Load-carrying capacity of dowelled connections

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1 Introduction

The load-carrying capacity of joints with dowel-type fasteners in Eurocode 5 (2010) is mainly based on the Johansen theory (Johansen, 1949), later extended by Meyer (1957). Even though Johansen's model is based on plastic hinge formation in the dowel-type fasteners for some of the failure modes considered, the elastic bending moment capacity of the fasteners is used. Eurocode 5 contains an empirical equation to calculate the fastener yield moment which in many cases results in values between the elastic and full plastic fastener bending capacity. However, Sandhaas (2012) showed that for large diameter dowels of high steel grades the predicted yield moment according to Eurocode 5 is even lower than the elastic moment capacity.

The introduction of the Johansen theory in the German design code DIN 1052:2004, being very similar to Eurocode 5, in many cases led to a significant decrease of the calculated load-carrying capacity of dowelled joints with drift pins compared to the design according to the former version DIN 1052:1988. The reason for this apparent decrease in load-carrying-capacity is mainly due to the much more stringent consideration of the group effect in DIN 1052:2004 using n_{ef} for dowels in line with load and grain direction. A comparison between the 1988 and 2004 versions of DIN 1052 also revealed that the difference in calculated load-carrying-capacity increases with increasing dowel diameter. These differences motivated the studies described in the following.

In order to find a more realistic bending moment capacity of dowel-type fasteners, the load-carrying capacity of dowelled joints with drift pins was comprehensively studied and evaluated, based on 1588 tests with dowelled connections reported in seven different research studies (Brühl, 2010; Ehlbeck & Werner, 1989; Jorissen, 1998; Kneidl, 2009; Mischler, 1998; Sandhaas, 2012; Schmid, 2002). Additionally, bending and tensile tests with dowels sampled in companies during third party quality control visits formed the basis for a more realistic equation for the calculation of the yield moment $M_{y,k}$.

2 Eurocode 5 versus DIN 1052:1988

Calculated load-carrying capacities of dowelled connections with drift pins according to EN 1995-1-1:2010 (Eurocode 5, 2010) are in many cases significantly lower than the corresponding values according to the former German DIN 1052:1988. Consequently, structures comprising connections designed according to DIN 1052:1988 might be unsafe or the design according to Eurocode 5 might be overly conservative.

Figures 2.1 to 2.4 exemplarily show a comparison between the load-carrying-capacities according to Eurocode 5 and DIN 1052:1988, respectively. The two design codes are based on different safety concepts: Eurocode 5 uses partial safety factors for both, actions and resistances while DIN 1052:1988 uses permissible loads for connections. In order to compare the load-carrying-capacities, the following assumptions were made:

- Design actions are calculated by multiplying characteristic actions with a partial factor of 1.4;
- The design load-carrying-capacity of a dowelled joint is calculated for service class 1 or 2 and load-duration class medium-term.

Using these assumptions, the permissible load according to DIN 1052:1988 was compared with the design resistance of the connection, divided by the partial action factor of 1.4:

$$R_{comp} = \frac{k_{\text{mod}}}{\gamma_M} \cdot \frac{F_{v,Rk}}{\gamma_{G/Q}} = 0.44 \cdot F_{v,Rk} \leftrightarrow zul\ N \tag{1}$$

Here, $k_{\text{mod}} = 0.8$, $\gamma_M = 1.3$, $\gamma_{G/Q} = 1.4$, $F_{v,Rk}$ is the characteristic load-carrying-capacity and *zul N* is the permissible load of a dowelled connection. In Figures 2.1 to 2.4, the dowel diameter d, the side and middle member's slenderness ratios λ_{sm} and λ_{mm} (timber member thickness over dowel diameter) as well as the number of fasteners n_h arranged parallel to the load and grain direction were varied.

If a single dowel is considered, Eurocode 5 results in higher load-carrying-capacities for small diameter dowels and low slenderness ratios (see Fig. 2.1). For larger diameters and slenderness ratios, Eurocode 5 shows lower load-carrying-capacities (see Fig. 2.2). For several dowels arranged in line with the load and grain direction ($n_h > 1$), the difference between Eurocode 5 and DIN 1052:1988 increases, especially for large diameter dowels and large slenderness ratios (see Fig. 2.3 and Fig. 2.4).

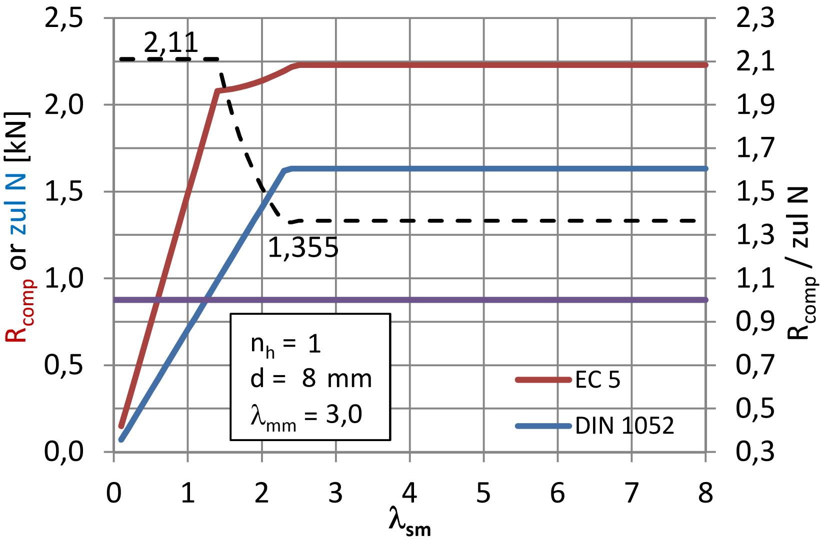

Figure 2.1. R_{comp} *versus zul N;* $n_h = 1$*,* $d = 8$ *mm, middle member slenderness ratio* $\lambda_{mm} = 3{,}0$

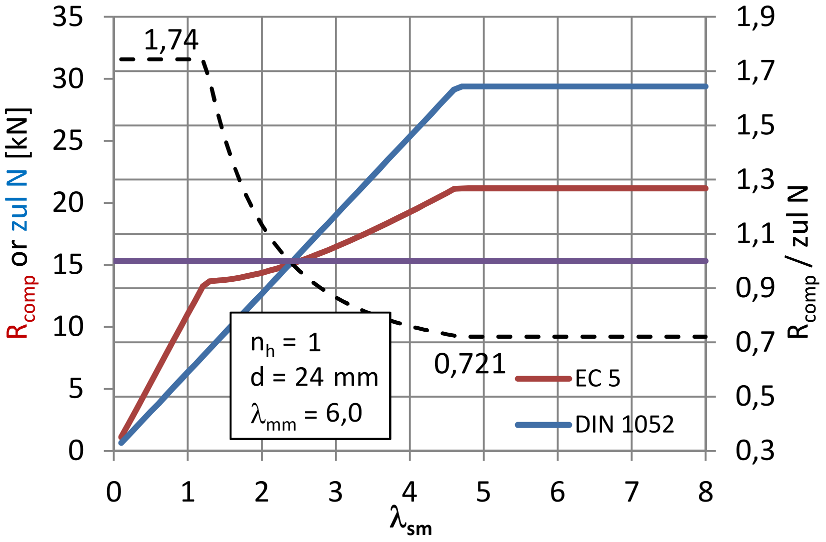

Figure 2.2. R_{comp} *versus zul N;* $n_h = 1$*,* $d = 24$ *mm, middle member slenderness ratio* $\lambda_{mm} = 6{,}0$

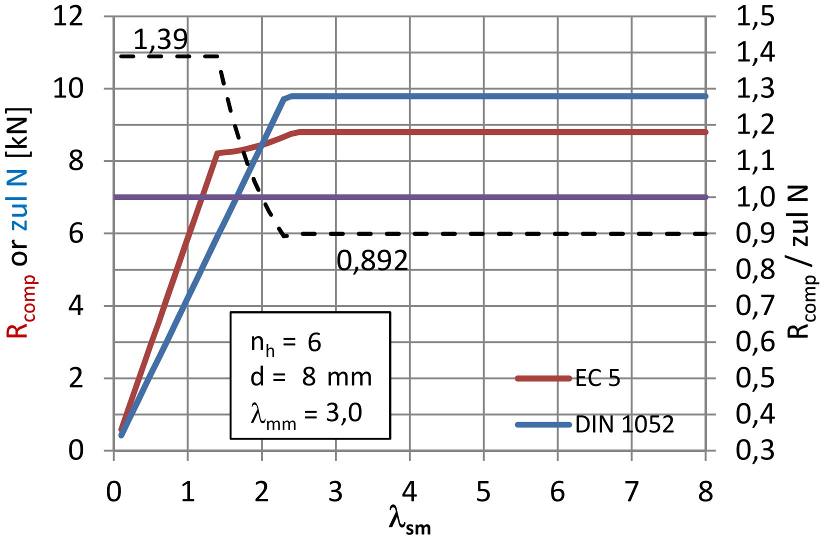

Figure 2.3. R_{comp} *versus zul N;* $n_h = 6$*,* $d = 8$ *mm, middle member slenderness ratio* $\lambda_{mm} = 3{,}0$

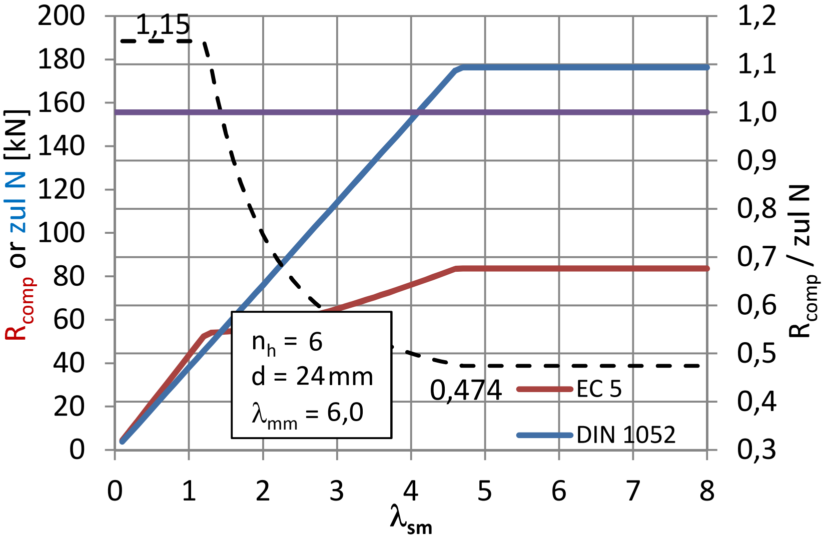

Figure 2.4. *R_{comp} versus zul N; $n_h = 6$, d = 24 mm, middle member slenderness ratio $\lambda_{mm} = 6{,}0$*

3 Connection test results

3.1 Test specimens

Altogether 1588 tests were evaluated, 1045 timber-to-timber and 543 steel-to-timber connections. The different sources yield the following tests with sufficient information regarding the test configuration, the timber members and the steel properties:

Jorissen:	919 timber-to-timber connections, tension and compression;
Ehlbeck and Werner:	126 timber-to-timber connections, tension and compression;
Kneidl:	58 steel-to-timber connections, tension;
Brühl:	22 steel-to-timber connections, tension;
Mischler:	190 steel-to-timber connections, tension;
Sandhaas:	179 steel-to-timber connections, tension;
Schmid:	94 steel-to-timber connections, tension;

The side member slenderness ratios λ_{sm} varied between 1.0 and 7.5, for timber-to-timber connections most tests were performed with $\lambda_{sm} < 5$. Dowel spacing a_1 parallel to the grain ranged from 3 d to 11 d with most test specimens between 5 d and 7 d.

The predominant dowel diameter used in the tests was 12 mm (see Fig. 3.1 left). The majority of the dowels were made of steel with lower grades (see Fig. 3.1 right).

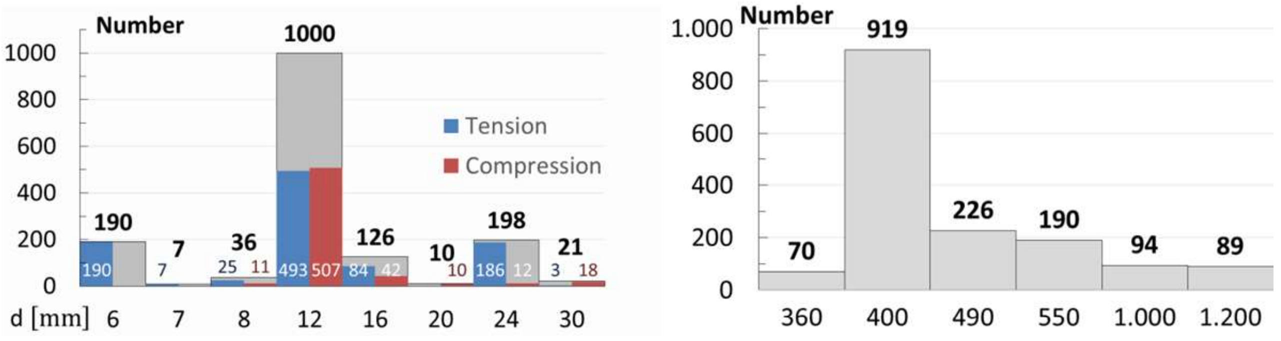

Figure 3.1. Used dowel diameters in the test specimens (left) and dowel steel tensile strength in N/mm² (right)

The arrangement of the dowels parallel (n_h) and perpendicular (n_n) to the load and grain direction is given in Fig. 3.2.

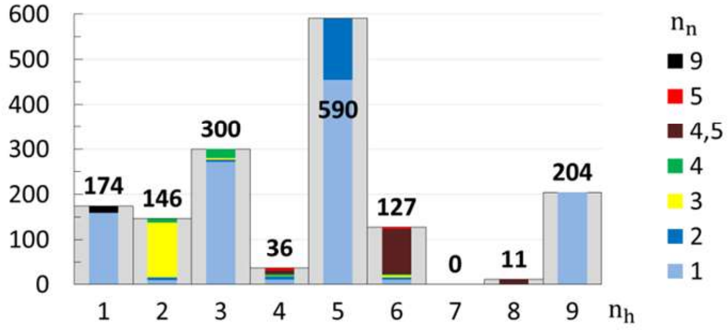

Figure 3.2. Number of dowels parallel (n_h) and perpendicular (n_n) to load and grain direction

Some of the tests were performed with parameters either outside the requirements of the design codes Eurocode 5 and DIN 1052:1988 or the parameters were quite exceptional for practical applications like side member slenderness ratio $\lambda_{sm} < 2$. Connection tests with hardwood showed significantly higher load-carrying-capacities compared to the expected values from the design codes. Therefore, test specimens fulfilling one of the following conditions were excluded from the evaluation:

- Spacing parallel to the grain $a_1 < 5$ d,
- Loaded end distance $a_{3,t} < 6$ d,
- Unloaded edge distance $a_{4,c} < 3$ d,
- Side member slenderness ratio $\lambda_{sm} < 2$,
- Density $\rho > 600$ kg/m³ (hardwood).

Discounting the excluded values, 561 test results with timber-to-timber and 325 with steel-to-timber connections remain for the following evaluation.

3.2 Test results versus calculated permissible load according to DIN 1052

This evaluation shows the ratio of the ultimate test load $F_{v,R}$ versus the calculated permissible load *zul N* according to DIN 1052:1988. In the calculation of *zul N* the dowel steel strength is not considered, only a minimum steel grade of S235 for dowels and 3.6 for bolts is required. Similarly, the strength class of solid or glued laminated softwood timber is not accounted for in the calculation. Only for more than six fasteners parallel to the load and grain direction a reduction of the effective number of fasteners, $n_{ef} < n_h$ is taken into account. Figures 3.3 and 3.4 show the ratios $F_{v,R}$/zul N for timber-to-timber and steel-to-timber connections, respectively. The ratios were calculated for every single test, the dark red triangles show the ratios for the excluded test results.

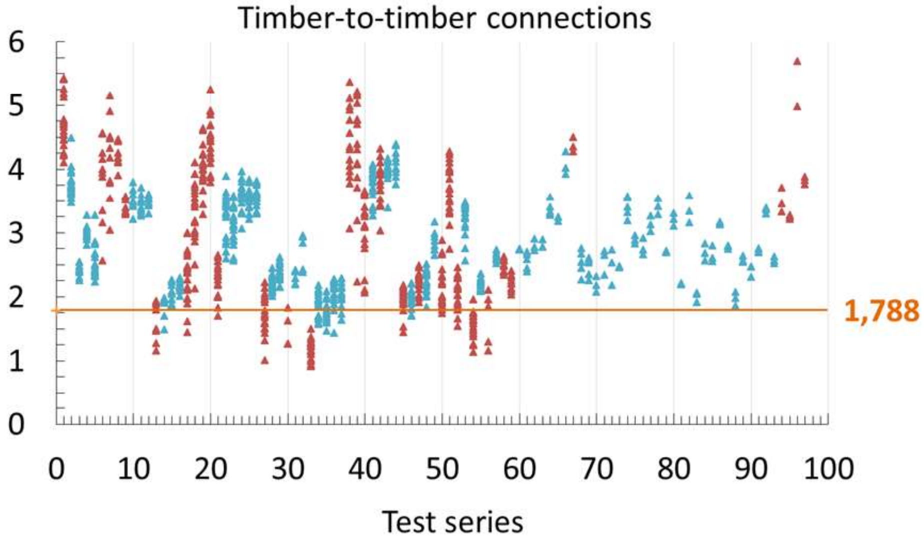

Figure 3.3. Ratios of the ultimate test load $F_{v,R}$ versus the calculated permissible load zul N according to DIN 1052:1988 for 1045 timber-to-timber connections

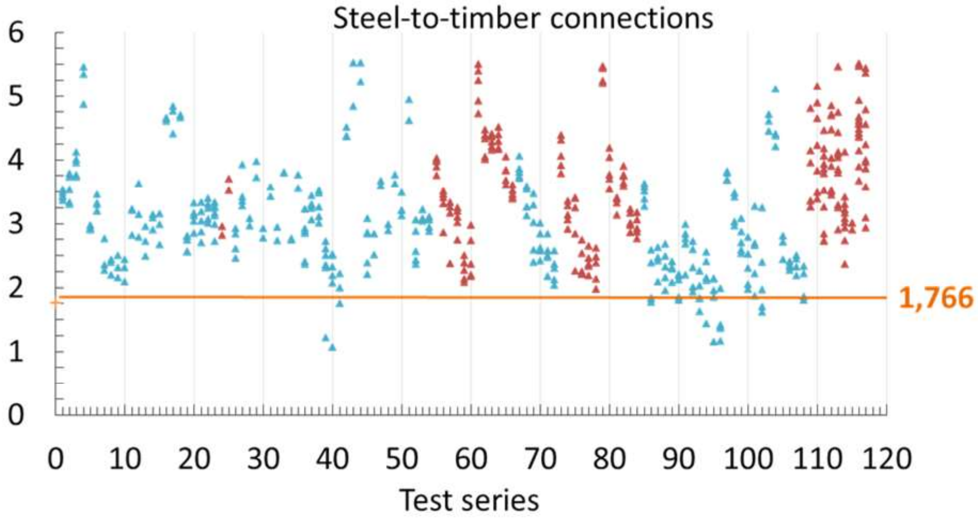

Figure 3.4. Ratios of the ultimate test load $F_{v,R}$ versus the calculated permissible load zul N according to DIN 1052:1988 for 543 steel-to-timber connections

The characteristic ratio calculated according to EN 14358 is 1.79 for timber-to-timber and 1.77 for steel-to-timber connections only calculated for the test results not excluded. The characteristic ratio corresponds to a global safety factor. Depending on the service and load-duration classes, it should be between 2.0 and 2.3. The results hence show a deficiency of 10% to 25% in the global safety factor for dowelled connections designed according to DIN 1052:1988.

3.3 Test results versus calculated characteristic load-carrying-capacity according to Eurocode 5

The second evaluation compares the ultimate loads $F_{v,R}$ in the connection tests to the calculated characteristic load-carrying-capacities $F_{v,Rk}$ according to Eurocode 5. When calculating the load-carrying-capacities, the factors 1.05 and 1.15 in sections 8.2.2 and 8.2.3 of Eurocode 5 are disregarded, since they only compensate the lower required partial factor and the use of the modification factor k_{mod} for the fastener's yield moment.

In order to determine the characteristic timber density, the mean density was determined for each test series and the associated characteristic density according to EN 338 or EN 14080 was assumed for the test series.

Similarly, a characteristic dowel tensile strength was assumed for dowels, where the tensile strengths were given in the test report. If only a steel grade of the dowels was given, corresponding characteristic tensile strength was used. If no information regarding the dowel steel grade was available, the characteristic tensile strength of steel grade S235 was assumed ($f_{u,k}$ = 360 N/mm²).

An effective number of dowels according to equation (8.34) of Eurocode 5 was used for connections with several dowels arranged parallel to load and grain direction.

Figures 3.5 and 3.6 show the ratios $F_{v,R}/F_{v,Rk}$ for timber-to-timber and steel-to-timber connections, respectively. The ratios were calculated for every single test, the dark red triangles show the ratios for the excluded test results. The characteristic ratio calculated according to EN 14358 is 1.074 for timber-to-timber and 1.073 for steel-to-timber connections only for the test results not excluded. Ideally, the characteristic ratio would be 1.0 for both cases. The calculation model according to Eurocode 5 is hence slightly conservative.

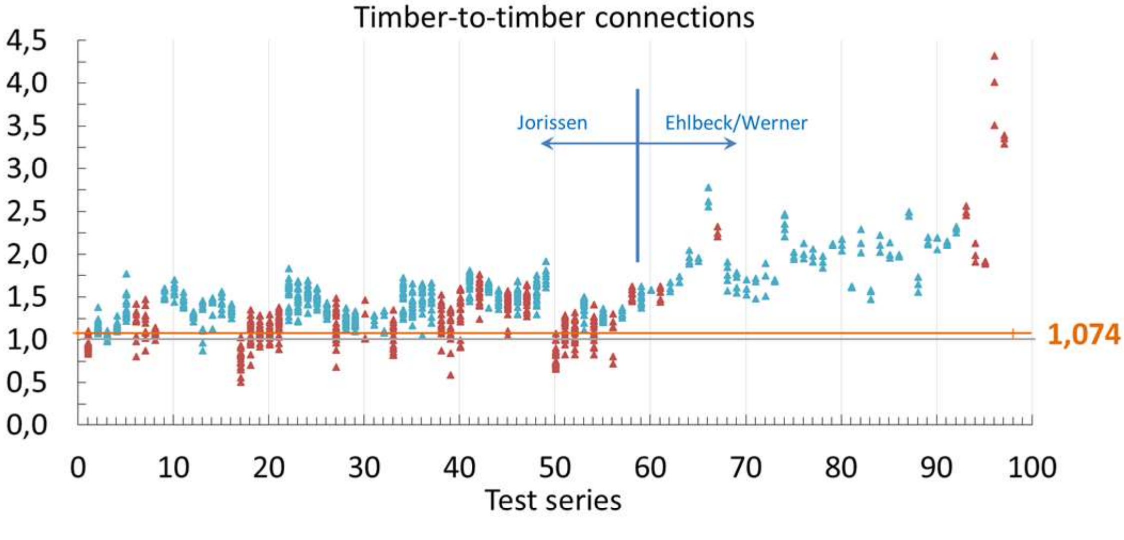

Figure 3.5. Ratios of the ultimate test load $F_{v,R}$ versus the calculated characteristic load-carrying-capacity $F_{v,Rk}$ according to Eurocode 5 for 1045 timber-to-timber connections

The ultimate test loads for timber-to-timber connections published by Ehlbeck and Werner (1989) are significantly higher than the calculated characteristic load-carrying-capacities (test series No. 59 and higher). The dowel slenderness ratios in the tests by Ehlbeck and Werner were significantly larger than those used by Jorissen (1998).

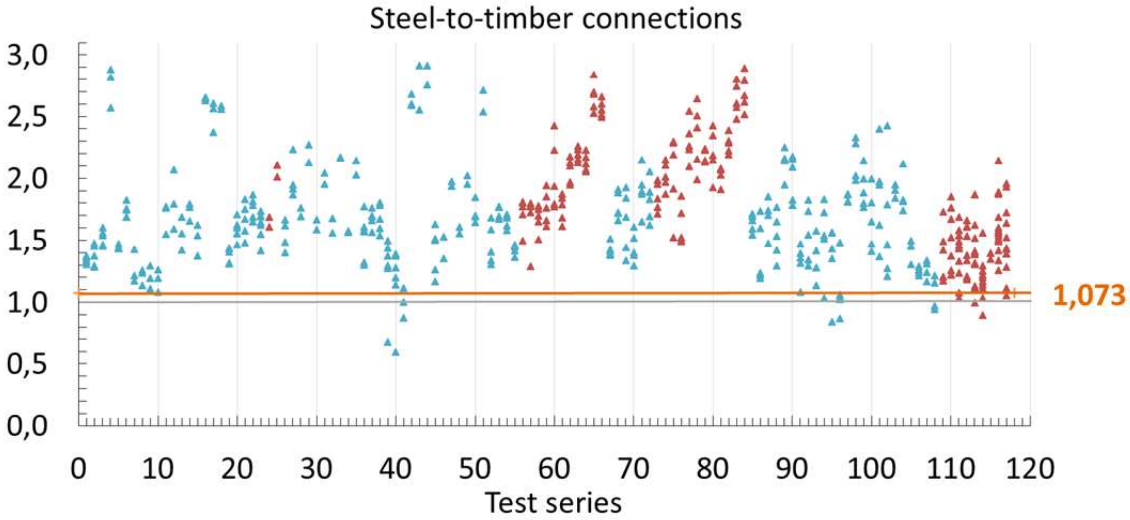

Figure 3.6. Ratios of the ultimate test load $F_{v,R}$ versus the calculated characteristic load-carrying-capacity $F_{v,Rk}$ according to Eurocode 5 for 543 steel-to-timber connections

Another tendency observed during the evaluation was that the difference between the ultimate test load and the calculated characteristic load-carrying-capacities increases with increasing dowel diameter. Obviously, the load-carrying-capacity of connections with large diameter dowels is underestimated by Eurocode 5.

4 Dowel test results

4.1 General

The evaluation of the connection tests in section 3 shows an increasing underestimation of the characteristic load-carrying-capacities for larger dowel diameters. The same holds for higher dowel slenderness ratios where failure modes including dowel bending occur and the yield moment of the dowel more and more influences the load-carrying-capacity. Therefore, dowel yield moments were experimentally determined for different dowel diameters and different steel grades. In order to check equation (8.30) of Eurocode 5, dowels were sampled in different timber construction companies as well as ordered from different suppliers. Altogether 159 dowel tensile tests in 31 series and 122 dowel bending tests in 38 series were carried out. If possible, part of each sample was tested in tension and another part in bending. Long dowels were cut in half and one half was tested in tension and the other in bending. Since the variation of test results within a test series was very low, the yield moments according to EN 409 could be compared to the calculated yield moments according to equation (8.30) of Eurocode 5 by directly using the tensile strength from the test. Figure 4.1 exemplarily shows dowels after tensile or bending tests.

Figure 4.1. 16 mm dowels after tensile tests (left) and 8 mm dowels after bending tests (right)

4.2 Yield moment M_y

The tests showed different moment-rotation behaviour of steel grades with low and high tensile strengths, respectively. For mild steel the bending moment still increased significantly after plastic deformation started. This increase is less pronounced for higher steel grades (see Fig. 4.2).

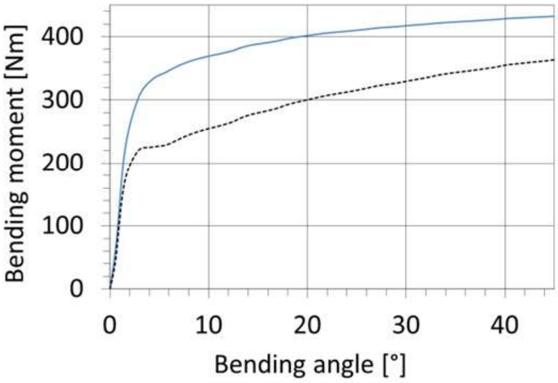

Figure 4.2. Bending moment – angle relation for 16 mm dowels made of mild steel (dotted line) and higher grade steel (solid line)

The yield moment was determined according to EN 409 at a bending angle α:

$$\alpha = \alpha_1 \cdot \left(\frac{2{,}78 \cdot \rho_k}{f_u} \right)^{0{,}44} \tag{2}$$

Here, ρ_k is the characteristic timber density and f_u the dowel tensile strength. Since the timber density is not known, $\rho_k = 350$ kg/m³ is assumed. Table 1 shows the yield moments M_y determined according to EN 409, and the steel tensile strengths f_u from the tensile tests. For comparison the yield moments M_y according to equation (8.30) of Eurocode 5 on the one hand using the tensile strength $R_{m,mean}$ of each test series and on the other hand on the basis of the nominal tensile strength of the dowel $f_{u,k}$. If $f_{u,k}$ was unknown, the tensile strength of S235 of 360 N/mm² was assumed.

Table 1. Results of dowel bending tests compared to calculated yield moments according to Eurocode 5.

Source	Diameter/Length [mm]	$R_{m,mean}$ [N/mm²]	$M_{y,EN409,mean}$ [Nm]	$M_{y,EC5,Rm,mean}$ [Nm]	$M_{y,EC5,fuk}$ [Nm]
SFS	7/233	584	32	28	26
GH	8/200	593	52	40	24
RB	8/140	662	59	44	24
Rög	8/160	634	56	42	24
Würth	8/115	687	60	46	24
Alberts	10/140	622	106	74	45
Murr	10/210	603	101	72	43
Rie	10/140	607	107	72	43
Würth	10/140	604	102	72	43
AHH	12/180	641	193	123	69
Alberts	12/220	631	184	121	73
Bsch	12/320	712	198	137	69
D	12/400	652	184	125	69
Gei	12/160	717	196	138	69
Gei	12/200	591	136	113	69
Gei	12/240	440	95	84	69
GH	12/200	604	174	116	69
RB	12/200	567	166	109	69
San	12/140	752	202	144	69
Würth	12/200	697	201	134	69
DX	16/200	397	198	161	146
Gei	16/240	535	377	217	146
GH	16/300	540	377	219	146
HO	16/140	446	257	181	146
RB	16/240	742	494	301	146
SF	16/220	542	349	220	146
VK	16/200	414	213	168	146
B	20/420	564	776	408	261
GH	20/300	572	759	414	261
RB	20/240	628	825	455	261
Rie	20/390	483	696	350	261

In order to enable a more realistic calculation of dowel yield moments, an alternative to equation (8.30) of Eurocode 5 is determined. Here, the different behaviour of steel dowels made of low or high grade steel (see Fig. 4.2) is taken into account. Those test results are used to derive an equation to determine the yield moment, where both tensile and bending tests were carried out with dowels from the same batch. The best agreement between test results and calculated values was found for the following expression, representing the mechanically correct full plastic bending moment of a circular cross-section:

$$M_y = \frac{f_{y,ef} \cdot d^3}{6} \tag{3}$$

$$f_{y,ef} = \begin{cases} \dfrac{0{,}9 \cdot (f_y + f_u)}{2} & \text{for } f_u < 450\,MPa \\ 0{,}9 \cdot f_u & \text{for } f_u > 450\,MPa \end{cases} \tag{4}$$

Here, d is the dowel diameter, f_y is the fastener yield strength and f_u is the fastener tensile strength.

Fig. 4.3 left shows the ratio between M_y according to EN 409 and the calculated value according to equation (3) for the 122 bending tests, on the one hand based on the mean tensile strength from the tests (diamonds) and on the other hand based on the nominal dowel tensile strength (squares). The ratio is independent of the dowel diameter. The average ratio for test based tensile strengths is 1.09, the characteristic ratio is 1.00. Equation (3) hence provides an excellent description of the dowel yield moments according to EN 409. Since in a real design situation nominal rather than real tensile strength values are applied, the proposed equation (3) is conservative in most cases due to the over-strength of the steel dowels.

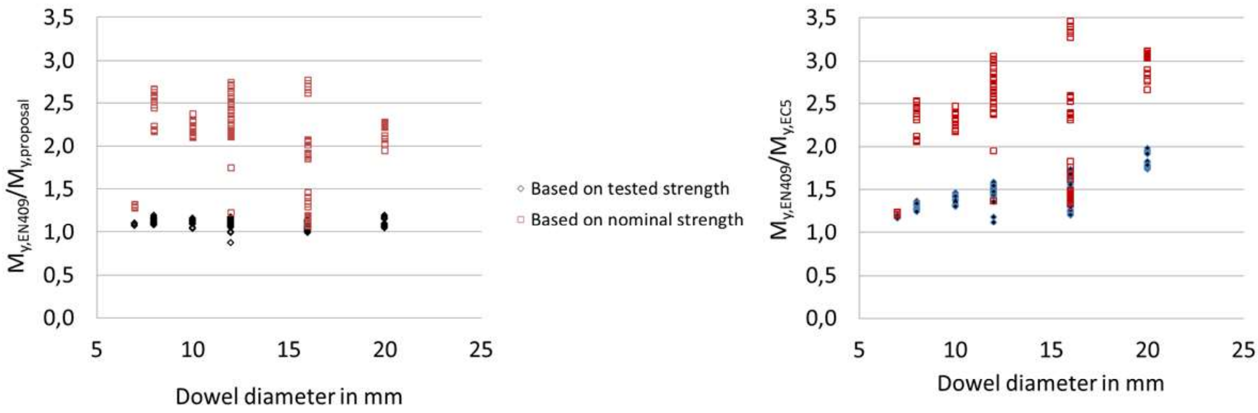

Figure 4.3. Ratio between M_y according to EN 409 and M_y according to equation (3) (left) or M_y according to Eurocode 5 (right)

For comparison the ratio between M_y according to EN 409 and the calculated value according to equation (8.30) of Eurocode 5 is shown in Figure 4.3 (right). It is obvious that Eurocode 5 is increasingly conservative for larger dowel diameters.

4.3 Influence of yield moment M_y on calculated results

Figures 4.4 and 4.5 again show the ratios $F_{v,R}/F_{v,Rk}$ for timber-to-timber and steel-to-timber connections, respectively. The ratios were calculated using equation (3) instead of equation (8.30) of Eurocode 5 to calculate the characteristic yield moment of the dowels. The characteristic ratio calculated according to EN 14358 decreases from 1.074 to 1.048 for timber-to-timber and from 1.073 to 1,001 for steel-to-timber connections, again only for the test results not excluded. The calculation model according to Eurocode 5 with the modified yield moment M_y hence is still slightly conservative for the tested timber-to-timber connections and appropriate for the tested steel-to-timber connections.

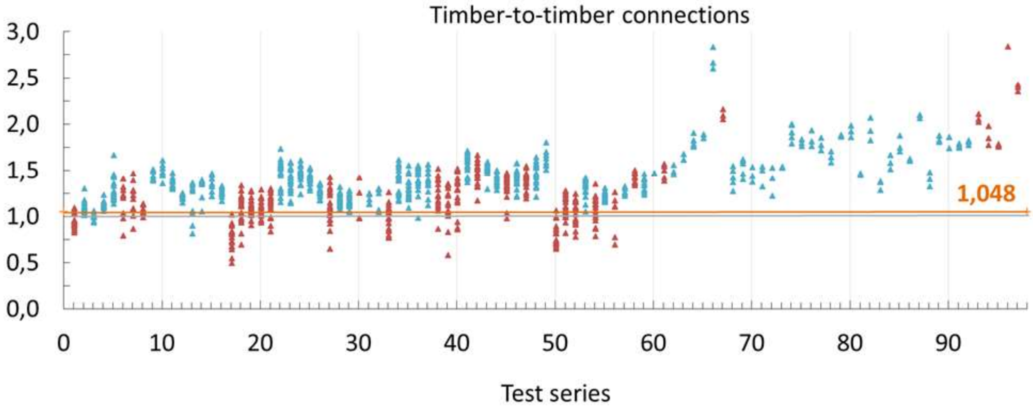

Figure 4.4. Ratios of the ultimate test load $F_{v,R}$ versus the calculated characteristic load-carrying-capacity $F_{v,Rk}$ taking into account My according to equation (3) for 1045 timber-to-timber connections

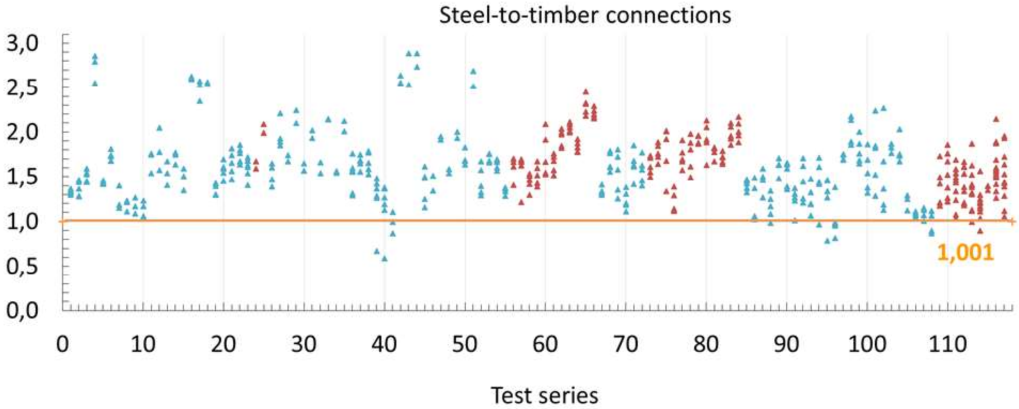

Figure 4.5. Ratios of the ultimate test load $F_{v,R}$ versus the calculated characteristic load-carrying-capacity $F_{v,Rk}$ taking into account My according to equation (3) for 543 steel-to-timber connections

In the average, the timber-to-timber connections tested by Ehlbeck and Werner (1989) still show higher ratios $F_{v,R}/F_{v,Rk}$ even with the modified equation for the dowel yield moment M_y (see test series 59 through 118 in Fig. 4.4). Apart from the plastic dowel bending capacity there seem to exist further causes for higher ratios with increasing dowel slenderness ratios. If a slenderness effect is taken into account for dowelled connections similar to the rope effect in Eurocode 5, leading to an increase of 25 % of the lateral load-carrying-capacity of dowels with a failure mode showing two plastic hinges per shear plane, the characteristic ratio for timber-to-timber connections would only drop to from 1,048 to 1,037, for steel-to-timber connections from 1,001 to 0,978.

Reasons for the additional safety margin for slender dowels could be friction between the dowel and the surrounding timber along the length of the dowel, especially in areas where the embedding strength is reached. This friction would create a withdrawal capacity leading to a twofold rope effect: friction between the timber or steel members and the fastener tensile component parallel to the shear plane. Further research is required to quantify this possible rope effect in dowelled connections with drift pins.

5 Conclusions

The load-carrying capacity of dowelled joints with drift pins was comprehensively studied and evaluated, based on 1588 tests with dowelled connections reported in seven different research studies (Brühl, 2010; Ehlbeck & Werner, 1989; Jorissen, 1998; Kneidl, 2009; Mischler, 1998; Sandhaas, 2012; Schmid, 2002).

The analysis of the short-term tests shows an overestimation of the load-carrying capacity according to DIN 1052:1988 by 10 – 25 %. Consequently, connections designed according to DIN 1052:1988 are below the reliability level required today. The evaluations also show that some load-carrying capacities according to Eurocode 5 are conservative and hence could be increased accordingly.

Based on bending and tensile tests with dowels sampled in companies during third party quality control visits, a modified equation for the calculation of the yield moment $M_{y,k}$ was derived, leading to higher calculated load-carrying capacities especially for large diameter dowels or higher steel grades. The dowel bending and tensile tests also revealed that actual steel strength values often show significant over-strength.

For dowelled connections with a failure mode showing two plastic hinges per shear plane, an additional slenderness effect was observed, increasing the load-carrying capacity of these connections in the order of 25 % compared to calculated values based on the Johansen model. This is surprising, since drift pins so far show no significant withdrawal capacity and hence a rope effect is hardly to be expected.

The design rules in DIN 1052:1988 were originally derived based on tests, where the dowel steel strength was not determined. This means that both effects mentioned above, namely the surplus strength of the steel dowels and the slenderness effect, were implicitly included in the permissible loads according to DIN 1052:1988.

Considering the consequences of these findings (modified equation for M_y, slenderness effect and steel over strength), the existing differences between the calculated load-carrying capacities according to DIN 1052:1988 and Eurocode 5, respectively, may be explained to a large extent.

A new equation for Eurocode 5 for calculating the characteristic yield moment of bolts and dowels is proposed.

6 References

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