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Experimental Evaluation of Tali Bamboo Trusses with FRP Connections for Sustainable Structural Applications

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Abstract. Tali Bamboo is a local material that is widely utilized in traditional construction due to its availability, strength, and flexibility. However, weaknesses in the connection system are a major obstacle in its application as a structural element. This research aims to evaluate the strength and stiffness of tali bamboo joints using Fiber Reinforced Polymer (FRP) as joint reinforcement in plane trusses. The method used was experimental testing of three truss models with varying numbers of FRP laminate layers (1, 2, and 3 layers) combined with Polyvinyl Acetate (PVAc) adhesive and epoxy resin. Tests were conducted with center point loading to assess the performance of the connection. The results showed that the connection with 2 layers of FRP was able to withstand the maximum load optimally, or was able to withstand an average maximum load of 25.2 kN with an average deflection of 3.1 cm. The highest value reached 30 kN and a deflection of 4.0 cm, indicating optimal efficiency and strength. The physical properties of tali bamboo in the internode section are weaker than those in the book section, but still generally meet the criteria for structural materials. The implications of this study suggest that the use of double-layered FRP connections in tali bamboo can be an effective solution in improving the performance of plane truss structures, although further testing is required for more complex connections between truss elements.

Keywords: Tali Bamboo Reeds, Fiber Reinforced Polymer, Laminated Joints, Sustainable Materials, Structural Testing.

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1. Introduction

The increasing need for sustainable and renewable resource-based solutions has prompted greater attention to the utilization of environmentally friendly materialsvv [1]. As in the construction sector, the exploration of natural materials as alternatives to conventional building materials in structural systems has been the focus of many scientific studies [2]. One material that has attracted attention is bamboo, which is known for its fast regrowth, light weight, and high tensile strength. These characteristics make bamboo an excellent candidate for sustainable construction [3]. Throughout Indonesi [4], bamboo has been a common material for ages, primarily for erecting modest houses and conventional bridges in rural settings. Its utility extends beyond construction, as it's also fashioned into an array of products such as furniture, domestic tools, and handmade items [4,5]. Meanwhile, the young parts of the bamboo plant known as bamboo shoots are even consumed as food and vegetables. This high utilization cannot be separated from the fact that bamboo is a cheap and easily found material in various regions in Indonesia [6,5].

String bamboo species, in particular, thrive in tropical climates and usually form small groups in clumps [8]. The frequent use of bamboo in buildings within low-income rural communities often creates the impression that the material is linked to poverty [9]. On the other hand, modern architectural trends have shown a change in perception, where bamboo is actually used in an exposed manner in buildings such as restaurants, villas, and meeting places to showcase its natural beauty and attract tourists [9,10].

According to a study by Manandhar et al. (2019) [12], this phenomenon is not only happening in Indonesia, but also in various other countries that are starting to look at bamboo as the main material in building construction [13]. Nonetheless, for bamboo to be more extensively applied as a building material and to comply with contemporary construction standards, it needs to be bolstered by scientific research [14]. Technical information on the performance of tali bamboo as a truss structural element is essential to support its utilization in modern construction. One crucial aspect of a bamboo truss structure is the connection system. So far, commonly used connection methods include the use of nails, palm fiber rope, rattan rope, or metal elements such as bolts and steel plates. Each method has its own advantages, such as availability of materials or ease of implementation, but also has disadvantages, especially in terms of connection strength, performance consistency and durability [15]. Therefore, it is necessary to explore alternative connections that are more efficient, stronger, and easier to apply, one of which is the use of composite materials such as Fiber Reinforced Polymer (FRP).

Several previous studies have examined the potential of FRP in improving the performance of bamboo joints. [16] evaluated the use of glass fiber-reinforced polymer (GFRP) to strengthen bolted connections in natural bamboo. The results showed that bamboo column specimens reinforced with GFRP experienced up to 2.5-fold increase in deformation capacity and 5.5% to 11.7% increase in bearing capacity. At the joints, GFRP even increased the bearing capacity between 3 and 6 times. Meanwhile, [17] examined bolted bamboo connections wrapped with FRP. The study showed that FRP lateral wrapping was able to increase tensile strength and reduce shear failure, and helped achieve more consistent mechanical properties in the joints.

On the other hand, [18] studied polyester composites reinforced with bamboo fibers. Although this study did not directly address the connection between FRP and intact bamboo, the findings indicated a substantial improvement in tensile strength when the proportion of bamboo fibers in the composite was increased, flexural strength, as well as vibration damping capability. These findings reinforce the assumption that bamboo fiber has high potential as a reinforcing material in composite systems. Local research by [19] Kuncoroalso showed that the use of FRP laminates in bamboo elements can significantly increase the joint capacity. Interestingly, this study found that it was not the number of FRP layers that had the most effect, but rather the area of attachment and the method of rolling the FRP that determined the strength and stiffness of the connection [20].

Although various studies have demonstrated the potential of FRP as a solution for strengthening bamboo connections, there are important gaps in the literature [21]. To date, there have not been many experimental approaches that test the performance of a complete tali bamboo truss system, particularly in the form of a plane-scale truss model with FRP-based connections. Most studies have been limited to simple tensile or compressive testing of connection elements, without integrating these elements into a more complex structural system. In addition, there has been no in-depth comparative analysis of the effect of varying the number of FRP layers on the load capacity and deformation behavior of the structure [22]. This gap is an important reason to conduct a more comprehensive follow-up research, in order to validate the effectiveness of FRP connections in bamboo frames under conditions close to real plane applications [23].

Based on the background previously described, this research aims to obtain relevant technical data regarding the utilization of rope bamboo as a truss structural component, specifically with connections reinforced using Fiber Reinforced Polymer (FRP). Referring to established research that has explored the physical and mechanical attributes of a range of bamboo types, with string bamboo being one example, this study uses that information as secondary data to inform its development and analysis [24]. Furthermore, this study modeled the complete truss structure as a representation of the truss system. The model was designed to assess the joint strength and structural performance of rope bamboo under actual loading conditions. Tests were conducted by applying direct loads at connection points until failure or damage to the structure occurred. In this testing process, the joints in the truss were assumed to behave like hinges (joints), so as to represent common connection conditions in the plane. In addition to observations of ultimate strength, deflection measurements were also taken to assess the rigidity of the truss system.

This study sought to assess the complete technical specifications related to the performance of FRP-strengthened tali bamboo joints in a basic truss system. This data is intended to give a clear picture of how tali bamboo could be utilized as an alternative construction material, especially for lightweight structural uses. This research is also expected to make a real contribution in assessing the strength and safety aspects of FRP-based connections in plane truss structures. Moreover, result hope this research's outcomes will help establish tali bamboo as a viable material for a range of basic structural uses. Potential applications include roof trusses for buildings with limited span, pedestrian bridges, and any structural elements needing renewable, lightweight, and sufficiently durable materials.

2. Methods

Research is conducted through direct experimental methods in laboratories that focus on structural testing. This laboratory is a result of the development of a previous facility that focused on soil mechanics and concrete, signaling the expansion of civil engineering research areas at Pakuan University. This research specifically tested the joints of rope bamboo reinforced using FRP laminates.

2.1 Materials and Specifications

This research primarily uses tali bamboo, selected for its light weight and strong mechanical properties. The connection was reinforced using FRP in the form of woven WR 400 roving with a variation in the number of layers of one, two, and three layers. The adhesives used were Polyvinyl Acetate (PVAc) and epoxy resin. PVAc is a water-based polymer that is fast drying, odorless, and non-flammable, while epoxy resin has high adhesive strength and good resistance to moisture. The lamination process was done by pressing technique and dried for 24 hours at room temperature before testing.

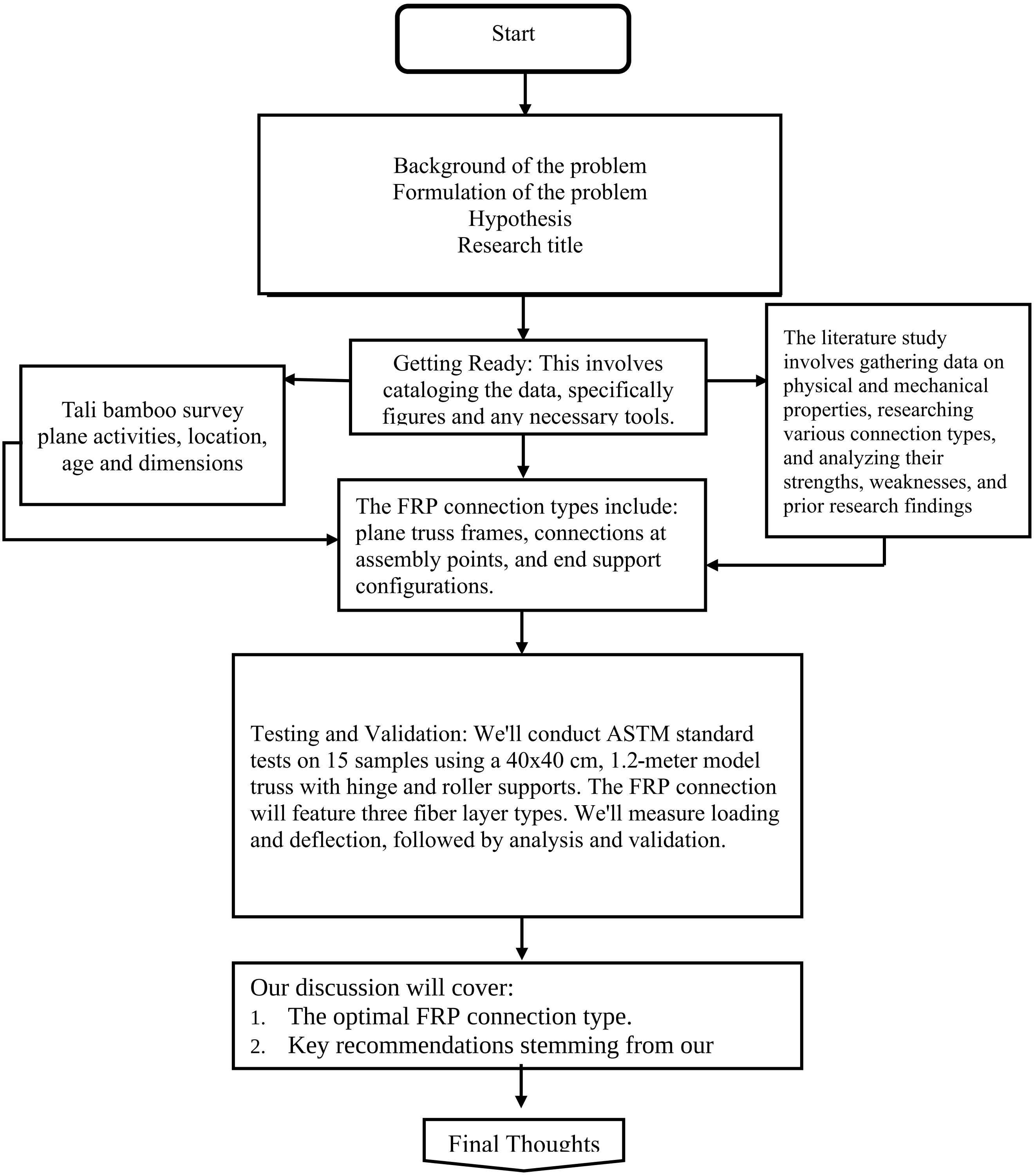

Figure 1. Steps In The Research Project

2.2 Sample Setup and Preparation

Fifteen specimens were used in this study, categorized into three planar truss model types based on their FRP layers: one, two, or three. The first model type featured a laminated connection with one FRP layer, the second type had two FRP lamination layers, and the third type included three FRP lamination layers. Each model type consists of 5 samples to ensure replication and data accuracy according to

ASTM test standards. The rod frame was made with a plane model size of 40 cm × 40 cm and a length of 1.2 meters with a support system in the form of joints and rollers at both ends. Connections were made at the intersection of the rods with an overlap length of ±15 cm using the lamination and clamp method.

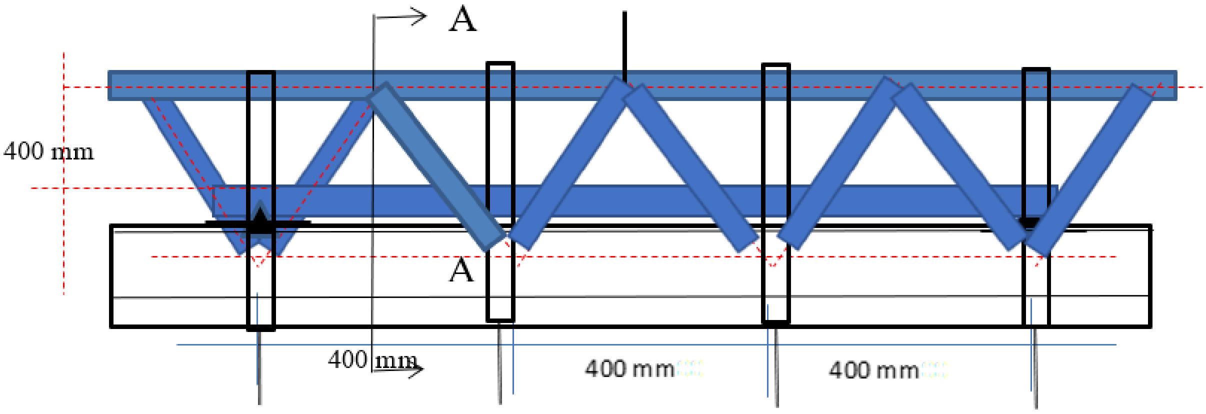

Figure 2. Depiction Of The Test Specimen Experiencing A Concentrated Load

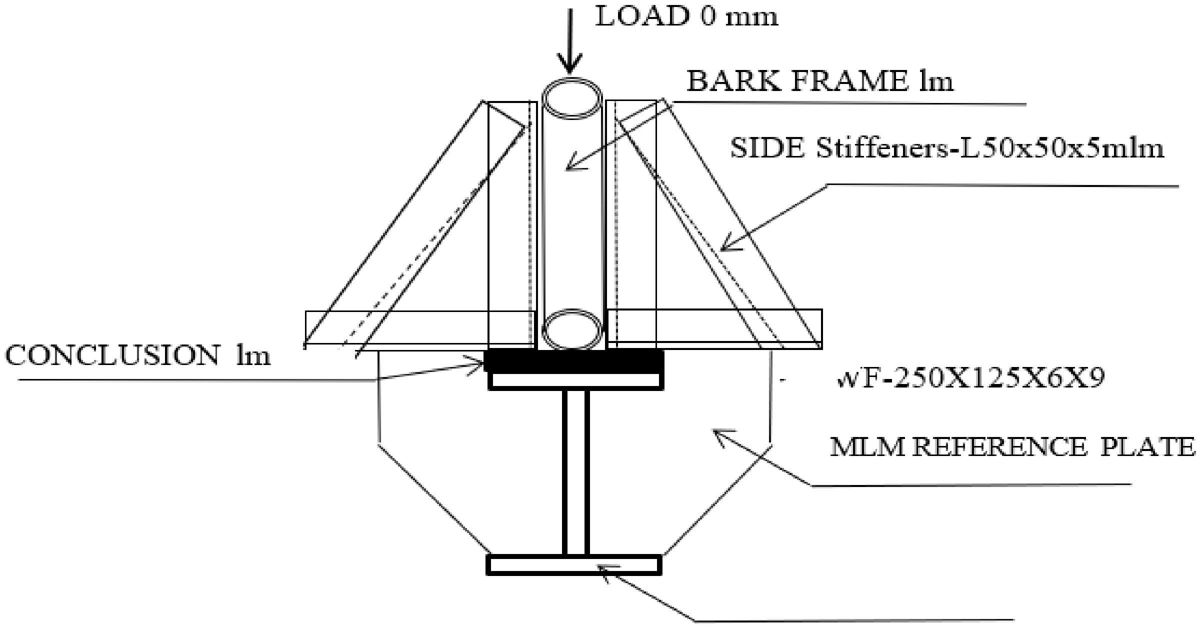

Figure 3. Section A-A view

2.3 Testing Procedure

Tests are conducted using the center point loading method, where a single vertical load is applied exactly at the center of the span of a planar truss. The load is applied gradually using a Universal Testing Machine (UTM), and the deflection at the center point is recorded using a dial gauge or digital sensor. Each specimen was tested until it reached the maximum condition or failure of the joint structure.

2.4 Analysis and Validation

The data obtained from the test results were analyzed to obtain the maximum load value and the average maximum deflection of each FRP layer variation. The analysis includes a comparison of strength between connection models and material use efficiency based on structural performance. Validation of the results was done with reference to ASTM testing standards and comparison between specimens to identify the effect of number of layers on joint behavior. In addition, a plane model was designed to represent the actual conditions of lightweight structural applications in the plane, supporting the relevance of the experimental results to real-world applications.

3. Results and Discussion

Mechanical Test Data of Bamboo Stem Assemblies Using FRP Joints

The study involved experimental tests on bamboo Tali trusses with a centric meeting point, utilizing multi-layered FRP for connections. We examined three types of trusses, differentiated by their FRP layer count (1, 2, or 3 layers), conducting a total of five trials. No twisting effect occurred during the loading test of the truss, thanks to the suitable stiffeners on its left and right sides. The trusses were separated by 40 cm, and loading was carried out using an ASTM C-39 Digital Compression Machine, a bending testing machine with a 2000 kN capacity. Dial gauge readings were recorded for every 5 kN load increment.

Table 1. Displays the Experimental Outcomes For the Truss Featuring A 1-Layer FRP Connection

Test Specimen	S1	S2	S3	S4	S5	Average
Peak Load (kN)	18	15	20	18	14	17.0
Peak Deflection (cm)	2,5	2,5	3,0	3,0	2,0	2.6

Data from the tests

As shown in Table 1, the maximum load carrying capacity for the bamboo truss with a 1-layer FRP connection is 14 kN to 20 kN, with a corresponding maximum deflection of 2.0 cm to 3.0 cm. The average maximum load that this truss can withstand is approximately 17 kN, with an average deflection of 2.6 cm. This value indicates that the use of 1 layer of FRP still results in fairly limited stiffness and joint strength. The relatively small variation in deflection indicates a consistent structural response, but the relatively low maximum load value indicates the limited capacity of the connection.

Table 2. Displays the Experimental Outcomes For the Truss Featuring A 2-Layer FRP Connection

Test Specimen	E1	E2	E3	E4	E5	Average
Peak Load (kN)	27	24	22	23	30	25,2
Peak Deflection (cm)	3,5	3,0	2,5	2,5	4,0	3,1

Data from the tests

Table 2 shows that the bamboo truss with 2-layer FRP connection had the most optimal structural performance among all test types. The maximum load it could withstand ranged from 22 kN to 30 kN, with deflections ranging from 2.5 cm to 4.0 cm. The average maximum load reached about 25.2 kN, and the average deflection was about 3.1 cm. These results show that the addition of the second FRP layer significantly improved the capacity of the joint to resist tensile and flexural forces. The deflection distribution was also within reasonable limits, reflecting good structural rigidity and flexibility.

Table 3. Displays the Experimental Outcomes For the Truss Featuring A 3-Layer FRP Connection

Test Specimen	F1	F2	F3	F4	F5	Average
Peak Load (kN)	25	28	26	20	20	23,8
Peak Deflection (cm)	3,5	4,0	3,5	2,5	2,0	3,1

Data from the tests

Table 3 shows that the connection of bamboo truss with 3 layers of FRP did not provide a significant improvement over 2 layers. The maximum loads ranged from 20 kN to 28 kN, with deflections ranging from 2.0 cm to 4.0 cm. The average maximum load was approximately 23.8 kN, slightly lower than the 2-layer FRP connection. The average deflection was 3.1 cm, equivalent to that of a 2-layer joint. These results show that the addition of a third layer of FRP is not directly proportional to the increase in joint strength. In fact, there was a tendency to decrease the strength in some samples (F4 and F5) which could only withstand 20 kN.

Table 4. Comparison of FRP Connection Performance on Bamboo Truss with 1, 2, and 3 Layers of FRP

Number of FRP Layers	Average Maximum Load (kN)	Average Maximum Deflection (cm)	Maximum Load Range (kN)	Maximum Deflection Range (cm)	Conclusion
1 Layer	17,0	2,6	14 – 20	2,0 – 3,0	Low load capacity; small deflection; stable but limited
2 Layer	25,2	3,1	22 – 30	2,5 – 4,0	Most optimal performance; significant increase in load resistance
3 Layer	23,8	3,1	20 – 28	2,0 – 4,0	No significant increase in strength; delamination potential

Data from the tests

Overall, the results show that the bamboo frame with a two-layer FRP connection provided the most optimal performance among all the different variations. In this configuration, the structure was able to withstand an average maximum load of 25.2 kN with a deflection of 3.1 cm. In contrast, the use of a single layer of FRP was only able to withstand an average maximum load of 17.0 kN with a deflection of 2.6 cm. This comparison indicates a significant increase in structural strength when the number of FRP layers is increased from one to two. This can be explained through the basic principles of material mechanics, where the addition of layers increases the effective cross-sectional area at the joint, so that the resistance to tensile and shear forces also increases.

However, when the number of layers was increased to three, the increase in strength did not continue proportionally. In fact, the results showed a decrease in structural performance. This phenomenon is most likely due to several technical factors. One of these is the overstiffening of the connection, where excessive stiffness causes uneven load distribution and encourages failure to occur in the bamboo culms rather than the connection. In addition, the potential for delamination between FRP layers due to weak adhesive bonds that can arise from resin accumulation or uneven lamination pressure also influences performance degradation. Another noteworthy factor is the decreased flexibility of the system, which impacts the ability of the joint to absorb energy under load, making the structure more susceptible to brittle failure.

This finding is in line with previous studies. [25] proved that the use of GFRP can significantly increase the capacity of bolted connections in bamboo. Similarly, a study by [16] showed that FRP coating of bamboo joints can increase tensile strength and stabilize shear performance. [26] also noted improved mechanical properties in polyester composites reinforced with bamboo fibers. Meanwhile, [5] confirmed that FRP laminates on bamboo elements can improve joint capacity.

However, an important contribution of this research is the finding that there is an optimal limit to the use of FRP layers. Excessive addition of layers does not necessarily lead to better results. On the contrary, it can have a negative effect on the effectiveness of the connection, mainly due to reduced ductility and increased stress concentration in certain areas, which can be the starting point for failure. Therefore, the efficient use of FRP as joint reinforcement should consider the optimal limit to maintain a balance between the strength, stiffness, and flexibility of the overall structure.

Subsequently, during the testing process a number of important observations were recorded regarding the behavior of the joints in various FRP layer configurations. In bamboo frames with a single layer of FRP, failure generally occurred due to detachment of the reinforcing layer from the bamboo surface. This phenomenon indicates that the adhesion strength and durability of a single layer is not sufficient to withstand the tensile and shear forces acting on the joint. In contrast, joints with two layers of FRP exhibited a better structural response. These joints exhibit stable plastic deformation, helping the structure to withstand the load for a longer time before finally failing. However, when the number of FRP layers was increased to three, the damage pattern changed. There were cracks at the joints that extended into the bamboo culms, indicating a stress concentration at a particular point as well as possible delamination between the FRP layers.

These findings corroborate the hypothesis that an appropriate number of FRP layers can significantly increase the capacity of bamboo joints. However, it is also important to consider the flexibility of the connection and the types of failures that may occur. The implications of these results suggest that bamboo connection systems reinforced with layered FRP have great potential for application in sustainable buildings. However, a number of technical limitations must be considered, such as the variability of bamboo's natural mechanical properties, the quality of adhesion between FRP layers, and the limitations of the small scale of the test model that does not reflect full-scale structural conditions.

Although the internodes of rope bamboo generally have lower mechanical properties than the knuckle sections, the overall strength of the bamboo is still considered suitable for use as a structural material. Therefore, this finding makes a practical contribution to the development of lightweight construction technology, particularly in rural areas. The use of double-layered FRP connections was shown to increase the efficiency and reliability of the bamboo structure, making it suitable for application in the construction of simple buildings and small bridges. This is in line with the concept of sustainable construction, which emphasizes the optimal utilization of local materials with the support of modern techniques that are efficient and environmentally friendly.

4. Conclusion

This study shows that tali bamboo (Gigantochloa apus) with Fiber Reinforced Polymer (FRP) connections has potential as a truss structural component in sustainable construction applications. The experimental test results proved that the connection with two layers of FRP laminate was able to withstand an average maximum load of 25.2 kN with an average deflection of 3.1 cm, and reached the highest value of 30 kN and a deflection of 4.0 cm. Despite the internode section of tali bamboo possessing inferior physical properties compared to the node section, its collective strength remains adequate for use as a structural material. The practical implications of this research show that the use of double-layered FRP connections increases the efficiency and reliability of lightweight bamboo structures especially for simple buildings and bridges in rural areas, in line with the principle of sustainable construction through the utilization of local materials and modern techniques. This conclusion provides a basis for engineers and material designers to develop innovative and economical bamboo structural systems. Suggestions for future research include testing various connection configurations, resistance to dynamic loads and environmental conditions, and cost and efficiency analysis for application in real-scale construction

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