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The Performance of Bamboo Truss with Gapit Form Under Vertical Loads

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Abstract

The connection in bamboo construction is frequently the weakest point. This research discusses the performance of the gapit form on bamboo truss that effectively optimises the bamboo's inherent strength and can sustain vertical loads. Gapit is a connection form where a member is located between two members which also serves as a construction reinforcement. This truss optimizes the strength of whole bamboo with a total span of 4 meters and height of 2 meters. The gapit form applied at the top chord member, bracing member, and "V" support and column connections which are strengthen with bolts on the bamboo node. This research uses a quantitative method where data collection is taken through an experiment. To test the strength of the truss, a vertical hydraulic compression test was conducted. It was found that the truss can withstand a maximum load of up to 8.72 kN, with a truss decline of 7.27 cm, and a shift of 2 cm. As a result, the use of the gapit form on the truss is considered effective in withstanding large vertical loads.

INTRODUCTION

Bamboo is one of the building materials found throughout Indonesia. According to Sharma (1980), more than 75 countries and 1250 species of bamboo have been recorded. This plant is one of the sustainable material choices because of its rapid growth compared to other natural building materials. Bamboo has a faster growth period than wood. Wood that is usually found in forests will be ready to be cut down and used with good quality after 10 to 30 years, while bamboo with good quality and mature material can be obtained in a period of 3 to 7 years (Mustakim et al., 2009). During its growth period, certain types of bamboo can grow vertically at 5 centimeters per hour or 120 centimeters per day (Artiningsih, 2012). Morphologically, the structure of the bamboo stem typically consists of a hollow cylinder consisting of node and internode sections (Huang et al., 2015).

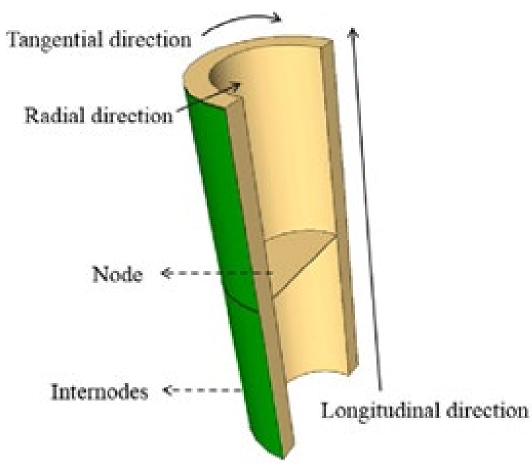

Fig. 1. Terminology of bamboo culms (Huang et al., 2015)

Bamboo as a material also has elastic or flexible properties due to its pipe-like shape that has a high moment of inertia. With high strength and low volume weight, building construction using bamboo material is more resistant to earthquake forces and easy to repair in the event of damage. Another important point to consider is the resistance of bamboo structures to fire. However, regarding the use of bamboo material in construction, some things that are considered for the selection of bamboo material as a construction material are bamboo's resistance to mold and insect attacks. This is why bamboo materials must go through a preservation or treatment stage to achieve the highest strength. Furthermore, to achieve the highest strength of bamboo construction, joint construction is also one of the things that need to be considered because bamboo joinery is related to low structural efficiency (Sharma, 1980).

The use of bamboo material in building construction can be found in trusses. Trusses are roof structures that provide certainty to the building so that it can remain standing under the loads and pressures that hit it such as wind loads, wind pressure, climate change, earthquake shocks, and others (Koesmartadi & Anandhita, 2018). Bamboo truss is one of the construction innovations where the application of bamboo as a truss is the right or ideal choice because of its strong, resilient, and lightweight nature. In its design, joint strength is a very important thing to consider.

The strength of conventional bamboo joints is generally very low. The parallel fibers with low shear strength make the bamboo break easily in bamboo joints with nails or pegs. On the other hand, rope connections are based solely on the frictional strength between the rope and the bamboo as shown in Figure 2, so the strength of the bamboo cannot be optimally utilized. In addition, the use of rope as a connection requires regular checking due to the potential for large bamboo shrinkage due to temperature changes, the frictional strength will decrease and cause the building to collapse. Therefore, a proper connection is needed in the use of bamboo construction, one of which is graphic form. *Gapit* form is a type of connection in bamboo that uses the strength of the bamboo itself as the basis for construction strength. The *gapit*an technique is also referred to as the connecting and reinforcing system of the structure. The *gapit* technique is used by clamping a bamboo with two other bamboo members at the top and bottom.

Fig. 2. Bamboo rope joinery (Dewagana & Arif, 2022)

METHODOLOGY

The research method used in this study is quantitative where data collection is taken through an experimental design process. The use of quantitative methods in this research is intended to solve problems or find answers through rigorous design such as experiments to be able to achieve objective results. Quantitative research is intended to make accurate measurements of something (Cooper & Schindler, 2014). In the research process, the design has been determined from the beginning before the implementation of the experiment. The design was designed using the standard formulation m=2j-r where m is the number of members, and j is the number of joinery. This was done to determine whether the truss was perfectly balanced. Cremona diagrams are also used to determine the strength generated by a design. The use of the diagram also determines the function of members in the truss as tensile loads or compressive loads.

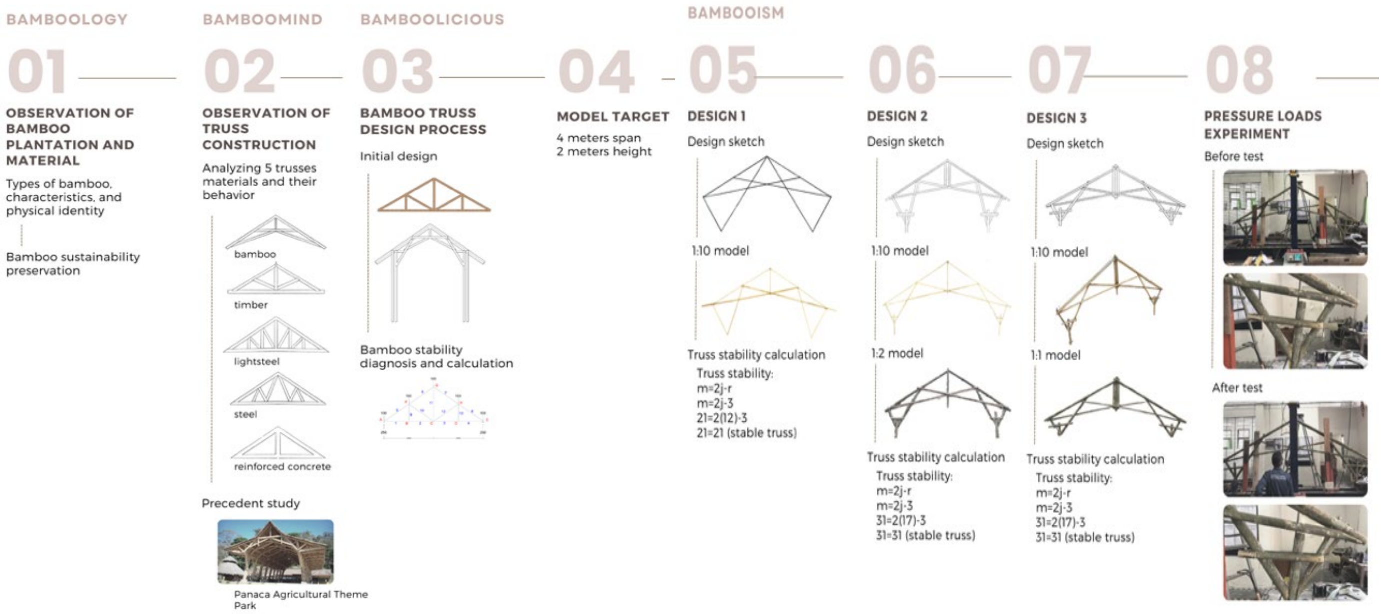

Fig. 3. Diagram methodology

In quantitative studies, the problem or research question is quantified, and the processes that ensure that one or more (quantitative) variables may influence another variable are established (Taheri et al., 2016). This experimental research method is also considered the most reliable scientific research because it is considered valid with strict control of the confounding variables outside the experiment. There are two variables, such as independent and dependent. The independent variable is something that impacts the dependent variable. On the other hand, dependent variable is something that is affected by the independent variable. In this context, the independent variable is vertical loads and the dependent variable is the bamboo truss with gapit form.`

The experiment started with the creation of a 1:10 prototype using bamboo sticks. After analysis using Cremona diagrams, there were several improvements to strengthen the construction of the truss. The manufacture of the 1:10 model was consistently organized based on the final design. Then, experiments were carried out to make a prototype with a size of 1:2 with the possibility of adding a column design. In the process, there was an improvement in the arrangement of the bamboo materials used with the *gapit* form in the 1:1 model.

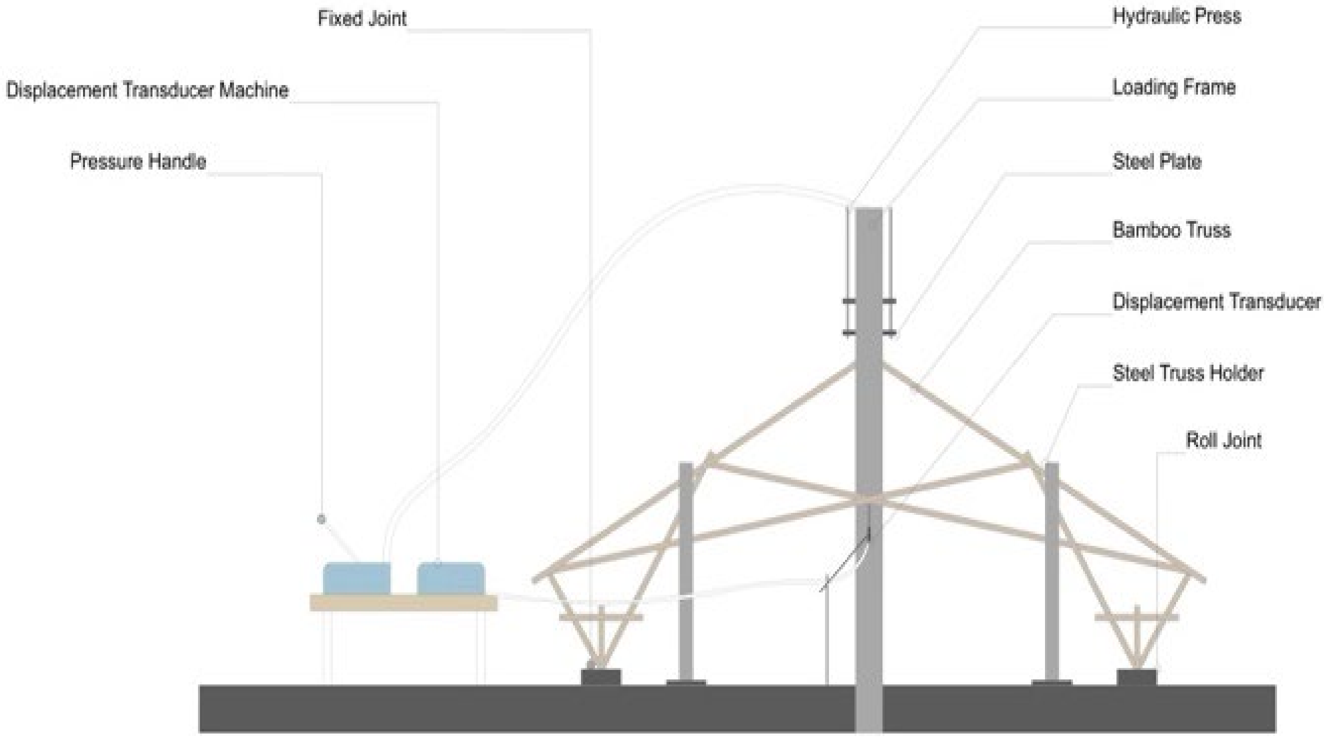

Fig. 4. Front view of hydraulic pressure test setup

Further experiments were carried out by a press test with a vertical load on the truss. The test used a hydraulic press that applied a vertical load resembling the original load of the roof truss. The compressive test was conducted in three stages, namely the preparation stage, the test process stage, and the test result stage. In the preparation stage, there is test equipment used to measure the research sample. Steps were taken in the preparation stage, including: (1). Setting the truss span of the test equipment at 4 meters with a height of 2 meters; (2) Placing the truss on the compression tester and fitting the tops of the truss to the center point of the compression tester; (3) Installation of pinned and rolled support points; (4) Placing an iron plate on the top of the truss as a vertical load pressure point; (5) Installation of ropes on the truss with a compressive test device to hold the truss; (6) Installing a displacement transducer at the bottom of the center of the truss to measure the decrease that occurs due to vertical pressure; (7) Marking at one end of the support with pinned joint to measure the starting point of the truss.

The following is the stage of the press test process carried out using hydraulic press test equipment. Testing was carried out with several recording instruments, namely video media, photo media, note-taking, and recording on hydraulic test equipment and displacement transducers. Then, in the data collection stage of the test results, the hydraulic device was not removed to see the behavior that occurred in the bamboo truss against the maximum vertical load that could be applied. Records of the maximum load, displacement of the fulcrum, and settlement of the easel due to the applied load were recorded for later analysis. The behavior of the damaged bamboo was also collected through photographs. Thus, quantitative and experimental research methods were conducted cumulatively so that understanding could be gained after data was collected.

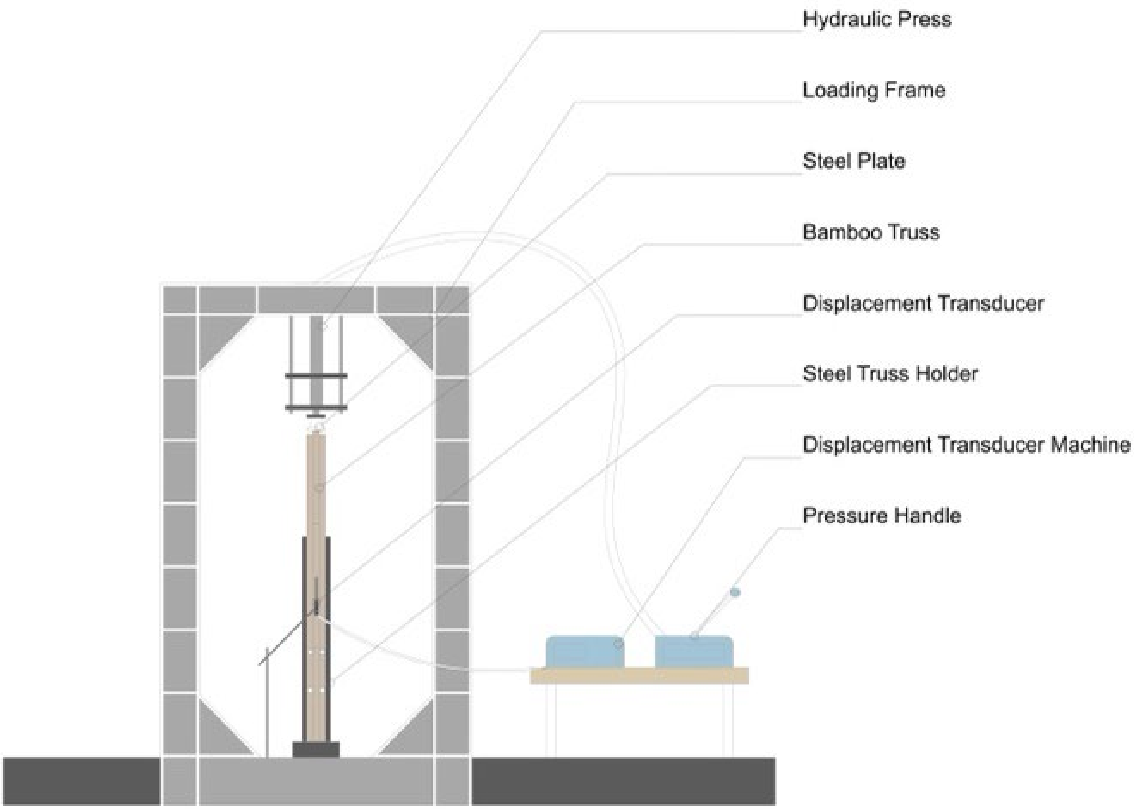

Fig. 5. Side view of hydraulic pressure test set up

RESULT AND DISCUSSION

The initial step in this research is the design of the truss with a maximum height of 2 meters and a span of 4 meters wide. The truss must also meet the stability requirements of the truss by proving the formula m = 2j-r. On the other hand, analysis with Cremona diagrams is needed to determine the tensile and compressive loads on the truss.

Design Process and Calculation

In the design process, there were improvements and development of the design by paying attention to the use of bamboo material. In the initial design as shown in Figure 6, the use of bamboo as a material is highlighted in the complexity of joinery and the arrangement of whole bamboo and bamboo slats. After calculations using the equine stability formula, it is evident that this design has a stable truss.

Truss stability:
$m = 2j - r$
$m = 2j - 321 = 2(12) - 3$
$21 = 21\ (stable\ truss)$

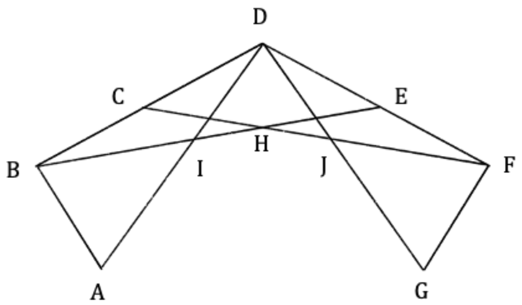

Fig. 6. First design sketch

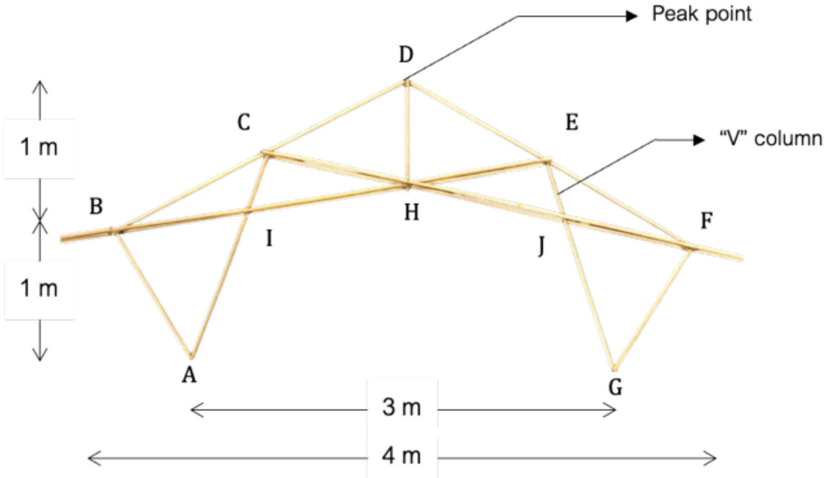

Fig. 7. First design 1:10 model

This design was continued by making a 1:10 model with some design improvements (Figure 7). Improvements were made to avoid connecting five different members in the same joinery, namely in the peak joinery or D point. It is because if too many members joined at the same point, it will cause the strength of the joinery to weaken. It is also related to the complexity of the construction process of the truss at the top joinery. In this design, the building column is a "V" column that becomes a united structure with the truss. This causes the span of the truss to be 3 which does not comply with the provisions, 4 meters. In addition, this design is considered unscalable because the overall height of the truss is 2 meters where the truss only has a space underneath with a height of 1 meter.

In the process, there were some changes to the design of the truss as shown in Figure 8. These were in the addition to the column support which is placed at the center of the "V" structure support of the truss with a span of 4 meters. The additional columns were then connected with "V" supports using slatted bamboo and *gapit* form to strengthen the connection. In addition, changes were made to the overall width of the truss to 5 meters.

Truss stability:
$m = 2j - r$
$m = 2j - 3$
$31 = 2(17) - 3$
$31 = 31\ (stable\ truss)$

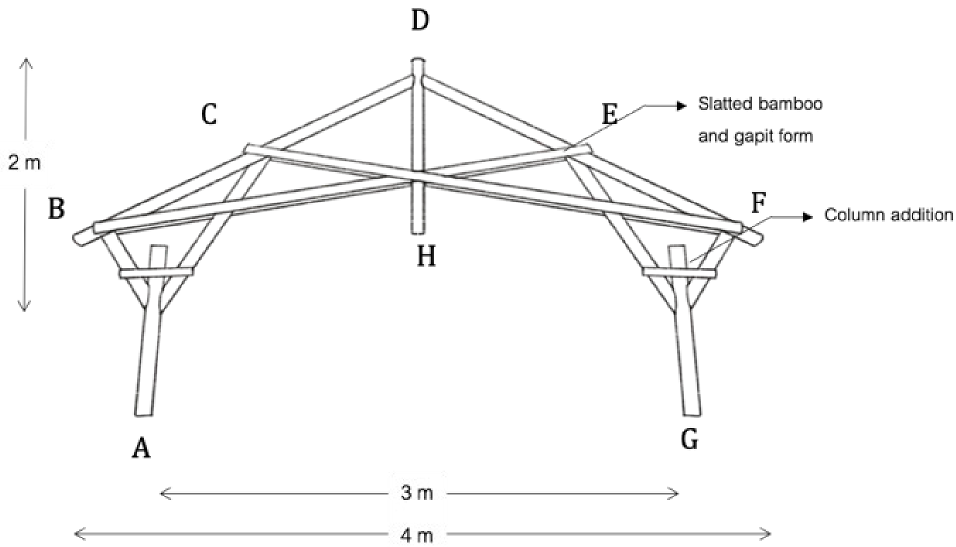

Fig. 8. Second design sketch

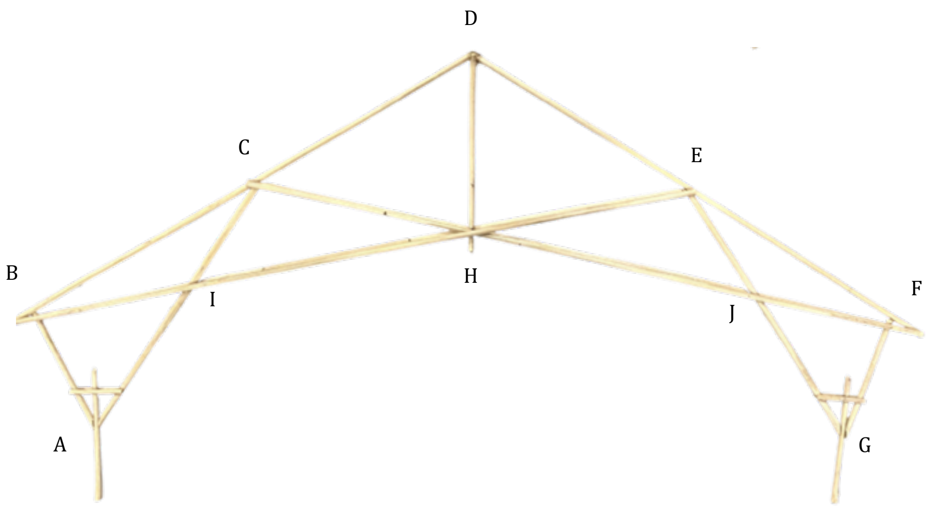

Fig. 9. Second design 1:10 model

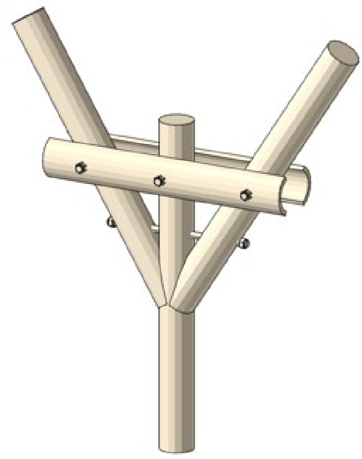

Fig. 10. "V" support and additional column with slatted bamboo and gapit form connection

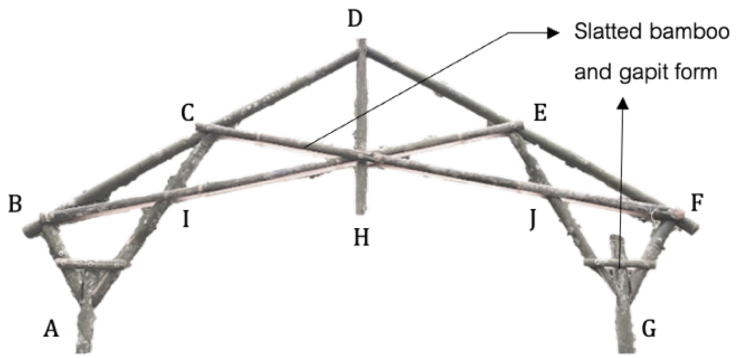

Fig. 11. Second design 1:2 model

In making the 1:10 model as shown in Figure 9, there were no design changes. Furthermore, in making the 1:2 prototype model as shown in Figure 11, most of the bamboo used in this design is whole bamboo, except for members CF and EB and the connection between the additional column and the “V” structure. Both parts used slatted bamboo with the *gapit* technique as shown in Figure Figure 10. In members CF and EB, the center of the two bamboo slats is filled with a piece of whole bamboo which consists of bamboo nodes to provide strength to the bamboo slats as shown in Figure 12. In addition, at the center of the truss, an additional king post member is added which has a longer size than the previous design. This is intended as an aesthetic of the truss.

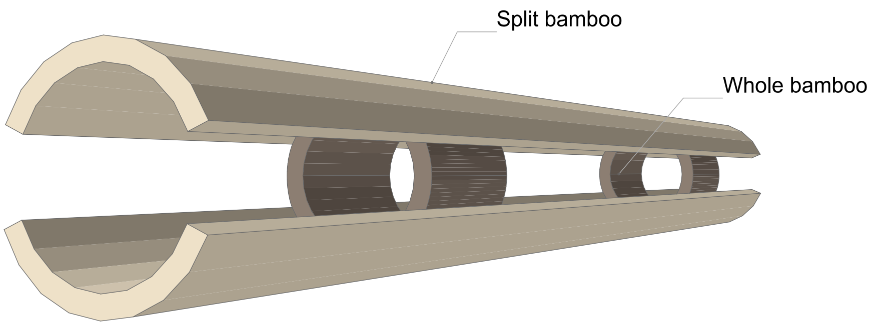

Fig. 12. Arrangement of slatted bamboo, whole bamboo, and gapit form

The final design (Figure 13) pays attention to the use of bamboo as the main strength. In this design, all truss members use the whole bamboo. The slatted bamboo in members CF and EB that existed in the previous design is replaced with whole bamboo using the *gapit* form on both sides of the truss in a crosswise manner. Both members (CF and EB) function as bracing that provides a tensile load to the truss. There are an additional three king post members for aesthetics purposes, the center of which has more length for score reinforcement and ornamentation. The three king post members are flanked by the legs of the truss or the top chord members on both sides. The analysis led to the change of the slatted bamboo material to whole bamboo to use the strength of the bamboo as the main key.

Truss stability:

$$m = 2j - r$$
$$m = 2j - 3$$
$$31 = 2(17) - 3$$
$$31 = 31\ (stable\ truss)$$

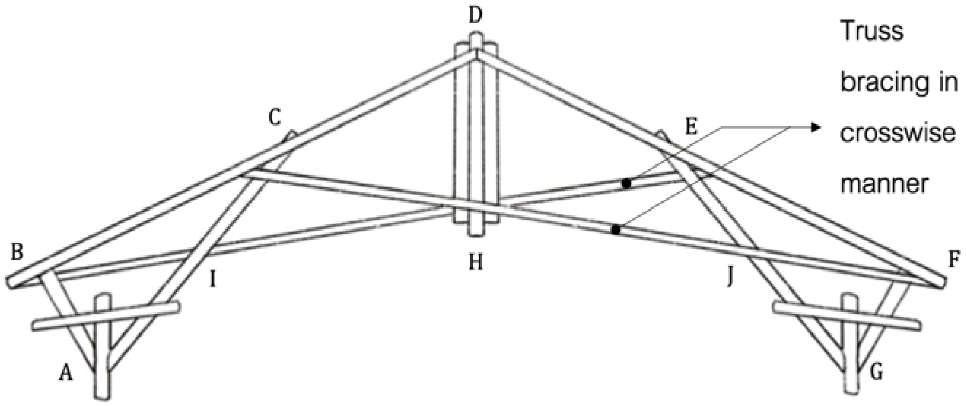

Fig. 13. Final design sketch

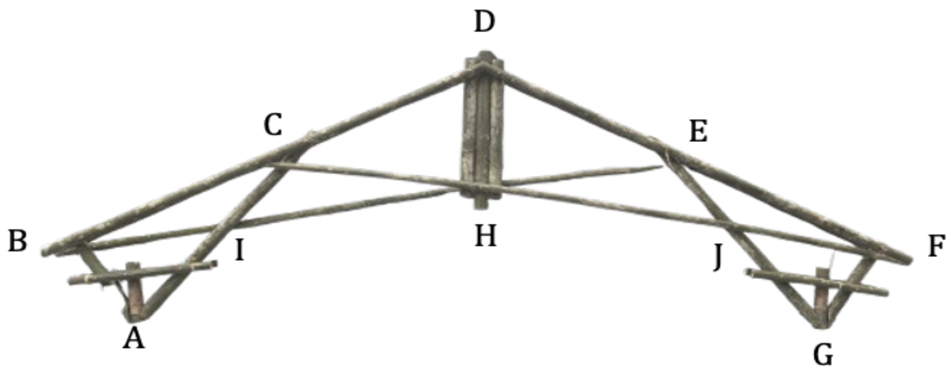

Fig. 14. Final design 1:1 model

Fig. 15. D point joinery detail

Fig. 16. B and F point joinery detail

Fig. 17. H point joinery detail

Fig. 18. C and E point joinery detail

Fig. 19. A and G point joinery detail

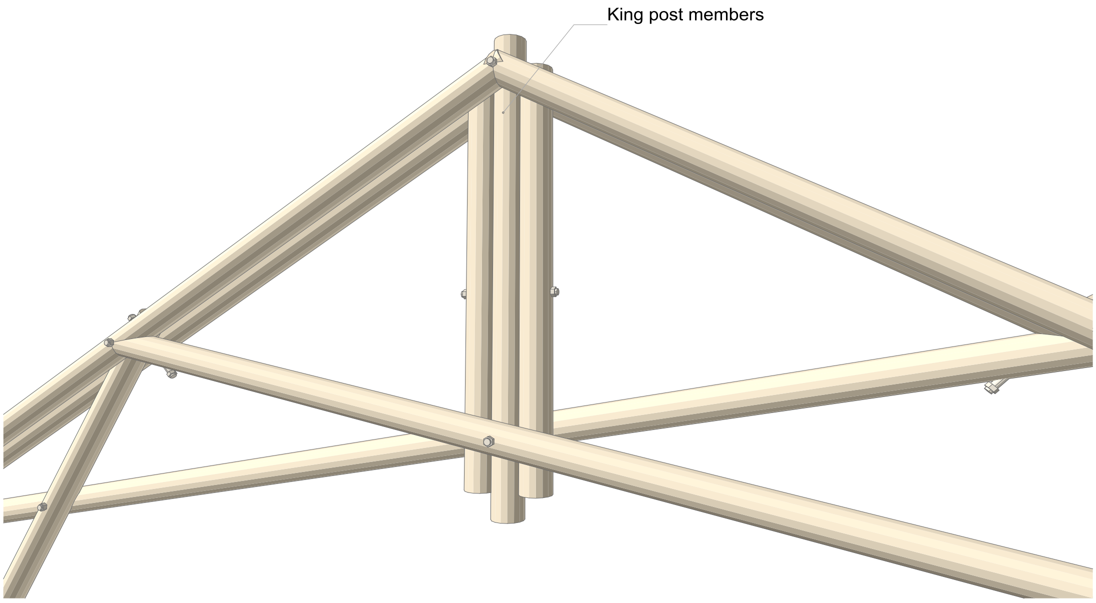

Fig. 20. King post members

Truss Arrangement and Analysis

Based on the truss design process, the arrangement of bamboo materials is an important thing to consider in the design of a bamboo truss. The strength of bamboo lies in the bamboo nodes. Bamboo is a very strong building material when used as a whole. On the other hand, bamboo slats do not have enough strength to support loads over wide spans. The slatted bamboo was considered to be a weakness due to its weakened tensile strength. This is because the strength of the bamboo has been reduced and the split bamboo will easily bend towards the inside of the split bamboo or against the bamboo skin.

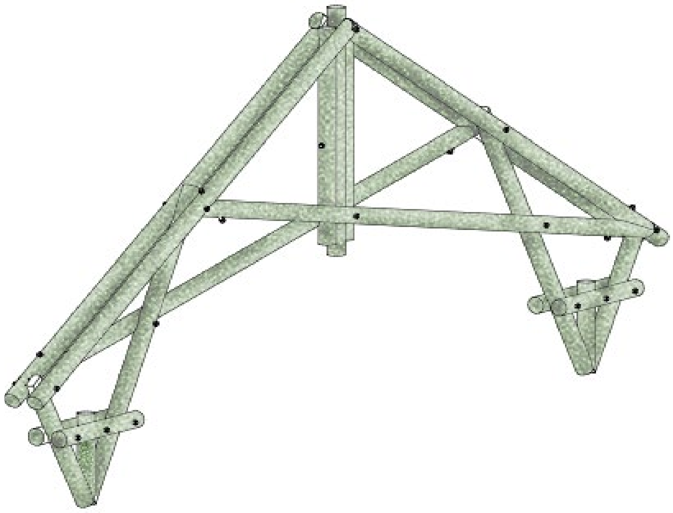

Fig. 21. Truss dimetric axonometry

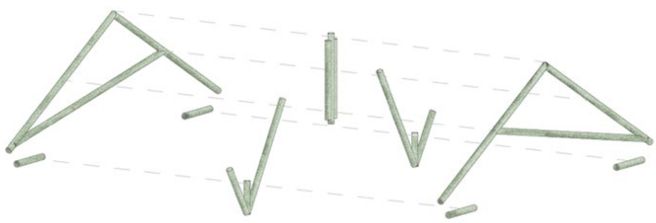

Fig. 22. Exploded arrangement of gapit form truss

On the other hand, bamboo joints are also crucial and contribute to the strength of the truss. The large number of members that meet at one point will be difficult to connect as only a tiny amount of the bamboo ends are attached. It will conclude that only a few bamboo sections can be joined and make the truss weaken. Therefore, the *gapit* form using whole bamboo is one of the right techniques to apply in bamboo construction. The *gapit* technique will utilize the full strength of the bamboo and facilitate connection at a joinery point.

Mitered butt joinery is one of the methods used in the truss construction process. This type of joinery creates an angle where the two sides of the member meet to link them together. Comparing this joinery to other forms of timber joinery, it is more sophisticated in terms of aesthetics and can sustain higher weights (Derikvand & Eckelman, 2015). In this situation, it would be easier to join the bamboo at both ends using a mitered butt joint. Additionally, the method in which the bamboo members are arranged looks more neatly organized and attractive as shown in the peak point of the truss.

The structural analysis of the truss was conducted which determine the role of the member parts in the truss as tensile bars and compression bars. The analysis is visualized in Figure 23. In this truss, the tensile members are located on the bracing arranged in a crosswise manner with *gapit* form as shown in Figure 24. The bracing members are flanking the king post members and fastened with an 8/12 mm bolt in the center. In addition, the ends of the bracing members are connected to the top chord members. Both ends of the bracing members are joined using the same technique on the bamboo nodes to maximize the strength of the bamboo itself.

In addition, tensile bars are also present in the "V" support members (Figure 25). When the top chord members are pressurized, the bracing members and the "V" support will tensile each other to the applied pressure. The “V” supports are also flanked by the top chord members. This is done to strengthen the construction of the truss when receiving roof loads and transferring them to the column. The “V” support and column support are also connected by a *gapit* form that is arranged horizontally to strengthen the connection between the three members.

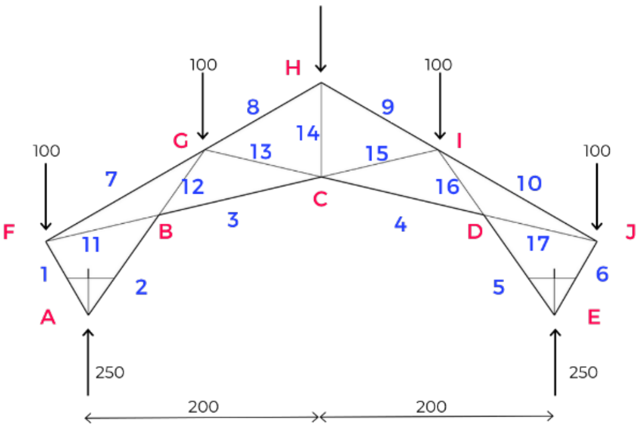

Fig. 23. Structural analysis of truss

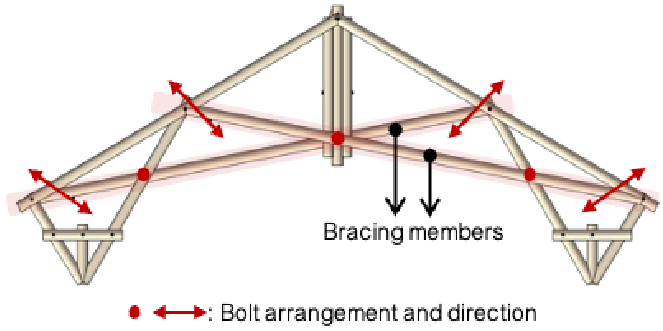

Fig. 24. Bracing members arrangement and joinery direction

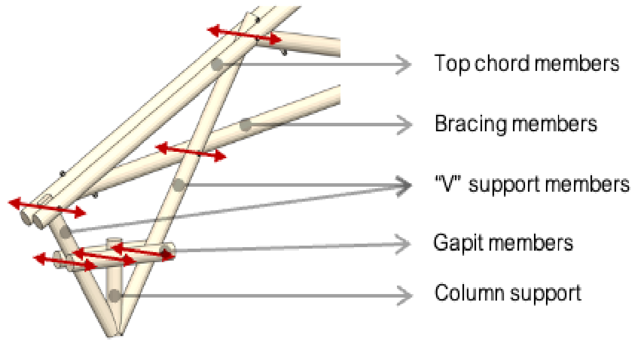

Fig. 25. "V" support members arrangement and joinery direction

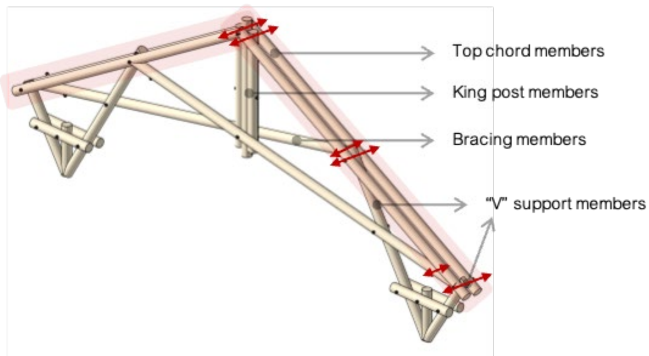

Fig. 26. Top chord members arrangement and joinery direction

Moreover, the top chord members are the members that play a role as the pressure members. The top chord members consist of four bamboo poles flanked by the king post members and "V" support. This technique is used to strengthen the construction and reduce excess members meeting at one joinery point. These top chord members act as pressure members considering that they are located at the very upper part that will be in direct contact with the roof envelope. These top chord members are also in direct contact with bracing members that are connected at the midpoint and ends of the top chord members to effectively transfer vertical pressure. In addition, a mitered butt joinery technique was also applied at the peak point by cutting the bamboo ends by 30 degrees. At the peak point, the edge of the top chord members is flanked and connected to the two outermost king post members with *gapit* form (Figure 26).

Experiment Result Analysis

In the experiments that have been conducted, it can be seen that there is a linear decrease in the truss subjected to vertical compressive loads. This truss design can withstand loads up to 8.72 kN or equivalent to 889.19 kg until the truss reaches the point of breakage. The decline of the truss was 72.71 mm calculated using displacement transducer (Figure 27). In addition, the column points on the right side of the truss shifted by 2 cm from the starting point.

Several damages occurred to the truss after the experiments were conducted, all of which had the role of tensile members. The most severe damage occurred at the "V" support, precisely at point G, which can be seen in Figures 29 and 32. In the "V" support member, the bamboo splits into two parts at its upper end. When vertical pressure was applied, the member would pull on the top chord members until it reached the point of breakage that caused the member to split into two. Not only that, but damage to the bamboo members also occurred at points A, B, and E in the form of cracking. This was also because the member had reached the highest level of resistance in tensile strength until cracking occurred at the edge of the member.

Table 1 Truss Decline to Pressure Load Chart

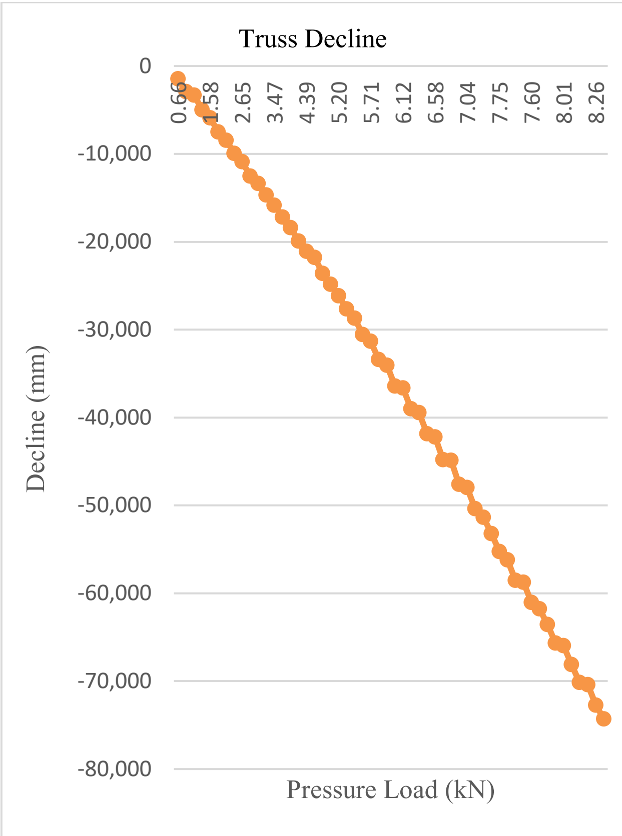

Fig. 27. Truss decrease with displacement transducer

Fig. 28. Before and after experiment of peak point

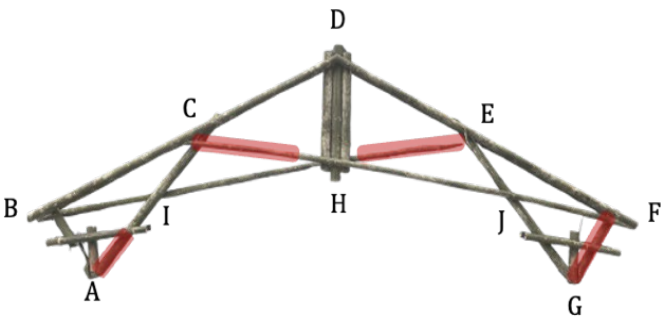

Fig. 29. Breakage points after experiment

Fig. 30. Before and after the experiment of the truss side view

Fig. 31. Before and after the experiment of "V" supporrt members

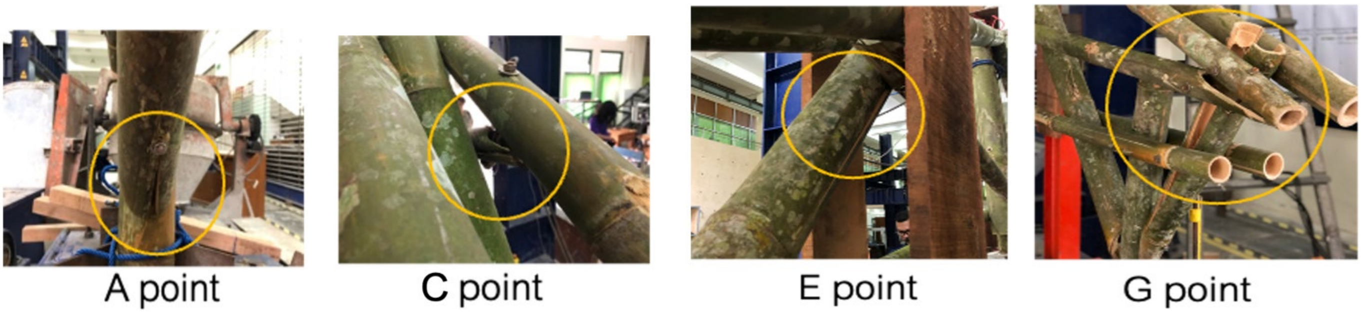

Fig. 32. Breakage points detail after experiment

CONCLUSION

From the results of the research conducted, the majority of the truss members are tensile members. This is because it utilizes the characteristics and advantages of bamboo material which is formed from fibers. In addition, a *gapit* form is applied to optimize the strength of the bamboo. It was found that the *gapit* form is one type of connection that is effective to be applied to truss roof construction. The *gapit* form is able to support the compressive and tensile loads acting on the truss optimally. On the other hand, the use of a *gapit* also optimizes the strength of the bamboo as a whole, compared to the use of split bamboo. This is because the bamboo nodes are still connected and thus have high strength.

The application of the mitered butt joinery technique and the use of long bolts is also an indicator of the strength of the truss. Mitered butt joinery is applied to each joint where the bamboo edges meet the other bamboo both on the stem and the edge. The connection is strengthened by using long bolts and also a *gapit* form. Both connection forms reinforce the *gapit* connection form in this truss construction.

In the experiments conducted, the *gapit* form was applied at all points. At the point of the column, there is also no significant shift where only a 2 cm shift occurs. With a maximum load weight of 8.72 kN, bamboo construction with a *gapit* form is considered effective enough to be applied to building construction that supports heavy loads.

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