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Study of mechanical properties of wooden bolt–nut connector I: effect of size and shape of thread on withdrawal strength

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Abstract The withdrawal strength of a bolt–nut connector made from wood-based material was evaluated. The thread strength of the wooden bolt–nut connector was tested to select various parameters of the connector and the type of wood material; the wood materials tested were hard maple, white oak, ebony, glue-laminated bamboo, and densified Japanese cedar. A plane model of wooden threads with various thread angles was also evaluated. The results showed that the maximum failure load of the thread increased with increasing bolt density and connection area, which was calculated from the diameter of the bolt and the thickness of the nut. The withdrawal resistance after reaching the maximum load underwent a graded decrease because the bolt threads were broken one by one. In addition, the thread strength depended on the thread angle. In the model with a thread angle of 90°, compressive deformation in the transverse direction occurred prior to shear deformation along the root of the threads; the model with this thread angle thus had higher strength than those with other angles.

Key words Bolt–nut connector · Withdrawal strength · Thread angle · Densified wood

Introduction

The strength and performance of any wooden structure depends heavily on its connections, which are mainly composed of metal fasteners. However, the heavy use of metal connectors contributes to the poor recycling and reuse rate of wood resources due to the difficulty of separating the metal from waste wood. Wood-based connectors such as a nails, wedges, dowels, and mortise–tenon joints have traditionally been used for timber structures.[1–6] In addition to not having to separate wood connectors from waste wood, such connectors are lightweight, do not rust, have a low heat bridge effect, and are easy to cut by wood machinery. Since the development and spread of wood densification technology, several attempts to make densified wood nails,[7] dowels,[8] and drift pins[9] have been reported.

Bolt–nut connectors are one of the most general connectors for timber structures. However, wooden bolt–nut connectors have not shown reliability in studies on their mechanical strength, durability, and productivity. For such bolts to be usable in a wooden structure, they especially need to have reliable bending strength, tensile strength, and withdrawal resistance of the thread. There have been many preliminary studies on enhancing bending and tensile strength in bolt shanks and nut bodies made of woody shaft materials by using densified materials,[10,11] but the withdrawal residence has not been reported. In this study, therefore, we investigated the withdrawal resistance of wooden bolt–nut joints for timber structures through the evaluation of thread strength. In addition, we examined the fracture pattern of the connectors using plane models of threads using various thread angles.

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Materials and methods

Manufacture of wooden bolt–nut connector

Hard maple (*Acer saccharum*), white oak (*Quercus alba*), ebony (*Diospyros* spp), madake bamboo (*Phyllostachys bambusoides*), and Japanese cedar (*Cryptomeria japonica*) timber was used as the bolt specimens. Hard maple edge-grain timber was used for the nut specimens. Air-dried madake and Japanese cedar flat-sawn timber were com-

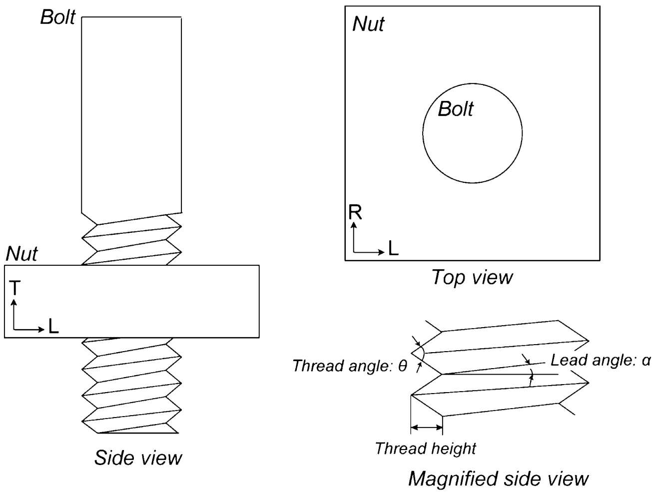

Fig. 1. Schematic of the wooden bolt–nut connector

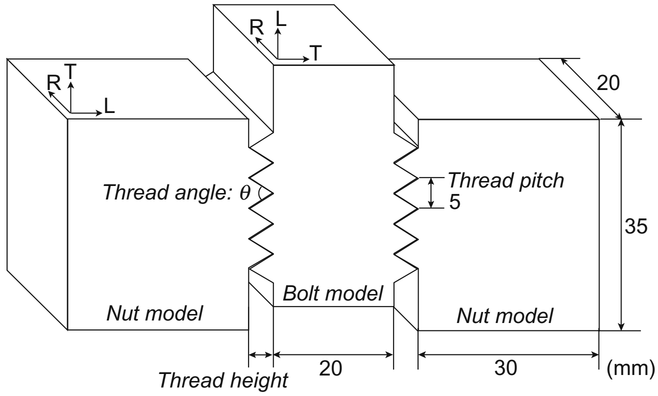

Fig. 2. Dimensions of the plane model of the bolt–nut connector

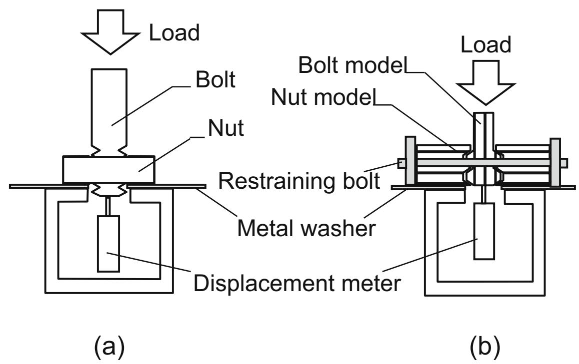

Fig. 3. Setup for the withdrawal test: **a** for the bolt–nut connector, **b** for plane model of the bolt–nut connector

pressed in the radial direction in a platen press at 80°C and then dried to fix the added deformation at 110°C for 6 h. The hard maple, white oak, and ebony were also processed using the same heat treatment but without the deformation process. The densification degrees of the madake and Japanese cedar were 23% and 67%, respectively. Furthermore, the densified madake timber was laminated with a phenol-formaldehyde resin until it became 30 mm thick. The final densities of hard maple, white oak, and ebony in the air-dried condition were 0.71, 0.82, and 0.90 g/cm^3, respectively. Those of madake and Japanese cedar increased to 1.22 and 1.31 g/cm^3 from 0.94 and 0.43 g/cm^3 initial density, respectively.

Figure 1 illustrates the wooden bolt–nut connector. The dimensions of the bolts were 12, 18, and 24 mm (diameter) × 80 mm (longitudinal direction). The nuts were cut from a 50-mm square (diameter of bolt: 12.0 and 18.0 mm) or a 70-mm square (diameter of bolt: 24.0 mm) of wood-based material. The thickness of the nuts was 5, 10, 15, and 20 mm. The bolt threads and nut holes were carved using woodworking tap and dies (Kanazawa Tekko, K321, 322, 323). The diameter of the bolt refers to the diameter of the shafts and of the external thread. A hole was drilled through the center of the nuts. The diameter of the hole was equal to that of the received bolt. The height, angle, and lead angle of the thread of all bolts and nuts were 3.0 mm, 66.5°, and 5.1°, respectively.

Manufacture of plane model of bolt–nut connector

Figure 2 illustrates a plane model of the wooden bolt–nut connector. White oak timber was used as the material for the plane model. The thread angle of the model was set at 60°, 90°, and 120° by using a wood router. As a result of processing, the thread height for each angle was 5.0, 2.5 and 1.3 mm, respectively. The thread lead angle was set at 0°.

Withdrawal test of wooden bolt–nut connector and plane model of bolt–nut connector

The setups for the withdrawal tests are shown in Fig. 3. Compression load was applied to the bolt shank (See Fig. 3a) or the bolt model (See Fig. 3b) at a displacement rate of 1 mm/min by using a material testing machine (Instron 4204). The displacements of the bolt shank or the bolt model were measured using a displacement meter. The maximum compression shear load to act on the connection area was considered the level of the withdrawal resistance. The plane model was fixed with a metal bolt so as not to open at the side during loading. In addition, the fracture behavior of the models during loading was observed with a florescence microscope (Micro Square, DS-3UX). Five specimens were measured for each condition.

The shear stress on the thread of the bolt of the bolt–nut connector (τ_B) and plane model (τ_M) are given by:

$$\tau_B = \frac{F}{S_B} = \frac{F}{\pi d_B p n}; n = \frac{T}{p} \quad (1)$$

$$\tau_M = \frac{F}{S_B} = \frac{F}{D_B p n}; n = \frac{T}{p} \quad (2)$$

where F and S_B are the compression shear load and connection area of the specimen in the withdrawal test; d_B and p are the minor diameter and pitch of the bolt thread; D_B is

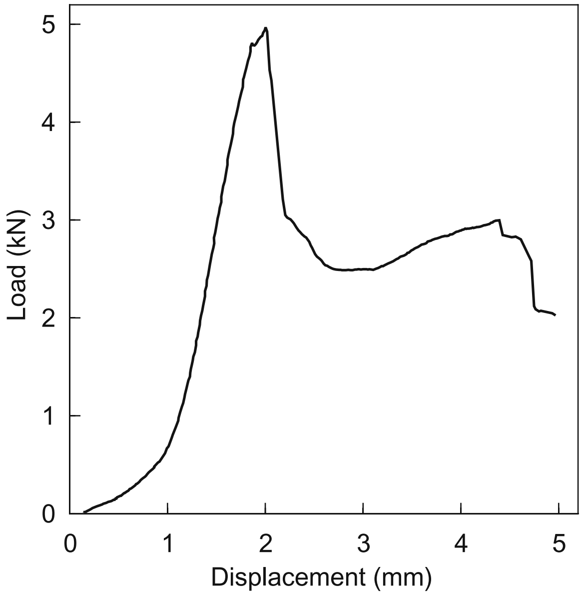

Fig. 4. Load–displacement curve of the wooden bolt–nut connector under axial loading. The wood species used for the bolt and nut was white oak. Bolt diameter was 18 mm and the nut thickness was 10 mm

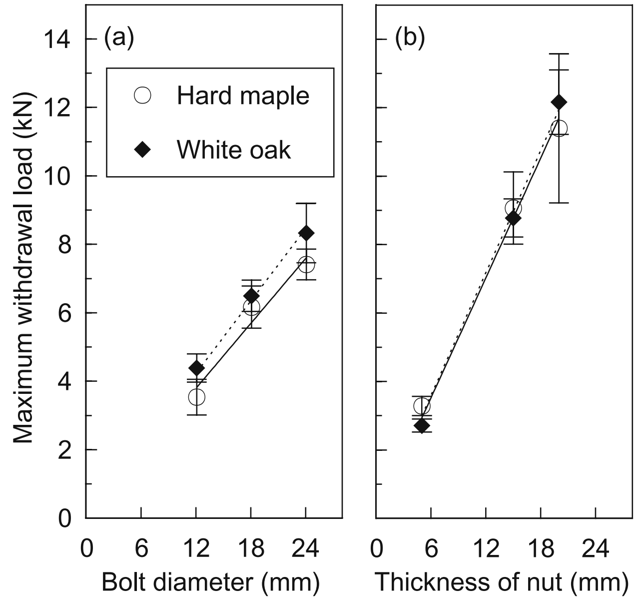

Fig. 5. Effect of bolt diameter (**a**) and nut thickness (**b**) on maximum withdrawal load of wooden bolt–nut connector. The wood species used for the bolt and nut were hard maple and white oak. **a** The nut thickness was 10 mm; **b** the bolt diameter was 18 mm. *Error bars* indicate SDs. *Solid and dotted lines* indicate regression lines for hard maple and white oak, respectively, by using the least-squares method

the depth of the bolt model; n is the number of threads in contact for the bolt and the nut; and T is the thickness of the nut.

Results and discussion

Withdrawal resistance of wooden bolt–nut connector

A representative load–displacement curve of a joint consisting of an 18-mm-diameter white oak bolt with a 10-mm-thick nut is shown in Fig. 4. After a little slip in the first phase, the load increased linearly and then reached a maximum. At this point, the bottom of some threads on the bolt cracked along the longitudinal direction. After a rapid decrease in the load, the load was maintained while the displacement increased. Then, the load decreased again when the remaining threads of the bolt broke. The reason why the load was maintained after initial failure was that the threads of the bolt that were not broken were in contacted with the threads of the nuts. In this study, all of the first breaks occurred in the thread of the bolt side, because the bearing area of the nut under shear loading is larger than that of the bolt and the shear strength of the TR plane was about two or three times as high as that of the LR plane.

Figure 5 shows the effect of the bolt diameter and the thickness of the nut on the maximum withdrawal load. Shear fracture in the root of the bolt thread occurred in all specimens. The maximum withdrawal load increased with increasing bolt diameter and thickness of the nut. The regression lines, which pass through the origin of the coordinate axes, had a high correlation coefficient. The relationships between the connection area and maximum shear stress of the bolt thread (τ_B) are shown in Fig. 6. τ_B of the hard maple and white oak are 11.4 and 11.7 MPa, respectively, regardless of the connection area. Therefore, the thread strength of wooden bolt–nut connectors depends on the shear strength of the bolt-side thread.

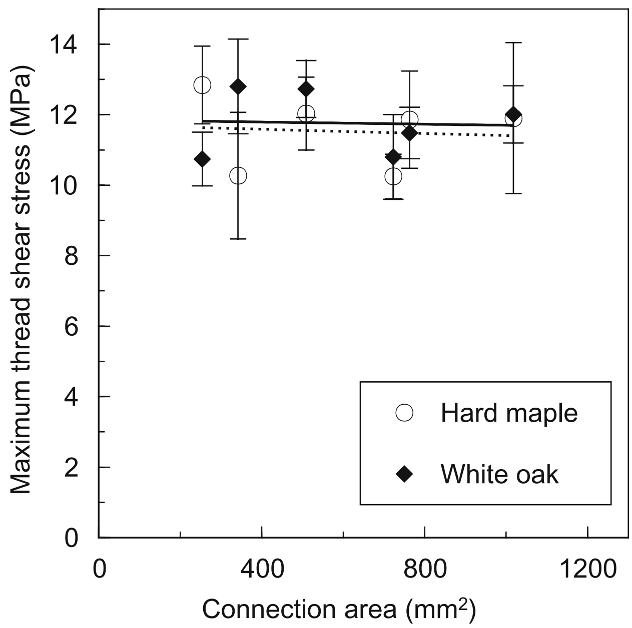

Fig. 6. Relationship between connection area and maximum thread shear stress under withdrawal test. *Error bars* indicate SDs. *Solid and dotted lines* indicate regression lines of hard maple and white oak, respectively, by using the least-squares method

Figure 7 shows the effect of bolt density on τ_B. τ_B increased with increasing bolt density. The regression line had a high

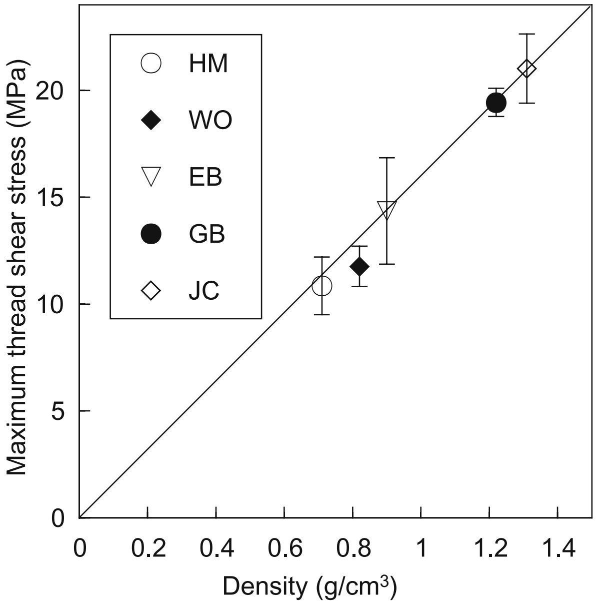

Fig. 7. Effect of density of the bolt on the maximum shear stress of the bolt thread in withdrawal tests. *HM*, hard maple; *WO*, white oak; *EB*, ebony; *GB*, densified madake; and *JC*, densified Japanese cedar. The bolt diameter was 18 mm and the nut thickness was 10 mm. *Error bars* indicate SDs and the *solid line* indicates the regression line by using the least-squares method

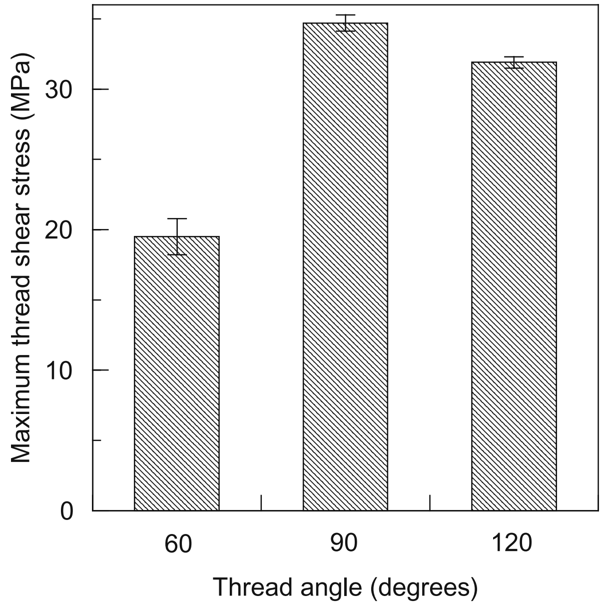

Fig. 8. Effect of thread angle in the plane model of the bolt–nut connector on maximum thread shear stress. *Error bars* indicate SDs

correlation coefficient and passed through the origin of the coordinate axes. The *t* test resulted in a *t* value of 8.23, indicating a significant difference (significance level = 1%) in τ_B between ebony (EB) and that of densified madake (GB). The *t* test results indicated that the values for any pair of wood species were significantly different with a significance level of 1%, except for the comparison between the hard maple (HM) and the white oak (WO) groups and the comparison between GB and densified Japanese cedar (JC).

Withdrawal resistance of plane model

Figure 8 shows the effect of thread angle on τ_M. The specimens with 90° and 120° thread angles had higher fracture strength than those with 60°. The *t* test results showed that values for any pair of thread angles were significantly different with a significance level of 1%. Figure 9 shows the behavior of representative load–displacement curves of the plane model for different thread angles. For the 60° thread angle, the load increased to the maximum value linearly and then decreased rapidly. For the 90° and 120° thread angles, the load after reaching the load peak decreased gradually. Photographs of the fracture behavior of the plane models are shown in Fig. 10. For a 60° thread angle, a shear fracture occurred along the root of the threads on the bolt side, and no thread collapsed. The final fracture behavior of the 90° thread angle was the same as that for 60°. However, the threads on the nut side were slightly collapsed in the direction perpendicular to the grain. On the other hand, shear fracture of the threads with 120° thread angle did not occur,

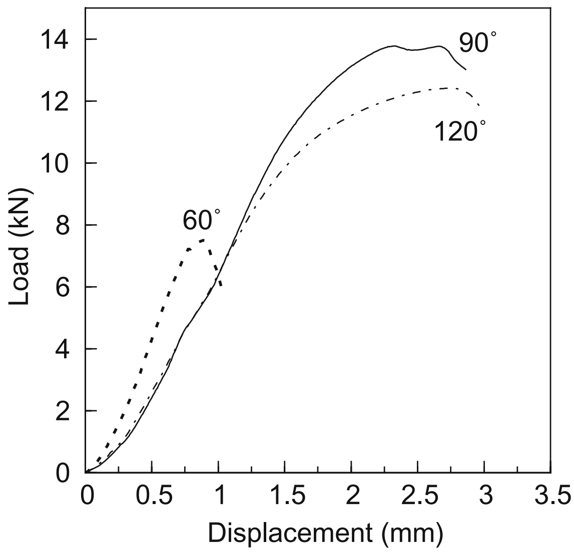

Fig. 9. Relationship between load–displacement curves and thread angles in plane model of the bolt–nut connector

and the threads on the bolt and nut sides completely collapsed. In the case of threads with wider angles, brittle shear fracture on the thread root is restrained because the bolt threads were densified by collapse deformation. However, shear force resistance of the thread does not work when the angle of the thread is too wide. In the case of narrower thread angles, bending fracture of the thread occurs in addition to shear fracture. The narrower the angle of the threads, the higher the thread height, as shown in Fig. 9. The stress at the root of the threads resulting from the withdrawal load increases with the thread height because the cantilever bending stress intensifies. Therefore, it is considered that a thread angle of at least 90° is required, in which the thread contributes to the high withdrawal resistance.

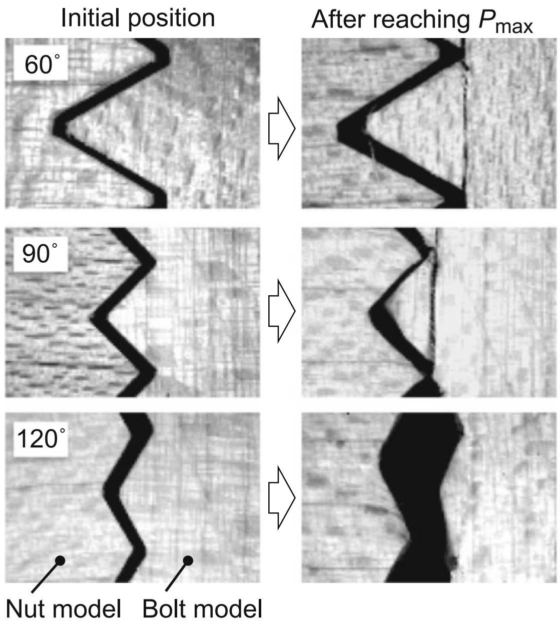

Fig. 10. Fracture behavior of threads in the plane model for various thread angles. P_{max}, maximum load in the withdrawal test

Conclusions

The maximum shear load, which has a close relationship with the withdrawal resistance, was affected by the bolt density and the connection area of bolt–nut connectors, as calculated from the bolt diameter and the thickness of the nut. The effect of the thread angle on shear loading was clarified by using plane thread models. Increasing the thread angle intensified the compression force against the threads and reduced the development of brittle cracks. For a narrow thread angle, the fracture pattern was shear fracture along the root of the thread on the bolt side. The fracture pattern for threads with a wide thread angle was caused by the thread slipping when the thread on the bolt side collapses. The wider the angle, the sooner slipping between threads occurs, which causes the threads to collapse slightly. Therefore, the increase rate of the maximum shear load was decreased. When the thread angle is 90°, the thread is initially collapsed and then broken by shear fracture, so the optimal value of the thread angle when using white oak timber will be nearly 90°.

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