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Bolted bamboo joints reinforced with fibers

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Abstract

Bamboo in Indonesia grows rapidly and is ready to be used after three to five years of planting. Bamboo has a pipe-like cross-section and excellent mechanical properties, especially tensile and compressive strength with a specific gravity varies from 0.55 to 0.75. Thus bamboo is now becoming an important sustainable construction material, especially in rural areas. One crucial issue in bamboo construction is the connection system where failure of the connection develops at low level of loading associated with bamboo splitting. In this study, seventeen single-bolted bamboo joints in total were prepared. Four joints are loaded in perpendicular loading direction, and the rest are loaded in parallel loading direction or overlap connections. These joints were a double-shear configuration of bamboo Wulung (*Gigantochloa atroviolacea*) connected by 12-mm bolts and were tested under a quasi-static load. Some of them were reinforced with natural fiber (Indonesian name, “ijuk”) and fiber reinforced plastic (FRP). The results showed that a significant increase of joint slip modulus and load carrying capacity was found in the joints reinforced with FRP. The wrapping effect caused by FRP sheets successfully postpones the bamboo splitting failure, while in the case of joints reinforced with natural fiber ijuk, this increase is negligible.

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Keywords: bamboo Wulung; joint stiffness; joint strength; natural fiber “ijuk”; plastic fiber.

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1. Background

Bamboo is an important construction material particularly in rural and remote areas where access to steel or reinforced concrete production complemented with heavy machinery is limited. In contrast to steel or concrete, bamboo offer various advantages such as its lightness with a specific gravity varies from 0.55 to 0.75, its ability to mitigate global warming or offset the green house gasses, as well as its sustainability aspect since a structural bamboo can be derived after 3-5 years of planting. Among the 143 species of bamboo grown in Indonesia [1], bamboo Petung (*Dendrocalamus asper*) and bamboo Wulung (*Gigantochloa atroviolacea*) are the two most commonly used bamboo for structural purposes such as sport halls, bridges, and housings, as shown in Fig. 1.

In Indonesia, development of bamboo engineering was initiated by Dr Morisco of Gadjah Mada University since 1995. His comprehensive report on the mechanical properties of some selected bamboo species published in 1999 became an important resource for many bamboo engineers [2]. He found that the tensile strength of bamboo fibre is relatively much greater than the yield strength of ordinary structural steel (yield strength around 240 MPa). This finding has inspired other researchers to utilize bamboo as reinforcement in concrete structures [3,4].

Fig. 1. Some aesthetic structures made from bamboo (location: Greenschool, Bali).

Unfortunately, this excellent tensile strength is accompanied by small magnitude of Young Modulus, around 1/20 to 1/10 times of the Young Modulus of structural steel. This implies that the excellent tensile strength of bamboo can be attained only when large deformation takes place. Of course this condition becomes a serious disadvantage when bamboo is used as reinforcement in concrete structures since large deformation is associated with wide concrete cracks that impair structural performance and integrity.

Robust utilization of bamboo in civil engineering structures is hindered due to several factors. First, bamboo is not a durable material; second, bamboo has a non-uniform cross-section and a wide variation of mechanical properties along the length; third, the splitting strength of bamboo is relatively low, leading to premature splitting (brittle failure). To overcome the first factor, bamboo preservation is compulsory in addition to the provision of complementary components in design such as introducing a roof element to protect the bamboo structure from direct exposure to sunshine and rain. The second factor can be resolved when the bamboo is formed into glued-laminated products as commonly found in glulam timber. The non-homogenous characteristics in terms of strength and the non-uniform cross-section of bamboo become less significant. The low splitting strength of bamboo creates significant difficulties or challenges in the connection system, which will be further explored in this study.

In a traditional way, structures made from bamboo use natural fibre “ijuk” rope (a product from coconut-like tree) at their connection as shown in Fig. 2. The mechanical characteristic of this jointing method completely relies on the wrapping tightness of the “ijuk” rope, which soon loses its strength due to continuous shrinkage-swelling activities of bamboo. Recent development introduces bolts in bamboo connections [2, 5-7]. It is important to note that in the connections with dowel-type fasteners such as bolted joints, tensile stress perpendicular-to-grain that tries to split the bamboo component appears as a result of bending deformation of the dowel. In this study, fiber reinforced plastic (FRP) available in the form of a sheet is used to wrap the bamboo connection. FRP material initially was applied in concrete structures for strengthening cracked beams, columns and plates as well. This study in general examines the applicability of FRP as joint reinforcement and the discussion will be focused on joint lateral load capacity, slip modulus, and ductility.

Fig. 2. Example of traditional bamboo jointing method – Natural fibre rope “ijuk”.

2. Literature review – bamboo connection method

In developing the traditional bamboo jointing method, Morisco et al [2] introduced bolts as a connector in bamboo joints. In addition to bolt connectors, they also injected cement mortar into the inner part of the bamboo at the connection as shown in Fig. 3(a). This jointing system has significantly improved the connection strength and created a large bending deformation of the bolts as a source of joint ductility. Awaludin [8] developed a set of equations based on the European Yield Model to predict the lateral load capacity of bolted bamboo connections with and without filler materials, such as injected cement mortar.

Morisco’s jointing technique, however, poses two important disadvantages: 1) the weight of the connections as well the structures increases, at least by 2.5 times; and 2) the different rate of shrinkage-swelling activities between the bamboo and the cement mortar creates a gap between these two materials, causing them act independently. Therefore, the long-term behavior of Morisco’s jointing method is questionable.

Inoue et al [5] proposed different jointing method where filler made from laminated bamboo split was used instead of cement mortar to fill the inner part of bamboo as illustrated in Fig. 3(b). They also used a bamboo connector instead of bolt. Having similar material used as filler, the connector and bamboo members definitely would minimize shrinkage-swelling problems found in Morisco’s jointing method.

As part of an effort in developing bamboo 3-D truss structure model, Bacthiar [6] proposed a jointing method as shown in Fig. 3(c) where a special steel tube was designed and attached to both ends of the bamboo member. Parallel to the longitudinal axis of the bamboo member, one steel rod is installed inside the steel tubes where its axial force capacity depends on the strength of the glue line between the wood block and the bamboo enclosed by the tube (see Fig. 3(c)). Her proposal successfully replaced the end of bamboo the member by one steel rod for further 3-D joint assembly processes.

The last development of bamboo jointing method is presented by Ohta et al [7]. They proposed a jointing method as shown in Fig. 3(d) where some parts of the bamboo are removed and the round shape of the bamboo was flattened and pressed together with a wooden spacer. In the gluing process between the wood spacer and the bamboo parts, the inner skin of the bamboo was removed and phenol-resorcinol resin adhesive was used with heat application.

In all of the discussed bamboo jointing methods above, bamboo splitting due to tensile stress perpendicular-to-grain around the bolt hole significantly limits the connection strength. This study considers if bamboo splitting can be effectively postponed by wrapping bamboo with FRP sheets.

3. Research Method

In this study, seventeen bamboo connections were prepared and tested according to the test configuration shown in Fig. 4. The descriptions of these connection specimens, including number of repetition, are summarized in Table 1. The parallel loading-to-grain connections or overlap joints were composed of three bamboo members and one steel rod, while the perpendicular loading-to-grain connections consisted of one main member and four side bamboo members connected with two steel rods. All the connections used bamboo Wulung (moisture content, 14%; specific gravity, 0.7) and a deformed steel rod 12 mm in diameter (bending yield stress, 513 MPa) plus standard nut and washer. The joint slip or relative displacement between the bamboo main member and side members was obtained by averaging the slip measurement data of two LVDTs shown in Fig 4. The load was applied under quasi-static monotonic and the test was terminated when failure of the connection was observed.

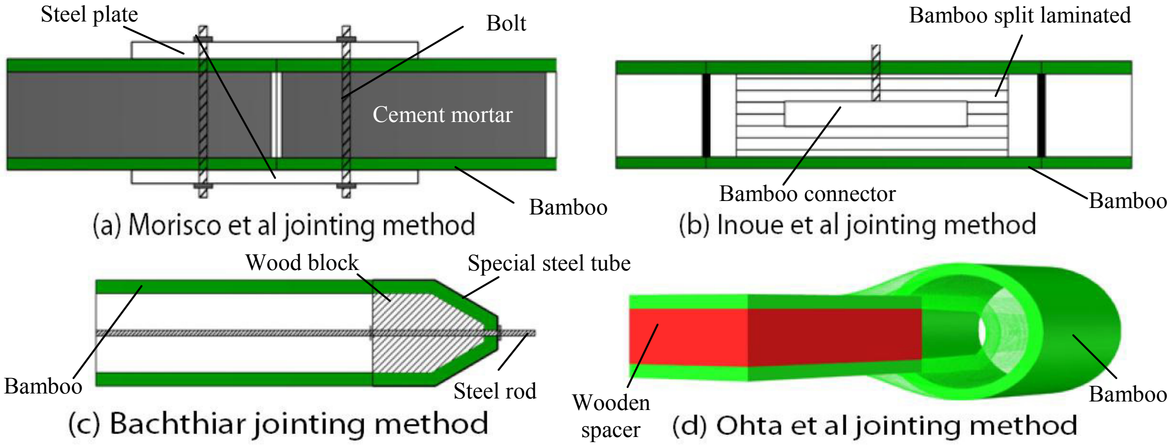

Fig. 3. Development of bamboo jointing method: (a) Morisco et al jointing method [2]; (b) Inoue et al jointing method [5]; (c) Bacthiar jointing method [6]; and (d) Ohta et al jointing method [7].

Fig.5 illustrates the attachment of "ijuk" rope into parallel loading-to-grain connection and FRP sheets into both parallel and perpendicular loading-to-grain connections. The FRP sheet has engineering properties obtained from the supplier as follows: ultimate tensile strength 575 MPa, maximum tensile strain 2.2% and tensile (young) modulus 2.61 GPa. Before attaching this FRP sheet, the surface of the bamboo members was cleaned using sand paper. Epoxy resin adhesive was used to attach the FRP sheet into the connection and the width of the sheet was made to be around 100 mm. There was no preliminary test on the engineering properties of the "ijuk" rope, and attachment of "ijuk" rope into the connection was made without adhesive.

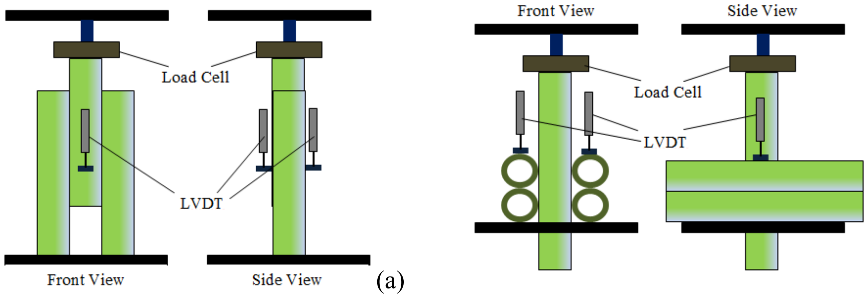

Fig. 4. Test set up of double-shear bamboo connection: (a) parallel loading-to-grain connection; (b) perpendicular loading-to-grain connection.

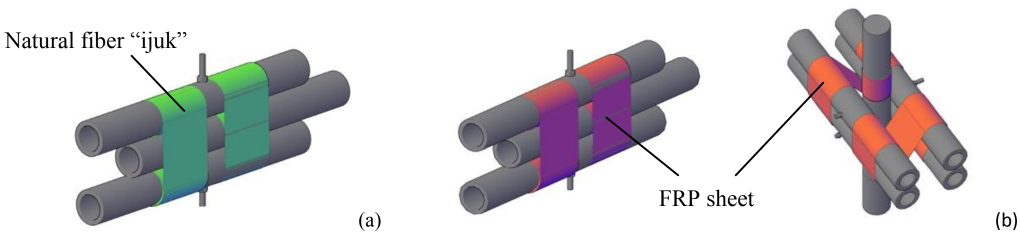

Fig. 5. Placement of reinforcement: (a) Natural fiber "ijuk"; (b) FRP reinforcement in parallel and perpendicular loading-to-grain connection.

Table 1. Description of bamboo connection specimens

Name	Description	Loading Direction	Number Repetition	Diameter of Bamboo (mm)
BJ0	bolt	parallel	7	71.8 (61.6 - 75.6)
BIJ0	bolt with "ijuk" rope	parallel	3	75.0 (70.5 - 78.4)
BFJ0	Bolt with FRP sheet	parallel	3	70.9 (66.2 - 78.0)
BJ90	bolt	perpendicular	2	76.6 (75.3 - 77.4)
BFJ90	bolt with FRP sheet	perpendicular	2	76.2 (75.0 - 77.5)

4. Results and Discussion

The experimental load-slip curves of the bolted bamboo connection are presented in Fig. 6(a) where the failure mode of all bolted connections was due to large bearing deformation of bamboo members beneath the bolt. After the elastic linear portion, most of the bolted connections showed constant applied load with joint slip increases. In this failure mode, the bending deformation of the bolt is negligible as the bolt remains straight. A variation of the lateral load capacity among the connection specimens was mainly due to the non-uniform cross-sectional dimension and embedding strength of bamboo members.

For further discussion, these following properties are determined from the load-slip curves. The joint slip modulus is defined as the slope of the curve segment between loads of 10% to 40% of the maximum load [9]. The apparent yield load is evaluated using 5% off-set method. In this method, a straight line to the initial linear portion of the curve is shifted in the positive x-direction by 5% of bolt diameter, and the apparent yield load is defined as the intersection of this line and the load-slip curve. The lateral load capacity is defined as the maximum load before a slip of 15 mm parallel to load direction is reached. The last property is ductility, and it is evaluated based on the joint slip at ultimate load divided by slip at the apparent yield load. The ultimate load is the load that causes connection fails or experiences load decrease to 20% of the maximum load, whichever occurs earlier.

Figure 6 (b-d) summarizes the above mentioned properties of all bolted connections. It is obvious that the application of the FRP sheet greatly increases the joint slip modulus of the joints as well as their lateral load capacities. This increase is substantially due to the wrapping effect developed between the bamboo surface and the FRP reinforcement, where gaps between the bamboo and FRP sheets are filled by a strong material which is epoxy resin. In this stage, the bending deformation and bearing deformation of the bamboo beneath the bolt is still relatively small. Progressive fracture of the hardened epoxy resin, however, finally deteriorates the connection as indicated by the sudden load decrease shown in Fig. 6(e) after reaching the maximum load. Following this sudden load decrease, the bolted joints with FRP reinforcement still show some resistance before completely failing. A typical failure of the FRP reinforced connection is shown in Fig. 7.

In the case of the bolted connection reinforced with natural fibre “ijuk”, the wrapping effect that leads to an increase of the connection load capacity was negligible as shown in Fig. 6(e) due to shrinkage and swelling activities of both the bamboo members and the “ijuk” fibre itself. The increase of the joint slip modulus and lateral load capacity caused by the FRP sheet wrapping effect also was not found in the bamboo connections under perpendicular loading as indicated by their load-slip curves shown in Fig. 6(f). This comes from the fact that the placement of the FRP sheet conducted in this connection creates an insignificant wrapping effect on the connection (see Fig. 5(b)) as no single layer of FRP sheet encloses all bamboo members (both vertical and horizontal members). Improvement on the FRP sheet arrangement is necessary to attain better connection performances, which will be discussed in the authors’ future paper.

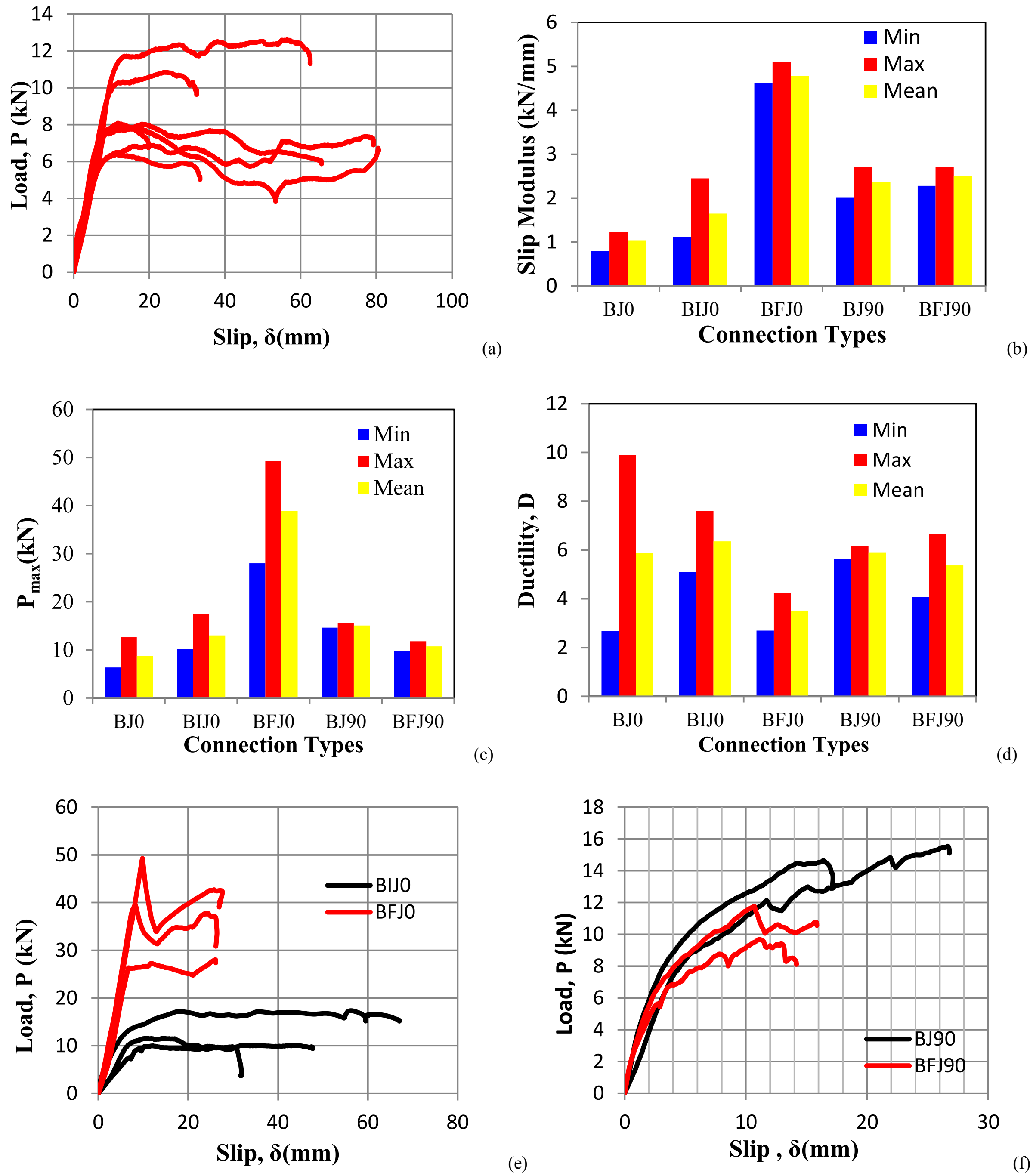

Fig. 6. Experimental result: (a) load-slip curves of bolted bamboo joints; (b) joint slip modulus of the bolted connection for various reinforcement materials and loading directions; (c) lateral load capacity of the bolted connection for various reinforcement materials and loading directions; (d) ductility of the bolted connection for various reinforcement materials and loading directions; (e) load-slip curves of bolted bamboo joints under parallel loading with FRP and natural fibre “ijuk” reinforcements; and (f) load-slip curves of bolted bamboo joints under perpendicular loading with and without FRP reinforcements.

The increase of the joint slip modulus and lateral capacity due to FRP reinforcement, however, is accompanied by a decrease of joint ductility as indicated in Fig. 6(d). The average ductility ratio of all bolted bamboo connections is higher than 4.0, except at the joints with FRP reinforcement, which is 3.5. This ductility behavior is solely contributed by the presence of bolt since the FRP sheet itself is brittle. An optimum combination of bolts and FRP sheet reinforcement in bamboo connection is necessary to ensure sufficient ductility.

Fig. 7. Failure mode of bolted bamboo joint reinforce with FRP sheets.

5. Conclusions

Connections in bamboo constructions are regarded as the weakest parts and have hindered the optimal utilization of excellent bamboo engineering properties. This paper discussed development of various methods of bamboo jointing, including the authors' proposal where Fiber Reinforced Plastic (FRP) in the form of sheets is used to improve the structural performance of bolted bamboo joints. The test results showed a significant increase of join slip modulus and lateral load capacity of the bolted bamboo connections due to wrapping effects when they are reinforced with FRP sheets, especially the overlap joints.

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