Connections for Bamboo Structures

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Abstract. Bamboo is an outstanding, widely used historical green building material that features high strength, economic, and sustainability. The joints in a structure are the important points for resisting the loads. However, the connection of bamboo pole is always the major challenge during the construction. The thin-wall, hollow and other irregularities of this natural material contribute to the challenges of making connection systems. To utilising bamboo in the construction industry, this paper summarises the existing bamboo connection methods including both traditional and modern ones.

1. Introduction

The construction industry is a notorious contributor to most environmental issues such as climate change [1-3]. The search for green building materials has been recognised as an alternative way to minimise environmental impact. Bamboo, as one of the sustainable resources that featured high strength, low self-weight, great flexibility and cost-effectiveness, is proved to be an alternative construction material [4-5]. The short harvest cycle, usually mature in three to four years, bamboo is more rapid-available than other woody material (i.e timber) [6]. Bamboo commonly known as Giant Grass having more than 1200 species world-widely, mainly located in the rapidly developing regions like Asia, Africa and South America [7-8]. Adopting bio-based building materials like bamboo not only can sequester the carbon dioxide emission during the construction, but also offer a unique appearance to the structure (figure 1).

The bamboo poles are composed of nodes and internodes (figure 2). The outside layer of the bamboo culm is made up of the cortex provides protection and waterproofing purpose [9]. Some sufficient scholars who have studied the mechanical performance of bamboo, that concluded the sclerenchyma fibre in the vascular bundle of bamboo is the major supporting tissue [10-15]. It can be observed in figure 3 that the vascular bundles have greater density and a smaller diameter toward the outside of the culm where stands the highest bending stress [9]. The shapes, sizes, arrangements and number of these vascular bundles determine the bamboo geometry, as well as the transverse appearance of the culm. However, the low tensile strength, due to the longitudinal fibres, applied in the direction that perpendicular to the grain, which is an essential factor to be considered in connection design [9]. The connection of culms is one of the limiting factors for the construction industry to expand the practice of this excellent green construction material [4,6,16,17]. The thin walls of the bamboo culm decrease its shear strength [18]. Further, the irregularity of bamboo geometry also brings difficulties in installing the connection of culm. This paper summarises the existing bamboo connections and provides further research on the application of this environmental-friendly construction material.
2. Traditional bamboo connections
Bamboo is a traditional building material, with a rich practice history and requires a delicate connection system during building, which covers two aspects: friction-tight lashing and mortise-tenon.

2.1. Friction-tight lashing
Lashing is a traditional prominent form of bamboo connection by using natural materials such as sisal, coconut, rattan and palm fibres [17]. Also, dried bamboo strips are used as lashing rope, because of their flexibility, straightforwardness and cost-effectiveness, in rural areas (figure 4). The strength of this type of connection relies on the frictions existing between the ropes, as well as between the rope and bamboo culm [20]. The bamboo poles can be tied like a bundle for an enhanced strength, applying the lashing techniques at the same time can effectively avoid failures (i.e. cracking and splitting) that result from the holes drilling in the bamboo poles. However, as an anisotropic natural product, the biological and physical characteristics of bamboo vary, such as the impact from its moisture content fluctuation. The attribute of hygroscopicity contributes to the absorb and desorb moistures frequency of the original bamboo pole to achieve the equilibrium moisture content and when the surrounding humidity and temperatures change, which results in the rapid swelling and shrinkage of bamboo poles [21]. Meanwhile, the natural fibres can be loosened due to the expansion and contract of bamboo poles under the various surrounding and cause the slackening at the joints. Further, with the extensive exposure of the bamboo ropes under natural climate, the fibres will be more ductile thus decrease the stiffness of the bamboo structure. Therefore, the are always pre-treated like oil immersion for improving its toughness and strength [6]. The advanced lashing materials include wires, textile polyester rope and bio-composite bandages (figure 5) [6,22].
2.2. Mortise-tenon joint

Mortise-tenon is one of the widely used historical connection in timber buildings, which operates as semi-rigid, binding the structure member without using a nail or bolt. The straight tenon joints and the dovetail joints are the two most common mortise-tenon joints (figure 6) [23]. The beam end is made as a tenon and a mortise is made on the column, thus the tenon-end beam can be inserted into the notch on a column to form a unique connection system (figure 7) [24]. The mortise is opened in the middle of the column, while the dovetail tenon is opened at the top end of the column. This connection method is more commonly applied in other woody materials than bamboo because of geometric attributes. Bamboo culms are known for their strong compressive strength; however, the tension strength perpendicular-to-grain is relatively low due to its longitudinal direction of fibres. Meanwhile, combining with its hollow characterisation, drilling holes like mortise in the middle of bamboo culm create negative impact on the performance of bamboo structure and may result in splitting or cracking. Therefore, it is more feasible to integrate mortise-tenon joints with some supplementary connecting components such as lashing and wooden clamp.
2.3. Other traditional bamboo joints

Plenty of literature has incorporated other popular connection joints, including a mixture of lashing and mortise-tenon techniques. (figure 8). The mortise-tenon joints have some limitations as mentioned, so the ancients would use a tie to enhance the reliability of the structure. The other option is the application of fasteners. Bamboo can be an exceptional material for structural enhancement itself, as shown in figure 9, round bamboo pegs are pierced through the bamboo poles. The pegs and the main bamboo structure can remain the same swelling/shrinkage rate, which can effectively mitigate the failures caused by the bamboo shrinkage. This is a typical complimentary for the other connection methods such as friction-tight lashing and mortise-tenon [25]. Furthermore, the risks of bamboo splitting can be reduced by minimizing the size of the drilled hole on the bamboo poles and locating the connection at or near nodes as the nodes are more resistant to splitting than the internodes [4].

3. Modern bamboo connections

In recent years, designers and researchers studied from established knowledge and former experiences and combine metal, concrete and PVC to improve joint stiffness. The modern bamboo connections can be concluded as metal-bolted joints, clamp joints, concrete-filled joints and pin-end joints.
3.1. Bolt joints

The metal connectors are very widely adopted in modern bamboo structure connections, while the bolted joint is one of the most practical methods as shown in figure 10. This connection method is attributed as an economic, low skill required, construction efficiency and strength reliable solution. Figure 11 illustrated the simplest bolted joints that require only one bolt and a pair of nuts. However, certain limitations involved are unavoidable, such as higher potentials of splitting and cracking after drilling. [8]. Further, the circular bamboo pole can create a lack-of-fit between bolts and culm surface due to the regular and fixed shape of bolts [8].

![Figure 10. Bamboo structures with bolted connections (a) bolted Guadua canes (b) a shelter on Playa Mann beach](image)

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![Figure 11. Bolted connections](image)

Figure 11. Bolted connections

3.2. Clamp joints

Moran [27] proposed to apply steel clamps, consisted of two semi-rings with culm size (figure 12) to variable bamboo culm dimensions and no drilling is required in this process. In his research, he conducted static monotonic tests and examined three different connection specimens, where results indicate his method could enhance the stiffness, strength and ductility of each sample at least 29% to 250% greater than the other conventional connections (i.e bolted). From cyclic tests, the hysteresis loops showed pinching regions of timber joints, which might lead to the large displacement of joints that result in the stiffness degradation during the earthquake. However, the stiffness degradation was not observed in any of the clamped specimens which could add to a good performance of the bamboo structure during the seismic activity. Meanwhile, the Drywall model was found to have an outstanding performance in both tests, of which the stiffness was two and a half more than the other two designed clamping approach. Morgan [27] explained that the extra drywall screws enhanced the resistance of the culm. Additionally, compared to the Through Screw model, the through-bolt connection had weakened stiffness of the entire bamboo pole.
Masdar [28] investigated an alternative material for the clamps of the connection system and suggested assisting the clamps with two wooden gusset plates in his study. Meanwhile, for sharing the stress applied on the bamboo culms as shown in figure 13, a bolt has installed to strengthen the clamp joint. The shape and angle of the wooden clamps can be adjusted with the varying bamboo culm geometry (i.e. dimensions), and the whole joint system weighs less than other forms of metal. Masdar [28] concluded for the study that the proposed solution can stand 40% of strength than the ones without the wooden clamps, as the wooden clamps can share the shear from the bamboo culms. Masdar [29] also further analysed the effect of bolt tightening on the connection performance by conducting the experiments and obtained 2830 N achieved the best connection strength.

Concrete filling technique cooperating with other connection methods like lashing, threaded bolt and clamps is another choice of the connection system (figure 16) [9,30]. By filling proper material into the hollow space of the bamboo, the mechanical performance of the bamboo is effectively improved during building construction [6]. Adhesive concrete is used to filling up the end of bamboo poles to install metal connection pieces, which requires no drilling, thus avoids the disruption of the longitudinal fibres.
in bamboo walls and reinforces the strength of the fibres. Although the stiffness of the joint is improved, there are some limitations such as the weight increased, construction challenge and the long-term use effect [6]. Therefore, the application of this connection technique needs further research, regarding the selection of filling materials and filling methods. One of the practical uses of applying this joint is the German-China House in EXPO 2010 (figure 17). The ends of the bamboo poles are filled with a high proportion fly-ash concrete mixture.

![Figure 16. Concrete filled joint](image)

![Figure 17. German-China House in EXPO 2010](image)

4. Conclusion

Bamboo features great mechanical performance. The fast mature cycle of bamboo contributes to its wide distribution and the sufficient supply in the construction industry, which help it become an alternate sustainable resource to replace non-renewable materials (i.e steel or concrete). Bamboo as a historical building material has become a new spotlight of the industry. Various studies and cases provide feasible connection systems with reasonable experiments undertaken, however, each of them has both pros and cons that require further studies. Meanwhile, due to the unique geometry of bamboo culms, the connectors such as clamp and hub are difficult to be standardised manufactured. Further, the selection of the bamboo connection needs to be examined based on the location for implementing the structure (i.e different humidity and temperature). The connection system still requires innovation while advocates bamboo as a green building material.

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