PRE-FABRICATED CONNECTORS USED IN BAMBOO FRAMES FOR TIMELY-EFFICIENT CONSTRUCTION

SUPREEDEE RITTIRONK

Faculty of Architecture and Planning, Thammasat University, Pathumthani, Thailand

Bamboo has become the choice of materials in sustainable architecture, due to its renewability and great mechanical properties. Bamboo architecture has very unique character of its craftsmanship. The challenge of bamboo construction is the connectivity, or to put structural members together. This can be done beautifully, but time-consuming. This research introduces the pre-fabrication as an innovative process to do connectivity more efficiently, especially construction time. The research is the design experiment to design steel connectors, prototype frames that are utilized by connectors, and architectural assemblies that are composed by those frames and with many different designs. The outcome productions will be steel connectors, typical frames, and series of building formations. One selected frame is selected to perform real construction to document construction time. Two methods are delivered to provide the comparison, pre-fabrication and conventional systems. Construction time to assemble architecture will be simulated and compared between two systems. The result shows that pre-fabrication using steel connectors can reduce overall construction by 62% because it offers working tasks in parallels. Moreover, workers can become familiar with repetitive tasks to build architecture, so construction time becomes less. While conventional system still has to deal with crafting bamboo and concrete pouring and curing, so construction time is more extensive. The research confirms that pre-fabricated connectors can reduce construction time in bamboo architecture, moreover they can create interesting and flexible designs and offer easy maintenance. The more uses of bamboo as an architectural material, they can greatly support the creation of future sustainable architecture.

Keywords: Pre-fabrication, Bamboo structure, Bamboo connections, Sustainable construction.

1 BAMBOO AS A SUSTAINABLE MATERIAL

Bamboo is a giant grass that is native to major part of the world, especially in tropical area and along coastline. Bamboo has become the 21st century trend of the sustainability, when the world has concerns over the climate change. Bamboo is renewable, due to short harvesting cycle of 3 years. Bamboo is abundant and accessible, so that it reduces carbon emission in transportation. Most important key for bamboo to be interested as a trend for construction material are its lightness and strength. Mechanical properties are stronger than many hard woods 1-1.5 times (Rittironk 2010). Bamboo then has become the material of interest for future and sustainable construction projects.
2 BAMBOO ARCHITECTURE & CONSTRUCTION

Nature of bamboo as a stick like has become a favorable form to create structure and architecture. Bamboo are abundant in most tropical areas, where many local people can access them and turn them to many domestic uses, from basketry to building. However, skills of builder are varied, depending on knowledge and know-how. Many modern-day designers and architects have creatively turn bamboo into state-of-art bamboo art & architecture. If bamboo architecture is designed to have a very unique form. They require interwoven and interlocking geometrical elements, which resemble Art & Craft from everyday objects and tools. Enlarged bamboo basketry with spatial functions then is become the vernacular style of bamboo architecture, (Rittironk 2020b). The construction of bamboo architecture is also exceptional. They are based on how each culture’s living and traditions are practiced. The geometrical forms and methods simply derive from how local people weave and connect their crafty tools. This makes the interesting characters of how bamboo culms come to connect and become structural nodes. Typical constructions in bamboo projects then are performed in simple ways using available tools and materials. Concrete is commonly used at footings and foundations because it is easy to cast multiple culms together at once. Structural framings are done by erecting frames one at a frame. It is seen that conventional methods require time and workers’ skill to put building together. In recent years, there have been some projects trying to make it easier by using steel connectors to make it easier for construction that is when the pre-fabrication had been experimented. These projects took great initiative, but it has not been verified or with serious studies on their effectiveness, (Rittironk 2020a). The comparison of two different construction methods is shown in Figure 1. This research then follows up the initiative idea of bringing pre-fabricated frames into the design experiment, and measure their effectiveness on time and working methods.

![Figure 1. Comparison of frames and joints between conventional construction (two left) and construction with pre-fabricated connections (two right).](image)

3 RESEARCH METHODOLOGY

This study is designed to be the experimental research using design & construction approach to collect data. The study starts with reviewing related research and performing survey of bamboo architecture projects to witness their problems and limitation. Collected data are brought to propose alternative approach to improve design and construction by introducing pre-fabrication system. The design of pre-fabrication frame and steel connectors to be used together. Then, the design frame is brought to real construction by putting together the prototype frame. In the meantime, information on construction time and assembling method are collected. Construction time for pre-fabrication is simulated to make frames into a building. Data is also collected from a previous similar project using conventional construction methods. Time efficiency of construction are compared and analyze. Furthermore, benefit of pre-fabricated frames are
explored to seek potential of design variety. Then lastly, finding benefits of pre-fabricated connectors are confirmed and concluded, in terms of time-efficiency and design aspects.

4 DESIGN AND CONSTRUCTION OF PROTOTPE FRAMES & CONNECTORS

It is mostly seen that bamboo architecture are created around bamboo-resourced region, such as tropical areas; Southeast Asia, Latin Americas, India, and China as such. It is interesting to see how bamboo architecture developed are based on each local’s culture, interpretation, and local tools and technology. However, there is a common issue that all bamboo architecture have is the structural connectivity or simply called Joints or connectors. Each local culture is done differently depending on available tools. Creations of connections in bamboo architecture is the complex process and time-consuming. Some people may have seen them as the-state-of-the-art masterpiece, due to its complexity. At the same time, there are efforts trying to make this connectivity process to be simpler and more manageable in construction, so the construction is more practical to do. Some projects were using pre-fabricated system, but they have come far along. Then, the research is initiated the idea of doing full experiments to see if the pre-fabricated system using creatively-designed connectors can assist the way of bamboo construction.

Figure 2. Typical frame is designed into three different possibilities.

This study then designed the prototyped frames and the connectors that go with the frames. The connectors were designed in simple way to build. One half pre-fabricated frame is designed at 4 meters, so that the total structural span is 8 meters. These three prototyped frames were designed to offer simple configuration, see Figure 2. Bamboo is a flexible material, but has problem with the stiffness, so the designed structures should be formed in triangular geometry (Rittironk 2021a) to help offering more bracing performance. The designed frames are using double roofs, so that the clearstory opening can offer the cross ventilation. The lower roof on both sides is extended to protect foundation joints, because bamboo is vulnerable to sunlight and rainwater (Rittironk 2010). This study is choosing frame 1 to perform a construction, due to its compact geometrical form.

The half section of prototyped Frame 1 is composed of five connections, so the steel connectors are designed to accommodate the frame configuration. Connectors are made of steel pipe, so bamboo culms are able to be inserted and fastened by nuts & bolts, so the most efficient and strong fastening methods (Pongthana 2014). Steel pipe is selected to use 60 mm diameter, so it can accommodate bamboo culm 40-60 mm diameter. Bamboo specie used for this prototype frame is *Bambusa multiplex*, because it is medium-sized and great tensile properties (Rittironk 2010), so it is easy to work with and suitable for simple truss frame. Connector A is at top rafter, and made to connect another half frame together. Connector B, C, and D are for roof rafter frames, while connector E is where frame is connected to the ground, see Figure 3.
5 ANALYSIS & DISCUSSION

After the construction time data are being collected and compared, the result shows that, at three-worker forces, putting together a half prototype frame tool 2.5 hours, see Figure 4 (left). At the same rate, putting together a full frame will take 5 hours. The entire building is simply designed to have 4 identical frames, so that a building can be done at 14.5 hours in using pre-fabricated connectors. Since workers are having experience in doing the first frame, then frames after can be finished in faster rate, from 5 hours per frame to 3.25 hours per frame when finishing at 4 frames, see Figure 4 (right). The conventional method information is collected from a real bamboo pavilion project with similar footprint. When comparing data with one in conventional method, it took 10 hours to do a full frame, and 38 hours to do all four frames. The result is very promising that using pre-fabricated connectors can reduce construction time from 38 to 14.5 hours, and that is 62% faster. For a bigger building, the construction efficiency can be expected in similar result. The projection of time up to 6 frames for pre-fabrication can reduce time from 54 to 20.5 hours, and that is about 62% as well. It seems that the optimization of construction speed has become constant at 3 hours per frame at 5 frames or more for pre-fabrication system, and 8 hours per frame for conventional method.

Figure 4. Pre-fabrication and conventional methods are compared of their construction durations (left) and construction efficiency (right).
In terms of loading capacity, steel connectors at footings are used to substitute conventional cast-in-place concrete foundation. Steel can perform excellently as it is also great in tension and compression. Only a factor that may be weakening the joints is shear connectivity of nuts and bolts between steel pipe and bamboo culm. From research experiment, this matter is also solved by grouting the joint with epoxy. This can enhance tension resistance in shear connectivity 2.4 times (Noichan 2015), while compression is not an issue. Loading capacity of pre-fabrication can perform equal or greater in conventional method by strengthening bonds between steel and bamboo and adding more culms in each structural member (Rittironk 2021b).

In terms of last long viability, bamboo structure is indeed vulnerable to moisture and sunlight, causing bamboo to crack or split, so the design of foundation connectors is needed to be elevated from ground (Rittironk 2010), and all connectors are staying under roof. As long as foundation connections stay off-ground like conventional joints, they can viably last long and be protected. Other pre-fabricated connectors at framing as well can gain the most durability because steel will take major role in structural performance. Only rust can do damages, but only at surface and not affects much structurally. However, they can be simply treated by anti-rust paint.

6 CONCLUSIONS

This finding shows the positive result that prefabricated connectors can assist the bamboo construction by reducing constructing time by 62% maximum over the conventional method. The reasons are that pre-fabrication can offer the assembling of connectors to be faster and manage by fewer workers. While connectors in conventional method require more laboring tasks and also involve concrete to achieve the joint stiffening. Concrete is used at foundation hub and pouring into joint, which require extension of time from curing, see Figure 5. Moreover, pre-fabrication can separate construction tasks in different working location, so that workers can continue their work in parallel. For example, the assembling frames can be done in different area from building location, while other working team can erect building’s frames.

Figure 5. Comparison of connectors between pre-fabricated and conventional systems, at foundation joint (pair on left) and a typical frame (pair on right).

It can be confirmed that prefabrication of connectors can expedite the construction duration. The construction duration is much less than a conventional way of construction by 62% maximum. The construction efficiency per frame can be reduced by 62.5% maximum, 3 hours per frame of pre-fabrication and 5 hours per frame for conventional method. Construction factors that make longer time for conventional construction are linear working process, concrete curing time, and labor intensive to do connections. However, this result may only be valid to small bamboo construction projects. For larger or more complex construction, the construction time reduction can result in similar way, but the efficiency rate may be varied, and can be figured out in different studies. In additional benefits, prefabricated connectors are explored further, and found that they can create bamboo frames to have many interesting designs of bamboo.
architecture by re-arranging frames in different configurations, see Figure 6. Hopefully, this innovative construction method for bamboo construction can be adopted into future way of how architects, engineers, and designers to do efficient construction, so bamboo architecture can be promoted, easy to build, having interesting designs, and lastly answering the way people live in a sustainable way.

Figure 6. Prefabricated frames can offer many possible design variations, so that it is an added value.

This design-built experiment is just the exploring of the opportunity for pre-fabrication system to be used in bamboo construction focused on minimizing construction time. It is yet having to investigate in the long term on the durability of bamboo construction. However, it is promising that they can be last long for extensive years due to the use of steel as connector material and their strength together of both steel and bamboo. In addition of future solutions of this system, pre-fabrication can offer the replacement of piece-by-piece if structural members or connectors are damaged, which is the great flexibility over ones in conventional construction that may need major repairs or partial demolition required. Moreover, since configurations of frames can offer a variety of forms, and after using buildings for years, the re-arrangement of building frames can be done to create the new interesting face-lift to a building from the same existing materials. At bottom line and in promising future, the pre-fabricated connectors in bamboo architecture can offer much more great benefit than it is previously expected in saving construction time.

References
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