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INNOVATIVE PRE-FABRICATED CONNECTORS FOR BAMBOO ARCHITECTURE

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Bamboo is the natural construction material that has become the trend for the sustainable architecture, due to its renewability. Bamboo connections are considered the most difficult process that consumes construction time. This study is the design experiment how innovative connections can expedite the fabrication and their performance. The study deals with the design of connection prototypes for bamboo framing and tests their performance in actual construction. Connectors are designed into the receivers and the nozzles. Receivers act like the female connector. They are receptors at foundation to transfer loads to ground. The nozzles are the male connector that looks like an extruder attached to the end of structural members to connect to the receivers. Nozzles are offered in both a single culm and split bundles. The experiment also designed the straps for bamboo splits, to wrap the split together into one bundle. Steel connectors are introduced to initiate the bamboo construction as pre-fabrication process, yet the strength of connections is maintained. These prototypes are also applied to actual construction to verify the constructability, performance, and architectural applications. It is found that connectors are effective to minimize construction time, but still have other limitation. The study took lesson learned to design more permanent connectors to solve all restricted issues. Finally, innovative connectors were created into many variety forms for fabrication. They can also perform greatly in strength and attractive look. These findings can motivate architects to explore possibility for bamboo architecture in pre-fabrication process, and to be more innovatively and effectively.

Keywords: Bamboo connectors, Bamboo joints, Pre-fabrication, Bamboo construction, Nozzle, Receptor.

1 INTRODUCTION

Bamboo architecture has become the new trend to contribute to the SDG goals No.11, Sustainable cities and community. Bamboo is a fast growing plant and abundant, especially in Tropical area, so it is considered the renewable material. Working with Bamboo then turns to gain more interest because of its sustainable aspects. Promoting more uses of this material will share contribution to a sustainable environment and low carbon production to every scale society. Interestingly when looking into the creation of Bamboo architecture, it has been corresponding to the local culture and available technology. Designing bamboo architecture is obviously expressed by local notions. Mostly they are done by local handy-men in the community, so that design and technology may not be too complex, and utilize all possible material properties. Many bamboo architectures have great design value, but in practicality they may not last long, in terms of construction methods, material limitations, and connections. It is important for designers and builders to have more understanding on how to work with this material.

2 PROBLEM STATEMENT

As previously mentioned that bamboo architecture cannot last for a long period of time and structures end up falling apart, one of reasons is that the capacity of connections are not properly designed (Rittironk 2011). They can also deteriorate through time via many factors. Local people do not mind because there are available materials to build new ones and inexpensive. However, that is not the sustainable way to utilize the material. So, the design of bamboo architecture should be aiming into a direction that can create the life-long sustainable buildings. The study then investigates ways of creating connections that is easy to pre-fabricate, can last long, and fit in a more advanced industrial production to answer modern day architecture, yet remains its sustainability aspect.

3 METHODS OF FINDING

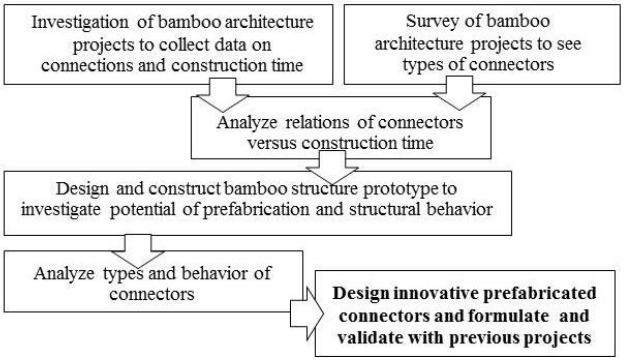

Figure 1. Diagram shows the method of this study to design innovative connectors.

4 BAMBOO GEOMETRY AND CONNECTIONS IN CONSTRUCTION

Firstly, bamboo architecture projects are investigated to find common type bamboo geometry and connections used in real construction. It is found that due to long cylinder form of bamboo, they offer straight lines of transferring load that should be kept. So, in order to make the most use of cylinder geometry, bamboo can be used as whole or broken pieces into different geometry. In real practice, there are three types of bamboo most people are working with; whole bamboo culm, bamboo halves, and bamboo splits (Rittironk 2019). This does not include manufactured bamboo, like bamboo laminates. When designing bamboo structure, architectural forms are shown to be curved, bended, weaved, and bundled, and so on. It is indeed that bamboo culms can offer strong member, but when it comes to making tight curves, bamboo splits may be better to use. Bamboo splits are made of series of smaller pieces that are easy to bend together, and also provide solid mass. Bamboo halves are offering one flat surface to work with, when there is a flat area for installation.

Figure 2. Three common types of bamboo used in construction: (a) Bamboo culms, (b) Bamboo halves, (c) Bamboo splits.

Bamboo geometry is like a form of long tubes. Constructing tube forms together may be simple. However, in real practice, putting bamboo together has become the most challenging process. Bamboo has nodes, irregular tube dimensions, hollow, and easy to split, so that they add extra attention to connect them. In designing connections, it is to understand how bamboo culms are configured together. We can simply call this "bamboo joint". This relates to how the structure is designed and put into geometrical arrangement, so we know how structure members are connected. In typical framing, joints are formed together in simple geometry. While in complex structure, joints can be arranged in advanced geometrical forms as well.

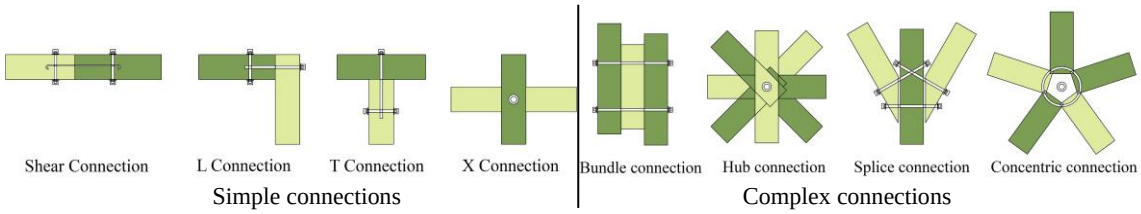

Figure 3. Bamboo connections are put together in many geometrical forms of joints, depending on the complexity of structure.

First four left images in Figure 3 show basic joints that most bamboo structure should use in their typical applications. Shear connection is needed when bamboo culms need to connect in extended or longitudinal direction. L, T, and X or cross connections are typical ways to align bamboo culms in those letter shapes (Noichan 2015). However, there are more chances that the design of structure can get complex when more materials are used and the scale of structure gets extended, so connections are also designed to accommodate the complexity, shown in another four images to the right. Bundle connections are to put many bamboo culms together to gain more strength than just few members. Cross bolt-thru or dowels inserted inside culms make all culms working together in one system and effective (Pongthana 2014). Hub connection is happening when all bamboo members are summed up into one point. It can be at top of roof or any main nodes in structure. Splice connection is occurring when adding supporting members in one load-transferring direction. Mostly splice geometry will be triangular formation. Lastly, concentric connection is quite similar to hub connection, but only receiving compression. These examples are common examples, though there are many more complicated connections seen in real construction projects. They require some craftsmanship and skills workers to put together. There should be new way to made bamboo joints more effective, so the study then decides to investigate the innovative connections using pre-fabrication process.

In order to get the real situation with connector issue in construction, 4 actual bamboo projects were investigated. They are actually built projects in Thailand. Every project uses bamboo as major material in construction. They vary in size, but similar function. Project 1 is a pool pavilion in hotel. Project 2 is school shelter. Project 3 and 4 are Landmark pavilion for a hotel and an institute respectively. Data is collected to investigate connections' quantity and density, and construction time of each project, as shown in Table 1.

It is obvious that smaller projects have fewer connections. Complex project will definitely require more connections significantly. Besides that quantity of connections, complex connections are found more proportion in complex project than in simple or smaller projects. When comparing overall construction time to quantity of connections, complex project has to build so many connections per day. This proves that if there is a way to ease the connections, it

will reduce overall construction time; yet extra time can contribute to quality of construction instead.

Table 1. Bamboo connections for four actual bamboo projects * (Katepetch 2014).

Project	Area (sq.m)*	Bamboo culm per area*	No. of Connections	Connection Density	Connector type ratio	Construction time	No. of Connections per day
	sq.m	culms/sq.m	connections	connection/sq.m	simple-complex	days	connections
Project 1	32	2.1	101	3.15	9-1	68	1.48
Project 2	35	1.3	68	1.95	6.5-3.5	49	1.39
Project 3	126	6.3	1191	9.45	7-3	225	5.29
Project 4	144	9.2	2385	16.56	5.5-4.5	103	23.15

5 EXPERIMENTING PROTOTYPE DESIGN

Therefore, introducing the pre-fabrication process then comes to consideration, especially to connect them. When preparing materials in the remote place and later assembling on site, it may offer the shortcut in construction time. The experiment then starts with designing connectors that can be done in off-site area. Then three innovative simple connectors and the structure were designed.

Figure 4. (Left) The model of structure prototype to explore connections, (Three on Right) Three experiment connectors to be installed on prototype. They are nozzles and receiver at base joints.

The study started the experimentation at the pavilion project in Nansha Bird Park in Guangzhou. This is the design & construction competition. Time offers to do construction only for ten days. The study then starts to focus on how the structure can be installed faster. That is why Pre-fabricated connectors were invented and used at this structure project. The structure is designed to look a flying bird as a small pavilion. Main component is a vault-like, made of two intersecting arches. Since the pavilion has tight-radius dimension, arches are made of split bamboo. The roof will be used bamboo culms connecting each other in multiple directions. So there will be two bamboo types at base, culms and splits. The connectors then are designed to have two connecting nozzles; one for culms and one for splits. The nozzles then will be inserted into the receivers at foundation. The bases should be able to receive both types of nozzle.

The structure of pavilion is designed to build in 3 identical modules right next to each other, while each module is about 2x2 square meters. Total area is about 12 square meters. The receiving plate is welded to the foundation piers, and the structural members are assembled in nearby location. The installation of pre-fabrication frame then started after every structural member was prepared. It is a result that preparation of materials took 5 days, 2 days to put them

together, and 3 days to finish (Rittironk 2020). The construction was quite effective. There are 13 connectors, and 2 days to fabricate them, so that at least 6 connectors to be installed in a day are extremely efficient and optimized with the quality of installation. Though there are some developments to do to finalize the connector design. This prototype is a small structure, and connectors are also semi-temporary. To be realistic, more substantial material, such as structural steel, should be used to accommodate more loads and movement. Therefore, next step is to design better connectors from experimental lesson learned.

Figure 5. (Two in Left) Images also show nozzles for culms and bamboo splits after being installed, and (Two in Right) Connectors were fabricated in real construction.

6 DESIGNING FINAL CONNECTORS

The experiment result is found that after the fabrication process has been introduced, it can minimize by half of the construction time. For the first experiment, the small structure of the same size should have taken 15-20 days alone for installation, but it took 10 days for construction, but only 2 days just for assembling. The pre-fabricated connectors were very effective. For the next experiment, it is more beneficial to bring in the lesson learned and develop more permanent connecters that can solve previous issues or make the improvement. More limitations during construction are that there are different sizes of bamboo, connector's material quality, connector's sizes that may offer small-scale structure, and joint at footing that can be more available to different types of foundation. Therefore, the experiment is explored to design connectors for a better performance to resolve the previous issues. The outcome design is proposed in variety of options, see Figure 6.

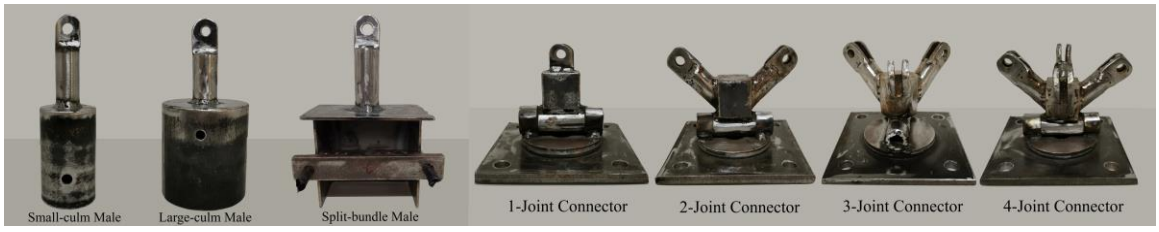

Figure 6. Innovative male and female connectors are designed to improve performances.

Male connectors are made into two common sizes to accommodate different diameter of bamboo. Split bundle male connector is using much thicker gauge of steel. Female connector is designed to sit on thick steel plate, yet they are able to rotate 360 in horizontal plane and 90 in vertical plane. Female connectors are made to receive from 1 to 4 receptors for male connectors. Bottom plate can be welded to steel frame or bolt-thru concrete foundation or slab easily. This

fabricated connector surely will minimize task and time to construction connection in bamboo architecture. Connectors with installed bamboo are demonstrated in Figure 7.

Figure 7. (Four Left) Designed male and female connectors are demonstrated when they are assembled together, (Right) Multiple axis of connector allows flexibility of structural member's movement.

7 CONCLUSION

These experiments are still the pilot study and to investigate potential of prefabricating bamboo connectors for faster bamboo construction. Though there have been many bamboo projects around the world working on many kinds of methods. However, as previously mentioned, each culture offers their own bamboo architectural language, due to different local technology and perception of material. Bamboo architecture in Thailand has been gaining more popularity because people are interested in sustainable material and attracted to how bamboo offers vernacular tectonic. Therefore, the research and design & development are still on process to keep making a better design and construction. This study then is one of efforts to inspire and to promote bamboo's innovation and possibility. It can be said that the pre-fabrication connectors in this study is possible and provide effectiveness in terms of construction time, durability, and lastly the attractiveness. It is hoped that these innovative connections can inspire and promote local people, designers, or architects to gain more interest of making bamboo architecture in the future. Lastly, the benefit will gain in contribution to our world's sustainability. These two experiments can be considered the success.

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