DESIGN-BUILT BAMBOO STRUCTURE USING MULTIPLE-MEMBER PRE-FABRICATED CONNECTORS

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Bamboo as the structural material has become the trend to respond to sustainability, due to its outstanding structural properties and renewable aspect. Though bamboo architecture is seen throughout the world, but they are still varied from culture to culture, due to limited knowledge and advanced applications. In order to move this material forward for industrialization, standard system of creating bamboo structure should be established. The most challenge of bamboo structure is the connectors. Though the conventional style is elegant and crafty, but they require special skills and lengthy construction time. Using pre-fabricated connectors to expedite construction are not quite common. This potential to introduce pre-fabricated connectors and more complex bamboo structure is needed to explore further. This research then takes the design-built approach as the methodology. The process starts with designing a complex structure with multiple-member at column-foundation nodes. Pre-fabricated steel connectors are designed to host at least six members in a single node. Four nodes are designed in this 30 sq. m bamboo pavilion. Each member is made of two different bamboo formats; bundled bamboo culms and bundled bamboo splits. Pavilion frames then are assembled using designed connectors in actual construction site. The construction is carefully monitored and documented for their strength and feasibility. It is found that pre-fabricated connectors can simply put the construction together with simple tools and in efficient time. Multiple-member at column-foundation nodes is strong and possible for complex structure. They perform well and still hold the elegant integrity of bamboo architecture.

Keywords: Bamboo construction, Bamboo architecture, Bamboo pre-fabrication, Sustainability, Construction technology.

1 RESEARCH SIGNIFICANCE

Bamboo is the great material that people in most part of the world can access, especially the tropical area. Bamboo is considered the sustainable material because it is renewable, which it can grow quickly. Bamboo can be harvested within 3-4 years, comparing to 20-25 years of timber (Rittironk 2021a). Bamboo has been used for many applications from household tools to building structure. Bamboo is known for it is being light and strong, and can be working with only simple tools. This research is aiming the larger benefit globally as well, with possible construction technology. Bamboo is still available to many areas and still affordable. There is still large amount of local people who do not have access to expensive materials, but they still have bamboo (Rittironk 2010) as their domestic and affordable material. Bamboo architecture is still not accepted as a commercial material, due to limited knowledge and building codes to support.
Therefore, we do not see many bamboo architectures in large scale. On the other hand, they were built in small structure because it is much simpler to handle structurally, and local domestic people are able to build at their own capacity. So, small bamboo pavilion then become common residential bamboo architecture to be seen, especially in Southeast Asia (Rittironk 2022a). Local craftsmanship indeed brings vernacular style and beauty to bamboo architecture, however mass production and faster construction must bring into consideration to be more practical. There should be a way to build in more efficient way or alternative way. A construction method like pre-fabrication could bring in to improve the pace of construction, so that local people or even urban people to realize that bamboo is another choice of materials to modern construction, yet sustainable.

2 PRE-FABRICATION IN BAMBOO ARCHITECTURE

Bamboo architecture has its own vernacular language from culture to culture. They require craftsmanship of local people that sometimes its knowledge has to be transferred from generations to generations. This gives the development of bamboo architecture only artistic value and limited. The connection is considered to be the most difficult work (Noichan 2014), but it has been limited knowledge and need high level of craftsmanship. To get into industrialization, pre-fabrication has brought to the construction industry. There have been some bamboo projects introducing pre-fabrication, See Figure 1, but there are still not too many, but only seen in small simple structure. There are researches about the uses of steel connectors and ways to connect them, showing that they were effective and efficient to do (Katepetch 2014), see Figure 2. They can make construction faster and require less work and with fewer workers (Rittironk 2022b). They were still shown as basic and less complex structures, while bamboo architecture should take advantage of industrialized construction method and the craft of itself at the same time. This research then explores further on how bamboo structure can maintain their craft quality and using steel connectors. It is possible the connectors will be complex and can handle multiple members in one node, especially where structure meets the ground or foundation.

Figure 1. Pre-fabrication was introduced to bamboo architectural projects.

Figure 2. Pre-fabricated steel connectors found in some bamboo pavilion projects.
3 RESEARCH METHODOLOGY

This research is designed to be the experimental research, using the design-built approach, see Figure 3 for methodology diagram. The research started with the investigation of pre-fabrication system in bamboo architecture. While the connectors are mostly the focus, the design of bamboo pavilion and connectors are created. The compact-size pavilion is selected as a study model because that is what local people can do at their own effort, and both individual household and community can be benefited to build their shelter or dwelling. The design took opportunity to have complex and multiple-member connectors at foundation, so it can receive more loads. Then the pavilion was put into the real construction. The construction is carefully documented, using information to advance the benefit of using pre-fabricated connectors. The entire construction process and pavilion itself were evaluated of their performance. Finding and conclusion are made to confirm the valid and vitality of this creative pre-fabrication.

Figure 3. Diagram of how research methodology is done.

4 DESIGN BAMBOO CONNECTORS AND STRUCTURE

The researcher took initiative to design the bamboo pavilion to maintain their craftsmanship and capacity to house multi-member bamboo at the connection. This is balance between the complex craft and industrialization. The small study model is used as a tool to demonstrate the design, then each potential connection is investigated in detail to design what pre-fabricated connectors will look like, see Figure 4.

Figure 4. A physical model of the pavilion to study types and how connectors will be used.
Bamboo pavilion is designed to have resemblance of a typical wood framing. There are series of columns bundled and connected at the ground, and framed together at top forming the triangular relationship (Pongthana 2014) for a strong stable framing. Multiple sets of frames are connected by the roof rafter. Connections then simply are made into sets. First set is at base, while the second set is at the roof rafter. 3D models are made to study the configuration of connectors will look like, see Figure 5. The connector at base is called as connector A, where there are two parts, female plates and male connectors. The plate is the key that can be designed to expand or enlarged to host as many bamboo members to come down and meet the foundation. It offers the most flexible way to connect, and fast to install. The male pipe is where bamboo culm is inserted and bolts through, so that it is a quick junction to connect to base plate. Steel pipes also offer the flexibility to use different geometry of bamboo, such as bamboo splits or bundles. The second connector is connector B where it is used to connect frames to the roof rafter. These connectors were designed carefully where the rafter is sat on top, using half steel pipe to carry, while frames down below have joints that can be rotated for flexible installation.

![Connector A](image1)

**Figure 5.** 3D designed models of pre-fabricated connectors using in the pavilion.

After finalizing the design, connectors are made, so there are 4 sets of connector A and 6 sets of connector B. Figure 6 shows how the bamboo pavilion is being constructed using the designed steel pre-fabricated connectors, where connector A are at foundation base to house multiple bamboo members as series of frames, and connector B are connecting at the other end of frame to the roof rafter.

![Pavilion Construction](image2)

**Figure 6.** Connectors after being installed at the pavilion structure.
5 EXPERIMENTING RESULTS

The aims for this pre-fabricated method introduced to bamboo construction are to ease, facilitate, and expedite the construction, yet to maintain the integrity of craftsmanship of bamboo architecture. The result of that is confirmed to be successful. The design of pavilion at the beginning is surely to keep the vernacular look and crafty pattern of bamboo, that is also quite distinguish from different structural materials. The construction for this 30 sq. m pavilion is about two months to assemble, using about six workers. This evidence also is proved to confirm that pre-fabricated connectors making the construction to efficient time and effective with not too many manpower. In comparing with same size bamboo pavilion for the conventional method, the construction can take up to six to eight months. The reason is that the conventional method will do bamboo carving at joint one by one, and connection at foundation will use concrete, so it will take time for concrete to cure (Rittironk 2021b). Pre-fabricated connectors at base with multiple members is just taking much less time to connect, see the completion in Figure 7.

Figure 7. Images of multiple-member connectors installed after the construction.

Figure 8. Overall complete bamboo pavilion using steel pre-fabricated connectors.

The pre-fabricated connectors also offer the flexibility to use different bamboo material in one single member, such as bamboo culm, bamboo splits, or bamboo bundle. They are also secured in steel pipe using cement epoxy, which make the connectors super strong. Cement
epoxy to fill the cavity in pipe is much easier to work with than concrete because it can settle faster within minutes. The male pipes to connect to base plate can be adjusted in angles if installed dimensions are slightly shifted, which is a great tool for flexibility. The complete pavilion with connectors installed are shown in Figure 8.

6 CONCLUSIONS

This finding shows the positive result that pre-fabricated connectors with multiple-members can be innovative method for bamboo construction. It introduces pre-fabrication system to bamboo construction, so that it is the mass production compared to conventional labor-intensive method. It can save time and labor. Yet the complex geometrical form of bamboo vernacular style can still be preserved and applicable. While various members are interwoven and connected, it is proved that this new construction method offers vernacular perimeter and as well the industrialization. The experimental research with the design-built approach also proved that the execution of material and method intervention are feasible and realistic. This is one of the most effective ways to clarify the outcome realistically. However, the experiment result is only valid for this research perimeter. If the perimeter is varied, it may affect the outcome differently. This research eventually will promote bamboo as a sustainable material to be used more and to prolong uses of other natural resources.

References


