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RESEARCH ARTICLES

EVALUATION OF THE MECHANICAL PROPERTIES OF BAMBUSA BAMBOO CULMS WITH METALLIC JOINTS THROUGH DESTRUCTIVE TESTING

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ABSTRACT

Bamboo in its raw state is difficult to incorporate in complex structures due to its tubular shape. In this research article, a novel approach to connect bamboo was designed and evaluated in order to integrate sustainable material into modern structures. Several bamboo joints for culm connection were designed based on strength and durability under various loading capacity. The conceptual joints were manufactured and subjected to destructive testing on the Universal Testing Machine, Testometric M500-50AT. From the mechanical properties generated, final modifications and refinements were incorporated into the joint design. Self-drilling metal screw joints were found to be the strongest with a maximum resisting force of around 11 kN in compression and 10 kN in tension. Riveted joints were the second strongest joint, while tightening ring joints, the weakest among the three, could only resist a peak load of 747 N in tension. The joints, designed with metal fittings, proved to be more practical for utilization in assembly design.

KEYWORDS

Bamboo, Joints, Structural, Universal Testing Machine

1. INTRODUCTION

In Mauritius bamboo is still widely used and is an indispensable component for sailing. A mast made out of bamboo can fully sustain the wind loadings exerted on the sails and thereby demonstrating the tremendous properties it possesses, namely a very high strength to weight ratio. Another advantage of bamboo, apart from its remarkable strength, is its regeneration rate, which completely outclasses timber in that category where one species even holds the world record for being the fastest growing plant on earth, with a growth rate that reaches 91 cm per day. With an area of about 2000 km^2, Mauritius has limited natural resources and heavily depends on imported raw materials, namely from Asia and Africa. Hence, in the local context and given the favorable tropical climate, bamboo is an ideal sustainable material that can be readily cultivated and processed into useful structures. Currently, bamboo culms are used in the agricultural sector in the development of greenhouse enclosures and has great potential for integration in both the aquaculture and eco-tourism sectors.

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Investigation on bamboo has been limited to full-culm structures, fiber composites and laminates subjected to standard test conditions. Little research has been carried out on the standardization and application of joints of bamboo culms for building standards and in construction. Bamboo culms in their raw state have limited application, namely due to their tubular cross-sectional geometry. The aim of this research investigation was to focus on the design of novel joining techniques in an attempt to render Bambusa ssp, the utilized species of bamboo, into a more versatile construction material. Assessment of this bamboo species' integration worthiness in structures was achieved by evaluating its mechanical properties through destructive testing.

Gutu (2013) studied the mechanical properties of bamboo in an attempt to maximize its use for construction. Tensile, compressive, bending and stiffness were among the tests carried out on bamboo. His test results showed that bamboo demonstrated better mechanical properties when compared to wood. The tensile strength test results of 14.8 kN per cm^2 showed that the material is very strong and can even be compared with steel. The bending results also showed good performance with a discrepancy recorded due to variation in the maturity of bamboo. Stephens (2012) conducted some tests on bolted bamboo connections for use in the bracing of informal housing. The tests were carried out to assess the maximum applied load which bolted bamboo joints could withstand. Bamboo specimens of the same species and from the same cultivation were used and underwent equivalent treatments as the bamboo used in SAFE (Society for Accident Free Environment) construction. Three specimens were loaded and failure resulted at 6.48 kN, 8.13 kN and 8.17 kN.

Awaludin *et al.* (2014) carried out further experiments on bamboo species, namely *Gigantochloa Atroviolacea*, using bolted bamboo joints with reinforced fibres. Seventeen samples were prepared using single bolts and various reinforcements. Natural fibres and fibre reinforced plastic (FRP) were the main reinforcement materials used. Displacement of the designed joint were taken using a Linear Variable Differential Transformer (LVDT). In parallel loading, the FRP sheets proved to be more resistant to loads of up to 50 kN with a slip (δ) of approximately 10 mm. The natural fibre reinforcement showed less load capacity of approximately 18 kN with an increasing slip up to 60 mm. In perpendicular loading, the natural fibre showed better resistance to a load of approximately 14 kN with a slip of up to 25 mm. The FRP sheets had a maximum load capacity of 12 kN with a slip of approximately 10 mm.

While joints of whole culms seemed to be complex, Villegas *et al.* (2015) performed tests using joints made out of bamboo slats. The species chosen was *Guadua Angustifolia*, which originated from South and Central America, and has excellent mechanical properties along the axial direction. In his research study, bamboo culms, split longitudinally into slats, were used instead of whole culm connections. The joint, which was connected using bolts and nuts, consisted of curved washers for compensation in the curvature of bamboo surfaces. Preliminary tensile tests of joints of single elements were performed and the result showed a failure at a load of 5052 N. Villegas *et al.* (2015) built two prototype structures to test the supportive capacity of the joints until failure. Prototype 1 (0.93 m length, weight of 70 N) failed due to buckling at a load of 15500 N (1.55 T) while Prototype 2 (3 m length weight of 310 N) failed at 12000 N (1.2 T).

The research studies mentioned above were limited to specific types, namely engineered and composite bamboo, while Stephens (2012) evaluated only bolted connections under specific conditions. Another factor that significantly influenced the mechanical property of the culm which was not addressed in aforementioned research is moisture content. According to Xu *et* *al.* (2014), increasing moisture content decreases the load resistance. In contrast, Meng *et al.* (2015) found that a greater moisture content would yield a better Specific Energy Absorption (SEA measured in kJ/kg) value. In fibrous bamboo walls, fibers are aligned longitudinally. The density of walls increase from inside to the outside since the vascular bundles and fibers are denser around the outer wall (Huang *et al.*, 2015).

Few research studies have been carried out on the evaluation of bamboo joints fitted with metallic fasteners. Joints are necessary in the assembly of components and to provide a consistent geometry when used as structural members. For construction application, the ideal maturity of bamboo lies between 3 to 5 years. Mechanical properties of bamboo are impressive and proved to be stronger in comparison to timber and concrete in many cases. *Phyllostachys* and *Bambusa* are the most common bamboo studied for construction purposes and have good resistance to an average load of 50 kN. *Bambusa*, however, is found to yield more consistent results than *Phyllostachys* when taking readings at culm height. According to Chung *et al.* (2002), the properties of *Phyllostachys* are observed to vary with the height of the culms.

The primary objective of this research was to probe alternative techniques and engineered new designs in order to improve connection types in culm-to-culm bamboo joints. Secondly, the mechanical properties, namely tensile and compressive strengths, of *Bambusa* bamboo culms fitted with metallic joints were evaluated through destructive testing.

2. MATERIALS AND METHODS

2.1 Bamboo Selection and Treatment

In comparison to locally available bamboo species, namely *Phyllostachys* and *Dendrocalamus*, *Bambusa bamboos* were found to grow in abundance in Mauritius' accessible regions. The *Bambusa* species has a smaller diameter ranging from 50 mm to 100 mm and culm length of approximately 12 m to 15 m, making it easier to work with. In order to standardize the test specimens used, variations in culm internal and external diameter and wall thickness were limited to a specific range of about 25 to 29 mm, 48 to 51 mm and 10 to 12 mm respectively as shown in Figure 1. Diameter and thickness tend to decrease with an increase in length from the root section.

The maturity of selected bamboo specimens ranged between three and four years. According to Fabiani (2014), the first 1 m from the root section should be discarded due to a non-straight development and the next 6 m of the culm could be used for testing purposes. In order to maintain the wall thickness and diameter specifications within the desired range, culm portions ranging between 1 m above the ground and up to 2 m in height were harvested using a machete. Joints are best implemented at the internode part of the culm as it possesses a good fibrous content for holding loads. Thus, culms used in the design of conceptual joints were divided at the midpoint of internodes as shown in Figure 2.

Subsequently, after collection, appropriate treatment must be applied to prevent degradation from termites and borers attack. The specimens were treated with a mixture of boric acid and borax at a ratio of 1:1.5 solution (5%). The 5% solution was produced by mixing 1 kg of boric acid and 1.5 kg of borax with 47.5 litres of water. The solution treatment applied was a clear, non-toxic and non-corrosive one, safe even when in contact with food. The specimens were immersed into the solution for about one week for optimum absorption. As per the literature, in order to achieve a moisture content below 12 %, all specimens were exposed and left to dry

FIGURE 1. Variation in culm's internal/external diameter and wall thickness.

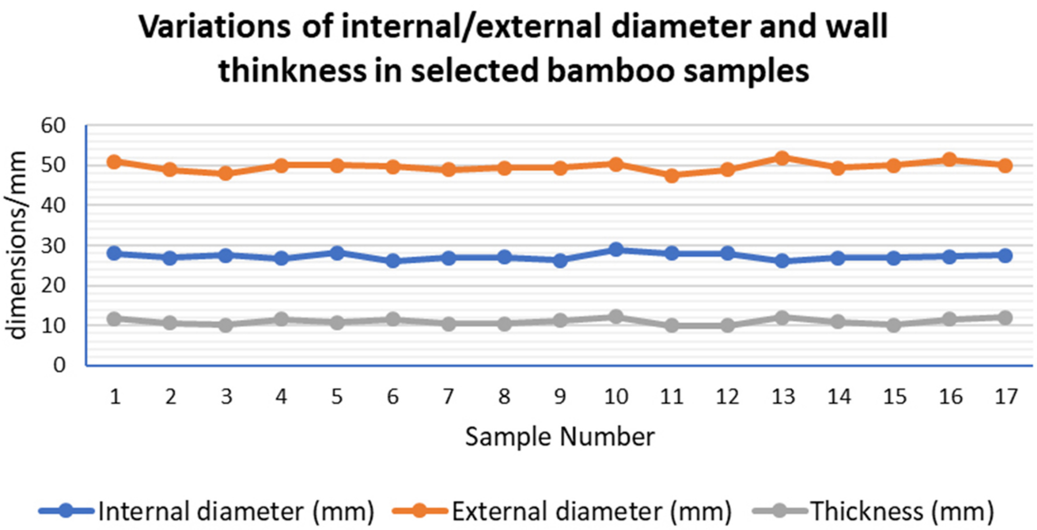


FIGURE 2. Sectioning of bamboo specimens.

in direct sunlight for a duration of approximately one month. The evaporated water prevented the bamboo from insect attack and fungi formation.

2.2 Joint Design

Since mechanical properties vary with culm length, only the basal portion was used for structural application. Bamboo joints were designed with the prime objective to withstand a maximum load bearing capacity. The selected bamboo specimen had internal diameter values less or equal to the diameter of steel tubes. The joint was prepared by inserting the tubes in the bamboo specimen to ensure a tight fit. The joints were then subjected to destructive testing so as to find the maximum load prior to failure.

2.2.1 Tightening Ring Joint.

As undried bamboo is affected by shrinkage over time, a first concept consisting of tightening rings was devised to address this problem. Bamboo specimens, split along their longitudinal section, were tightened using tightening rings as shown in Figure 3. Mild steel tubes of diameter 2.54 cm and length 15 cm were used and secured into the bamboo specimens using tightening rings. In order to produce a strong joint between the two components, the bamboo was split at three equal sections. Due to the cost of the tightening rings, this conceptual joint was the highest priced one in comparison with other designs.

2.2.2 Riveted Joint Design.

Mild steel tubes of diameter 2.54 cm and length 15 cm were selected as they corresponded closely to the range of the internal diameter of the bamboo which was 25 mm to 29 mm. The outermost portion of the tube was used as a gripping support for tests in the Universal Testing Machine. The two components were drilled with a drill bit of diameter 5 mm and riveted using rivets of diameter 4.7 mm. A total of 8 rivets was used in a complete joint with four on each side. Rivets were aligned with a distance of 25 mm and 50 mm from one end of the bamboo specimen as shown in Figure 4.

2.2.3 Self-Drilling Metal Screw Joint.

Self-drilling metal screws have good resistance to wearing and can bear high loadings. Their rubber ring provided a tight grip when combined with the curved surface of bamboo. Additionally, the load was uniformly distributed over that surface. Mild steel tubes of diameter 2.54 cm and length 15 cm were used. The number of screws used in the third concept was equivalent to the total number of rivets used in concept 2. The self-drilling metal screws of diameter 10 mm were tightened by the use of a portable drilling machine as shown in Figure 5.

FIGURE 3. Concept 1—Tightening ring joint.

FIGURE 4. Concept 2—Riveted joint.

FIGURE 5. Concept 3—Self-drilling metal screw joint.

3. RESULTS AND DISCUSSION

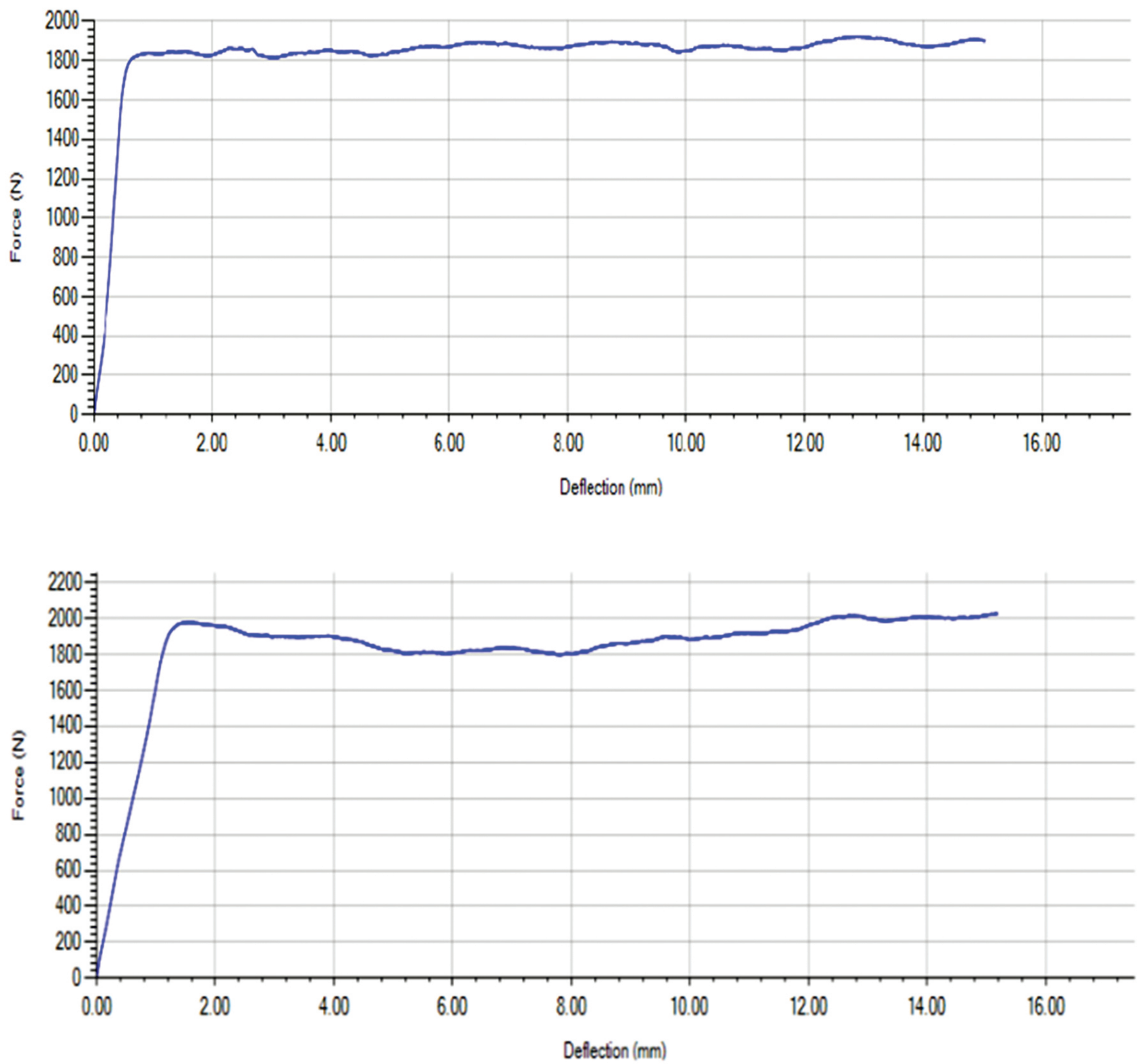
Both compressive and tensile tests were conducted on the Testometric M500-50AT Universal Testing Machine which had a maximum capacity of 50 kN force. ISO 22157, which is the determination of physical and mechanical properties of bamboo specimens, was not applicable to mechanical evaluation of bamboo joint. Hence, ISO 6891, which is the standard for evaluating timber joints and fasteners, was considered. As per ISO 6891, the loading should be divided into 3 stages, namely application of 40 % of F_{max}, the maximum loading capacity of the apparatus, for 30 seconds, application of 10 % of F_{max} for another 30 seconds and finally continuous loading till failure.

Since the rate of loading as specified by ISO 6891 could not be applied on the Testometric M500-50AT Universal Testing Machine, all tests were carried out using continuous load application. A test speed of 3 mm/min was maintained in both compressive and tensile tests while a preload of 5 N was only enabled in compressive tests. Four samples of each conceptual joint design were tested and the maximum force to joint failure was recorded and analyzed.

3.1 Tightening Ring Joint Test Results

This joint proved to be the worst among the three concepts. The rings, manually secured using screw drivers, did not provide enough tightness of the split bamboo. From Figure 6, the first stage of compressive test showed a linear progression of deflection and force till 1800 N. Beyond this point, the joint started to slip continuously, while the resisting force increased from 1800 N to 1923 N. The second compressive test gave quite similar results to the first one, giving a linear progression up to approximately 2000 N. The force then remained constant and the joint slipped by a further 15 mm. The variation of the force during the slip ranged between approximately 1800 N to a maximum of 2028 N. The large deflection in both tests occurred as a result of a loss of tightness between the tightening ring joint and the outer wall of the bamboo specimen after exceeding the maximum force that the joint could withstand. Both compressive

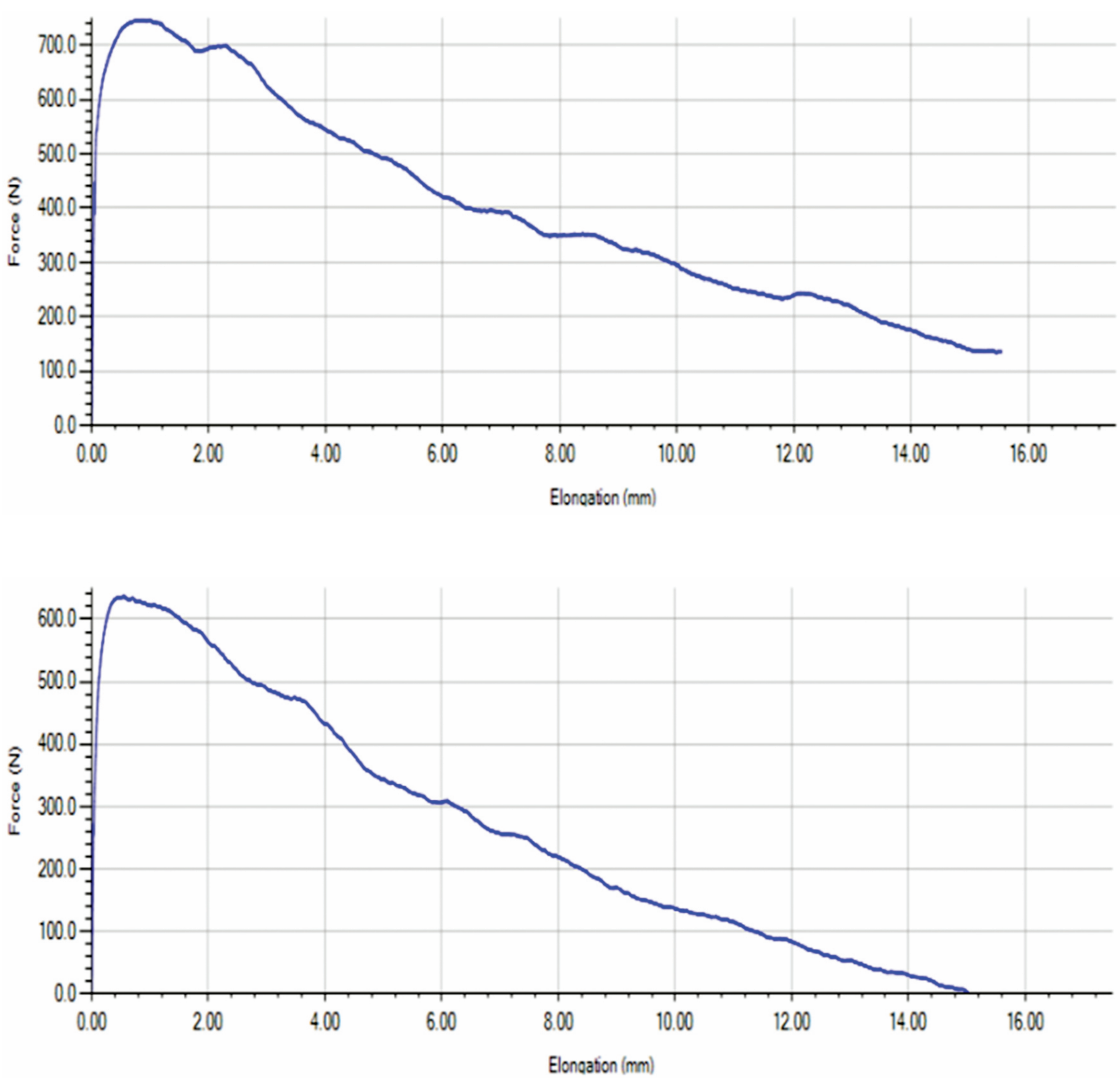
FIGURE 6. Load—slip curve of tightening ring joint in first and second compressive tests.



tests were conducted according to ISO 6891 which specifies that failure of the joint shall be considered even though no distinct visual failures have been observed after reaching a displacement of 15 mm.

From Figure 7, the tensile test showed a sudden rise in load resistance with little extension. A peak load of 747 N was noted and the joint was observed to slip beyond that force. The second tensile test showed a similar trend to the first one, reaching a peak of 637 N before slipping. Even though they are weak in terms of structural design, tightening ring joints have the ability to resist forces at a constant loading. Failure in the joints resulted mainly due a lack of tightness in between the rings, the bamboo and the metal rod. The only advantage of this joint was its ease of implementation and the ability to be dismounted for repair and replacement.

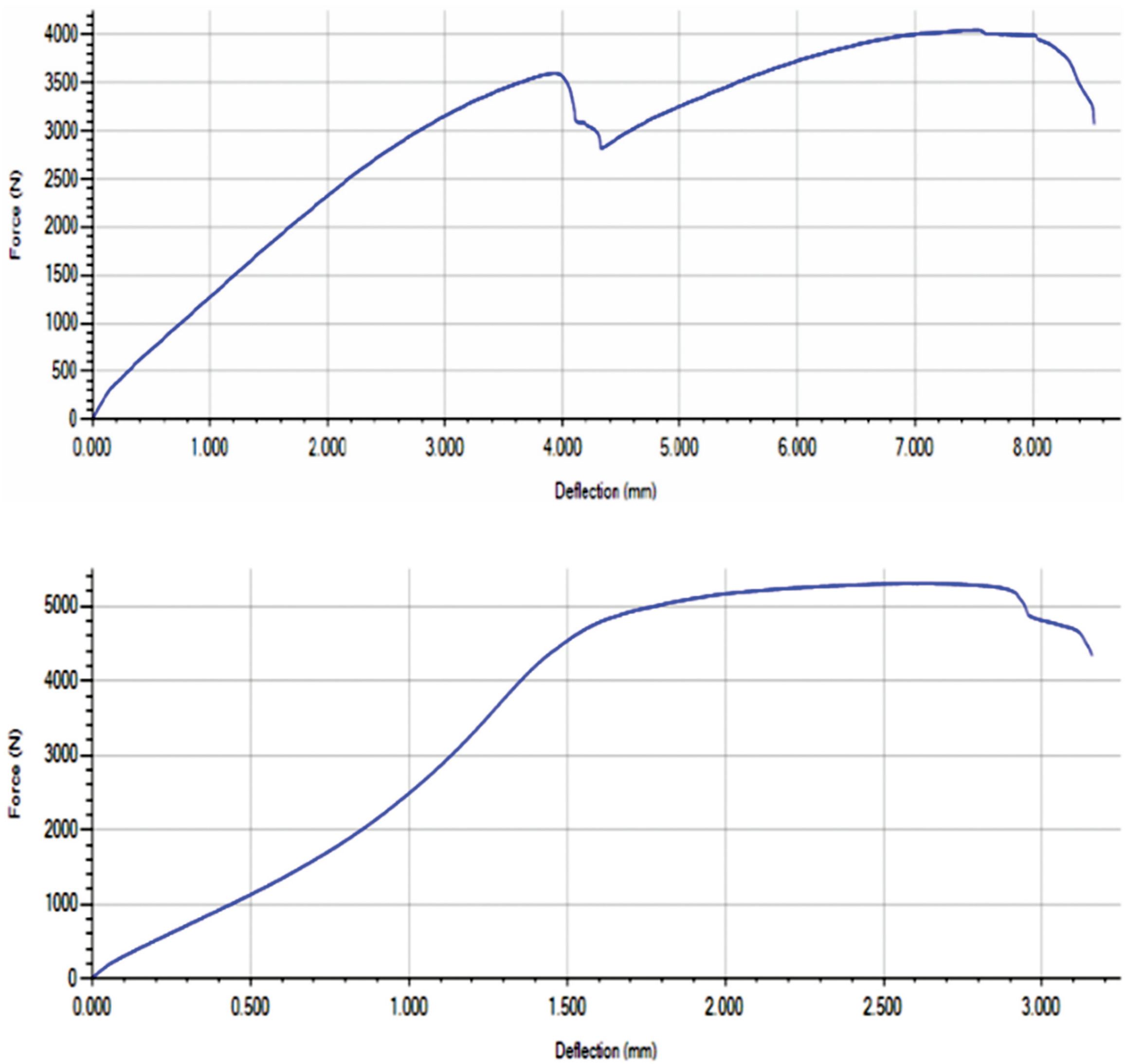
FIGURE 7. Load—slip curve of tightening ring joint in first and second tensile tests.



3.2 Riveted Joint Test Results

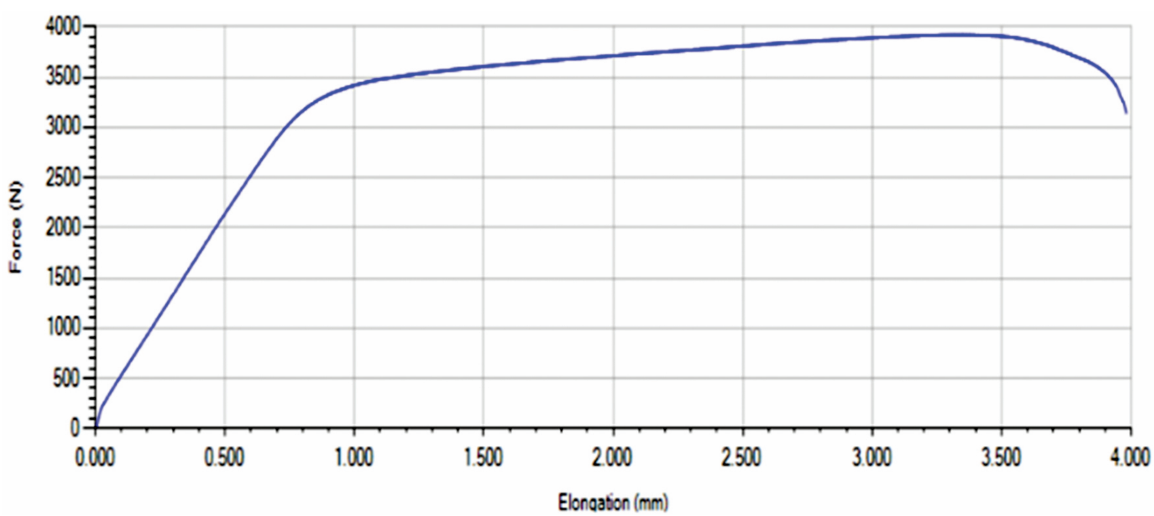
Test results involving the riveted joints were different to the one obtained in 3.1. It was noted that the bamboo remained unaffected during failure of the joints. Failure occurred in the rivets which sheared internally leading to failure of the joint. This observation also indicated a better shear strength in the bamboo walls as compared to the rivets. The graph in Figure 8 showed that the joint could bear a maximum load of about 3500 N in the first stage. This was followed by an abrupt decrease at a deflection of 4 mm due to failure in one or more of the eight rivets holding the joint together. The maximum load the remaining rivets could withstand prior to failure was 4051 N. From the test results of the second sample, the maximum load till failure was noted as 5300 N. The bamboo remained undeformed throughout and the rivets were found to bend towards the node.

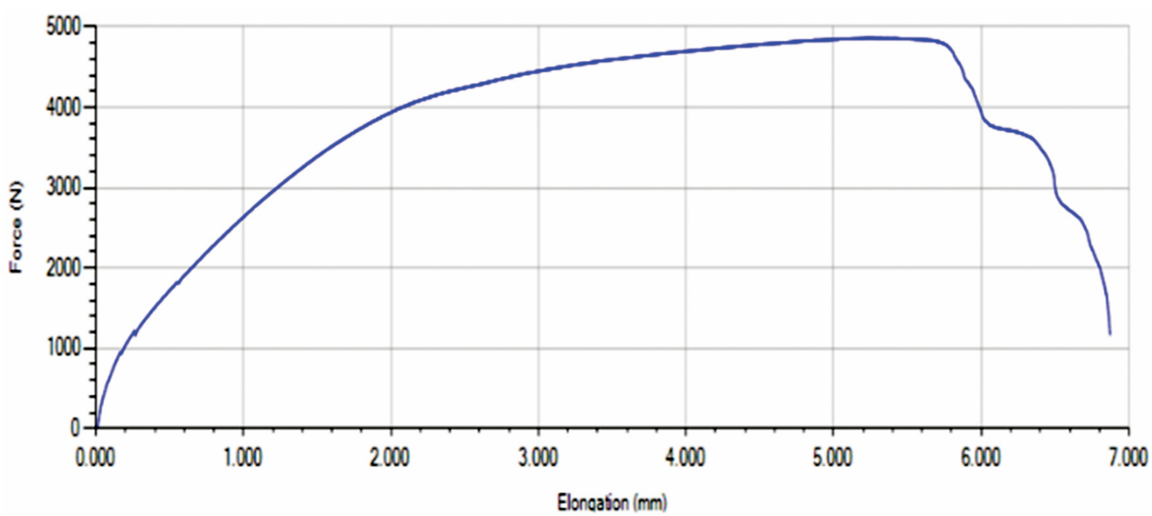
FIGURE 8. Load—slip curve of riveted joint in first and second compressive tests.



From Figure 9, the results of the first tensile test showed that the joint could withstand a maximum load of 3900 N. In the first stage, there was a linear progression of the force and elongation until approximately a load of 3000 N, which indicated failure of the rivets due to shearing. However, the maximum load the second test sample could bear was about 4862 N. The observations made after testing of the four samples revealed that premature failure in rivets took place, followed by the bamboo specimen. Discrepancies in results may be due to non-uniformity in the bamboo walls and the variations in the shrinkage force might have also affected the results obtained. Bamboo-joint design, involving rivets, should be refined into one which would withstand a greater load, uniformly distributed across its structural members.

FIGURE 9. Load—slip curve of riveted joint in first and second tensile tests.



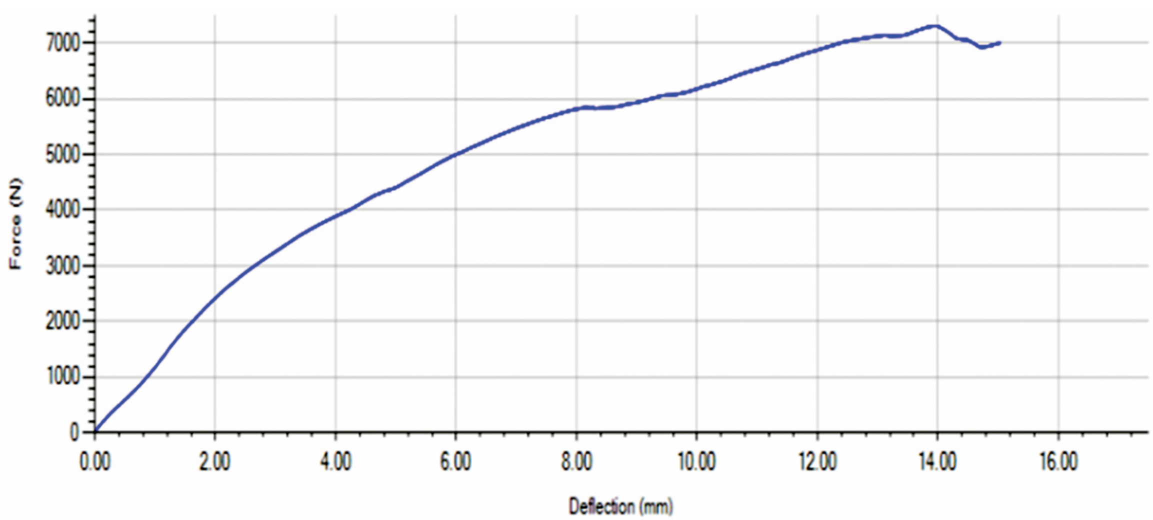


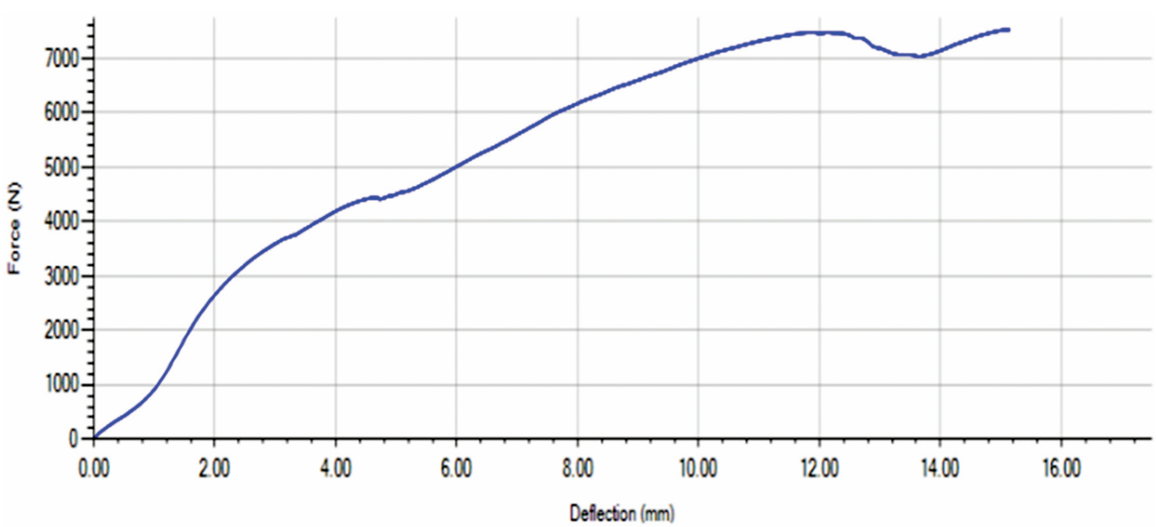
3.3 Self-Drilling Metal Screws Joint Test Results

The compressive tests involving self-drilling metal screws showed better results than those obtained in the tensile test. The first and second sample joints from Figure 10 could resist a maximum load of 7309 N and 7530 N respectively. In the first compressive test at a load of about 6000 N, the screws were observed to deform towards the node until maximum load was reached.

In the first tensile test, the self-drilling metal screw joint proved to be the strongest of all three designs by withstanding a maximum load of 5477 N as shown in Figure 11. Failure of the joints resulted due to rupture of the bamboo itself. At peak loading, the bamboo specimen failed by longitudinal shear plugs, a mode of failure described by Reynolds *et al.* (2016). Results involving the second sample turned out to be slightly stronger than the first one by withstanding a maximum load of about 5900 N.

FIGURE 10. Load—slip curve of self-drilling metal screw joint in first and second compressive tests.





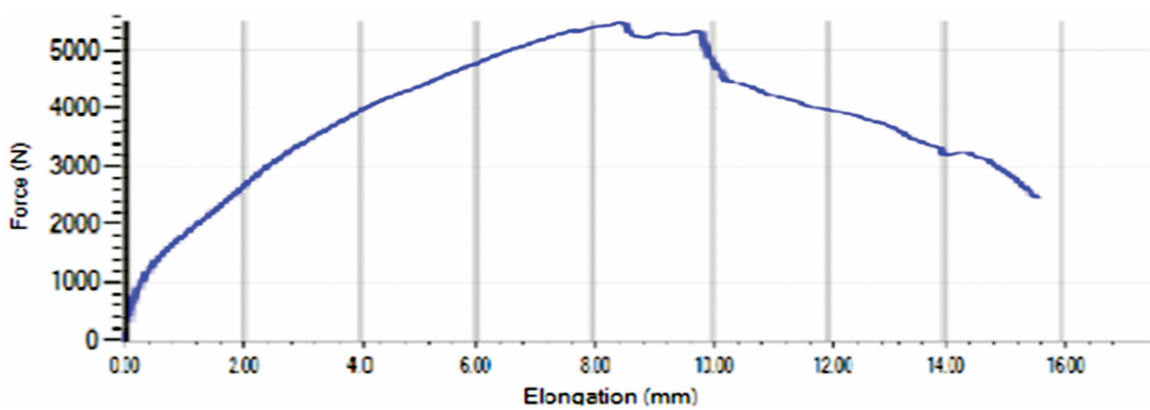
Failure by shear plug formation in the bamboo specimen as shown in Figure 12 resulted due to a greater rigidity in both the metal rod and self-drilling metal screw components. After the testing of sample joints, observations made on the disassembled joints revealed that damage occurred on the rubber sealing of the screw surface. Test parameters of all conceptual joints, as recorded in Table 1, were generated by the Testometric M500-50AT Universal Testing Machine.

3.4 Evaluation and Implementation

The strongest joint among all three concepts was found to be the self-drilling metal screw joint. Formation of shear plugs affected only part of the bamboo, mainly a longitudinal section where the screws were fastened. The riveted joint was the second best as failure occurred mainly as a result of the shearing of rivets. The tightening ring yielded the lowest readings of all three joints. Additionally, other variable factors, namely fibrous content, maturity and moisture content, which have a direct influence on the readings obtained, could be further investigated in other research studies.

In order to consolidate the joint design, a further refinement was introduced to the self-drilling metal screw joint. A major alteration in the design was the repositioning of the fasteners

FIGURE 11. Load—slip curve of self-drilling metal screw joint in first and second tensile tests.



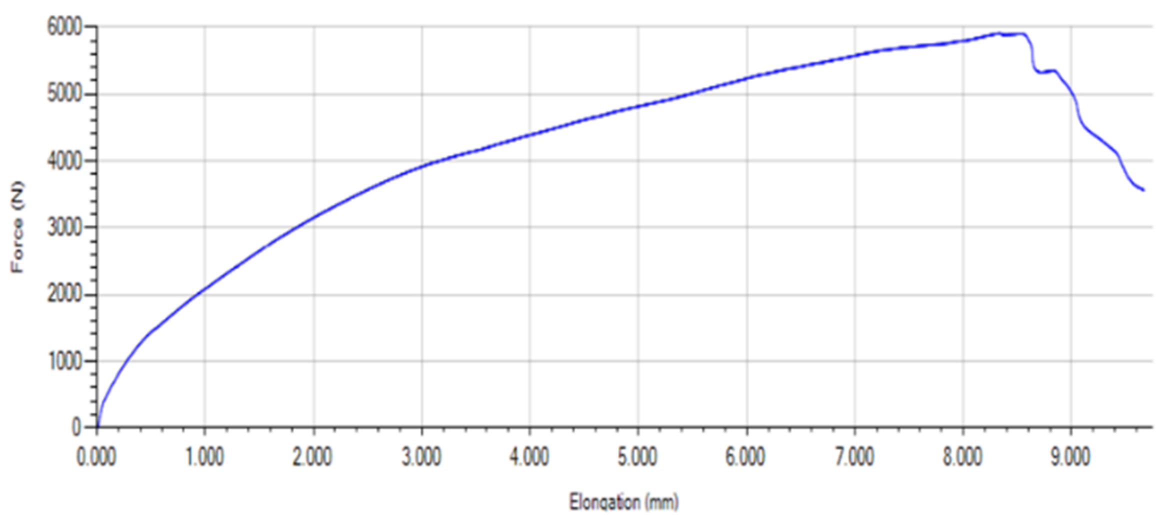
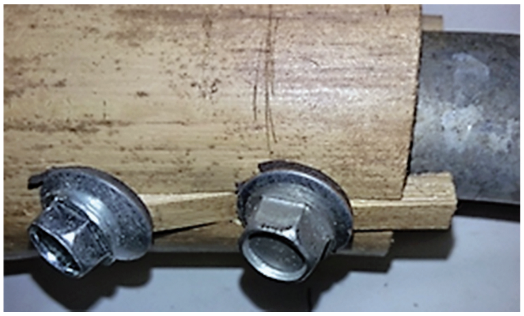


FIGURE 12. Shear plug formation in self-drilling metal screw joint.



on different portions of the bamboo specimen as shown in Figure 13. The total number of fasteners used remained constant in both joint designs. The new joint samples, which were expected to resist twice the load, were subjected to destructive testing on the Universal Testing Machine.

From Figure 14, the first compressive test carried out on the refined sample was promising as it withstood twice the load with a maximum value of approximately 11032 N. Failure originated as in previous cases due to shearing of wall sections at various locations in the sample. The second test sample yielded a lower reading mainly due to a lack of tightness in the fasteners.

The tensile tests conducted led to similar conclusions whereby the joint was able to resist twice the amount of tensile forces than before as shown in Figure 15. The load which was

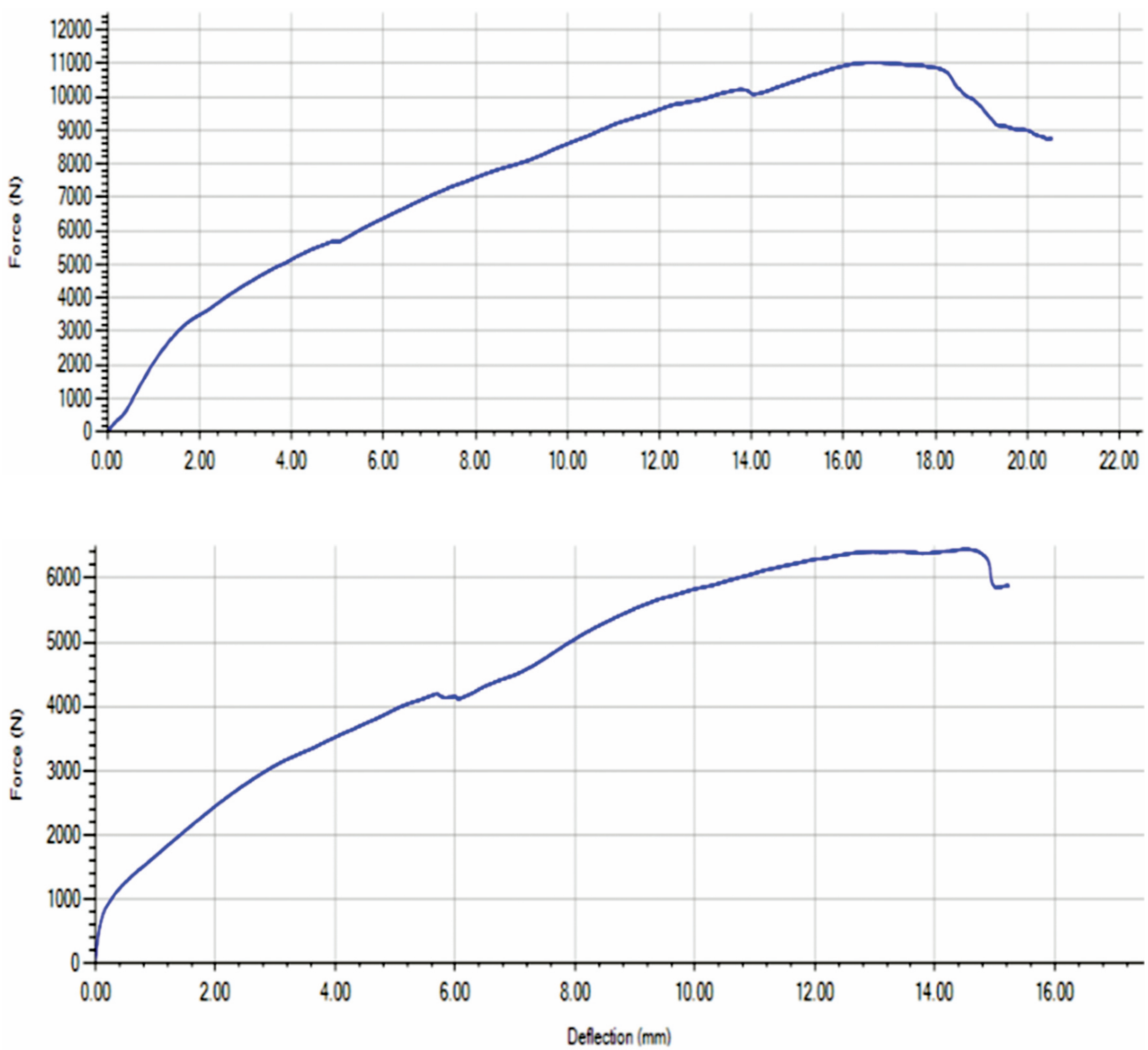
TABLE 1. Recorded tensile and compressive test results.

Joint	Test	Force at break (N)	Force at peak (N)	Stress at break (N/mm^2)	Stress at peak (N/mm^2)	Strain at break (%)	Strain at peak (%)	Young's Modulus (N/mm^2)
Tightening ring	C	1901.1	1923.4	0.808	0.818	10.0	8.593	181.7
	C	2024	2028	0.861	0.862	10.1	10.1	117.2
	T	135.0	747.5	0.217	1.20	7.40	0.500	4048.3
	T	3.2	637.7	0.005	1.02	0.380	7.2	2747.1
Riveted	C	3073.0	4015.3	1.306	1.722	6.1	5.4	64.9
	C	4343.2	5309.3	1.846	2.257	2.105	1.733	137.1
	T	3138.8	3922.8	5.042	6.303	2.655	2.233	947.9
	T	1168.7	4861.7	1.877	7.813	4.583	3.80	786.3
Self-Drilling screws	C	7001.9	7308.9	2.977	3.107	10.022	9.327	87.8
	C	7531.5	7534.4	3.202	3.203	10.098	10.095	129.2
	T	2461.3	5478.0	3.953	8.803	10.384	5.60	372.1
	T	3563.8	5911.5	5.724	9.50	6.446	5.67	462.5

Note: C—Compressive Test, T—Tensile Test

FIGURE 13. Initial and improved design of self-drilling metal screw joint.

FIGURE 14. Load—slip curve of refined self-drilling metal screw joint in first and second compressive tests.



approximately doubled, showed an average maximum value of 9000 N. As envisaged before testing, the orientation of the screw was a key contributing factor to further strengthening of the joint. By using additional locations for connection of fasteners, the load experienced by the bamboo specimen was uniformly distributed over a greater surface area than before. Hence, the joint could resist additional load even though the number of fasteners used was the same. Table 2 shows a summary of the test results of the refined joint.

3.5 DISCUSSION

Based on the initial test results obtained, it was found that the self-drilling metal screw joint was the most reliable one when compared to the other joints. In compressive tests, this joint design could withstand a maximum peak force of about 7500 N, while the tightening-ring joint and the riveted one could withstand only a maximum peak force of about 2000 N and 5300 N respectively. The design flaw in the tightening-ring joint resulted in a lack of frictional resistance

FIGURE 15. Load—slip curve of refined self-drilling metal screw joint in first and second tensile tests.

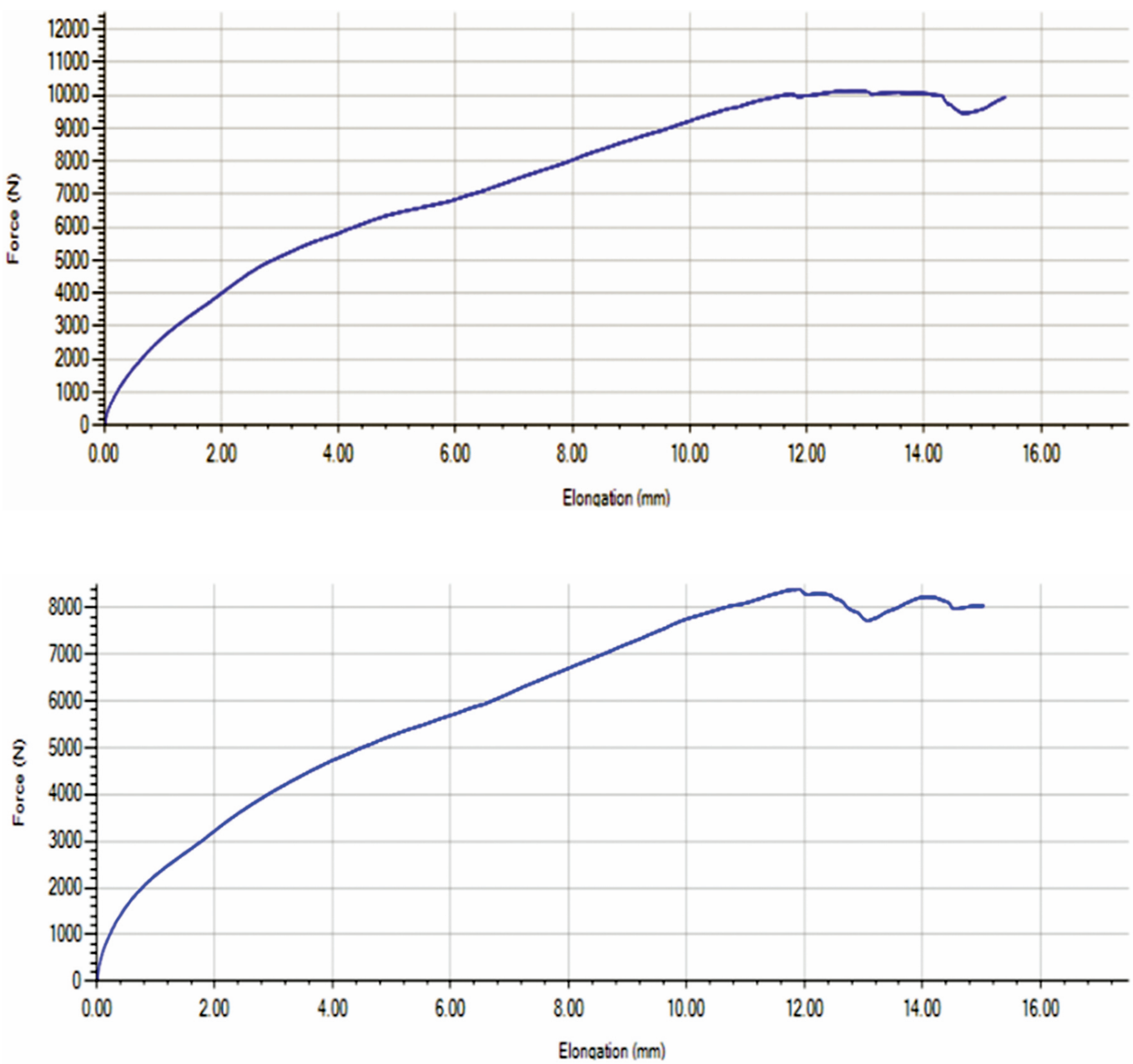


TABLE 2. Recorded tensile and compressive test results of refined joint design.

Joint	Test	Force at break (N)	Force at peak (N)	Stress at break (N/mm^2)	Stress at peak (N/mm^2)	Strain at break (%)	Strain at peak (%)	Young's Modulus (N/mm^2)
Improved SDMS	C	5883.9	6456.7	2.50	2.745	10.156	9.65	50.7
	C	8757.3	11032.5	3.723	4.70	13.7	11.0	125.2
	T	9941.0	10131.2	16.0	16.3	8.55	6.83	564.8
	T	8036.5	8392.5	12.9	13.5	8.35	6.55	437.5

Note: C—Compressive Test, T—Tensile Test

between the outermost wall of the bamboo specimen and the galvanized metal rod. By contrast, failure in the riveted joint occurred in the fasteners rather than in the bamboo specimen itself. The rivets were found to shear in-between the inner wall of the bamboo specimen and the outer wall of the metal rod. A third and final concept of the joint was designed whereby improvement in the mechanical fasteners were affected. Self-drilling metal screws were used instead of rivets and the results showed they could withstand greater loads without deformation and failure. Both the self-drilling metal screw and the metal rod were found to be unaffected by the maximum loading. Failure of the joint occurred in the wall of the bamboo specimen whereby formation of shear plugs was observed. After consideration of results obtained in the three conceptual designs, a final improvement of the self-drilling metal screw joint was carried out. This refined joint design could withstand a maximum peak force of 11000 N in compressive testing. Design modification in re-distribution of the load over a wider surface area proved to be more effective in rendering the joint stronger.

Further studies using a similar testing rig, as constructed by Villegas *et al.* (2015) involving trusses made out of bamboo slats, could be tested with whole culm portion. As mentioned by Burger et al. (2017), one of the main challenges for current development of bamboo as a sustainable alternative was to maximize its utilization in the mass market. In order to do so, investigation strategies to standardize the material for manufacturing process chains, namely for bicycle components was conducted. This research study, by comparison, was perfectly in line with the standardization process of bamboo culms. Key factors which influenced the process, namely diameter and wall-thickness, were resolved by using standardized metallic joints.

4. CONCLUSION

This research study involving *Bambusa* bamboo, conducted through a series of tests on conceptual designs, revealed that by applying appropriate joining techniques, the material could be rendered more versatile, and hence suitable for a much wider application. In destructive tensile testing, the failure of the initial conceptual joint involving self-drilling metal screws by shear plug formation revealed a major weakness in the material. This evaluation of the developed concepts led to a refined version of the joint design with better mechanical properties, namely, compressive and tensile strengths of about 11000 N and 9000 N respectively. Variations, namely in maturity, wall thickness and moisture content, in the bamboo specimens could be addressed in other research studies to achieve joint members with uniform properties. For sustainable development, this research study has shown that bamboo has the full potential to be commercialized and integrated into modern infrastructures, agriculture and so forth.

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