Nail plate reinforced joints with dowel-type fasteners

Blass, Hans J.1 Schmid, Martin2 Litze, Harald3 Wagner, Barbara4

ABSTRACT

A theoretical model is presented to calculate the load-carrying capacity of connections with dowel-type fasteners, where the timber members are reinforced in the joint area with punched metal plate fasteners. The model represents an extension of the Johansen theory for dowel-type fasteners, also known as the European Yield Model. Ultimate loads from tests with reinforced and non-reinforced connections show a very good agreement with the calculated load-carrying capacities. The behaviour of the reinforced connections is very ductile, leading to a high capacity for energy dissipation. The reinforcement enables load-carrying capacities of the connection exceeding the load-carrying capacity of the connected members.

INTRODUCTION

The design of joints with dowel-type fasteners in a number of codes is based on Johansen’s theory of plasticity (Johansen 1949), later extended by Meyer (1957). The equations based on this theory predict the load-carrying capacity of a single fastener depending on the material properties of the timber and the fastener, respectively, and on the geometry of the connection. For both, the fastener in bending and the timber under embedding stresses it is assumed that the behaviour is ideal rigid-plastic.

If more than one fastener is used in a connection, the load-carrying capacity per fastener is lower than predicted by the Johansen theory. This decrease in load-carrying capacity compared with a single fastener connection is mainly caused by preliminary splitting of timber members and is more severe if the number of fasteners increases and the ratio of penetration depth to fastener diameter decreases. Hence, Johansen’s equations are less conservative in multiple fastener connections and if stout fasteners are used.

One method to prevent splitting of timber members is to reinforce the connection area e.g. by glued-on wood-based panels. If the embedding strength of the reinforcement is larger than that of the timber member, the reinforcement not only increases the load-carrying capacity by preventing the splitting, but additionally by providing a high embedding strength close to the member joints where embedding stresses reach their maximum first.

Using nail plates to reinforce the connection area has several benefits: no adhesives are necessary and the reinforced member is ready to use after the nail plates have been pressed into the timber. Furthermore, the embedding strength of steel is much higher than that of timber or other wood-based materials. Using nail plate reinforced joints therefore leads to connection capacities exceeding the capacities of the timber members. Consequently, connection design does not govern the timber member sizes anymore and more economic engineered timber structures result. In addition, the reinforcement significantly increases joint ductility and energy dissipation.

MECHANICAL MODEL FOR THE LOAD-CARRYING CAPACITY

The capacity of nail plate reinforced joints may be theoretically determined using an extended Johansen theory. Kevarimäki et al. (1995) proposed to calculate the load-carrying capacity of nail plate reinforced bolted connections using the
original Eurocode 5 equations for non-reinforced connections, where the embedding strength is calculated as a weighted average of the embedding strength of the timber and the nail plate, respectively. While this is correct for failure modes where the fastener is not deformed plastically and remains straight, their proposal significantly underestimates the load-carrying capacity of reinforced connections with slender fasteners.

The model used here is based on the work of Blass and Werner (1988), originally developed for glued-on reinforcements using plywood. It takes into account the different embedding strength values of the reinforcement and the timber, respectively. A prerequisite for the load-carrying capacities derived below is a failure mode determined by reaching the embedding strength of both the reinforcement and the timber member, in the case of slender fasteners together with plastic deformation of the fasteners. The anchorage capacity as well as the steel capacity of the punched metal plate have to be sufficiently large to prevent a failure of the punched metal plate before the failure of the dowel-type fastener connection.

On the basis of Johansen's ultimate load equations (Hilson 1995) the load-carrying capacities of reinforced single and double shear timber-to-timber as well as steel-to-timber connections are derived. It is assumed that the fastener, the reinforcing nail plate and the timber are ideal rigid-plastic materials. The following notation is used:

- \( s_1, s_2 \) timber thickness or fastener penetration,
- \( t \) nail plate thickness,
- \( f_{h,1}, f_{h,2} \) embedding strength corresponding to \( s_1 \) or \( s_2 \), respectively,
- \( f_{h,t} \) nail plate embedding strength,
- \( M_y \) fastener yield moment,
- \( d \) fastener diameter,
- \( \beta = \frac{f_{h,2}}{f_{h,1}} \),
- \( \eta = \frac{f_{h,t}}{f_{h,1}} \),
- \( R \) load-carrying capacity per shear plane.

\[ R = \min \left( \frac{s_1}{\beta}, \frac{s_2}{\eta}, \frac{M_y}{N_{y,1}} \right) \]

Figure 1: Failure modes of reinforced single (top) and double shear (bottom) connections

The load-carrying capacity per fastener per shear plane in reinforced single shear timber-to-timber connections results as the lowest value of the following expression:

\[ R = \min \left( \frac{s_1}{\beta}, \frac{s_2}{\eta} \right) \]
The corresponding failure modes are shown in the upper part of figure 1.

The load-carrying capacity per fastener per shear plane in reinforced double shear timber-to-timber connections is calculated as the lowest value of the following expression with the corresponding failure modes shown in the lower part of figure 1:

$$R = \min \left[ \beta \cdot f_{h,1} \cdot d \cdot \left( \frac{s_1 - 4t \eta^2}{\beta \cdot f_{h,1}} - (s_1 + 4t) \right) + f_{h,1} \cdot t \cdot d \right]$$

For steel-to-timber connections with thin steel plates and fasteners in single shear the load-carrying capacity is the lowest value of the following two equations:

$$R = \min \left[ \beta \cdot f_{h,1} \cdot d \cdot \left( \frac{s_1 - 4t \eta^2}{\beta \cdot f_{h,1}} - (s_1 + 4t) \right) + f_{h,1} \cdot t \cdot d \right]$$

The corresponding expressions for steel-to-timber connections with thick steel plates and fasteners in single shear and for steel-to-timber connections with inner steel plates and fasteners in double shear are:
The load-carrying capacity per fastener per shear plane in reinforced double shear steel-to-timber connections with outer thin steel plates is calculated as the lowest value of the following expression:

\[
R = \min \left[ \begin{array}{c}
\frac{f_{h,1} \cdot s_i \cdot d + f_{h,1} \cdot t \cdot d}{\sqrt{2 \cdot s_i^2 + 2 \cdot (2 - \eta) t^2 + 4ts_i + \frac{4M}{d \cdot f_{h,1}}} - (s_i + 2t)} + f_{h,1} \cdot t \cdot d \\
\frac{f_{h,1} \cdot d \cdot \left( (1 - \eta) t^2 + \frac{4M}{d \cdot f_{h,1}} - t \right)} + f_{h,1} \cdot t \cdot d
\end{array} \right]
\]

The corresponding expressions for steel-to-timber connections with outer thick steel plates and fasteners in double shear are:

\[
R = \min \left[ \begin{array}{c}
0.5 \cdot f_{h,2} \cdot s_2 \cdot d + f_{h,1} \cdot t \cdot d \\
\frac{f_{h,2} \cdot d \cdot \left( \frac{1 - \eta}{\beta} t^2 + \frac{2M}{\gamma} \right)} + f_{h,1} \cdot t \cdot d
\end{array} \right]
\]

The last addend \(f_{h,i} \cdot t \cdot d\) in all of the above expressions is the part of the load transferred by the reinforcement. This part is used to design the anchorage capacity and the steel capacity of the punched metal plate.

**TESTS WITH REINFORCED CONNECTIONS**

Tests with reinforced and non-reinforced connections were performed to verify the applicability of the theoretical model. Double shear timber-to-timber as well as steel-to-timber connections were tested using different fastener diameters and nail plate orientations. The nail plates used were MiTek M14 plates with a thickness of 2 mm, a nail length of 20 mm and a yield strength of the unpunched steel plate of 250 N/mm². An overview of the different tensile test series is given in table 1. Additional tests were carried out with moment resisting connections.

<table>
<thead>
<tr>
<th>Series/Number</th>
<th>Side member</th>
<th>Middle member</th>
<th>Plate Orientation</th>
<th>Fastener diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a/5</td>
<td>Steel</td>
<td>LVL</td>
<td>0°</td>
<td>16 mm</td>
</tr>
<tr>
<td>1b/5</td>
<td>Steel</td>
<td>LVL</td>
<td>90°</td>
<td>16 mm</td>
</tr>
<tr>
<td>1c/10</td>
<td>Steel</td>
<td>LVL</td>
<td>no plate</td>
<td>16 mm</td>
</tr>
<tr>
<td>2a/5</td>
<td>Steel</td>
<td>Spruce</td>
<td>0°</td>
<td>16 mm</td>
</tr>
<tr>
<td>2b/5</td>
<td>Steel</td>
<td>Spruce</td>
<td>0°</td>
<td>16 mm</td>
</tr>
<tr>
<td>2c/10</td>
<td>Steel</td>
<td>Spruce</td>
<td>no plate</td>
<td>16 mm</td>
</tr>
<tr>
<td>3/10</td>
<td>LVL</td>
<td>Steel</td>
<td>90°</td>
<td>24 mm</td>
</tr>
<tr>
<td>4a/10</td>
<td>Steel</td>
<td>Spruce</td>
<td>0°</td>
<td>12 mm</td>
</tr>
<tr>
<td>4c/10</td>
<td>Steel</td>
<td>Spruce</td>
<td>no plate</td>
<td>12 mm</td>
</tr>
<tr>
<td>5a/5</td>
<td>Spruce</td>
<td>Spruce</td>
<td>0°</td>
<td>12 mm</td>
</tr>
<tr>
<td>5b/5</td>
<td>Spruce</td>
<td>Spruce</td>
<td>90°</td>
<td>12 mm</td>
</tr>
</tbody>
</table>
Nail plates used to reinforce connections with dowel-type fasteners are most effective, if a number of nail rows around the fasteners are not punched out, leaving an undisturbed steel plate area in the centre of the reinforcing plate (see figure 2). The undisturbed plate area leads to a larger embedding strength compared with the punched metal plate. The plates are pressed into the timber on both sides of the joint between the members. Subsequently, the fastener holes are drilled through the timber and the steel plate and the fasteners are installed.

Figure 2: Middle member including nail plate reinforcement for test series 1a and 2a (left) and 1b and 2b (right); dimensions in mm

Figure 3: Opened test specimen of series 3 after the test
All tests with reinforced connections revealed a very ductile failure mode, caused by the plastic embedding deformations of the nail plate and – for some test series – by the bending of the dowel-type fasteners (see figures 3 and 4). After performing the tests with the reinforced specimens in series 1a, 1b, 2a, 2b, and 4a, the reinforced part was cut off and, for comparison, the tests were repeated with the non-reinforced middle members. Figure 5 shows as an example the load-slip diagrams of the same test specimen tested first as a reinforced specimen in series 1a and subsequently as a non-reinforced specimen in series 1c.

The failure mode in test series 1 and 2 was a pure embedding failure of the timber and the reinforcement, respectively. The dowels remained straight and therefore their bending capacity did not influence the ultimate load. In test series 3 and 5 one plastic hinge per shear plane was observed (see e.g. figure 3). Only in test series 4 two plastic hinges per shear plane occurred in the dowels.
COMPARISON BETWEEN TEST RESULTS AND MECHANICAL MODEL

In order to determine the theoretical load-carrying capacity of the tested specimens, the ultimate load equations according to the extended Johansen theory given above were evaluated. The fastener yield moment \( M_y \) was determined experimentally for the dowels used in the tests. The average bending capacity for the 12 mm dowels was 85 Nm, for the 24 mm dowels 1080 Nm. The embedding strength of the spruce timber and LVL, respectively, was calculated using the corresponding equations given in Eurocode 5, based on the characteristic density and the fastener diameter. The characteristic densities used were 380 kg/m\(^3\) for spruce and 480 kg/m\(^3\) for LVL. For the embedding strength of the reinforcing punched metal plate, a value corresponding to twice the yield strength was used irrespective of the plate orientation.

Table 2: Comparison of test results and theoretical values of reinforced connections

<table>
<thead>
<tr>
<th>Test series</th>
<th>Theoretical Load-carrying capacity</th>
<th>Theoretical Load-carrying capacity reinforced</th>
<th>Minimum ultimate load from test</th>
<th>Maximum ultimate load from test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a, 1b</td>
<td>23.8 kN</td>
<td>55.8 kN</td>
<td>63.9 kN</td>
<td>68.7 kN</td>
</tr>
<tr>
<td>2a, 2b</td>
<td>18.8 kN</td>
<td>50.8 kN</td>
<td>56.4 kN</td>
<td>60.7 kN</td>
</tr>
<tr>
<td>3</td>
<td>60.2 kN</td>
<td>106 kN</td>
<td>114 kN</td>
<td>128 kN</td>
</tr>
<tr>
<td>4a</td>
<td>21.2 kN</td>
<td>42.0 kN</td>
<td>44.3 kN</td>
<td>50.0 kN</td>
</tr>
<tr>
<td>5a, 5b</td>
<td>50.4 kN</td>
<td>139 kN</td>
<td>143 kN</td>
<td>167 kN</td>
</tr>
</tbody>
</table>

Ratios between the calculated load-carrying capacities of reinforced and non-reinforced connections are between 1.76 and 2.76, the corresponding ratios for the average ultimate loads reached in test series 1, 2 and 4, respectively are 2.94, 3.62 and 2.18.

In all cases the ultimate loads reached in the tests exceed the predicted load-carrying capacities based on the extended Johansen theory, and the test results show a very good agreement with the theoretical values. Consequently, the theoretical model presented above leads to conservative load-carrying capacities of nail plate reinforced connections. Increases of up to 250 % in load-carrying capacities due to the reinforcements are reached.

CONCLUSIONS

Based on test results and their comparison with calculated load-carrying capacities of connections with nail-plate reinforced joint areas, the following conclusions can be drawn:

- Punched metal plate fasteners as local reinforcement represent a very effective method to increase the connection capacity of joints with dowel-type fasteners by preventing preliminary splitting of timber members and by providing a high embedding strength close to the joint.
- Load-carrying capacities of reinforced connections readily exceed the load-carrying capacity of the connected members enabling smaller connections and significant savings in timber volume.
- The behaviour of nail plate reinforced connections is very ductile. Contrary to non-reinforced connections, the influence of numbers of fasteners and fastener arrangement on the load-carrying capacity of the connection therefore is expected to be negligible. Moreover, the large ductility enables reinforced connections to be used in earthquake-prone areas.

REFERENCES


