their shearing strength. A sample of the glubam material, shown in Fig. 5, was used to measure its shear stress. The specimen has a base dimension of 50 mm x 20 mm, and the upper portion has a size of 30 mm x 20 mm [18].

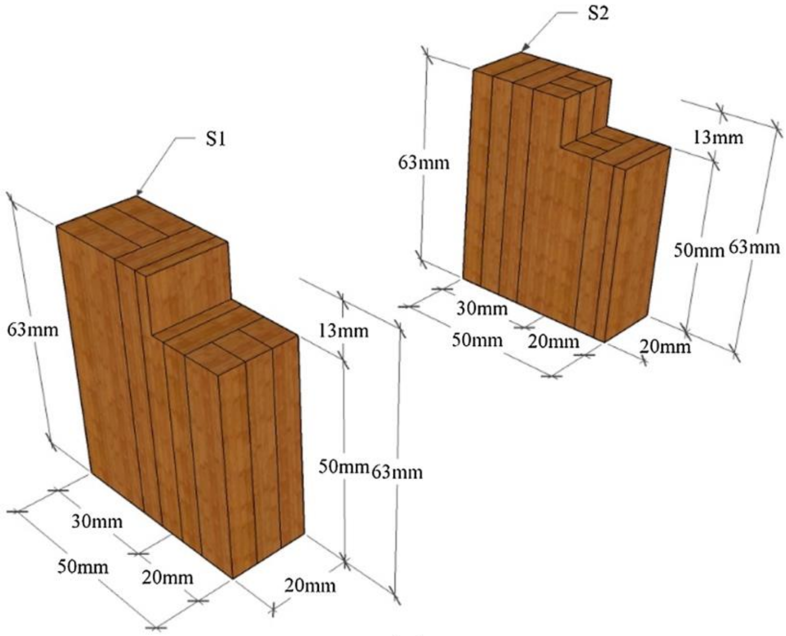

Fig. 5 - Shape and size of bamboo specimen for shearing strength test [18]

A similar specimen shape is required in ASTM D143-0,9, having a base of 50 mm x 50 mm image. During the test, the loads were continuously applied with the rate of motion of the movable crosshead of 0.6 mm/min [25].

The modulus of elasticity of a truss member is necessary to determine the theoretical displacement of truss nodes and the deformation of truss members. A study by Javadian cited a method for determining the modulus of elasticity of bamboo following ASTM D143-09. The Epsilon axial extensometer having a gauge length of 80 mm, was used during the test to determine the deformation of the sample with a set load rate equal to 1 mm/min. Plotting the load-deformation curve and getting the slope of the initial linear portion gives the value of the modulus of elasticity [28].

3.4 Truss Joints for Bamboo and Glubam

There are few established studies on the connection of trusses made of bamboo culms or glubam materials. Truss joints, in theory, act as smooth pins in a truss; therefore, they should not be rigid to eliminate resistance against bending. However, it is hard to attain a perfectly smooth pin. Truss members are also exposed to axial loads in practice and are susceptible to various internal responses. Structural analysis of truss commonly overlooks other internal reactions in truss members considering only the axial force developed on the members.

Trusses made from bamboo culms were connected using split clamps formed by two semi-rings. Depicted in Fig. 6 are the clamps used for bamboo truss joints. The bolts tightened the clamps to ensure grip on the culm. The tightened clamp wraps around a culm with a 95-135 mm diameter. The researcher used steel plates (ASTM A-36) having a thickness of 3.2 mm and a width of 25.4 mm to form the clamp. The consistency is enough for the clamp to follow the irregularity of the circumference of the culm. The circumferential interference is lower than 23 mm to avoid damage to the culm [26].

The clamp configurations in Fig. 6 can carry a maximum axial load of 18,686 N. The study used Guadua Angustifolia culm; the results are in Table 6.

A more direct connection was made by connecting two culms using only 16 mm dia. bolts. A study found that the connection can carry an average maximum axial load of 1.66 kN [32]. Mortar filled the culms near the connections to increase the capacity of the joint further. The connection increased the ability to average 3.70 kN axial force on members [32].

Fig. 6 - Steel clamping configurations for bamboo culm truss connections [26]

Table 6 - Measurements and maximum axial load capacity of different steel clamp configurations [26]

Configuration as shown in Fig. 6	Diameter of culm (mm)	Thickness of culm (mm)	Circumferential Interference (mm)	F_{max} (N)
a	110.6	10.5	14	18,275
b	107.6	10.3	14.5	18,686
c	105.5	10.1	14.6	15,414

There is also a study on the utilization of Polyvinyl Chloride (PVC) joints for bamboo culms that maintain the nature of the bamboo truss that is lightweight. In a survey by Albermani, nonlinear analysis under 10 kN applied load determines the member forces of the truss. Fig. 7 shows the values of nodal displacement as the load increases. The total removal for the 10 kN load is 2.5 mm [19].

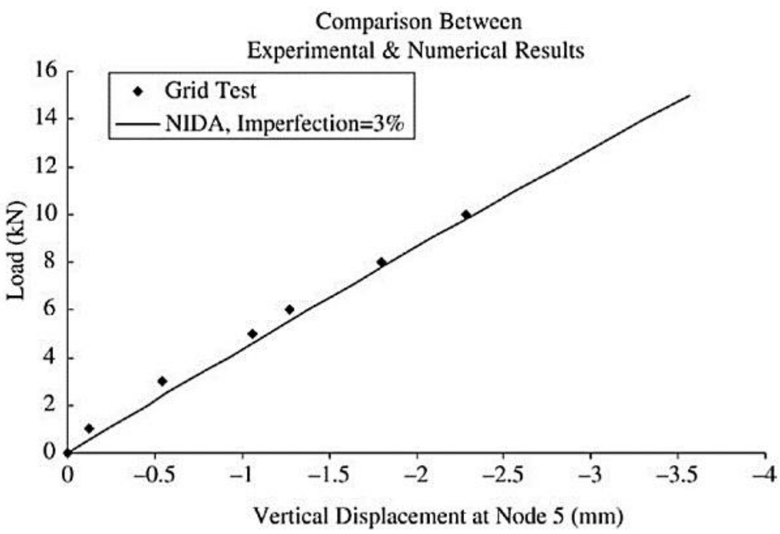

Fig. 7 - Load-displacement diagram of bamboo truss with PVC joint material [19]

The stress distribution within the PVC joint was analyzed using the Von Mises stress contour plot for a particular node. The study found that the stress is within the acceptable limit for a PVC material of 50% of its capacity. Therefore, lightweight trusses in medium spans are recommended for bamboo truss systems with PVC joints [19].

Glubam members do not have as much irregularity in shape as the culm bamboo member, for the glubam member of a truss studied by Wu, a simple design of steel clamping plate having a thickness of 6 mm and bolted [18]. The pre-drilled holes on the glubam are oversized by 0.5 mm relative to the bolt size. From the experiment, the maximum load the space truss could carry reached 27 kN/m^2, and no excessive deformation of the system joints occurred [18].

Xiao used steel plates and bolt connections to analyze the glubam truss[17]. Eccentricity usually occurs at the heel and web joints of trusses made of timber [33]. The evaluation of the truss performed by Xiao neglects eccentricity for the simplicity of analysis [17]. Shown in Fig. 8 is the sample of a glubam truss with steel connections.

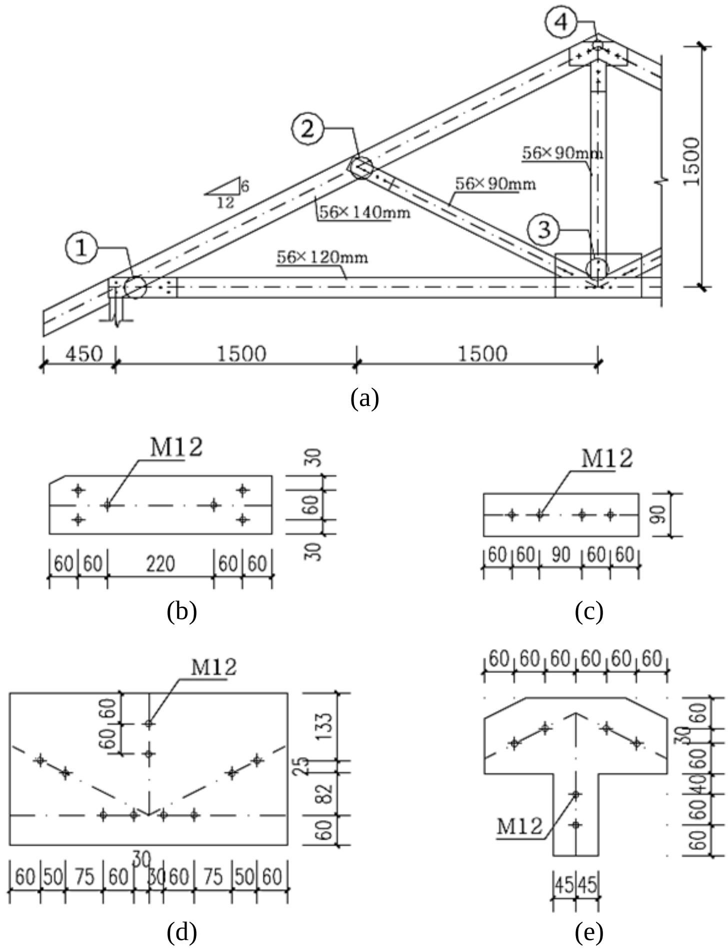

Fig. 8 - The plate and bolt connection geometry for the glubam truss [17]

The ultimate bearing capacity of the glubam joint connection can be determined using Eq. (1) [34]:

$$F_v = min \begin{cases} f_h t_1 d \\ f_h t_1 d \left[\sqrt{2 + \frac{4M_y}{f_h d t_1^2}} - 1 \right] + \frac{F_{ax}}{4} \\ 2.3 \sqrt{M_y f_h t_1 d} + \frac{F_{ax}}{4} \end{cases} \tag{1}$$

In the equation f_h is the embedment strength of glubam, t_1 being the thickness of the minor glubam member in connection; d is the diameter of the bolt; M_y is the yield moment of the bolt and can be determined or estimated to be $0.3 f_u d^{2.6}$; and F_{ax} is the withdrawal capacity of the fastener [34]. In the study of Li et al. [35], the value of F_{ax} is taken as zero because the bolts used for glubam connections only have threads on the head part.

3.5 Test Setups and Theoretical Procedures for Evaluation of the Performance of Bamboo Truss

Villegas made a setup to test the actual stress of the truss made from the culms of Guadua angustifolia [26]. Placed above the truss are levers in contact with the primary nodes of the upper chords. The experiment increased the weight carried by the lever at an increment of 112.8 N. Each increase in the load has an interval of 3 mins, and the complete application of the load lasts 30 minutes. Dial gauges were installed in different locations of trusses, as shown in Fig. 9, to measure the displacements. The dial gauges have a resolution of 0.0254 mm. The study made four samples and the results from the experiment. Villegas compared the experimentation result to the theoretical model analyzed in ANSYS 16.0. The difference in the values is due to the variations of elastic constants and nonuniformity of size samples of bamboo culms. In comparison, the results from the ANSYS model show a linear curve because of the non-consideration of primary sources of non-linearities like slippage at the joints, permanent plastic deformation of clamp lugs, and deviations [26].

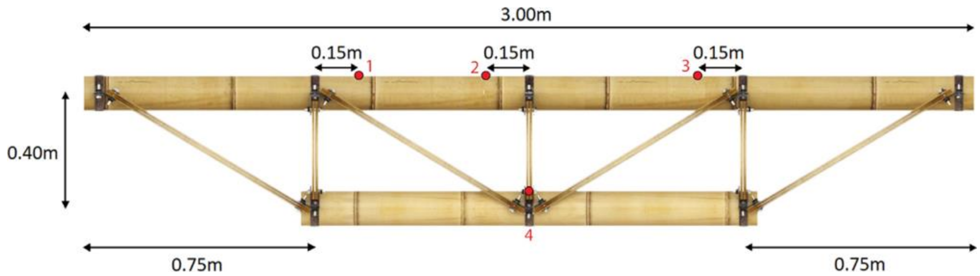

Fig. 9 - Sample bamboo truss made from *Guada angustifolia* [26]

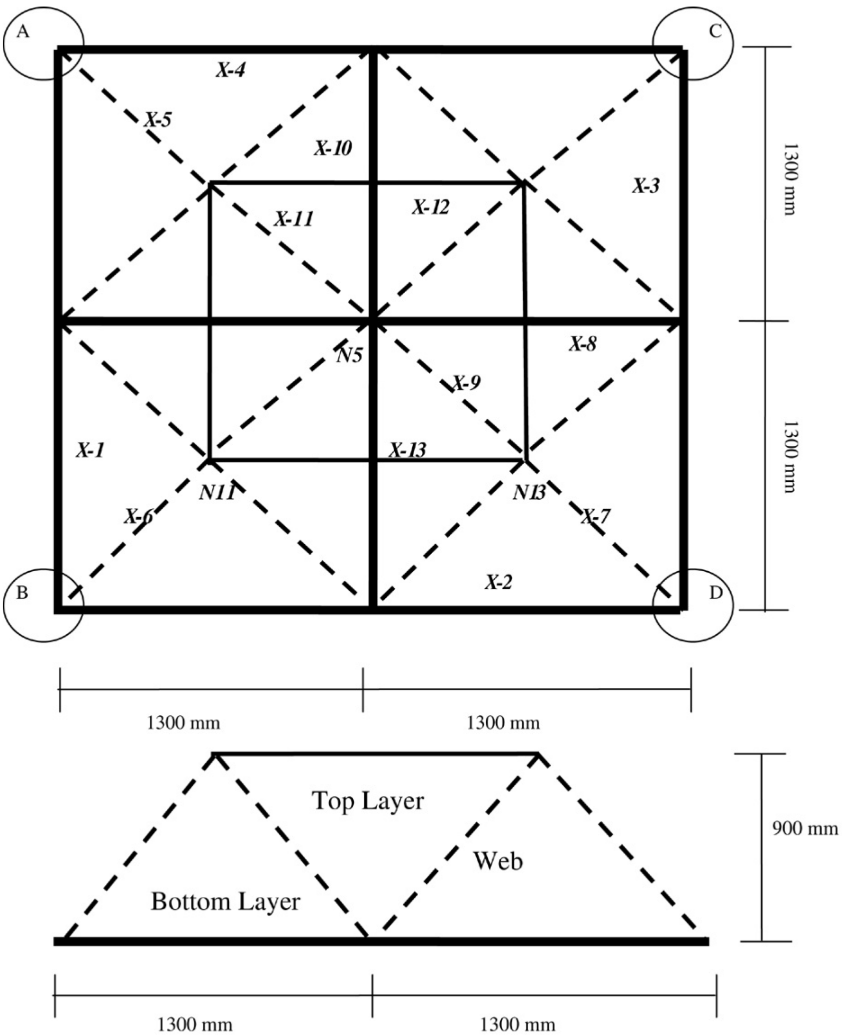

Fig. 10 - Sample space truss made of *Phyllostachys pubescens* [19]

A loading jack is attached to three nodes at the top of the truss in a similar arrangement designed by Kariuki [21]. The three nodes to which the loading jack is linked receive a concentrated load carried by the loading jack. In addition, deflection meters, load cells, and strain gauges are attached to the experiment's truss and connected to a data logger.

Albermani [19] developed a prototype of a double-layer grid space truss made from *Phyllostachys pubescens* culms. The prototype has a configuration, as shown in Fig. 10. The base is a rectangular panel having a dimension of 2.6 m x 2.6 m and a height of 0.9 m. It comprises 32 bamboo culm members with an average length of 1.15 meters. The support at A restrained all the degrees of freedom, while supports B, C, and D allowed in-plane translation and rotation about the vertical axis. The middle of each member on opposite sides has an attached strain gauge. The researcher monitored the nodes, and a rigid frame was placed inside the grid and used as a reference in measuring linear displacements with Linear Variable Differential Transformer (LVDT). The load was incrementally applied using a timber pallet carrying a concrete mix bag weighing 10 kN. The load applied increased in six increments [19]. The strain results from the grid experiment were compared to the predicted results using elastic geometric nonlinear analysis [36]. Research can determine stress distribution on the PVC joint of the space truss using the Von Mises stress contour plot [19].

Wu [18] conducted a test procedure on his fabricated space truss made of glubam. They mounted the glubam space truss on four steel supports. Two hinges on one side and two rollers on the other support the truss. Each upper joint carries a bag carrying containing steel blocks. Installed along the longitudinal direction of the upper joints are seven LVDTs. Are also three LVDTs installed in the transverse direction of upper joints located at the midspan. For the displacement of the bottom joints, there are six LVDTs along the longitudinal direction on one side and another two LVDTs in the midspan on the other side. Computer software like SAP2000 used static linear analysis to validate the experimental results. Evaluating the truss using SAP2000 used the elastic and physical properties as parameters determined from tests [18].

4. Fiber-Reinforced Composite

Multiphase composites offer fascinating design possibilities. It can exhibit an enormous array of materials with property combinations that no monolithic traditional metal alloys, ceramics, or polymeric materials can meet. The matrix and the scattered phase made up the composite materials. The matrix is a continuous phase surrounding the dispersed phase [37]. Glass fiber reinforcements, thermosetting resins, and additives comprise fiberglass composites developed and produced to meet specific functional performance standards [38].

The amount, nature, distribution, and arrangement of glass fiber reinforcement significantly influence fiberglass's mechanical strength and other properties [37], [38]. Fig. 11 shows the schematic representation of the orientation of fiber-reinforced composite. The arrangement of fiber reinforcements at (a) is continuous and aligned; at (b), The fibers are discontinuous despite the aligned arrangement; and at (c), fibers are discontinued and are randomly oriented.

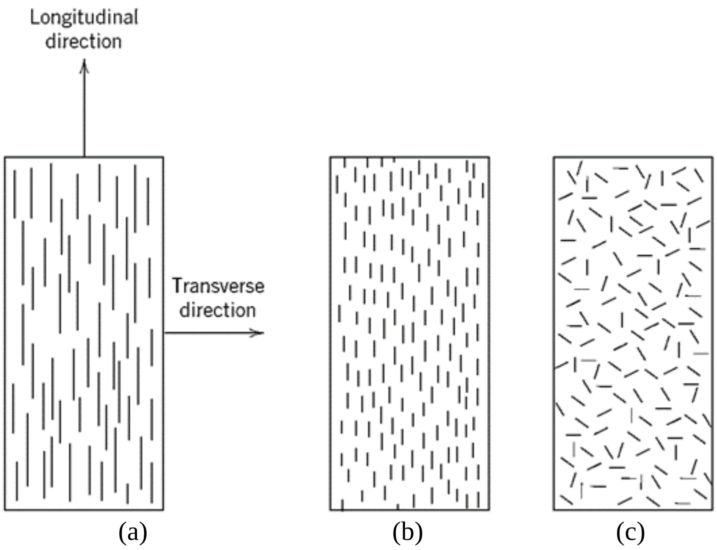

Fig. 11 - Schematic representation of the orientation of fiber-reinforced composite [37]

4.1 Tensile Strength of Fiber-Reinforced Composite

The direction of load about the arrangement affects the composite's strength value. As can be observed from Table 7, three different composites exhibit different strengths for typical longitudinal and transverse tensile stress. The three materials are Glass-polyester, carbon epoxy, and Kevlar epoxy.

Table 6 - Typical longitudinal and transverse tensile strengths for three unidirectional fiber–reinforced composites [39]

Material	Longitudinal Tensile Strength (MPa)	Transverse Tensile Strength (MPa)
Glass -polyester	700	20
Carbon (high modulus)-epoxy	1,000	35
Kevlar-epoxy	1,200	20

A study on the reinforcement efficiency of fiber-reinforced composite by Krenchel stated that the efficiency of fibers is 1 when all threads are parallel [40]. When the fibers are in random and uniform dispersion in three dimensions of space, and the stress applied is in an arbitrary order, the direction of the applied pressure is identical to the direction of the fibers. This kind of composite's efficiency is 20%; however, the mechanical properties are isotropic [40]. This value is consistent with the data presented by American Water Works that the strength of fiberglass with multi-directional (isotropic) arrangement shows nearly equal modulus and stability in all directions [38]. The results of a similar study to ascertain the impact of fiber orientation on the mechanical properties of the fiberglass-reinforced composite are in Table 7. The 0°/90° orientation of fibers exhibited the highest ultimate tensile strength at ultimate tensile strain and the highest modulus of elasticity. Meanwhile, the chopped strand matt (CSM) fiber reinforcement exhibited higher ultimate tensile strength and modulus of elasticity than fiberglass with unidirectional fibers of ±45°[41].

Table 7 - Mechanical properties of fiberglass polyester composite [41]

Orientation	Mechanical Properties		
	Ultimate Tensile Strength (MPa)	Ultimate Tensile Strain (mm/mm)	Modulus of Elasticity (MPa)
CSM	71.6	0.11	995.2
0°/90°	166.2	0.21	1,947.7
±45°	40.7	0.18	713.9

4.2 Standard Test Methods for Determination of Mechanical Properties of Fiber-Reinforced Composite

There are several standards to test the mechanical properties of different composites. ASTM D3039 defines tensile testing as determining the force required to break a polymer composite specimen and the period the sample stretches or elongates to reach that breaking point [42]. A tensile test can generate a stress-strain diagram and calculate the tensile modulus [42]. ASTM D3410 can determine the compressive strength of the composite. This standard is most suited for composites reinforced with high-modulus fibers, such as tapes and textiles. The test fixture compressively loads the specimen's unsupported center, which ranges in gauge length from 12 to 25 mm (0.5 to 1 inch). This approach determines in-plane compressive characteristics using a compressive force on the sample at wedge grip contacts [43]. The ASTM D5961 standard tests the bearing response of pinned or fastened joints made of multi-directional polymer matrix composite laminates reinforced with high-modulus fibers. Tension or compression loading generates the bearing force[44]. Depending on the test technique, a moderately torqued fastener (or pin) can create a bearing force that responds in single or double shear [44].

5. Challenges and Research Gaps

Glubam truss members or bamboo culms are the two most common materials for bamboo trusses based on the 220 records obtained from various journals and other references. Some parameters of designing truss members involve their compressive and tensile strengths. From the review, glubam truss members can exhibit a tensile strength ranging from 53 MPa to 106 MPa and a compressive strength ranging from 57.03 MPa to 71.2 MPa. On the other hand, bamboo culm truss members have tensile strengths ranging from 40.03 MPa to 78.74 MPa and a wide range of compressive strengths ranging from 2.70 MPa to 340 MPa.

Mechanical properties used to determine performance involve the following: tensile strength, compressive strength, shearing strength, and elastic modulus. ASTM D143 - Standard Test Methods for Small Clear Specimens of Timber is a standard procedure performed to determine the mechanical properties of glubam. One bamboo truss prototype used PVC jointing material; this study recommends using fiber-reinforced composite material as a truss joint. Fiber-reinforced composite is a versatile material that can form different shapes. In addition, the tensile strength of the fiber-reinforced composite can reach a value of 700 MPa, higher than the tensile strength of steel commonly used in truss joints.

Several studies have conducted tests on the mechanical properties of bamboo, which designers of truss members primarily require. However, there is a lack of study on the shearing strength of bamboo culms. The shearing strength of a truss member material is one of the parameters needed in designing connections because of the bearing force of the bolt with a direction parallel to the grain of the bamboo material. Moreover, studies involving experiments on the performance of glubam truss with steel connections have identified necessary mechanical properties for truss design but recommend further investigation on the behavior of connections. Studying the quantification of long and short-term slippage of connection is also recommended.

Fiber-reinforced composite, having a close mechanical property of steel and at the same lighter weight, can also be molded into different shapes. In addition, it can be synthesized with glubam material to create a truss prototype made from both lightweight members and connectors.

6. Conclusions

Studies determine the performance of bamboo truss prototypes by conducting actual experimentation. The setup involves the imposition of weights on nodes and analysis of nodal displacements and internal stresses on members. LVDT is an instrument installed on truss nodes to measure nodal displacement, while strain gauges determine stresses on members. Theoretical analysis of trusses can use finite element analysis and software simulation (ANSYS or SAP 2000). Results obtained from actual experimentation are comparable to results obtained from theoretical analysis. Bamboo as a truss material is an excellent alternative to steel because of the following: 1) It performs similarly to timber, which is also a common truss material because of its high compressive and tensile strength, and 2) it exhibits linear static behavior up to twice the design load. Therefore, the researchers recommended using bamboo as a truss member and fiber-reinforced polymer as a truss jointing material.

Acknowledgment

The authors fully acknowledged Technological University of the Philippines Taguig and Polytechnic University of the Philippines for supporting this work.

References

[1] Kassimali A. (2011). Structural Analysis. Cengage Learning.
[2] Makowski Z. S. (2002). Book review: Analysis, design and construction of steel space frames. International Journal of Space Structures, 17(2–3), 243-243. doi: 10.1260/026635102320321905.
[3] Segui W. T. (2007). Steel Design. Chris Carson.
[4] Aggangan R. (2015). The Philippine bamboo industry: Issues, potentials, strategies and action programs. The 10th World Bamboo Congress, 17–22.
[5] Page M. J., McKenzie J. E., Bossuyt P. M., ... & Moher D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ. 10.1136/bmj. n71
[6] Leclercq V., Beaudart C., Ajamieh S., Rabenda V., Tirelli E. & Bruyère O. (2019). Meta-analyses indexed in PsycINFO had a better completeness of reporting when they mention PRISMA. Journal of Clinical Epidemiology, 115, 46–54.
[7] Agha R. A., Fowler A. J., Limb C., Whitehurst K., Coe R., Sagoo H., Jafree D. J., Chandrakumar C. & Gundogan B. (2016). Impact of the mandatory implementation of reporting guidelines on reporting quality in a surgical journal: A before and after study. International Journal of Surgery, 30, 169–172.
[8] Panic N., Leoncini E., de Belvis G., Ricciardi W. & Boccia S. (2013). Evaluation of the endorsement of the preferred reporting items for systematic reviews and meta-analysis (PRISMA) statement on the quality of published systematic review and meta-analyses. PLoS One, 8(12), e83138.
[9] Page M. J.,Shamseer L., Altman D. G.,Tetzlaff J., Sampson M., Tricco A. C., Catalá-López F., Li L.,Reid E. K.,Sarkis-Onofre R. & Moher D. (2016). epidemiology and reporting characteristics of systematic reviews of biomedical research: A cross-sectional study. PLoS Med, 13(5), e1002028.
[10] Moher D., Liberati A., Tetzlaff J. & Altman D. G. (2010). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. International Journal of Surgery, 8(5), 336–341.
[11] dela Cruz O. G. & Ongpeng J. M. C. (2022). Building information modeling on construction safety: A literature review. Advances in Architecture, Engineering and Technology, 89–102.
[12] Lasda Bergman E. M. (2012). Finding citations to social work literature: The relative benefits of using Web of Science, Scopus, or Google Scholar. The Journal of Academic Librarianship. https://doi.org/10.1016/j.acalib.2012.08.002
[13] Yadav M. & Mathur A. (2021). Bamboo as a sustainable material in the construction industry: An overview. Materials Today: Proceedings, 43, 2872–2876.
[14] Gill S., Bansal A. K. & Sighal A. (2017). Comparative study of bamboo material performance in civil engineering structure. International Journal of Scientific and Engineering Research, 8(10), 1-10.
[15] Harison A., Agrawal A. & Imam A. (2017). Bamboo as an alternative to steel for green construction towards low cost housing. Journal of Environmental Nanotechnology, 6(2), 100–104.

[16] Nayak A., Bajaj A., Jain A., Khandelwal A. & Tiwari H. (2013). replacement of steel by bamboo reinforcement. IOSR Journal of Mechanical and Civil Engineering, 8(1), 50–61.
[17] Xiao Y., Chen G. & Feng L. (2014). Experimental studies on roof trusses made of glubam. Materials and Structures, 47(11), 1879–1890.
[18] Wu Y. & Xiao Y. (2018). Steel and glubam hybrid space truss. Engineering Structures, 171, 140–153.
[19] Albermani F., Goh G. Y. & Chan S. L. (2007). Lightweight bamboo double layer grid system. Engineering Structures, 29(7), 1499–1506.
[20] Woubshet S. (2021). Investigation on mechanical properties and suitability of highland bamboo (Yushania Alpina) for use in structural truss members. Science Development, 2(2), 3–29.
[21] Kariuki J. K (2014). Performance of Glue Laminated Bamboo Beams and Trusses. Pan African University.
[22] GB/T 1928-2009 (2009). General requirements for physical and mechanical tests of wood.
[23] JG/T 199-2007 (2007). Testing methods for physical and mechanical properties of bamboo used in building.
[24] GB/T 1933-2009(2009). Method for determination of the density of wood.
[25] ASTM D143 (2009). Standard test methods for small clear specimens of timber.
[26] Villegas L., Morán R. & García J. J. (2019). Combined culm-slat Guadua bamboo trusses. Engineering Structures, 184, 495–504.
[27] Dinie Awalluddin D, Mohd Azreen Mohd Ariffin M. A., Mohd Hanim Osman M. H., Mohd Warid Hussin M. W., Ismail M. A., Han-Seung Lee H. -S. & Abdul Shukor Lim N. H. (2017). Mechanical properties of different bamboo species. MATEC Web of Conferences, 138, 01024.
[28] Javadian A., Smith I. F. C. Saeidi, N. & Hebel D. E. (2019). Mechanical properties of bamboo through measurement of culm physical properties for composite fabrication of structural concrete reinforcement. Frontiers in Materials. https://doi.org/10.3389/fmats.2019.00015
[29] Oka G. M., Triwiyono A., Awaludin A. & Siswosukarto S. (2014). Effects of node, internode and height position on the mechanical properties of gigantochloa atroviolacea bamboo. Procedia Engineering, 95, 31–37.
[30] ISO 22157:2019(E) (2019). Bamboo structures - Determination of physical and mechanical properties of bamboo culms - Test methods. International Organization for Standardization.
[31] Garcia J. J., Rangel C. & Ghavami K. (2012). Experiments with rings to determine the anisotropic elastic constants of bamboo. Construction and Building Materials, 31, 52–57.
[32] Phanratanamala S. (2014). The Study of Design and Structural Potential of Bamboo Practical Joints and Frame Truss System. Kyushu University.
[33] Li Z., Gupta R. & Miller T. H. (1998). Practical approach to modeling of wood truss roof assemblies. Practice Periodical on Structural Design and Construction, 3(3), 119–124.
[34] Eurocode 5 (2004). Design of timber structures - Part 1-1: General-common rules and rules for buildings. European Committee for Standardization.
[35] Li Z., Li T., Wang C., He C. & Xiao Y. (2019). Experimental study of an unsymmetrical prefabricated hybrid steel-bamboo roof truss. Engineering Structures, 201, 09781.
[36] NIDA (2022). Nonlinear Integrated Design and Analysis of Steel Frames. Hongkong Polytechnic University.
[37] Callister W. Jr. D. & Rethwisch D. G. (2010). Materials Science and Engineering: An Introduction. John Wiley & Sons.
[38] Turkopp R. C. & Sharff P. (2014). Fiberglass Pipe Design. American Water Works Association.
[39] Hull D. & Clyne T. W. (1996). An Introduction to Composite Materials. Cambridge University Press.
[40] Krenchel H. (1964). Fibre Reinforcement. Akademisk Forlag.
[41] Jimit R. H., Zakaria K. A. & Bapokutty O. (2017). Influence of fiber orientation on mechanical properties of fiberglass reinforced composite. Proceedings of Mechanical Engineering Research, pp. 318–319.
[42] ASTM D3039/D3039M-08 (2014). Standard test method for tensile properties of polymer matrix composite materials. ASTM International.
[43] ASTM D3410/D3410M-16e1 (2021). Standard test method for compressive properties of polymer matrix composite materials with unsupported gage section by shear loading. ASTM International.
[44] ASTM D5961/D5961M-17 (2017). Standard test method for bearing response of polymer matrix composite laminates. ASTM International.