Mechanical properties of laterally loaded threaded rods embedded in softwood

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Abstract

At present, the mechanical properties of laterally loaded threaded fasteners with large diameters embedded in timber elements remain unknown. An experimental study of laterally loaded threaded rods with wood screw threads embedded perpendicular to grain in softwood elements (spruce and pine glulam and spruce LVL) is presented in this paper. Embedment tests with the load acting parallel and perpendicular to grain were carried out and the embedment strength and stiffness were quantified. For some test series, the experimental embedment strengths were lower compared to the predictions according to Eurocode 5 in terms of both mean and characteristic values. This finding indicates that the predictions by Eurocode 5 are not always conservative. To investigate the effect of the thread, additional series of embedment tests were carried out with smooth dowels featuring a diameter approximately equal to the core diameter of the threaded rods. Finally, the yielding moment of threaded rods was quantified based on a series of three-point bending tests of threaded rods. The experimentally determined yielding moment was significantly higher than the prediction of Eurocode 5.

1 Introduction

1.1 Background

Steel threaded rods with wood screw threads feature high axial capacity and stiffness, and they are a promising alternative to dowel-type fasteners (i.e. fasteners loaded perpendicular to their axis) for highly resistant and stiff connections in timber structures. Due to their axial properties, the design of connections with threaded rods should aim for axial loading of the rods. However, in some configurations threaded rods may be loaded with combined axial and lateral loading (e.g. Lied and Nordal 2016; Cepelka and Malo 2018) or pure lateral loading. The axial properties of threaded rods have been investigated in a series of studies (see e.g. Blaß and Krüger 2010; Mori et al. 2008; Stamatopoulos and Malo 2016, 2015, 2020). However, the properties of threaded rods subjected to lateral loading remain largely unknown. The

embedment strength and the yielding moment are necessary input parameters for the determination of the load-carrying capacity of connections with laterally loaded fasteners according to the European Yield Model based on the work of Johansen (1949), which is adopted by EN1995-1-1 (CEN 2004).

The embedment strength and stiffness of laterally loaded fasteners can be determined by testing. The most common test standards for embedment tests are the EN383:2007 (CEN 2007), ISO10984-2:2009 (ISO 2009b) and ASTM D5764-97a (ASTM 2013); see also an overview of the test methods in Franke et al. (2018). Two main experimental set-up variations have been proposed in these standards: the half-hole test and the full-hole test. Half-hole and full-hole test set-up variations are proposed by ISO10984-2:2009 (ISO 2009b) and ASTM D5764-97a (ASTM 2013). The experimental set-up proposed by EN383:2007 (CEN 2007) is a full-hole test set-up similar to ISO10984-2 (ISO 2009b). A typical force–displacement embedment curve obtained by an embedment test is shown in Fig. 1 ($F - v$ curve). This curve may be approximated as bi-linear with stiffness moduli $K_{v,ser}$ (elastic) and $K_{v,NE}$ (non-elastic). The embedment strength f_h of dowel-type fasteners is determined by test results by Eq. (1):

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Fig. 1 Typical force–displacement embedment curve

$$f_h = \frac{F_h}{d \cdot t} \quad (1)$$

where F_h is the embedment capacity, d is the diameter of the fastener and t is the thickness of the specimen.

The determination of the embedment capacity F_h is not straight-forward, as the embedment behaviour is typically characterized by hardening after the elastic behaviour and lack of maximum force level; see Fig. 1. Two alternative methods are widely used to determine F_h , namely the 5%-offset method and the 5 mm/max f_h method. According to the 5%-offset method, the capacity is determined as the force obtained at the intersection between the embedment curve and the linear-elastic part of the curve with an offset equal to 5% of the fastener's diameter (see $F_{h,5\%-offset}$ in Fig. 1). According to the 5 mm/max f_h method which is adopted by EN383:2007 (CEN 2007), the capacity is determined as the force at a displacement level of 5 mm (see $F_{h,5mm}$ in Fig. 1), if a clear maximum force is not observed up to a 5 mm displacement. In the work by Whale and Smith (1986), which has been used for the development of the equations of EN 1995-1-1 (CEN 2004) for the embedment strength, the embedment capacity was determined at a displacement of 2.1 mm (see $F_{h,2.1mm}$ in Fig. 1). By use of the bi-linear approximation as shown in Fig. 1, the embedment force $F_{h,i}$ at the intersection of the two linear branches may also be defined.

According to EN383:2007 (CEN 2007) and ISO10984-2:2009 (ISO 2009b), the embedment stiffness is determined as follows:

$$K_{v,ser} = \frac{0.4 \cdot F_{h,est}}{4/3 \cdot (v_{04} - v_{01})} \quad (2)$$

where $F_{h,est}$ is the estimated embedment capacity used in the tests, and v_{01} and v_{04} are the displacements at force levels recorded at 10% and 40% of $F_{h,est}$ respectively. It is often convenient to express the embedment stiffness per unit length, i.e. by use of the foundation modulus $k_{v,ser}$ according to Eq. (3):

$$k_{v,ser} = \frac{K_{v,ser}}{t} \quad (3)$$

The yielding moment of fasteners is also a necessary parameter for the prediction of the load-carrying capacity of connections with dowel-type fasteners according to Johansen's equations (Johansen 1949), which are adopted by EN1995-1-1 (CEN 2004). For the determination of the yielding moment, EN409:2009 (CEN 2009) specifies a four-point bending configuration while in ISO10984-1:2009 (ISO 2009a), both three-point and four-point bending configurations are specified. Blaß et al. (2000) showed that the theoretical yielding moment may not render safe-side results and proposed the determination of yielding moment for more realistic bending angles. Therefore, EN409:2009 (CEN 2009) and ISO10984-1:2009 (ISO 2009a) specify an effective bending angle of $110/d$ degrees for screws for four-point bending tests. In EN14592:2008 (CEN 2012b) a bending angle of $45/d^{0.7}$ degrees is specified instead. In three-point bending tests according to ISO10984-1:2009 (ISO 2009a), the 5%-offset method is used for the determination of the yielding moment. For a comprehensive overview of testing standards for the determination of the yielding moment of dowel-type fasteners, the interested reader is kindly referred to Franke et al. (2018).

The present version of EN1995-1-1 (CEN 2004) does not explicitly cover threaded rods. According to EN1995-1-1 (CEN 2004), the characteristic embedment strength and yield moment of dowels and bolts are given by Eqs. (4)–(6) (Eqs. (4), (5) based on Ehlbeck and Werner 1992, Eq. (6) based on Blaß et al. 2001):

$$f_{h,k} = \frac{0.082 \cdot \rho_k \cdot (1 - 0.01 \cdot d)}{k_{90} \cdot \sin^2 \beta + \cos^2 \beta} \quad (4)$$

$$k_{90} = \begin{cases} 1.35 + 0.015 \cdot d, & \text{Softwood} \\ 1.30 + 0.015 \cdot d, & \text{LVL} \end{cases} \quad (5)$$

$$M_{y,Rk} = 0.3 \cdot f_{u,k} \cdot d^{2.6} \quad (6)$$

where:

- $f_{h,k}$ is the characteristic embedment strength of wood in N/mm²;
- $M_{y,Rk}$ is the characteristic yielding moment of the fastener in N · mm;
- ρ_k is the characteristic wood density in kg/m³;
- β is the angle between the embedment stress and the grain direction;
- $f_{u,k}$ is the characteristic ultimate strength of the fastener in N/mm².

According to EN1995-1-1 (CEN 2004), the stiffness of laterally loaded dowels, bolts and screws per shear plane and fastener $K_{v,ser}$ (in N/mm) is given as function of the mean timber density ρ_{mean} (in kg/m³) and the diameter of the fastener d (in mm) by:

$$K_{v,ser} = \rho_{mean}^{1.5} \cdot d/23 \quad (7)$$

In the present version of EN1995-1-1 (CEN 2004), laterally loaded threaded fasteners with an effective diameter $d_{ef} \geq 6$ mm are treated as bolts. For threaded fasteners not featuring a smooth shank, the effective diameter is equal to 1.1 times the core diameter d_1 , i.e., $d_{ef} = 1.1 \cdot d_1$, and Eqs. (4)–(6) apply by use of d_{ef} . On the other hand, it is not specified whether the outer-thread or the effective diameter should be used in Eq. (7). Some variations of Eq. (4) can be found in European Technical Assessments (abbr. ETAs) for screws embedded in softwood or hardwood and laminated veneer lumber (abbr. LVL) elements (see e.g. ETA Danmark A/S (2017, 2019)). In these ETAs, the angle between the screw axis and the grain direction, and the angle between the screw axis and the wide face of LVL (for LVL elements) are also taken into account.

To the knowledge of the authors, there are no systematic experimental studies with respect to the mechanical properties of laterally loaded threaded rods with wood screw threads. Size-wise, threaded rods are comparable to bolts and dowels with large diameters, i.e. $d > 12$ mm. Table 1 summarizes available selected embedment test results for fasteners with large diameters embedded in softwood glued-laminated timber (abbr. glulam) and LVL, based on different standards. Type-wise, threaded rods have similarities with self-tapping screws. An extensive experimental study of laterally loaded self-tapping screws with $d \leq 12$ mm can be found in Bejtka (2005). Based on these tests, the following expressions were derived for embedment strength and the foundation modulus, respectively (f_h in N/mm², $k_{v,ser}$ in N/mm², ρ in kg/m³, d in mm):

$$f_h = \frac{0.022 \cdot \rho^{1.24} \cdot d^{-0.3}}{(2.5 \cdot \cos^2 \alpha + \sin^2 \alpha)} \quad (8)$$

$$k_{v,ser} = \frac{(0.22 + 0.014 \cdot d) \cdot \rho}{1.17 \cdot \sin^2 \beta + \cos^2 \beta} \quad (9)$$

where α is the angle between the screw axis and the grain direction.

1.2 Outline

This paper presents an experimental study on the mechanical properties of laterally loaded threaded rods with outer-thread diameter $d = 22$ mm and core diameter $d_1 = 16.1$ mm, embedded perpendicular to grain in softwood elements (spruce and pine glulam and spruce-LVL). The tests were carried out for both parallel and perpendicular to grain loading and the embedment strength and stiffness were quantified. To investigate the effect of the thread, a series of tests were performed with smooth dowels with a diameter ($d = 16$ mm) approximately equal to the core diameter of the threaded rods. Measurements of the compressive strength and the density of the laminations in which the rods were inserted in the embedment tests were also performed to investigate possible correlations. Finally, a series of three-point bending tests of threaded rods were performed to determine the yielding moment.

2 Experimental methods

2.1 Embedment tests

The experimental set-up for the embedment tests is shown in Fig. 2. A stiff loading assembly consisting of 20 mm-thick steel plates was used in order to apply the loading in the two ends of the threaded rods, as shown in Fig. 2a, b. Specimens were loaded in compression parallel (Fig. 2a) and perpendicular (Fig. 2b) to the grain direction. The specimens were produced from the following materials:

- S-series: Inner lamellas from glulam of strength class GL30c (CEN 2013) made of spruce (*Picea abies*)
- P-series: Glulam of strength class GL30c (CEN 2013) made of pine (*Pinus sylvestris*), either inner or outer lamellas.
- LVL-series: LVL made of spruce (*Picea abies*) with some veneers (approx. 1/5) oriented in the transverse direction. Product details are specified by ETA-13/0504 for KertoQ (VTT Expert Services 2013)

The target dimensions of the specimens were $L = 340$ mm (parallel to grain), $b = 220$ mm (width) and $t = 40$ mm (thickness); confer Fig. 2a, b. The dimensions of the specimens were the same for parallel and perpendicular to grain loading (see Fig. 2a, b), resulting in variations compared

Table 1 Mean results from selected embedment tests of dowels with diameters greater than 12 mm embedded in softwoods (in parenthesis: coefficient of variation of experimental values)

Source	$\beta = 0^\circ$		$\beta = 90^\circ$	
	$k_{v,ser,0}$ [N/mm ²]	$f_{h,0}$ [N/mm ²]	$k_{v,ser,90}$ [N/mm ²]	$f_{h,90}$ [N/mm ²]
Santos et al. (2010)	1586 (20.7%) ^a	46.4 (9.1%) ^a	521 (23.7%) ^a	21.1 (17.1%) ^a
Pine (<i>Pinus pinaster</i>), $MC \approx 12\%$, $t = 30$ mm	1693 (17.7%) ^b	46.2 (12.6%) ^b	504 (24.4%) ^b	28.6 (18.2%) ^b
Dowels: $d = 14$ mm				
^a EN383, $\rho_m \approx 550 - 570$ kg/m ³				
^b ASTM D5764, $\rho_m \approx 584 - 615$ kg/m ³				
Karagiannis et al. (2016)	$d = 12$ mm:	$d = 12$ mm:	$d = 12$ mm:	$d = 12$ mm:
Spruce (<i>Picea abies</i>), $MC \approx 10\%$	376 (15.4%)	29.4 (7.9%)	137 (30.7%)	14.7 (11.9%)
$\rho_m \approx 430$ kg/m ³ , $t = 40$ mm	$d = 16$ mm:	$d = 16$ mm:	$d = 16$ mm:	$d = 16$ mm:
EN383, Dowels: $d = 12/16$ mm	1034 (17.3%)	29.6 (8.7%)	241 (7.1%)	14.6 (17.2%)
Strength: intersection of bi-linear approximation				
Franke and Quenneville (2011) ¹	No data	$d = 16$ mm:	No data	$d = 16$ mm:
Radiata pine, $\rho_m \approx 600$ kg/m ³ , $t = 46$ mm		35.2 (15.0%)		16.9 (17.6%)
Dowels: $d = 16/20$ mm		$d = 20$ mm:		$d = 20$ mm:
ASTM D5764, 5%-offset method		34.0 (16.3%)		17.9 (16.6%)
Franke and Quenneville (2011)	$d = 12$ mm:	$d = 12$ mm:	$d = 12$ mm:	$d = 12$ mm:
Radiata pine LVL, $MC \approx 11\%$	742	44.2 (8.2%) ^a	230	26.7 (7.1%) ^a
$\rho_m \approx 600$ kg/m ³ , $t = 46$ mm		45.6 (7.2%) ^b		38.0 (8.1%) ^b
ASTM D5764 (Half hole)	$d = 16$ mm:	$d = 16$ mm:	$d = 16$ mm:	$d = 16$ mm:
Dowels: $d = 12/16/20$ mm	896	42.6 (5.4%) ^a	265	27.2 (7.8%) ^a
^a 5%-offset method		43.6 (5.7%) ^b		35.1 (6.7%) ^b
^b Values at 5 mm displacement (or max f_h)	$d = 20$ mm:	$d = 20$ mm:	$d = 20$ mm:	$d = 20$ mm:
	1212	40.4 (5.9%) ^a	328	27.5 (5.5%) ^a
		40.6 (5.7%) ^b		33.2 (6.0%) ^b
Sawata and Yasumura (2002)	No data	$d = 12$ mm:	No data	$d = 12$ mm:
Spruce (<i>Picea jezoensis</i>)		35.4 (10.5%) ^a		14.2 (15.5%) ^a
Fir (<i>Abies sachalinensis</i>)		37.1 (10.6%) ^b		18.6 (17.4%) ^b
$\rho_m \approx 400$ kg/m ³		$d = 16$ mm:		$d = 16$ mm:
EN383, Dowels: 12/16/20 mm, $t = 32$ mm		32.6 (13.2%) ^a		14.3 (17.3%) ^a
^a Values using 5% offset method		33.8 (12.9%) ^b		17.9 (16.1%) ^b
^b Values at 5 mm displacement (or max f_h)		$d = 20$ mm:		$d = 20$ mm:
		33.9 (11.2%) ^a		13.3 (20.3%) ^a
		34.3 (11.1%) ^b		15.3 (20.9%) ^b
Bader et al. (2016)	No data	$d = 12$ mm:	No data	$d = 12$ mm:
Spruce LVL, $\rho_m \approx 495$ kg/m ³ , $t = 51$ mm		33.1		24.9
MC : (20 °C-65% relative humidity)		$d = 20$ mm:		$d = 20$ mm:
EN383, (5 mm/max f_h)		37.7		23.3
Dowels: $d = 12/20$ mm				

In these studies, there may be variations in the deformation measurements

¹Results reported by Franke and Quenneville (2011) taken from original studies by Suffiad (2008) and Mills (2008). The original sources could not be found

to the dimensions specified by EN383:2007 (CEN 2007). Prior to testing, all specimens were conditioned to standard temperature and relative humidity conditions (20 °C/65% R.H.), resulting to approximately 12% moisture content (abbr. MC) in wood. The density for each specimen was determined in accordance with ISO13061-2 (ISO 2014), based on the average density of two rectangular blocks cut from the same laminations where the fastener was inserted. In addition, the density of the whole specimen as shown in Fig. 2 was measured.

Threaded rods with outer-thread diameter $d = 22$ mm and core diameter $d_1 = 16.1$ mm were used in the tests. The steel grade of the rods was 8.8 according to ISO 898-1 (ISO 2013), i.e. the nominal yielding and ultimate strengths were $f_{y,k} = 660$ N/mm² and $f_{u,k} = 830$ N/mm², respectively. These threaded rods were purpose-made, and they are not commercially available. The pitch distance of the rods was 8 mm and the thread angle was 45°, confer Fig. 2c. The thread was maintained in the embedded length of the rods, but it was removed from their ends in order to allow smooth transfer

Fig. 2 Test set-up and dimensions: **a** embedment test parallel to grain, **b** embedment test perpendicular to grain, **c** threaded rod used in the embedment tests, all dimensions in mm

of stresses between the loading assembly and the threaded rods; see in detail Fig. 2c.

Each test series was named based on the material (series *S*, *P* or *LVL*) and the angle between the loading and the grain direction (0 or 90). Additional series of embedment tests with a smooth dowel (also of steel grade 8.8) instead of a threaded rod were carried out to investigate the influence of the thread on the embedment properties (series *SD*, *PD* or *LVL*). The diameter of the smooth dowel was $d = 16\text{ mm}$, i.e. approximately equal to the core diameter of the threaded

rod. A summary of the test series is given in Table 2. All specimens were monotonically loaded without a preloading cycle. A constant rate of displacement was applied on the loading assembly equal to 2.5 mm/min for loading parallel to grain and 5.0 mm/min for loading perpendicular to grain.

The displacement was continuously monitored by use of six linear variable differential transducers (abbr. LVDTs); confer Fig. 2a, b. Four of the LVDTs (LVDTs 1–4) measured the relative displacements between the wood specimen and the threaded rod on both sides in accordance with

Table 2 Experimental series for embedment tests

Series	Fastener type	Material	Load-to-grain angle, β (deg)	Mean density ^a , ρ_{mean} (kg/m ³) in parenthesis: range	ρ_k (kg/m ³)	Number of tests
S-0	Threaded rod $d = 22\text{ mm}$ $d_1 = 16.1\text{ mm}$	Spruce glulam	0	401 (361–444)	328	6
S-90		Spruce glulam	90	414 (372–451)	360	10
P-0		Pine glulam	0	454 (418–526)	384	10
P-90		Pine glulam	90	464 (404–560)	357	10
LVL-0	Smooth dowel $d = 16\text{ mm}$	Spruce LVL	0	515 (463–545)	461	10
LVL-90		Spruce LVL	90	507 (484–552)	454	10
SD-0		Spruce glulam	0	420 (402–446)	367	5
SD-90		Spruce glulam	90	401 (380–427)	354	6
PD-0	Smooth dowel $d = 16\text{ mm}$	Pine glulam	0	430 (407–449)	377	5
PD-90		Pine glulam	90	448 (439–465)	393	5
LVL-0		Spruce LVL	0	515 (505–545)	451	5
LVL-90		Spruce LVL	90	517 (492–550)	453	5

^aDetermined according to ISO 13061-2 (ISO 2014)

EN383:2007 (CEN 2007). The average value of these displacements v was used as the embedment displacement:

$$v = \frac{v_{LVDT,1} + v_{LVDT,2} + v_{LVDT,3} + v_{LVDT,4}}{4} \quad (10)$$

Moreover, the absolute displacement v_{abs} was measured by LVDTs 5 and 6 and the average value was used:

$$v_{abs} = \frac{v_{LVDT,5} + v_{LVDT,6}}{2} \quad (11)$$

The embedment capacity was determined by using both the 5%-offset method and the 5 mm/max f_h method; see Fig. 1. For comparison, the embedment capacities at a displacement of 2.1 mm ($F_{h,2.1mm}$) and at the intersection of the bi-linear approximation ($F_{h,i}$) were also determined.

2.2 Compression tests

After the completion of the embedment tests, rectangular blocks were cut from the specimens and tested in compression; see e.g. Fig. 3. These test series were carried out in order to study possible correlations between the embedment and the compressive strength. The rectangular blocks were cut from the non-damaged part of the lamination in which the threaded rod was inserted in the embedment tests. The target dimensions of these blocks were 50 mm (parallel to grain) and 40 × 40 mm (transverse grain). In a few cases, it was not possible to achieve these target dimensions due to damage in the original specimen and the dimensions were reduced accordingly. The angle between the compressive force and the grain direction was the same as in

Fig. 3 Example of compressive test of a rectangular block

the original embedment tests, i.e. the rectangular blocks cut from 0-series and 90-series were loaded parallel and perpendicular to grain, respectively. These tests were also monotonic, and the rate of loading was the same as in the embedment tests: 2.5 mm/min for loading parallel to grain and 5.0 mm/min for loading perpendicular to grain. For blocks coming from series S-0, P-0, LVL-0 and LVL-90 a maximum force was observed in the tests and therefore the compressive strength was determined as the maximum force divided by the cross-sectional area. For blocks coming from series S-90 and P-90, the behaviour was characterized by a continuously increasing force and the compressive strength was determined by use of the offset-method specified by EN408 (CEN 2012a), i.e. at the intersection of the curve and elastic part with an offset equal to 1% of the height of the specimen.

2.3 Bending tests of the threaded rods

Three-point bending tests of the threaded rods were also carried out according to *Method B* by ISO10984-1:2009 (ISO 2009a). The test set-up is shown in Fig. 4. The span length was equal to $l_4 = 160$ mm. The load was applied by a purpose made steel part fitted within one thread pitch; see Fig. 4b. The thread was removed at the supports, in order to allow for proper contact. The loading was monotonic, applied at a constant rate of 2 mm/min. The yielding moment was determined by Eq. (12):

$$M_y = \frac{F_y \cdot l_4}{4} \quad (12)$$

The yielding force F_y was determined by use of the 5%-offset method (similar to Fig. 1), according to *Method B* by ISO10984-1:2009 (ISO 2009a). The core diameter of the rod was used for the determination of the offset, i.e. the offset was set to $0.05 \cdot d_1$. The mid-span deflection was measured by use of two LVDTs, see Fig. 4b. Based on the mean measurement of the two LVDTs, the mid-span deflection and the bending angle were quantified. Ten bending tests were performed in total.

3 Results and discussion

3.1 Embedment tests

The mean experimentally determined capacities according to the 5%-offset and the 5 mm/max f_h methods are summarized in Table 3. The force–displacement curves obtained in the embedment tests and representative failure modes are summarized in Fig. 5. The embedment capacities were determined based on the relative embedment displacement

Fig. 4 Three-point bending tests of threaded rods: **a** drawing and dimensions according to Method B in ISO10984-1:2009 (ISO 2009a), **b** photograph of the set-up

Table 3 Mean embedment capacity and coefficient of variation by use of 5%-offset and 5 mm/max f_h methods for all test series (based on displacement measured by LVDTs 1, 2, 3, 4 according to Eq. (10))

Property	Spruce glulam				Pine glulam				Spruce LVL			
	S-0	SD-0	S-90	SD-90	P-0	PD-0	P-90	PD-90	LVL-0	LVLD-0	LVL-90	LVLD-90
Method: 5%-offset ^a												
$F_{h,mean}$ (kN)	18.48	16.39	9.19	7.52	14.90	14.40	9.11	8.11	24.24	20.70	16.88	15.24
CoV_ F_h	0.14	0.07	0.15	0.12	0.18	0.21	0.15	0.12	0.06	0.10	0.08	0.05
$\frac{F_{h,rod,mean}}{F_{h,dowel,mean}}$	1.13		1.22		1.03		1.12		1.17		1.11	
Method: 5 mm/max f_h												
$F_{h,mean}$ (kN)	20.82	17.29	12.02	9.82	18.87	15.67	12.00	10.15	26.66	22.99	19.75	17.66
CoV_ F_h	0.13	0.07	0.11	0.09	0.13	0.14	0.14	0.14	0.05	0.04	0.07	0.08
$\frac{F_{h,rod,mean}}{F_{h,dowel,mean}}$	1.20		1.22		1.20		1.18		1.16		1.12	

^aThe reported 5%-offset capacities in this Table are based on an offset of 1.10. d_1 for threaded rods according to Eq. (13). By use of an offset of d_1 for threaded rods (to be comparable with the calculation for smooth dowels), the capacities are 1.1–2.2% lower, i.e. the difference is not significant

measured by LVDTs 1, 2, 3, 4 according to Eq. (10). The use of the absolute displacement according to Eq. (11) yielded very similar capacities; the difference compared to the values obtained by use of Eq. (10) was of the order of 0–3.0%. The embedment force levels at a displacement of 2.1 mm ($F_{h,2.1mm}$) and at the intersection of the bi-linear approximation ($F_{h,i}$) were very similar to the values obtained by the 5%-offset method; the differences compared to the 5%-offset method were of the order of 3.0–4.0%. Due to these small differences, only results by use of the 5%-offset method and the 5 mm/max f_h method are presented here.

As shown by the results in Table 3 and in Fig. 5, threaded rods reached higher embedment capacity compared to smooth dowels, i.e. the thread has a clearly positive effect on the capacity. The ratio $F_{h,rod,mean}/F_{h,dowel,mean}$ between the mean capacity of threaded rods over the mean capacity of smooth dowels was characterized by some variability.

Compared to the smooth dowels, the presence of the thread resulted in 13% higher capacity for the 5%-offset method and 18% higher for the 5 mm/max f_h method on average.

According to EN1995-1-1 (CEN 2004), Eq. (4) applies to bolts and dowels. To take into account the influence of the thread, an effective diameter equal to 1.1 times the core diameter should be used for screws according to EN1995-1-1 (CEN 2004), i.e.:

$$d_{ef} = 1.10 \cdot d_1 \quad (13)$$

Compared to the results in Table 3, Eq. (13) is conservative, as it underestimates the effective diameter. In Johansen's Equations which are adopted by EN1995-1-1 (CEN 2004), the embedment strength f_h always appears multiplied with the diameter d (i.e. the term is $f_h \cdot d$). Therefore, it is important that the embedment strengths to be used in Johansen's Equations are consistent with the -reference- diameter used

Fig. 5 Representative failure modes and embedment force–displacement curves obtained in the tests; displacement based on LVDTs 1, 2, 3, 4 according to Eq. (10)

to derive the embedment strength in Eq. (1). In this paper, we have chosen to determine the embedment strength according to Eq. (1) by use of the effective diameter according to EN1995-1-1 (CEN 2004), i.e. Equation (13)—although the results in Table 3 show a higher influence of the thread. This choice was made to be consistent with the rules that apply to screws according to EN1995-1-1 (CEN 2004). Thus, the rules of EN1995-1-1 (CEN 2004) for screws can be used for benchmarking. Moreover, the reported embedment strengths in this paper can be used in a more unified manner with the rules for screws according to EN1995-1-1 (CEN 2004).

The experimentally determined mean and characteristic embedment strengths, the corresponding compressive strengths and the foundation moduli for threaded rods (according to the bi-linear approximation as shown in Fig. 1) are summarized in Table 4. The embedment strength was determined by Eq. (1), by use of the effective diameter given by Eq. (13). The characteristic values were determined assuming a lognormal distribution according

to EN14358:2016 (CEN 2016). Moreover, the predictions by Eq. (4) according to EN1995-1-1 (CEN 2004) (using the measured density values of the series) are also provided in Table 4.

As shown in the values of Table 4, the strength levels according to 5 mm/max f_h method are considerably higher than the corresponding ones according to the 5%-offset method (13%, 31%, 27%, 32%, 10%, 17% higher for mean strength for series S-0, S-90, P-0, P-90, LVL-0 and LVL-90, respectively, and 16%, 42%, 41%, 36%, 12% and 20% higher for characteristic strength for series S-0, S-90, P-0, P-90, LVL-0 and LVL-90, respectively). The embedment strength is higher for parallel to grain loading. The ratio between parallel and perpendicular to grain loading (i.e. the factor k_{90} according to Eqs. (4), (5)) is smaller for the LVL series which can be explained by the transverse grain veneers of the LVL. For spruce and pine specimens, Eq. (5) predicts $k_{90} = 1.62$ (by use of $d_{ef} \approx 1.10 \cdot d_1$) which is in good agreement with the experimentally determined

Table 4 Mean and characteristic embedment and compression strengths and foundation modulus of threaded rods

Property	Spruce glulam		Pine glulam		Spruce LVL	
	S-0	S-90	P-0	P-90	LVL-0	LVL-90
Foundation modulus, Eq. (3)						
$k_{v,ser,mean}$ (N/mm ²)	461.2	285.6	595.5	328.8	499.2	367.3
$CoV_{-k_{v,ser}}$	0.47	0.42	0.43	0.28	0.25	0.39
$(k_{v,NE}/k_{v,ser})_{mean}$	0.00	0.07	0.05	0.06	0.02	0.05
Compressive strength						
$f_{c,mean}$ (N/mm ²)	31.67	4.06	34.91	4.35	32.95	14.14
CoV_{-f_c}	0.12	0.21	0.11	0.23	0.08	0.07
$f_{c,k}$ (N/mm ²) ^a	24.14	2.45	27.70	2.67	27.73	12.31
Emb. strength (Method: 5%-offset) ^b						
$f_{h,mean}$ (N/mm ²)	26.45	13.17	21.64	13.07	32.44	22.55
CoV_{-f_h}	0.15	0.15	0.17	0.15	0.06	0.08
$f_{h,k}$ (N/mm ²) ^a	18.56	9.71	15.09	9.27	28.46	18.74
$k_{90,mean} = f_{h,0,mean}/f_{h,90,mean}$	2.01		1.66		1.44	
$k_{90,k} = f_{h,0,k}/f_{h,90,k}$	1.91		1.63		1.52	
$(f_h/f_c)_{mean}$	0.84	3.37	0.62	3.12	0.99	1.60
$CoV_{-(f_h/f_c)}$	0.13	0.25	0.11	0.26	0.11	0.08
$f_{h,k}/f_{c,k}$	0.77	3.96	0.54	3.48	1.03	1.52
Emb. strength (Method: 5 mm/max f_h) ^b						
$f_{h,mean}$ (N/mm ²)	29.80	17.22	27.44	17.21	35.68	26.39
CoV_{-f_h}	0.13	0.11	0.12	0.15	0.05	0.07
$f_{h,k}$ (N/mm ²) ^a	21.58	13.81	21.29	12.58	31.91	22.57
$k_{90,mean} = f_{h,0,mean}/f_{h,90,mean}$	1.73		1.59		1.35	
$k_{90,k} = f_{h,0,k}/f_{h,90,k}$	1.56		1.69		1.41	
$(f_h/f_c)_{mean}$	0.94	4.41	0.79	4.12	1.09	1.87
$CoV_{-(f_h/f_c)}$	0.07	0.22	0.13	0.25	0.11	0.07
$f_{h,k}/f_{c,k}$	0.89	5.63	0.77	4.72	1.15	1.83
Eurocode Predictions, Eq. (4)						
$f_{h,mean}$ (N/mm ²) ^{b,c}	27.03	17.31	30.65	19.39	34.74	21.86
$f_{h,k}$ (N/mm ²) ^{b,c}	22.16	15.04	25.89	14.91	31.11	19.57

^aThe characteristic values were determined assuming lognormal distribution according to EN14358:2016 (CEN 2016)

^bThe embedment strength was determined by use of the effective diameter, $d_{ef} = 1.10 \cdot d_1$

^cThe mean and characteristic embedment strength was determined by use of the mean and characteristic density of the series in Eq. (4), respectively

values in Table 4 by use of the 5 mm/max f_h method. The results for LVL are less variable in general; this can be explained by the fact that LVL is a more highly engineered product than glulam.

The ratios between the embedment and the compressive strength are also given in Table 4. Based on results by the 5 mm/max f_h method, the mean ratio is equal to 0.94, 0.79 and 1.09 for series S0, P0 and LVL0, respectively and equal to 4.41, 4.12 and 1.87 for series S90, P90 and LVL90, respectively. For the 5%-offset method, these ratios are accordingly lower, due to the lower capacity according to the 5%-offset method. The smaller values for LVL90-series can be explained by the transverse grain veneers of the LVL.

Figure 6 shows the correlation between the experimentally determined embedment strengths and the corresponding predictions by EN 1995-1-1 (CEN 2004), i.e. Equation (4). Both the individual and the characteristic values are provided. The predictions by Eq. (4) are determined based on the actual density values of the specimens. As shown in this plot, EN 1995-1-1 (CEN 2004) overestimates the strength determined by the 5%-offset method for all series; confer also the values in Table 4. The predictions of Eq. (4) are better, compared to the experimental results according to the 5 mm/max f_h method. However, these predictions are still not safe-sided for four series, namely S-0, S-90, P-0 and P-90. Based on mean values and

Fig. 6 Correlation between experimentally determined embedment strengths and predictions by EN1995-1-1 (CEN 2004), Eq. (4). (Grey symbols: individual tests, predictions based on individual densities; coloured symbols: characteristic values from tests, predictions by use of characteristic density of the set) (colour figure online)

according to the 5 mm/max f_h method, Eq. (8) provides, in general, safe-side predictions. However, it underestimates severely the embedment strength parallel to grain since it does not take into account the load-to-grain angle, which was found to have a significant effect in the present study. The mean strengths in Table 4 are in good agreement with the strengths reported in the existing literature for dowels with large diameters (Table 1), for similar species and densities; i.e. the results for spruce are in good agreement with the results by Karagiannis et al. (2016) and the results for LVL are in good agreement with the results by Bader et al. (2016).

All force–displacement curves were approximated by bi-linear curves using the principle shown in Fig. 1; confer Fig. 5. The mean elastic foundation moduli ($k_{v,ser,mean}$) for all series are provided in Table 4. These values are determined based on the relative displacement recorded by LVDTs 1, 2, 3, 4, according to Eq. (10). The values recorded by LVDTs 5, 6, according to Eq. (11) resulted in approx. 40% smaller stiffness values of $k_{v,ser}$ on average. Moreover, the mean ratios between the non-elastic and the elastic foundation moduli are given in Table 4. As indicated by these ratios, the elastic behaviour was followed by a slight increase in the force level (hardening) with the exception of series S-0, where the post-elastic behaviour was characterized by a rather constant force level for increasing deformation. The hardening behaviour was more profound in specimens

Fig. 7 Correlation between experimentally determined stiffness and predictions by EN1995-1-1 (CEN 2004) according to Eq. (7) by use of the effective diameter according to Eq. (13) (grey symbols: individual tests, coloured symbols: mean values) (colour figure online)

loaded in the perpendicular to grain direction; confer Table 4. The experimental results are compared to the predictions by EN1995-1-1 (CEN 2004)-Eq. (7) in Fig. 7. The comparison is made in terms of the embedment stiffness ($K_{v,ser}$). The predictions are made by using the effective diameter according to Eq. (13) in Eq. (7). The experimental set-up (Fig. 2a, b) resembles a double-shear connection with external steel plates and therefore the value of Eq. (7) was multiplied by 4 (2 shear planes $\times$ 2 for steel-to-timber configuration according to EN1995-1-1 (CEN 2004)). This is an approximation and thus the comparison in Fig. 7 should be considered as indicative. As shown in Fig. 7, the predictions by Eurocode overestimate the stiffness. This observation may be explained by the fact that the thickness is not taken into account by Eq. (7), although it has a significant (almost linear) influence for short penetration lengths (Stamatopoulos and Malo 2020). Moreover, according to experimental results, specimens loaded parallel to grain have higher stiffness compared to specimens loaded perpendicular to grain, which is not taken into account by Eq. (7). Equation (9) underestimates significantly the foundation modulus and cannot be extrapolated for threaded rods.

Figure 8 presents the correlation between the embedment strength (determined by the 5%-offset method and the 5 mm/max f_h method) and the density or the compressive strength. The corresponding Pearson correlation coefficients are given in Table 5. Due to relatively small sample sizes, these values should be treated as indicative. Based on the values in Table 5, the compressive strength is positively correlated with the embedment strength (with the exception of LVL-0 series). For spruce and pine glulam specimens, the density is positively correlated only for loading parallel to grain, while for perpendicular to grain loading the density seems to be uncorrelated with the embedment strength. For LVL specimens, the embedment strength was positively correlated with density. Finally, the embedment strength was positively correlated with the density of the whole specimens for all series; see the values in parentheses in Table 5. This finding

Fig. 8 Correlation between embedment strength and density or compressive strength **Table 5** Pearson correlation coefficients between embedment strength and density-compressive strength

Parameters	Spruce glulam		Pine glulam		Spruce LVL	
	S-0	S-90	P-0	P-90	LVL-0	LVL-90
$\rho - f_{h,5\%-\text{offset}}$	0.86 (0.48)	− 0.05 (0.39)	0.39 (0.42)	− 0.04 (0.33)	0.16 (0.36)	0.64 (0.56)
$f_c - f_{h,5\%-\text{offset}}$	0.47	0.39	0.77	0.33	− 0.17	0.53
$\rho - f_{h,5\text{mm}/\text{max}f_h}$	0.87 (0.51)	− 0.31 (0.53)	0.47 (0.25)	− 0.21 (0.23)	0.35 (0.53)	0.63 (0.50)
$f_c - f_{h,5\text{mm}/\text{max}f_h}$	0.83	0.48	0.39	0.25	− 0.23	0.56

Values in parenthesis: correlation with the density of the whole specimen

may be explained by the fact that the embedment strength is dependent on the deformation levels, and therefore the stiffness of a specimen as a whole may influence the embedment strength, especially for perpendicular to grain loading.

3.2 Bending tests of threaded rods

Figure 9a shows the curves obtained by testing (in terms of bending moment-bending angle) and Fig. 9b depicts a photograph taken during testing. The yielding moments were determined by use of the 5%-offset as specified by ISO10984-1:2009 (ISO 2009a); see also Fig. 9. The mean and the characteristic yielding and ultimate moments obtained by tests are summarized in Table 6. The characteristic values were determined according to EN14358:2016 (CEN 2016), as specified by EN14592:2008 (CEN 2012b). The characteristic values in Table 6 are much higher than the prediction of EN1995-1-1 (CEN 2004), Eq. (6), i.e. $M_{y,Rk} = 4.38 \cdot 10^5 \text{ N mm}$ (by use of $f_{u,k} = 830 \text{ N/mm}^2$ and $d_{ef} \approx 1.10 \cdot d_1$ as an approximation). This overestimation may partly be explained by the fact that rods are hardened

during the rolling of their threads. However, the huge deviation to the experimental results suggests that Eq. (6) underestimates the yielding moment of threaded rods.

4 Conclusion

An experimental study on the mechanical properties of laterally loaded steel threaded rods with wood screws embedded in softwood was presented in this paper. The core and outer thread diameter of the threaded rods were $d_1 = 16.1 \text{ mm}$ and $d = 22.0 \text{ mm}$, respectively. Embedment tests were performed on glulam specimens made of spruce and pine, and LVL specimens made of spruce. Specimens were loaded either parallel or perpendicular to grain. The embedment strength was determined both by use of the 5%-offset and the 5 mm/max f_h methods. Moreover, the elastic and non-elastic foundation moduli were determined. Tests were also carried out with a smooth dowel instead of the threaded rod. The diameter of the smooth dowel was 16 mm, i.e. approximately equal to the diameter of the core diameter of the threaded

Fig. 9 Bending moment–angle curves (a) and photograph from test (b)

(a)

(b)

Table 6 Results from bending tests: yielding and ultimate moments

Parameter	Units	Mean value (CoV)	Characteristic values ^a
$M_{5\%-offset}$	(N mm)	7.63×10^5 (0.02)	6.87×10^5 (7.25×10^5)
M_u	(N mm)	9.76×10^5 (0.02)	8.79×10^5 (9.40×10^5)
$M_{5\%-offset}/M_u$	(–)	0.78	0.78 (0.77)

^aThe value in parenthesis is determined without assuming a minimum coefficient of variation of 5% according to EN14358:2016 (CEN 2016)

rod. To investigate possible correlations between the embedment and the compressive strength, series of compressive tests were carried out on rectangular blocks cut from the specimens; these blocks were cut from the same lamination where the threaded rod or dowel was inserted. Moreover, the density was also measured in the same lamination. Finally, a series of three-point bending tests of threaded rods was carried out. The main conclusions of the present study are summarized as follows:

- The embedment strength determined at 5 mm displacement (or as the maximum if there is a clear maximum) according to EN383:2007 (CEN 2007) was considerably higher compared to the 5%-offset method according to ISO10984-2:2009 (ISO 2009b).
- The embedment strength parallel to grain is higher than perpendicular to grain. This is in agreement with the predictions by EN1995-1-1 (CEN 2004), but in contrast to the expression for self-tapping screws derived by Bejtka (2005).
- The experimentally determined mean embedment strength was found to be in good agreement with experi-

mental results in the literature from tests with large-diameter dowels and similar species, for example with Karagiannis et al. (2016) for spruce and Bader et al. (2016) for LVL.

- The predictions for the characteristic embedment strength according to EN1995-1-1 (CEN 2004) are not safe-sided in general.
- The embedment capacity of specimens with threaded rods was higher compared to smooth dowels, i.e. the thread has a positive effect on the strength. The presence of the thread resulted—on average—in 13% higher mean capacity for the 5%-offset method and 18% higher mean capacity for the 5 mm/max f_h method. To allow benchmarking with the rules for screws, the embedment strengths were determined by use of the effective diameter according to EN1995-1-1 (CEN 2004), i.e. an effective diameter of 1.1 times the core diameter was used.
- The embedment stiffness was quantified in the tests. It was found that the arrangement of the displacement sensors has an influence on the elastic foundation modulus. The load-to grain angle has also an effect on the embedment stiffness, as specimens loaded parallel to grain were stiffer. Moreover, the experimental results indicate that the predictions of EN1995-1-1 (CEN 2004) overestimate the stiffness.
- In general, the compressive strength was found to be positively correlated with the embedment strength. For spruce and pine glulam, the density according to ISO13061-2 (ISO 2014) was found to be positively correlated with the embedment strength for parallel to grain loading. The correlation between the embedment strength and the density of the whole specimen (instead

of the density according to ISO13061-2 (ISO 2014)) was positive for all series.

- The characteristic yielding moment of threaded rods is significantly higher compared to the prediction by EN1995-1-1 (CEN 2004). This observation may be explained by steel-hardening during the rolling of the threads, but also suggests that the expression by EN1995-1-1 (CEN 2004) underestimates the yielding moment.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

- ASTM (2013) ASTM D5764–97a standard test method for evaluating dowel-bearing strength of wood and wood-based products. ASTM, West Conshohocken
- Bader TK, Schweigler M, Serrano E, Dorn M, Enquist B, Hochreiner G (2016) Integrative experimental characterization and engineering modeling of single-dowel connections in LVL. *Constr Build Mater* 107:235–246. <https://doi.org/10.1016/j.conbuildmat.2016.01.009>
- Bejtka I (2005) Verstärkung von Bauteilen aus Holz mit Vollgewindeschrauben (Reinforcement of components made of wood with fully threaded screws). Universitätsverlag Karlsruhe, Karlsruhe
- Blaß HJ, Bienhaus A, Krämer V (2000) Effective bending capacity of dowel-type fasteners. In: Paper presented at the proceedings of the 33rd CIB-W18 meeting, Delft, Netherlands
- Blaß HJ, Bienhaus A, Krämer V (2001) Effective bending capacity of dowel-type fasteners. In: Paper presented at the proceedings of international RILEM symposium on joints in timber structures, Stuttgart, Germany
- Blaß HJ, Krüger O (2010) Schubverstärkung von Holz mit Holzschrauben und Gewindestangen (Shear reinforcement of wood with wood screws and threaded rods). KIT Scientific Publishing, Karlsruhe
- CEN (2004) NS-EN 1995-1-1:2004 + A1:2008 + A2:2014: Design of timber structures—part 1–1: general—common rules and rules for buildings. European committee for standardization, Brussels
- CEN (2007) EN 383:2007—timber structures. Test methods. Determination of embedment strength and foundation values for dowel type fasteners. European Committee for Standardization, Brussels
- CEN (2009) EN 409:2009 timber structures—tests methods—determination of the yield moment of dowel type fasteners. European Committee for Standardization, Brussels
- CEN (2012a) EN 408:2010+A1:2012: timber structures—structural timber and glued laminated timber—determination of some physical and mechanical properties. European Committee for Standardization, Brussels
- CEN (2012b) EN 14592:2008+A1:2012: timber structures—Dowel type fasteners—requirements. European Committee for Standardization, Brussels
- CEN (2013) EN 14080–2013: timber structures—glued laminated timber and glued solid timber—requirements. European Committee for Standardization, Brussels
- CEN (2016) EN 14358:2016: timber structures: calculation and verification of characteristic values. European Committee for Standardization, Brussels
- Cepelka M, Malo KA (2018) Moment resisting on-site splice of large glulam elements by use of mechanically coupled long threaded rods. *Eng Struct* 163:347–357. <https://doi.org/10.1016/j.engstruct.2018.02.071>
- Ehlbeck J, Werner H (1992) Softwood and hardwood embedding strength for dowel-type fasteners. Background of the formulae in Eurocode 5, draft April 1992. In: Paper presented at the proceedings of the 25th CIB-W18 meeting Åhus, Sweden
- ETA Danmark A/S (2017) European technical assessment ETA-11/0024: Screws for use in timber constructions, Denmark
- ETA Danmark A/S (2019) European technical assessment ETA-11/0030: Screws and threaded rods for use in timber constructions, Denmark
- Franke S, Quenneville P (2011) Bolted and Dowelled connections in radiata pine and laminated veneer lumber using the European Yield Model. *Aust J Struct Eng* 12(1):13–27. <https://doi.org/10.7158/13287982.2011.11465075>
- Franke S, Franke B, Tuhkanen E (2018) Test methods for determination of design parameters of fasteners. In: Sandhaas C, Munch-Andersen J, Dietsch P (eds) Design of connections in timber structures: a state-of-the-art report by COST Action FP1402/WG3. European Cooperation in Science and Technology, pp 33–59
- ISO (2009a) ISO10984–1 timber structures—Dowel type fasteners—part 1: determination of yield moment. International Organization for Standardization
- ISO (2009b) ISO10984–2 timber structures—Dowel type fasteners—part 2: determination of embedding strength. International Organization for Standardization
- ISO (2013) ISO 898–1 mechanical properties of fasteners made of carbon steel and alloy steel—part 1: bolts, screws and studs with specified property classes—coarse thread and fine pitch thread. ISO
- ISO (2014) ISO 13061–2:2014(E): physical and mechanical properties of wood—test methods for small clear wood specimens—part 1: determination of density for physical and mechanical tests. ISO

- Johansen KW (1949) Theory of timber connectors: vol publication no. 9. International Association of Bridges and Structural Engineering, Bern
- Karagiannis V, Málaga-Chuquitaype C, Elghazouli AY (2016) Modified foundation modelling of dowel embedment in glulam connections. *Constr Build Mater* 102:1168–1179. <https://doi.org/10.1016/j.conbuildmat.2015.09.021>
- Lied K, Nordal K (2016) A conceptual study of glulam connections using threaded rods and connecting circular steel profiles. Master thesis. NTNU Norwegian University of Science and Technology, Trondheim, Norway
- Mills M (2008) Bolted timber connections (internal research report). University of Auckland
- Mori T, Nakatani M, Kawahara S, Shimizu T, Komatsu K (2008) Influence of the number of fastener on tensile strength of lagscrew-bolted glulam joint. In: Paper presented at the Proceedings of the 10th World Conference on Timber Engineering, Miyazaki, Japan
- Santos CL, De Jesus AMP, Morais JLL, Lousada JLPC (2010) A comparison between the EN 383 and ASTM D5764 test methods for Dowel-Bearing strength assessment of wood: experimental and numerical investigations. *Strain* 46(2):159–174. <https://doi.org/10.1111/j.1475-1305.2008.00570.x>
- Sawata K, Yasumura M (2002) Determination of embedding strength of wood for dowel-type fasteners. *J Wood Sci* 48(2):138–146. <https://doi.org/10.1007/BF00767291>
- Stamatopoulos H, Malo KA (2015) Withdrawal capacity of threaded rods embedded in timber elements. *Constr Build Mater* 94:387–397. <https://doi.org/10.1016/j.conbuildmat.2015.07.067>
- Stamatopoulos H, Malo KA (2016) Withdrawal stiffness of threaded rods embedded in timber elements. *Constr Build Mater* 116:263–272. <https://doi.org/10.1016/j.conbuildmat.2016.04.144>
- Stamatopoulos H, Malo KA (2020) On strength and stiffness of screwed-in threaded rods embedded in softwood. *Constr Build Mater* 261:119999. <https://doi.org/10.1016/j.conbuildmat.2020.119999>
- Suffiad J (2008) Bolted timber connections perpendicular to the grain (internal research report). University of Auckland
- VTT Expert Services (2013) European Technical Approval ETA-13/0504: Metsä Wood Kerto glued components, Finland
- Whale LRG, Smith I (1986) The derivation of design clauses for nailed and bolted joints in Eurocode 5. In: Paper presented at the proceedings of the 19th CIB-W18 meeting Florence, Italy

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