MOMENT RESISTING TIMBER JOINTS WITH HIGH-STRENGTH STEEL DOWELS: NATURAL FIBER REINFORCEMENTS

Ali Awaludin¹, Yoshihisa Sasaki², Akio Oikawa³, Takuro Hirai² Toshiro Hayashikawa³

ABSTRACT: Evaluation of cyclic behavior of moment resisting timber joints with high-strength dowels was carried out in this study. The evaluation was also extended to some joints that were locally reinforced with plywood, plybamboo and desinfied veneer wood (DVW). In addition, some joints with normal-strength dowels were prepared and tested using the same loading protocol for comparison. The high-strength dowels used in this study was 10.9grade bolts, the normal-strength dowels was 4.8grade bolts and the wood member was Abies sachalinensis glulam having oven-dry density of 339 kg/m^3. The test results of un-reinforced joints showed premature wood-splitting caused the effect of dowel grade on both moment resistance and hysteretic damping insignificant. However, in the case of reinforced joints, the increase of joint resistance or hysteretic damping was noticed especially in the joints with DVW reinforcements. Strength increase of the joints was found in the order: plywood-reinforced joints > plybamboo-reinforced joints > DVW-reinforced joints, which could be inferred to be proportional to the reinforcements' embedding strength.

KEYWORDS: Embedding strength, High-strength dowels, Moment resisting joints, Natural fiber reinforcements

1 INTRODUCTION

Yield theory [1] implicitly shows the joints that fail due to a combination of large bending deformation of steel dowels and bearing of wood beneath the fasteners may attain higher yield loads if high-strength dowels are used. Investigation on load-slip characteristic of double-shear timber joints with high-strength steel dowels has been reported by few researchers [2-4]. They found that the experimental joint load-carrying capacity was in a good agreement with what is to be expected from the Yield theory. Under monotonic tension tests, normal-strength dowels which typically are grade 4.8 and 5.8 have ultimate strength not exceeding 530 MPa. While high-strength steel dowels of grade 10.9 and 12.9, their ultimate tensile strength may reach 1,040 MPa and 1,300 MPa, respectively. As for an example, timber-to-timber joint under yield mode k described in Eurocode 5 would give about 40% increase of load-carrying capacity when grade of the dowel is altered from 5.8 to 10.9. Besides using high-strength bolts, increase of load-carrying capacity of timber joints can be obtained by gluing or embedding reinforcement materials locally at connection shear-planes. Up to present time, many reinforcement materials have been proposed and most of them are also capable to enhance the connection ductility [5-8]. Among those reinforcements, densified veneer wood (DVW) and plywood are probably the most widely used. They are also more compatible materials in timber connections as their dowel embedding performance is similar to that of timber. In addition, they are wood-based sheets so that to glue them to wood members does not require special technique.

This study was initially addressed at assessing the structural performance of moment resisting joints that are fastened with high-strength dowels in comparison to those joints assembled by normal-strength dowels. The evaluation of mechanical behavior of moment resisting joints with high-strength dowels was also conducted at joints that were reinforced with plywood, plybamboo and DVW. Plybamboo panel was derived from two bamboo boards (each board consists of several dried bamboo strips) placed perpendicular to each other. Then finally all bamboo strips were glued using phenol formaldehyde and hot-pressed at a constant pressure and temperature of 3 MPa and 140-150°C, respectively. The use of densified plybamboo as reinforcement material in timber joints has been initiated in recent years [9-11].

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2 MATERIALS AND METHODS

*Abies sachalinensis* glued-laminated members were used in this study. Average moisture content and oven-dry density of the glulam members was 8.2% and 339 kg/m³ (standard deviation, 8 kg/m³), respectively. And their dynamic elastic modulus determined using non-destructive stress wave method was 10.56 GPa with a coefficient of variation of 2.4%.

**Figure 1:** Three-point bending test of the bolts

The normal-strength dowels were 4.8grade bolts and the high-strength dowels were 10.9grade bolts. Dowel yield moment was evaluated according to three-point bending test [12] shown in Figure 1. A perfect elastic-plastic behavior of the normal-strength dowels was noticed with bending yield moment of 0.15 kNm. In the case of high-strength dowels, strain hardening of the inelastic part was observed with bending yield moment equalled to 0.34 kNm.

There were four groups of the joints: (1) joints without reinforcement, (2) joints reinforced with DVW of 280x280x8 mm³, (3) joints reinforced with plywood of 280x280x9.5 mm³ and (4) joints reinforced with plybamboo of 280x280x8 mm³. In group 1 and 2, three joints with high-strength dowels and one joint with normal-strength dowels were produced. While in the remaining groups, only one joint with high-strength dowels and one joint with normal-strength dowels were fabricated. The reinforcements were glued to the wood members with polyurethane adhesive and cold pressed at 0.9 MPa for 24h to ensure good contact during curing process. Lead-holes of the main and side members were made during one-time drilling process and their diameters were the same as diameter of the dowel ($d = 12$ mm).

Geometry of the joint including the simplified test setup is shown in Figure 2 where square washers of 40-mm width were used. Figure 3 shows the rotation-based loading protocol used in this study where joint rotation ($\theta$) is evaluated using two displacement measurements (LVDT 1 and 2, see Figure 2). The cyclic loading protocol consisted of four joint rotation levels: 0.01, 0.02, 0.03, and 0.04 radians with three repetitions each. After performing the cyclic test, the joints were loaded monotonically in up-ward direction until failure or the load decreased to 80% of the maximum load. Both cyclic and monotonic loading tests were carried out using displacement control at a constant rate of 8.5mm/min.

3 RESULTS AND DISCUSSIONS

3.1 HYSTERESIS LOOPS

Typical hysteretic loops of the un-reinforced joints with 4.8grade and 10.9grade bolts are shown in Figure 4 where the loop of the joint with 10.9grade bolts was reversed for an easy comparison. The moment resistance
was evaluated by taking into consideration the change of lever arm due to bending deformation of the timber members. Opening the joint by the bending of timber members shortens the lever arm. In this study, change of lever arm was estimated by calculation written in [13] based on the joint geometry and elastic properties of the wood member.

Figure 4: Hysteresis loops of the un-reinforced joints (blue line, 4.8grade bolt joints; red line, 10.9grade bolt joints)

Figure 5: Premature wood-splitting of the un-reinforced joint

Hysteretic damping or the area enclosed by the loop of the un-reinforced joint with 10.9grade bolts is smaller than that of the un-reinforced joint with 4.8grade bolts. In addition, removing the load within the cyclic load region was followed by a relatively small inelastic joint rotation. These are potentially caused by small bending deformation of the 10.9grade bolts that leads to minimum inelastic bearing deformation of wood member beneath the dowels. Although the average maximum resistance of the joint with 10.9grade bolts, 10.14 kNm, is a slight higher than that of the joint with 4.8grade bolts, 8.84 kNm, this difference is considerable small. Maximum resistances of both joints were found at similar rotation levels and their failure was due to premature wood-splitting of the side member as can be seen in Figure 5.

Figure 6: Hysteresis loops of the reinforced joints. (a) Plywood-reinforced joint; (b) Plybamboo-reinforced joint; and (c) DVW-reinforced joint. (Blue line, 4.8grade bolt joints; red line, 10.9grade bolt joints)

Since the test results of un-reinforced joints showed a negligible influence of dowel strength on moment resistance, especially within the cyclic load application, it was decided to increase the cyclic rotation level by
100%. Experimental hysteresis loop of the joints with three different types of reinforcements are shown in Figure 6. Note that the rotation of the joints with 10.9grade bolts was reversed for a better representation. In contrast to the un-reinforced joints, the reinforced joints had large joint deformation and no visible wood cracks up to joint rotation equaled to 0.15rad. The rotation of 0.15rad corresponded to a 15-mm fastener slip which is often used to evaluate the (ultimate) lateral resistance of joints. Test of the DVW-reinforced joints unfortunately had to be stopped before completing the cyclic load since their resistances were much higher than the designed strength of loading points.

Method described in European standard to determine yield rotation of loops shown in Figure 6 was adopted. The yield rotation is defined as the intersection of two well-defined lines, one representing the elastic part and the other is the plastic part. Table 1 summarizes the joint rotation and its corresponding moment resistance at the yield point, and the rotational stiffness which is obtained by dividing the yield moment with the yield rotation. Increase of the joint stiffness due to the three different reinforcements was found in the order: plywood-reinforced joint > plybamboo-reinforced joint > DVW-reinforced joints as indicated by the \( S_f \) values. (\( S_f \) is the stiffness ratio of the reinforced joint over the un-reinforced joints.) The \( S_f \) value of DVW-reinforced joint with 10.9grade bolts might be improved when the information of moment-rotation curve at higher rotation levels is available. Using plywood or plybamboo reinforcements, the stiffness of the joint with 10.9grade bolts more or less was the same as the stiffness of the joint with 4.8grade bolts. However, significant increase of joint stiffness because of high-strength dowels adoption was found in the DVW-reinforced joints.

### 3.2 MAXIMUM MOMENT RESISTANCE

Maximum moment resistance of the joints was estimated by the product of lateral force acting on each dowel and distance of dowel to the centroid of dowel pattern. It was further assumed that all dowels reached their maximum load-carrying capacities as expressed by the yield theory during maximum resistance takes place. Load-carrying capacity of a single-bolt joint without or with local reinforcement is determined according to this following set of equations [8, 14] of which some symbols are explained in Figure 7.

### Table 1: Joint properties at the yield point according to European Standard

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>4.8grade bolts</th>
<th>10.9grade bolts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \theta _y )</td>
<td>( M_r )_y</td>
</tr>
<tr>
<td>No</td>
<td>0.017</td>
<td>3.26</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.016</td>
<td>5.36</td>
</tr>
<tr>
<td>Plybamboo</td>
<td>0.016</td>
<td>7.39</td>
</tr>
<tr>
<td>DVW</td>
<td>0.020</td>
<td>9.79</td>
</tr>
</tbody>
</table>

\( \theta \_y \), yield rotation; \( M_r \)_y, yield moment; \( k_r \)_y, rotational stiffness; and \( S_f \), stiffness ratio of reinforced joint over the un-reinforced joint.

Load-carrying capacity of single-bolt joint per shear-plane without reinforcement:

\[
R = \min \left\{ \frac{f_{s,yd}}{2 + \beta} \left( \frac{2\eta}{(2 + \beta)(2 + \beta)} + \frac{f_{s,yd}}{f_{s,yd}} \right) \right\}
\]

Load-carrying capacity of single-bolt joint per shear-plane with reinforcement:

\[
R = \min \left\{ \frac{f_{s,yd} + f_{s,yd}}{2 + \beta} \left( \frac{2\eta}{(2 + \beta)(2 + \beta)} + \frac{f_{s,yd} + f_{s,yd}}{f_{s,yd}} \right) \right\}
\]

where \( f_{s,yd} \) and \( f_{s,yd} \) are embedding strength corresponding to \( s_1 \) or \( s_2 \), respectively, \( f_{s,yd} \) = embedding strength of reinforcement, \( M_r = \) dowel moment, \( \beta = f_{s,yd}/f_{s,yd} \), \( \eta = f_{s,yd}/f_{s,yd} \), and \( k_{ad} = 1.2 \).
Table 2: Predicted and experimental maximum resistance of the joints (kNm)

<table>
<thead>
<tr>
<th></th>
<th>Un-reinforced joint</th>
<th>Plywood joint</th>
<th>Plybamboo joint</th>
<th>DVW joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8grade bolts</td>
<td>8.40 (8.84)</td>
<td>10.05 (14.31)</td>
<td>13.57 (16.72)</td>
<td>17.15</td>
</tr>
<tr>
<td>10.9grade bolts</td>
<td>11.37 (10.14)</td>
<td>14.73 (18.55)</td>
<td>18.46 (19.33)</td>
<td>22.28</td>
</tr>
</tbody>
</table>

Values in the parentheses are obtained from the tests.

Supplying information of joint geometry described in Figure 7, embedding strength of glulam member and reinforcements (30 MPa for glulam member; 37.58 MPa for plywood; 86.2 MPa for plybamboo; and 135 MPa for DVW sheet), and dowel yield moment (0.15 kNm for 4.8grade bolts; and 0.34 kNm for 10.9grade bolts) to either Equation (1) or Equation (2), the load-carrying capacity of single-bolt joint per shear-plane can be estimated. Finally make use of this information to evaluate the moment resistance of the joint shown in Figure 2, one obtains predicted joint resistance as given in Table 2. Those equations also informed that the un-reinforced joints connected with 4.8grade bolts or 10.9grade bolts failed with dowel yield in bending at one point. While the reinforced joints, they failed with dowel yield in bending at two or more points. These predicted yield modes well agreed with the test results.

Experimental maximum resistances of the reinforced joints shown in Table 2 were determined as the maximum resistance or joint resistance corresponded to joint rotation of 0.15rad. Table 2 indicated that less deviation is found between the prediction and the experimental results for the un-reinforced joints, but this discrepancy is significant in the reinforced joints. All the reinforced joints were capable to undergo high rotation deformation so that their resistances were significantly increased by axial force associated with dowel bending deformation.

4 CONCLUSIONS

This study examined the cyclic behaviour of moment resisting joints with two kinds of dowel grade: 4.8grade and 10.9grade bolts. Some of them were locally reinforced with 9.5-mm-thick plywood, 8-mm-thick plybamboo and 8-mm-thick densified veneer wood (DVW). The cyclic test showed that increase of joint resistance or hysteretic damping due to high-strength dowel adoption was small since most of the un-reinforced joints failed by premature wood-splitting. In the case of the reinforced joints, this increase was clearly observed. The increase was in the order: plywood-reinforced joints > plybamboo-reinforced joint > DVW-reinforced joints, which could be inferred to be proportional to the reinforcements’ embedding strength. Due to significant dowel axial forces (associated with dowel deformation), maximum moment resistance of the reinforced joints attained from the experiment was much higher than that of the yield theory prediction.

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