Proposing Joints for Bamboo Tensegrity

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Abstract

Tensegrity is an abbreviation of tensile and integrity. The structure consists of compression members connected with wires or strings until forming a balance and stability without connecting each compression members. Tensegrity for building is still rarely applied because of its large deformation. Furthermore, the tensegrity structure using bamboo as the compression material is still limited on temporary structure.

Usually the tension member of bamboo tensegrity is in the form of wire or cable, and the compression member is in the form of bamboo pole. Bamboo as a compression member has a good elasticity. This elasticity is used in some tensegrity structures, which are designed in such ways, that there is no need of turnbuckle to accommodate high tension at the wires.

The main problem in using bamboo as tensegrity structure material is how to transfer the force in the wire into the whole section of the bamboo. This research will describe some examples of proposed bamboo tensegrity joints and discuss 2 (two) of the built proposed bamboo tensegrity sculptures.

The proposed bamboo joints for tensegrity structure are fall under many categories based on their load transferring systems. The built proposed joints used installations built by university students under the author supervision. Problems arise from the construction process are (1) weak and (2) over strong pre-tensioning process, (3) wire winding problem, (4) crushing of the bamboo wall around the hole by the wire, (5) early failure at the weakest wire clip connection, and (6) movement of the steel rod from its axis.

The recommendation for those problems are (1) to do the pre-tensioning and the winding process strongly but carefully and gradually, (2) to add additional wire clip at the wire connections, and (3) to use the plate with a mechanism to attach rigidly with the bamboo wall.

Introduction

Tensegrity

Tensegrity structure consists of compression members connected with wires or strings until forming balance and stability without connecting each compression members. Widuri (2014) explained that there are three controversial inventors of tensegrity structure. First, Buckminster Fuller was an inventor who patented his tensegrity in 1959 and received it in 1962. Fuller gave the name ‘Tensile Integrity’, thus he was the founder of the name ‘tensegrity’. Second, George D. Emmerich was also one of the inventors who submitted his tensegrity at the time around the Fuller’s, but received it in 1964. The third inventor is

Kenneth Snelson, an artist who wasthe student of Fuller. He submitted his patent in 1960 and received the patent in1965 under the title "*Continuous tension, discontinuous compression structures*".

Even though it has been developed since 1960's, tensegrity for building is still rarely applied because of its large deformation. Though the structure stability could be achieved with the compression and tension member only, large deformation is still difficult to avoid. Thus, if it is used in a functional building, it is mostly not a pure tensegrity or some of the compression members that are connected with each other. Furthermore, the tensegrity structure using bamboo as the compression material is still limited to temporary structure.

Bamboo as tensegrity material

Tensegrity structure is a structure consists of 2 (two) elements: tension member and compression member. The compression member does not connect with each other. Usually the tension member of bamboo tensegrity is in the form of wire or cable, and the compression member is in the form of bamboo pole.

In the tensegrity construction process, there is a stage where the wire or string should be strengthened so that the whole structure could be rigid and stable. This could be mentioned as pre-tensioning and usually a turnbuckle is used. The bamboo used as a compression member has a good elasticity. This elasticity is used in some tensegrity structures, which are designed in such way, that there is no need of turnbuckle to accommodate high tension at the wires.

The main problem of using bamboo as tensegrity structure material is how to transfer the tension force in the wire into the whole section of the bamboo. Since there are not many tensegrity buildings made of bamboo as compression materials, there is not much example for its joinery. This research will describe some examples of proposed bamboo tensegrity joints and discuss 2 (two) of the built bamboo tensegrity structures and its joints.

Development of Bamboo Tensegrity Joinery

Since the bamboo tensegrity is relatively new, there is no joint that is especially developed for bamboo tensegrity. Some joints have been be proposed and analyzed in the following section.

Joint 1: Hollowed Wheel

The hollowed wheel is the head of a cylindrical steel pipe, used to connect tension elements. The strings are gripped to the wheel. It is connected to hollow steel pipe, which goes directly to the inside of the pole. As the resultant forces in the pipe will always a compression force (in tensegrity structure), the force will be transferred to the bamboo wall through perpendicular screws or bolts. In the new classification of bamboo joints by Widyowijatnoko (2012), the joint is part of Group 4a *Transferring force through bearing stress and shear to the bamboo wall from perpendicular element connected from inside.* Though the pipe is inserted inside bamboo hole, it is difficult to transfer the force through friction from inside due to the variation of the diameter of the hole.

Fig. 1. Hollowed Steel Joint (Courtesy of *Lehrstuhl für Tragkonstruktionen* RWTH Aachen)

The advantage of this joint is the flexibility to determine the length of compression elements. To avoid crack, there should be a node in the end of the pole. Finding the poles in certain numbers with a certain length and with the presence of node in the end could lead into a big problem. This joint will solve this problem.

The disadvantages of this joint are the difficulty to fit the diameter of the steel pipe to the diameter of the hole. If the bamboo inner diameter is much bigger than the produced steel pipe, the shearing force from the long screws may introduce fracture.

Joint 2: Flexible Cylinder

This connection belongs to Group 3 *Transferring force through the friction from the outer surface* and the Group 4b *Transferring force through bearing stress and shear to the bamboo wall from perpendicular element connected from outside* according to the bamboo joints classification by Widyowijatnoko (2012). The upper part of the component could adapt to different diameter by using metal sheet and fixing by bolted joint.

The advantages of this joint are the flexibility to fit with different diameter of bamboo in certain range and the use of friction on the outer surface which is the strongest part of bamboo. However, the joint should be placed very close to the end of the pole. Therefore there is no much flexibility in the length of compression elements. The presence of perpendicular element in the end of the pole may introduce splitting or crushing failure because of shearing force.

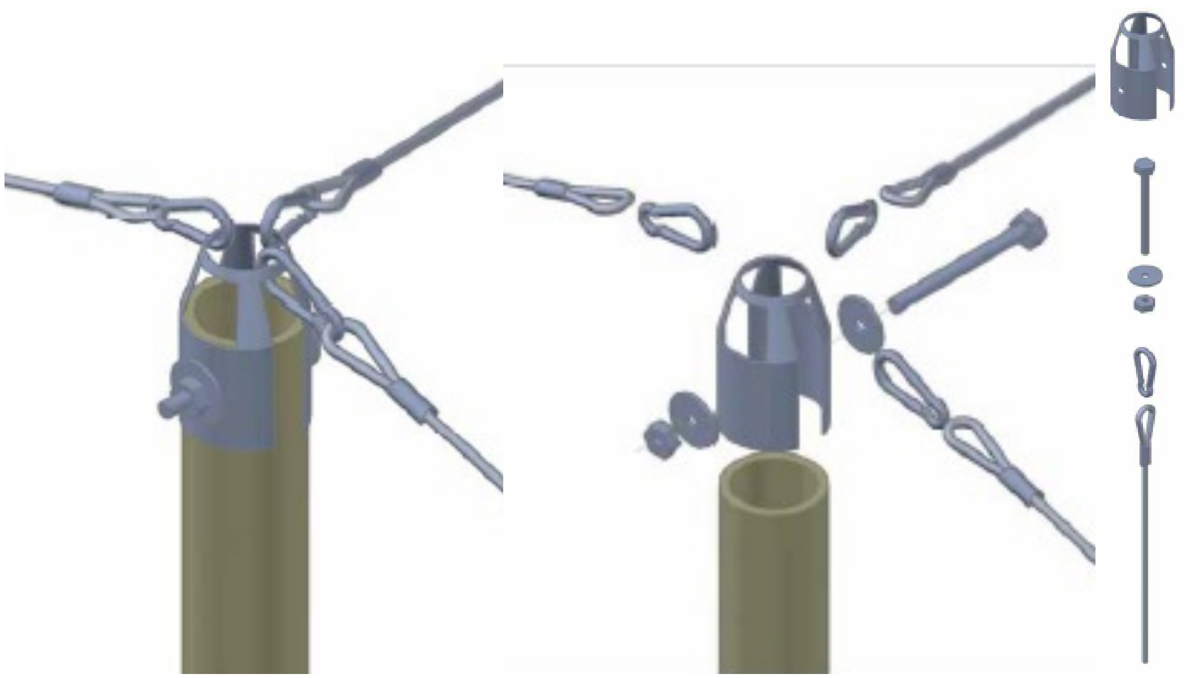

Fig. 2. Flexible Cylinder (Courtesy of *Lehrstuhl für Tragkonstruktionen* RWTH Aachen)

Joint 3: Intersecting Circular Tube

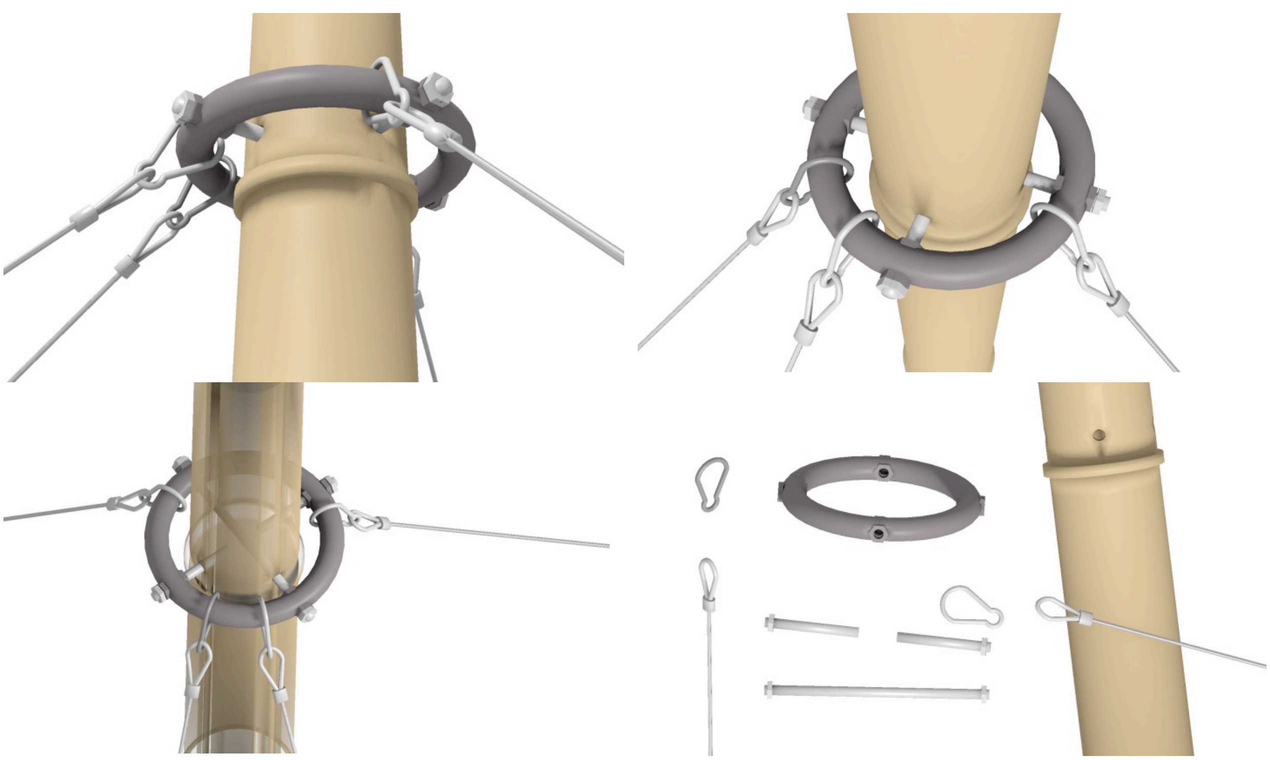

Fig. 3. Intersecting Circular Tube (Courtesy of *Lehrstuhl für Tragkonstruktionen* RWTH Aachen)

This connection belongs to Group 4b *Transferring force through bearing stress and shear to the bamboo wall from perpendicular element connected from outside* (Widyowijatnoko, 2012). The wires are attached to the circular steel rod which is connected to the bamboo by 3 (three) intersecting steel screws.

The advantage of this joint is the high flexibility and possibility to attach the wire with the wide circular steel. This joint is adaptable to different diameter of bamboo and can be placed not just in the end of the pole, but also in the middle of the pole. The disadvantage of this joint is that the transferring force relies only on bearing stress.

Joint 4: Lashing Joint 1

This joint uses the principle of lasso joint, the more tension introduced to the wire, the more radial compression perpendicular to the fiber to the center of the pole will be. The more tension introduced to the wire, the wire will squeeze the pole and generate more friction on the outer surface. This connection belongs to Group 3 *Transferring force through the friction from the outersurface* and the Group 1 *Transferring compression through contact to the whole section* (Widyowijatnoko, 2012). The components are one ring and a set of wire with a branched part. One part is made of one thick wire and the other part is made of two smaller wires. It is created by encircling the a section of the bamboo by the branched wire from the inside. Then the ends of the two smaller wires are connected with the other one thick wire. The ring is used to protect the edge from the friction of the string.

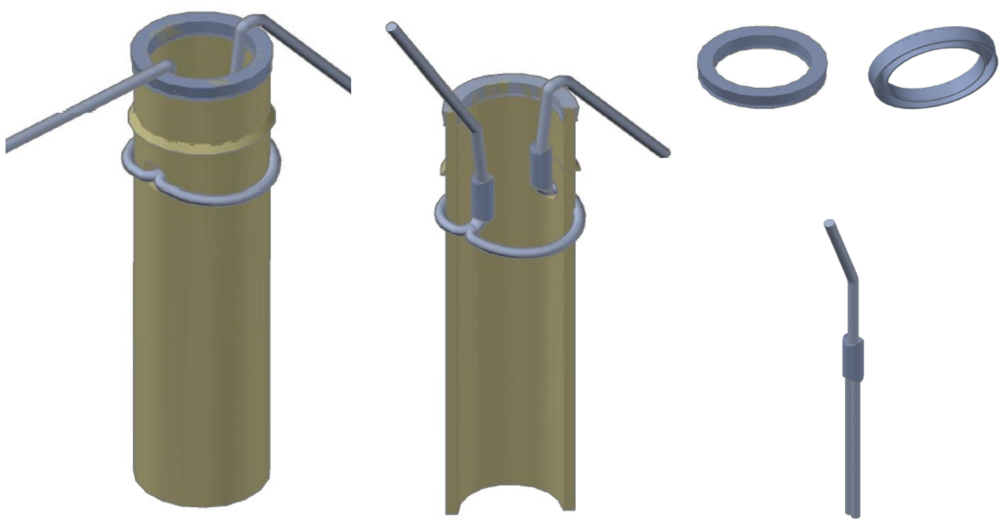

Fig. 4. Lashing Joint 1 (Courtesy of *Lehrstuhl für Tragkonstruktionen* RWTH Aachen)

The most significant advantage of this lashing-based joint is the adaptability of the joint to the various diameter of the pole. Lashing joint is also considered as the easiest bamboo joint. Using the outer surface means also using the strongest part of the bamboo.

The disadvantage of this joint is the difficulty in fixing the position of the ring to protect the edge of bamboo wall. Different force introduced to the wire will lead to the movement of the ring to an uncertain position. To protect the edge of the bamboo pole, the diameter of the ring should be similar to the diameter of the bamboo with the same thickness with bamboo wall.

Joint 5: Lashing Joints 2

This configuration is based on the traditional lashing method. It just consists of a wire and a wire clip. The wire crosses the bamboo, encircles the bamboo one time, and crosses the bamboo again and come out in the initial hole. The position and amount of wire output depends on the winding configuration. This connection belongs to Group 3 *Transferring force through the friction from the outersurface* (Widyowijatnoko, 2012). This joint uses the same principle as the previous one.

To measure the strength of the joint, a radial compression test has been conducted in RWTH Aachen using *Guadua angustifolia* with diameter of 95-100 mm and wall thickness of 9-15 mm. The result showed that the radial compression strength of bamboo without node could resist an average load of 16.08 kN until the initial crack (Widyowijatnoko, 2012).

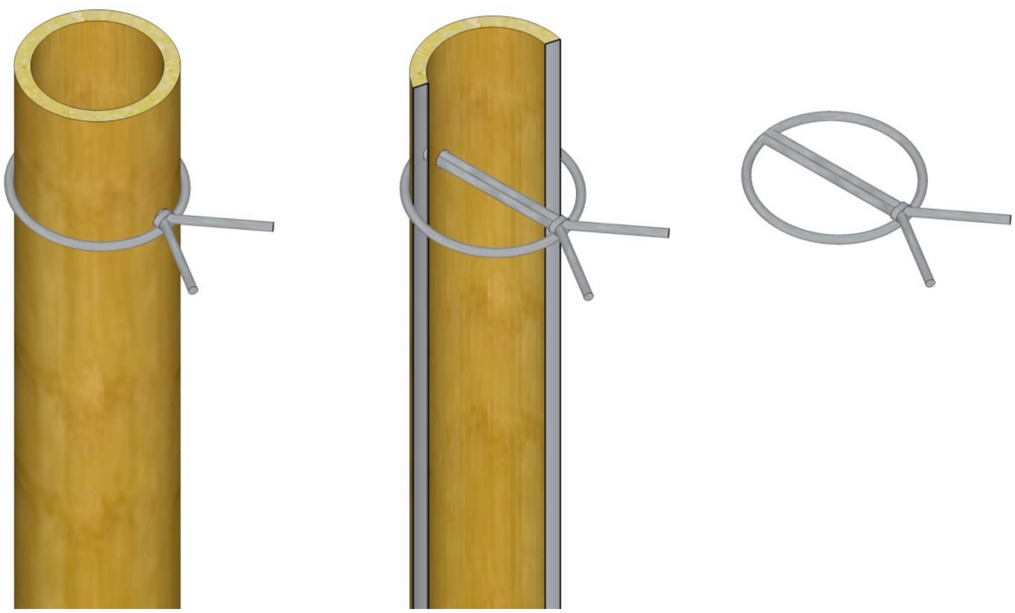

Fig. 5. Lashing Joint 2

The advantages of this joint are its practicability, economics and flexibility. This joint uses the strongest part of the bamboo and the character of round shape bamboo. There will be lesser shear failure possibility since the wire encircles the bamboo under the hole. The passing wire pushes against the knot.

A more complex winding configuration for more wires output may create difficulties when crossing the wire through the bamboo. This will be the biggest disadvantages of this joint. Pre-tensioning the wire is difficult with the presence of winding mechanism. Friction on the surface makes the winding of the wire cannot perfectly be done. Thus, the wire might be loose when the structure is erected.

Joint 6: Lashing Joint 3

This joint consists of short parts (usually at least 1 node length) at the end of bamboo pole is introduced to compression stress by the winding wire under and the wood/steel plate over. The winding wire is used for stabilizing the steel rod, not for distributing the compression force from the structural wires. This configuration enables the pre-tensioning mechanism by rotating the nut at the plate to pull the steel rod out. This pre-tensioning mechanism is significant for bamboo tensegrity structure since its wire might be loose over time. This mechanism could replace the use of turnbuckle in each wire. This connection also belongs to Group 3 *Transferring force through the friction from the outersurface* and the Group 1 *Transferring compression through contact to the whole section*. It is also an adaptation of proposed joint by the author in Traditional and Innovative Joints in Bamboo Construction (2012).

Fig. 6. Lashing Joint 1

The most significant advantage of this joint is the mechanism of pre-tensioning to tighten the wire in a system of tensegrity. The winding system in previous lashing joint may cause the tension stress to decrease overtime. This problem is solved by using a simple connection of wire to the eye nut.

The disadvantage is that a too long protruding rod after the pre-tensioning may suffer buckle failure. Shear failure might happen in area between the plate and the winding wire after the pre-tensioning.

Built Example of Bamboo Tensegrity Joint

In this chapter, an example of lashing joint 2 and lashing joint 3 will be explained. Both are Institut Teknologi Bandung university projects that were built by students and supervised by the author. This chapter will explain the built tensegrity, the construction problems and solutions in the site, and the condition of those after months.

Lashing Joint 2

The tensegrity structure using this lashing is a snub dodecahedron tensegrity ball. It is built as an installation for Artepolis 5 Conference in Institut Teknologi Bandung. It used 30 bamboo and 30 set of wire. Each bamboo end had 3 wire output. One wire acted as the main wire that attached to the both ends of each bamboo using lashing joint 2. The other 2 wire outputs are main wire of other bamboo member that attached to the other side of the winding wire using a wire clip.

Fig. 7. Snub dodecahedron tensegrity ball

The problems during the construction were (1) connecting the last wire and (2) pre-tensioning process. The construction process essentially was to attach each module from the upper part to the lower part, one at a time. The modules were the bamboo with attached main wire. Since no scaffolding was used for the first time, the last module had the highest tension collected from the weight of its upper parts. It was the cause of the first problem. It made the process of stretching the wire to its member difficult. The solution came up were to lift, manually, by several students, the finished upper part during the assembling process of the lower parts.

Fig. 8. Initial process and lowest member pre-tensioning

The second problem might be caused by the imprecision and the imperfect winding of the model that was used. The model that was used did not accommodate the small variations in the bamboo diameter, and deformation of the model after the erection. The built construction was mainly built from an ideal model. Thus, after the whole construction was finished, the wire stretched and the winding wires were strengthened into fitter winding. Then the whole model deformed into an elliptical shape. The solution came up were to strengthen the wire again until the deformation was not significant. It was done by redoing the lowest module with stronger pre-tensioning, rotating the whole model, and the same cycle was done until the deformation was satisfying. Since the deformation caused some of the lowest part not to participate in the force distribution, redoing the lowest part was easy.

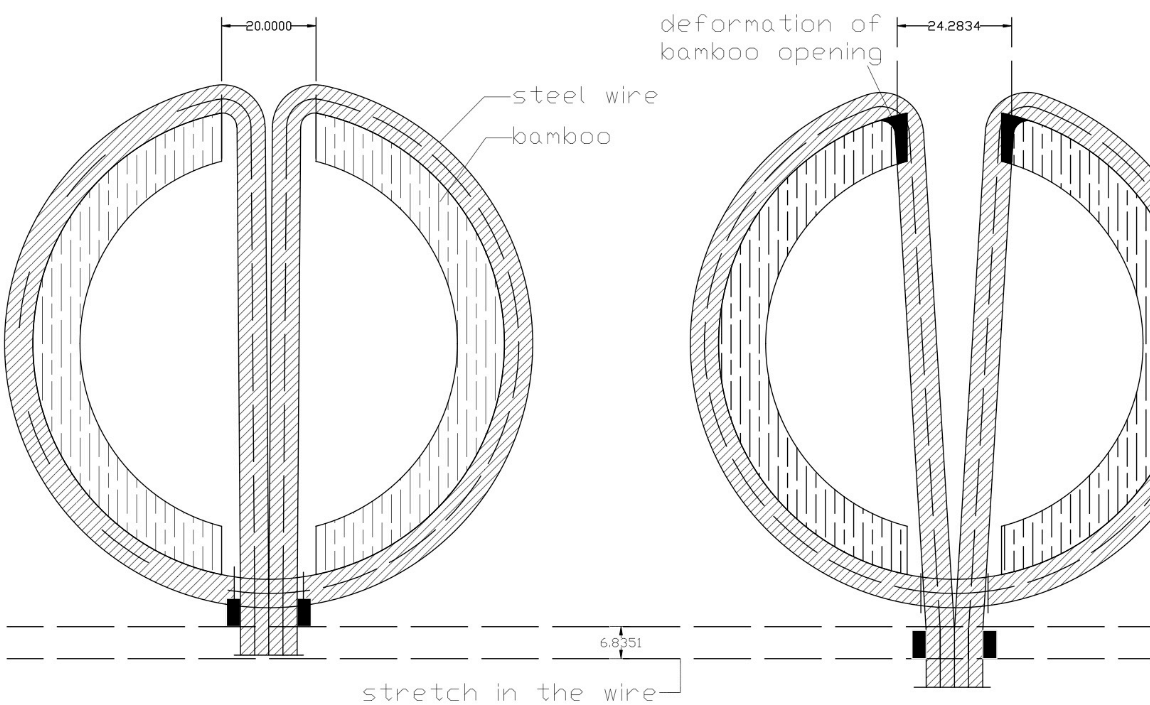

Fig. 9. Stretching caused by crushed bamboo hole

After 3 (three) months of its erection, the installation was evaluated. The installation was more elliptical that when it was built. It was found that the wire clip, that should be near the hole, had moved further away. It was a sign that the winding of the wire was strengthened through time by the internal tension force or the tangential force caused by the wire to the bamboo wall at the hole that had crushed the bamboo wall slightly and caused the winding wire to stretch (Fig 9)

Lashing Joint 3

The difficulty of pre-tensioning process of the lashing joint 2 was the trigger to develop the lashing joint 3. It was applied to a three legged tensegrity tower built during a joint bamboo workshop between Institut Teknologi Bandung, Kitakyushu University, Universitas Pendidikan Indonesia, and Universitas Bandar Lampung. It consisted of 9 (nine) bamboos with 24 sets of wire. The wire had 4 different lengths. Three bamboo acts as the legs. Six (6) other bamboos were floating in the middle of the legs. Each end of the floating member has 4 (four) wire attached while the legs have 2 (two).

Fig. 10. Three-legged tensegrity tower

The wires at the bottom end of the legs were used to adjust pre-tensioning the whole structure at the final stage. The author, who is also the supervisor and the designer of the tensegrity, considered that it would be difficult to use the Lashing Joint 2 as usual. Thus, the Lashing Joint 3 was proposed.

The stages of the construction proses were (1) constructing the joints in each members, (2) arranging the 6 floating members and connecting all the wire, (3) lying down the 3 leg members and connecting the upper wires, (4) standing up the structure, (5) connecting the lowest wires to the legs and pre-tensioning it. The problems occurred in the second and the fifth stage.

At the first stage, the problem was at determining which wire was connected to each member since the members were still lied down. The wire also had to be sure that not to be stacked wrongly or twisted with each other. It was solved simply by using tags in each wire and each end of the members.

The last stage were the processes of attaching, pre-tensioning, and redoing. The process was repeated until the structure was stable and rigid. Yet, unlike the Lashing Joint 3, the problem was not the difficulty in pre-tensioning it, but at how easy to pre-tensioning it. The pre-tensioning was just done by tying the wire to the eye nut and pulling it until it feels rigid enough before attaching the wire clip. Since there was no winding the bamboo involved, the pre-tensioning was so easy that, once, one of the wire in the floating member was disconnected from its eye nut the structure collapsed. It was because the pre-tensioning was too strong and the connection of the wire was weak. It was then solved by doubling the wire clip on each wire and doing the pre-tensioning carefully.

Fig. 11. Deformations at the bottom end of the legs.

After two months of erection, the structure was evaluated. Unlike the Lashing Joint 2, there was no stretching occur in the wire. The deformation occurred at the leg joints. The wood plates were also moved from its place. It was actually predicted since there were protruding thin rods, the plates were only attached in place by friction, and the stress was accumulated there.

Conclusion and Recommendation

The proposed bamboo joints for tensegrity structure are fall under many categories based on their load transferring systems, such as transferring the load through (1) the friction of the outer skin, (2) the friction of the inner skin, (3) the bearing and shear stress of the bamboo wall, and (4) through contact with its whole section.

The built proposed joints were Lashing Joint 2 and Lashing joint 3. From the construction process, there were several evaluations for each joint. For the Lashing joints 2, the problems were in the pre-tensioning process, winding process, and the crushing of bamboo wall around the hole by the wire. The pre-tensioning process made the strengthening process of the whole structure difficult. The winding problem and the crushing of bamboo wall around the hole by the wire, on the other hand, were the cause of the weakening and the further deformation of the structure over the time. The recommendation is to do the pre-tensioning and the winding process strongly. It might be done by different technique other than doing it manually by hand, such as using a weight to pull the wire.

For the Lashing Joint 3, the problems were easiness of the pre-tensioning, the weakness in the wire clip, and the deformation of the steel rod. The first and second problems were connected with each other. The over strong pre-tensioning made the weakest wire connection failed. The recommendation for this problem is to do the pre-tensioning slowly, carefully and gradually, and to add additional wire clip at the wire connections. The last problem occurred in the highest loaded end. The steel rod moved from its original axis and moved the plate. The recommendation for this problem is to use the plate with a mechanism to attach rigidly with the bamboo wall.

This research only discussed the construction aspect of the joints. Future research is needed to evaluate its exact structure performance. Future research could also be realized and could discuss other proposed joints. From this research, it could be seen that the pre-tensioning problem was a major problem for a lashing joints. Other lashing joint could be proposed with pre-tensioning advantage.

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