ROW SHEAR AND BLOCK SHEAR FAILURE OF CONNECTIONS WITH AXIALLY LOADED SCREWS

H.J. Blass\textsuperscript{1,2}, M. Flaig\textsuperscript{2} \& N. Meyer\textsuperscript{1}

\textsuperscript{1}Timber Structures and Building Construction, Karlsruhe Institute of Technology
\textsuperscript{2}Blaß und Eberhart GmbH, Karlsruhe

This paper was originally published for INTER 2019.

KEYWORDS

timber, axially loaded screws, block shear failure, brittle failure, tension perp. to grain, rolling shear

1 INTRODUCTION

The failure mode of an axially loaded screw generally is governed by the withdrawal capacity of the threaded part of the screw in the timber member (Figure 1 (a)), the tensile capacity of the screw itself and for partially threaded screws in timber-to-timber connections the head pull-through capacity of the screw. In connections with groups of axially loaded screws, also brittle timber failure modes are observed as e.g. row shear failure for reduced fastener spacing $a_1$ (Figure 1 (d)) or timber splitting for low ratios of penetration length of the screw to the depth of the timber member (Figure 1 (e)).

In the design of timber connections with groups of axially loaded fasteners, an effective number of fasteners $n_{ef} < n$ is used, where $n$ is the number of axially loaded fasteners. $n_{ef}$ takes into account the uneven load distribution between fasteners for withdrawal or tensile failure, but also brittle failure modes. Only for failure mode (e) in Figure 1 specific design models are available in codes.

Mahlknecht and Brandner (2016) published a model describing block shear failure in timber members around groups of axially loaded screws perpendicular to grain. Their model takes into account the stiffness as well as the load-carrying capacity of the contributing planes around the group of screws, where tensile stresses perp. to grain, shear or rolling shear stresses are transferred. Carradine et al. (2009) presented test results with single and groups of axially loaded screws and for the latter often observed row shear failure (Figure 2).

Figure 1: Timber failure modes in connections with axially loaded screws perp. to grain, (a) Withdrawal, (b) Splitting, (c) Block shear, (d) Row shear, (e) Tensile perp. to grain.

Figure 2: Row shear failure (mode (d) in Figure 1) in connections with axially loaded screws perpendicular to grain in LVL from Carradine et al. 2009 [2].

Meyer and Blass (2018) describe row shear failure of glued-in rods as a combination of rolling shear capacity in the timber member and withdrawal capacity of the first and last rod in the row, respectively.

Koch (2018) performed tests with axially loaded screws in softwood glulam. He confirmed the row shear model in Meyer and Blass also for screws and...
observed block shear as well as row shear failures. In his tests and contrary to Figure (3), the block often only comprised a part of the penetration length of the screws close to the screw heads while the lower screw parts were withdrawn from the timber member.

Figure 3: Block shear failure (mode (c) in Figure 1) with rolling shear failure over the complete beam depth caused by axially loaded screws perpendicular to grain in glulam.

2 ROW SHEAR

Meyer und Blass (2018) studied the behaviour of connections with axially loaded glued-in rods in Beech LVL. Connections with axially loaded metric steel rods arranged between 0° and 90° between rod axis and grain direction were tested to failure. Connections consisting of a group of rods showed lower load-carrying capacities per rod compared to single rod connections. This apparent loss in load-carrying capacity in connections with rods arranged perpendicular to grain was caused by row shear failure: a small block of timber between two consecutive rods arranged in a row parallel to grain is withdrawn together with the glued-in rods (see Figure 4).

Figure 4: Rolling shear failure (mode (d) in Figure 1) between two axially loaded fasteners.

The load-carrying capacity $F_{90,R}$ for failure mode row shear is derived from the sum of the contributions of rolling shear in two planes and half of the axial withdrawal capacity of the two outer fasteners:

$$F_{90,R} = 2 \cdot (r-1) \cdot f_{\text{v,r}} \cdot \ell_{\text{ef}} \cdot 0.5 + f_{\text{ax}} \cdot \ell_{\text{ef}} \cdot 0.5$$

where:
- $r$ is the number of fasteners arranged parallel to grain;
- $f_{\text{v,r}}$ is the rolling shear strength in N/mm²;
- $\ell_{\text{ef}}$ is the fastener penetration depth in mm;
- $f_{\text{ax}}$ is the fastener withdrawal parameter in N/mm²;
- $d$ is the fastener diameter in mm.

The tensile perp to grain resistance of the plane formed by the fastener tips is disregarded.

In order to trigger row shear failure, the screw holes were predrilled allowing a minimum spacing $a = 4d$ parallel to grain. Self-tapping screws with diameters $d = 6$ mm and $d = 8$ mm were used with a penetration depth of the thread of $\ell_{\text{ef}} = 10d$. Both, radial and tangential screw arrangement was used in the tests. Screw tensile and withdrawal capacity were determined for single screws as a basis for the test evaluation. The test results were compared with equation (1) using the following parameters:

- Expected screw’s tensile capacity: $f_{\text{tens}} = 15$ kN for $d = 6$ mm and $f_{\text{tens}} = 26$ kN for $d = 8$ mm
- Characteristic tensile capacity of the screws: $f_{\text{tens,k}} = 12.5$ kN for $d = 6$ mm and $f_{\text{tens,k}} = 23$ kN for $d = 8$ mm
- Expected withdrawal parameter: $f_{\text{ax}} = 1.25 \cdot f_{\text{ax,k}} \cdot (\rho / 350)^{0.8}$
- Characteristic withdrawal parameter: $f_{\text{ax,k}} = 11.5$ N/mm² for $d = 6$ mm and $f_{\text{ax,k}} = 11.0$ N/mm² for $d = 8$ mm
- Characteristic glulam density: $\rho_s = 385$ kg/m³
- Expected rolling shear strength: $f_{\text{v,r}} = 2$ N/mm²
- Characteristic rolling shear strength: $f_{\text{v,r,k}} = 1$ N/mm²

Table 1 shows the comparison between the test results and the expected and characteristic capacities $F_{90,R}$ and $F_{90,R,k}$ according to equation (1) and, additionally, the expected and characteristic capacities according to the screws’ ETAs without a specific row shear design.
The average ratio between ultimate test load and expected load-carrying capacity is $F_{\text{max}} / F_{90,R} = 0.93$ or $F_{\text{max}} / F_{\text{ETA},R} = 0.98$, respectively. The design according to the screws’ ETAs with $n_{\text{ef}} = n_{0.9}$ hence represents the average test results better than the row shear model according to equation (1).

The characteristic ratio determined according to EN 14358 is $F_{\text{max}} / F_{90,Rk} = 1.14$ and $F_{\text{max}} / F_{\text{ETA},Rk} = 1.03$, the minimum ratios from 28 tests $F_{\text{max}} / F_{90,Rk} = 1.19$ and $F_{\text{max}} / F_{\text{ETA},Rk} = 1.01$. The required characteristic ratio is 1.0. Both, the row shear model as well as the design of the screws taking into account the effective number of screws, $n_{\text{ef}}$, lead to an adequate load-carrying capacity of axially loaded screws arranged in rows parallel to grain. Here, the row shear model is more conservative.

### Table 1: Comparison between ultimate test loads and load-carrying capacities $F_{90,R}$ according to equation (1) and according to the ETAs of the screws, respectively.

<table>
<thead>
<tr>
<th>Test</th>
<th>$F_{\text{max}}$ in kN</th>
<th>$\rho$ in kg/m$^3$</th>
<th>$F_{90,R}$ in kN</th>
<th>$F_{90,Rk}$ in kN</th>
<th>$F_{\text{ETA},R}$ in kN</th>
<th>$F_{\text{ETA},Rk}$ in kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS1.1V1</td>
<td>18.1</td>
<td>470</td>
<td>18.6</td>
<td>10.2</td>
<td>19.0</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.1V2</td>
<td>19.4</td>
<td>491</td>
<td>18.8</td>
<td>10.2</td>
<td>19.7</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.1V3</td>
<td>13.4</td>
<td>434</td>
<td>18.2</td>
<td>10.2</td>
<td>17.8</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.1V4</td>
<td>26.0</td>
<td>435</td>
<td>18.2</td>
<td>10.2</td>
<td>17.9</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.1V5</td>
<td>12.2</td>
<td>371</td>
<td>17.4</td>
<td>10.2</td>
<td>15.7</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.2V1</td>
<td>17.8</td>
<td>445</td>
<td>18.3</td>
<td>10.2</td>
<td>18.2</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.2V2</td>
<td>16.4</td>
<td>476</td>
<td>18.7</td>
<td>10.2</td>
<td>19.2</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.2V3</td>
<td>17.5</td>
<td>418</td>
<td>18.0</td>
<td>10.2</td>
<td>17.3</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.2V4</td>
<td>13.1</td>
<td>446</td>
<td>18.3</td>
<td>10.2</td>
<td>18.2</td>
<td>12.0</td>
</tr>
<tr>
<td>RS1.2V5</td>
<td>15.5</td>
<td>473</td>
<td>18.6</td>
<td>10.2</td>
<td>19.1</td>
<td>12.0</td>
</tr>
<tr>
<td>RS2.1V1</td>
<td>36.4</td>
<td>440</td>
<td>31.9</td>
<td>17.8</td>
<td>30.7</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.1V2</td>
<td>42.1</td>
<td>426</td>
<td>31.6</td>
<td>17.8</td>
<td>29.9</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.1V3</td>
<td>26.5</td>
<td>393</td>
<td>30.9</td>
<td>17.8</td>
<td>28.0</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.1V4</td>
<td>28.2</td>
<td>393</td>
<td>30.9</td>
<td>17.8</td>
<td>28.0</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.1V5</td>
<td>27.9</td>
<td>467</td>
<td>32.4</td>
<td>17.8</td>
<td>32.2</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.1V6</td>
<td>24.2</td>
<td>378</td>
<td>30.6</td>
<td>17.8</td>
<td>27.1</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.2V1</td>
<td>28.0</td>
<td>455</td>
<td>32.2</td>
<td>17.8</td>
<td>31.5</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.2V2</td>
<td>32.0</td>
<td>412</td>
<td>31.3</td>
<td>17.8</td>
<td>29.1</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.2V3</td>
<td>30.4</td>
<td>432</td>
<td>31.7</td>
<td>17.8</td>
<td>30.2</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.2V4</td>
<td>28.6</td>
<td>408</td>
<td>31.2</td>
<td>17.8</td>
<td>28.9</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.2V5</td>
<td>34.8</td>
<td>437</td>
<td>31.8</td>
<td>17.8</td>
<td>30.5</td>
<td>20.4</td>
</tr>
<tr>
<td>RS2.2V6</td>
<td>37.0</td>
<td>422</td>
<td>31.5</td>
<td>17.8</td>
<td>29.6</td>
<td>20.4</td>
</tr>
<tr>
<td>RS3.1V1</td>
<td>16.2</td>
<td>456</td>
<td>21.3</td>
<td>11.7</td>
<td>18.6</td>
<td>12.0</td>
</tr>
<tr>
<td>RS3.1V2</td>
<td>20.3</td>
<td>376</td>
<td>20.3</td>
<td>11.7</td>
<td>15.9</td>
<td>12.0</td>
</tr>
<tr>
<td>RS3.1V3</td>
<td>15.3</td>
<td>407</td>
<td>20.7</td>
<td>11.7</td>
<td>16.9</td>
<td>12.0</td>
</tr>
<tr>
<td>RS3.1V4</td>
<td>16.7</td>
<td>445</td>
<td>21.2</td>
<td>11.7</td>
<td>18.2</td>
<td>12.0</td>
</tr>
<tr>
<td>RS3.1V5</td>
<td>15.7</td>
<td>405</td>
<td>20.7</td>
<td>11.7</td>
<td>16.9</td>
<td>12.0</td>
</tr>
<tr>
<td>RS3.1V6</td>
<td>15.5</td>
<td>458</td>
<td>21.3</td>
<td>11.7</td>
<td>18.6</td>
<td>12.0</td>
</tr>
</tbody>
</table>

### 3 BLOCK SHEAR

#### 3.1 Design model

The only block shear model for axially loaded fasteners with force components perpendicular to grain was published by Mahlknecht and Brandner (2016). They studied the behaviour of axially loaded groups of screws in glulam and cross laminated timber loaded under 45° (only glulam) or 90° to the grain direction. Their model is similar to the model of Zarnani (2013) for block shear failure caused by loads parallel to grain. The stiffnesses of the shear, tensile and rolling shear planes (see Fig. 5) are determined as linear springs. In a first step the area with minimum ratio of load-carrying capacity to stiffness - or minimum failure deformation - is identified. The loads carried by the remaining planes are added to the load-carrying capacity of the plane failing first. The sum...
of the loads of the three planes just before failure of the first plane is the load-carrying capacity of the connection, unless after failure of the first plane the load-carrying capacities of the remaining planes are higher. This is checked by an iterative calculation where the planes fail progressively in the order of their respective failure deformations.

![Figure 5: Failure planes loaded in shear, tension perp. to grain or rolling shear according to Mahlknecht and Brandner (2016).](image)

However, shear failure in the planes $A_{bs}$ was not observed in tests. The block shear failure was rather characterised by rolling shear planes exceeding the actual length of the connection. Another ambiguity of the model is that the spring stiffnesses of the possible failure planes are independent of the edge distance perpendicular to the grain, $a_{2,CG}$, and of the ratio $\ell_{ef}/H$. For small edge distance $a_{2,CG}$ and low ratio $\ell_{ef}/H$ the failure will rather be tensile perpendicular to grain failure over the complete member width $B$ without rolling shear failure, see e.g. Ehlbeck and Görlacher (1995). On the other hand, for high ratio $\ell_{ef}/H$ and not to small an edge distance $a_{2,CG}$, the rolling shear failure planes will cover the complete member depth $H$ and no tensile perp. to grain failure is going to occur. Obviously, the model of Mahlknecht and Brandner could be extended to take into account alternative failure plane patterns, however, this would further complicate the application of the already complex model.

As an alternative to the model by Mahlknecht and Brandner, Blass and Flaig (2019) proposed a simplified design model taking into account block shear failure. The modifications related to the model of Mahlknecht and Brandner are as follows:

- Shear failure in planes perpendicular to the grain is not considered,
- Brittle failure is either caused by tension perpendicular to the grain in a plane defined by the screw tips or by rolling shear in planes defined by the outer screw rows, simultaneous load transfers via rolling shear and tension perpendicular to the grain are not taken into account,
- The tension perpendicular to the grain capacity is determined according to the German national annex to Eurocode 5 (DIN EN 1995-1-1/NA),
- Rolling shear failure planes exceed the length of the connection parallel to the grain on each end by 0.75 $\ell_{ef}$,
- It is considered that only a part of the load component perpendicular to the grain causes tension perp. to grain stresses or rolling shear stresses.

If rolling shear initiates failure, only part of the force component perpendicular to the grain causes rolling shear stresses. This is illustrated using a connection where $\ell_{ef} = h$ (see Fig. 6).

![Figure 6: Bending member with axially loaded screws.](image)

The beam in Fig. 6 is loaded by a concentrated force introduced over the complete beam depth using screws. In the case of rolling shear failure, the central part of the cross-section between the two outermost rows of screws is pulled down over a certain beam length (see also Fig. 3). Before rolling shear failure occurs, the load $F_{w0}$ causes a deformation of the complete beam width $b$. For this purpose, the cross-sectional parts outside the connection width $(s - 1) \cdot a_q$ are also pulled downwards.

The load $F_{w0}$ may be subdivided into two parts: the first part causes the deformation of the central beam
The characteristic load-carrying capacity for the failure mode rolling shear follows as:

$$f_{v,r,k} = \frac{F_{0,k} \cdot (b - (s - 1) \cdot a_2)}{2 \cdot b \cdot \ell_{ef} \cdot (1,5 \cdot \ell_{ef} + (r - 1) \cdot a_1)}$$  \hspace{1cm} (2)$$

where:
- $f_{v,r,k}$ is the characteristic rolling shear strength in N/mm²;
- $b$ is the beam width in mm;
- $r$ is the number of screws parallel to grain;
- $s$ is the number of screws perpendicular to grain;
- $a_1$ is the screw spacing parallel to grain in mm;
- $a_2$ is the screw spacing perpendicular to grain in mm;
- $\ell_{ef}$ is the screw penetration depth perpendicular to grain in mm.

The characteristic load-carrying capacity of a group of axially loaded screws hence is the minimum of the load-carrying capacities associated to the failure modes “screw tensile failure”, “withdrawal failure”, “tensile failure perpendicular to grain” and “rolling shear failure”:

$$F_{90,Rk} = \min\left\{f_{\text{tens,k}}, f_{\text{ax,k}}, f_{\text{t,90,Rk}}, f_{v,r,k}\right\}$$  \hspace{1cm} (3)$$

where:
- $f_{\text{tens,k}}$ is the characteristic screw tensile strength in N/mm²;
- $F_{\text{ax,Rk}}$ is the characteristic screw withdrawal capacity according to ETA or EN 1995 1-1 in N;
- $n_d$ is the effective number of screws according to EN 1995-1-1, equation (8.41);
- $F_{\text{t,90,Rk}}$ is the characteristic tensile perp. to grain strength in N/mm²;
- $F_{v,90,Rk}$ is the characteristic rolling shear capacity according to equation (3) in N.

### 3.2 Test results

Tests with groups of axially loaded screws in spruce glulam were performed by Mahlknecht and Brandner (2016), Ringhofer and Schickhofer (2015) and Koch (2017). Mahlknecht and Brandner only give average load-carrying capacities of the test series, Ringhofer and Schickhofer as well as Koch provide single test results.

The tests by Mahlknecht and Brandner showed different failure modes depending on the joint configuration. Test series A to E were performed with screws arranged under 45° to the grain, series H to I with screws perpendicular to the grain. Screw tensile and withdrawal capacity were determined for single screws as a basis for the test evaluation. The test results were compared with equation (4) using the following parameters:

- Average ultimate load per series perpendicular to member axis: $F_{\text{max}}$
- Expected screw’s tensile capacity: $F_{\text{tens}} = 15,6$ kN for $d = 6$ mm and $F_{\text{tens}} = 27,8$ kN for $d = 8$ mm
- Expected withdrawal parameter: $F_{\text{ax}} = 1,25 \cdot F_{\text{ax,k}} \cdot \left(\frac{\rho}{350}\right)^{0.8}$
- Characteristic withdrawal parameter: $F_{\text{ax,k}} = 12,1$ N/mm² for $d = 6$ mm and $F_{\text{ax,k}} = 10,9$ N/mm² for $d = 8$ mm
- Characteristic glulam density: $\rho_k = 385$ kg/m³
- Expected rolling shear strength: $f_{v,90} = 2$ N/mm²
- Expected tensile strength perpendicular to grain: $f_{t,90} = 1$ N/mm²

Table 2 shows the comparison between the test results and the expected capacities $F_{90,Rk}$ according to equation (4) for the different failure modes. A significant difference between the test results for load directions 45° and 90°, respectively, could not be found. The simultaneous occurrence of rolling shear and shear stresses in the rolling shear planes for load direction 45° obviously did not influence the test results. This does not prove, however, that there is no shear/rolling shear interaction since the rolling shear capacity did not govern the design.
The present paper considers brittle failure modes in connections with screws loaded axially perpendicular to grain. The available test data are evaluated and compared with design proposals from Mahlknecht and Brandner (2016) for block shear, Meyer and Blass (2018) for row shear as well as with the approach only based on an effective number of fasteners $n_{ef}$.

Even if an effective number of fasteners $n_{ef}$ primarily incorporates the influence of uneven load distribution between the single screws in a connection, it obviously also at least partly compensates for brittle failure modes as block shear failure or row shear failure.

The analytical model derived for glued-in rods taking into account row shear failure in connections with axially loaded fasteners arranged in rows parallel to grain and loaded perpendicular to grain also very well predicts the load-carrying capacity of similar connections with screws. This model may also be used for groups with several rows of screws, if the spacing $a_2$ perpendicular to grain is large.

The analytical model proposed by Mahlknecht and Brandner for block shear failure in connections with groups of axially loaded screws and load components perpendicular to grain was modified as follows:

- Shear planes perpendicular to the grain are not considered,
- Brittle failure is either caused by tension

<table>
<thead>
<tr>
<th>Test series</th>
<th>$F_{\text{max}}$ in kN</th>
<th>$\rho$ in kg/m$^3$</th>
<th>$n_{ef}F_{\text{ax},R}$ in kN</th>
<th>$n_{ef}/f_{\text{tens}}$ in kN</th>
<th>$F_{1,90,R}$ in kN</th>
<th>$F_{90,9,R}$ in kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>155</td>
<td>486</td>
<td>177</td>
<td>119</td>
<td>393</td>
<td>366</td>
</tr>
<tr>
<td>B</td>
<td>148</td>
<td>486</td>
<td>177</td>
<td>119</td>
<td>393</td>
<td>366</td>
</tr>
<tr>
<td>C</td>
<td>147</td>
<td>486</td>
<td>141</td>
<td>119</td>
<td>212</td>
<td>259</td>
</tr>
<tr>
<td>D</td>
<td>120</td>
<td>486</td>
<td>105</td>
<td>119</td>
<td>128</td>
<td>177</td>
</tr>
<tr>
<td>E</td>
<td>127</td>
<td>486</td>
<td>105</td>
<td>119</td>
<td>128</td>
<td>274</td>
</tr>
<tr>
<td>H</td>
<td>275</td>
<td>428</td>
<td>252</td>
<td>221</td>
<td>1061</td>
<td>675</td>
</tr>
<tr>
<td>N</td>
<td>179</td>
<td>428</td>
<td>123</td>
<td>181</td>
<td>166</td>
<td>315</td>
</tr>
<tr>
<td>K</td>
<td>171</td>
<td>428</td>
<td>150</td>
<td>221</td>
<td>144</td>
<td>282</td>
</tr>
<tr>
<td>O</td>
<td>184</td>
<td>461</td>
<td>160</td>
<td>221</td>
<td>548</td>
<td>372</td>
</tr>
<tr>
<td>J</td>
<td>191</td>
<td>461</td>
<td>160</td>
<td>221</td>
<td>548</td>
<td>282</td>
</tr>
<tr>
<td>I</td>
<td>183</td>
<td>461</td>
<td>131</td>
<td>181</td>
<td>543</td>
<td>280</td>
</tr>
</tbody>
</table>

The average ratio between ultimate test load and expected load-carrying capacity is $F_{\text{max}}/F_{90,R} = 1.23$. Since the calculated rolling shear failure was not governing in any of the test series, the design according to the screws’ ETAs also represents the average test results well. Even though the single test results are not given, the research report shows that for all 103 single tests $F_{\text{max}}$ was higher than the characteristic load-carrying capacity according to the screws’ ETAs.

The ultimate loads of the single tests by Ringhofer and Schickhofer (2015) and Koch (2018) were also compared with the results of equation (4). The comparison was performed for expected values of the load-carrying capacity as for the tests by Mahlknecht and Brandner but also on a characteristic level. For the latter, the characteristic load-carrying capacity was calculated according to equation (4) and the ratio $F_{\text{max}}/F_{90,Rk}$ was calculated for each one of the 64 tests. For 28 out of the 64 tests the rolling shear capacity was governing.

Subsequently, the characteristic ratio according to EN 14358 was calculated. The characteristic load-carrying capacity of the connections is seen as sufficient, if the characteristic ratio according to EN 14358 does not fall below 1.0.

The average ratio between ultimate test load and expected load-carrying capacity is $F_{\text{max}}/F_{90,R} = 1.49$.

The calculation model underestimates the expected load-carrying capacity of the connections.

The characteristic ratio determined according to EN 14358 is $F_{\text{max}}/F_{90,Rk} = 1.20$, the minimum ratio $F_{\text{max}}/F_{90,Rk} = 1.10$ and the COV of the ratio $F_{\text{max}}/F_{90,Rk}$ is 11%. The required characteristic ratio is 1.0. The block shear model according to equation (4) hence leads to an adequate load-carrying capacity of groups of axially loaded screws with a load component perpendicular to grain.

4 CONCLUSIONS

The present paper considers brittle failure modes in connections with screws loaded axially perpendicular to grain. The available test data are evaluated and compared with design proposals from Mahlknecht and Brandner (2016) for block shear, Meyer and Blass (2018) for row shear as well as with the approach only based on an effective number of fasteners $n_{ef}$.

Even if an effective number of fasteners $n_{ef}$ primarily incorporates the influence of uneven load distribution between the single screws in a connection, it obviously also at least partly compensates for brittle failure modes as block shear failure or row shear failure.

The analytical model derived for glued-in rods taking into account row shear failure in connections with axially loaded fasteners arranged in rows parallel to grain and loaded perpendicular to grain also very well predicts the load-carrying capacity of similar connections with screws. This model may also be used for groups with several rows of screws, if the spacing $a_2$ perpendicular to grain is large.

The analytical model proposed by Mahlknecht and Brandner for block shear failure in connections with groups of axially loaded screws and load components perpendicular to grain was modified as follows:

- Shear planes perpendicular to the grain are not considered,
- Brittle failure is either caused by tension
perpendicular to the grain in a plane defined by the screw tips or by rolling shear in planes defined by the outer screw rows, simultaneous load transfers via rolling shear and tension perpendicular to the grain are disregarded,

- The tension perpendicular to the grain capacity is determined according to the German national annex to Eurocode 5 (DIN EN 1995-1-1/NA),
- Rolling shear failure planes exceed the length of the connection parallel to the grain on each end by 0.75 $\ell_{ef}$,
- It is considered that only a part of the load component perpendicular to the grain causes tension perp. to grain stresses or rolling shear stresses.

In order to verify the modified analytical model, ultimate test loads of axially loaded screwed connections are compared with the results of the model. The ultimate loads from the tests agree well with the model predictions. For the comparison, the model parameters screw tensile strength and withdrawal capacity were determined separately by tests. If block shear design is disregarded, the design of axially loaded screwed connections according to the screws’ ETAs still leads to an adequate load-carrying capacity.

5 REFERENCES


Ringhofer, A. and Schickhofer, G. (2015). „Ausziehprüfungen von Schraubengruppen in Anlehnung an das EAD 130015-00-0603, Abschnitt 2.2.1.10 zur Bestimmung der Mindestabstände a1 und a2“. Prüfbericht NR. PB15-471-1-01, Lignum Test Center (LTC), TU Graz, 42 S.