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. 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
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 \( F_h,5\text{mm} \) 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 \( F_h,2.1\text{mm} \) 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:

\[
F_h = \frac{F_{h,i}}{d \cdot t} \tag{1}
\]

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

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):

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

\[
k_{90} = \begin{cases} 
1.35 + 0.015 \cdot d, & \text{Softwood} \\
1.30 + 0.015 \cdot d, & \text{LVL} 
\end{cases} \tag{5}
\]

\[
M_{y,k} = 0.3 \cdot f_{h,k} \cdot d^{2.6} \tag{6}
\]

where:
- $f_{h,k}$ is the characteristic embedment strength of wood in N/mm²;
- $M_{v,Rk}$ is the characteristic yielding moment of the fastener in N·mm;
- $\rho_k$ is the characteristic wood density in kg/m³;
- $\beta$ 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/mm²) is given as function of the mean timber density $\rho_{\text{mean}}$ (in kg/m³) and the diameter of the fastener $d$ (in mm) by:

$$K_{v,ser} = \rho_{\text{mean}}^{1.5} \cdot d/23$$  \hspace{1cm} (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, $\rho$ in kg/m³, $d$ in mm):

$$f_h = \frac{0.022 \cdot \rho^{-0.24} \cdot d^{-0.3}}{(2.5 \cdot \cos^2 \alpha + \sin^2 \alpha)}$$  \hspace{1cm} (8)

$$k_{v,ser} = \frac{(0.22 + 0.014 \cdot d) \cdot \rho}{1.17 \cdot \sin^2 \beta + \cos^2 \beta}$$  \hspace{1cm} (9)

where $\alpha$ 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 | $\beta = 0^\circ$ | $\beta = 90^\circ$ |
|--------|------------------|------------------|
|        | $k_{s,0}$ [N/mm²] | $f_{s,0}$ [N/mm²] | $k_{s,90}$ [N/mm²] | $f_{s,90}$ [N/mm²] |
| Santos et al. (2010) | 1586 (20.7%)$^a$ | 46.4 (9.1%)$^a$ | 521 (23.7%)$^a$ | 21.1 (17.1%)$^a$ |
| Pine (Pinus pinaster), MC ≈ 12%, t = 30mm Dowels: $d = 14$ mm | 1693 (17.7%)$^b$ | 46.2 (12.6%)$^b$ | 504 (24.4%)$^b$ | 28.6 (18.2%)$^b$ |
| EN383, $\rho_m \approx 550 – 570$ kg/m$^3$ | 400 kg/m$^3$, $t = 40$ mm | 430 kg/m$^3$, $t = 40$ mm | 495 kg/m$^3$, $t = 40$ mm | 600 kg/m$^3$, $t = 40$ mm |
| Karagiannis et al. (2016) | $d = 12$ mm: | $d = 12$ mm: | $d = 12$ mm: | $d = 12$ mm: |
| Spruce (Picea abies),MC ≈ 10% $\rho_m \approx 430$ kg/m$^3$, $t = 40$ mm | 376 (15.4%) | 29.4 (7.9%) | 137 (30.7%) | 14.7 (11.9%) |
| 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 Dowels: $d = 16/20$ mm | 35.2 (15.0%) | $d = 20$ mm: | 34.0 (16.3%) | 17.9 (16.6%) |
| ASTM D5764, 5%-offset method | | | | |
| Franke and Quenneville (2011) | 742 ($d = 12$ mm: | 44.2 (8.2%)$^a$ | 230 | 26.7 (7.1%)$^a$ |
| Radiata pine LVL,MC ≈ 11% $\rho_m \approx 600$ kg/m$^3$, $t = 46$ mm | 45.6 (7.2%)$^b$ | 38.0 (8.1%)$^b$ | 4.5 (6.7%)$^b$ | 35.1 (6.7%)$^b$ |
| ASTM D5764 (Half hole) | 896 ($d = 12/16$ mm: | 42.6 (5.4%)$^a$ | 265 | 27.2 (7.8%)$^a$ |
| Dowels: $d = 12/16/20$ mm | 43.6 (5.7%)$^b$ | 43.6 (5.7%)$^b$ | 35.1 (6.7%)$^b$ | 35.1 (6.7%)$^b$ |
| $^a$Values at 5 mm displacement (or max $f_{s,0}$) | $d = 20$ mm: | 1212 | 40.4 (5.9%)$^a$ | 27.5 (5.5%)$^a$ |
| | | | 40.6 (5.7%)$^b$ | 33.2 (6.0%)$^b$ |
| | $d = 20$ mm: | | | |
| Sawata and Yasumura (2002) | No data | $d = 12$ mm: | No data | $d = 12$ mm: |
| Spruce (Picea jezoensis) | 35.4 (10.5%)$^a$ | 37.1 (10.6%)$^b$ | 18.6 (17.4%)$^b$ | 18.6 (17.4%)$^b$ |
| Fir (Abies sachalinensis) | 32.6 (13.2%)$^a$ | 33.8 (12.9%)$^b$ | 14.3 (17.3%)$^a$ | 17.9 (16.1%)$^b$ |
| $\rho_m \approx 400$ kg/m$^3$ | $d = 16$ mm: | 33.9 (11.2%)$^a$ | 34.3 (11.1%)$^b$ | 13.3 (20.3%)$^a$ |
| EN383, Dowels: 12/16/20 mm, t = 32 mm | $d = 20$ mm: | 34.3 (11.1%)$^b$ | 15.3 (20.9%)$^b$ | 15.3 (20.9%)$^b$ |
| $^a$ Values using 5% offset method | | | | |
| | $d = 20$ mm: | | | |
| 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 | 24.9 | 24.9 |
| $MC$: (20 °C-65% relative humidity) | $d = 20$ mm: | $d = 20$ mm: | $d = 20$ mm: | $d = 20$ mm: |
| EN383, (5 mm/max $f_{s,0}$) | 37.7 | | | |
| Dowels: $d = 12/20$ mm | | | | |

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

$^1$Results 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 $f_{s,0} = 660$ N/mm² and $f_{u,0} = 830$ 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.
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 $LVLD$). 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, $\beta$ (deg) | Mean density* $\rho$ (kg/m$^3$) in parenthesis: range | $\rho$ (kg/m$^3$) | Number of tests |
|--------|---------------|----------------|------------------------------------|------------------------------------------------------|------------------|-----------------|
| S-0    | Threaded rod  | Spruce glulam  | 0                                  | 401 (361–444)                                         | 328              | 6               |
| S-90   | Threaded rod  | 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  | Spruce LVL    | 0              | 515 (463–545)                       | 461                                                   | 10               |
| LVL-90 | Spruce LVL    | 90             | 507 (484–552)                       | 454                                                   | 10               |
| SD-0   | Smooth dowel  | Spruce glulam  | 0                                  | 420 (402–446)                                         | 367              | 5               |
| SD-90  | Smooth dowel  | Spruce glulam  | 90                                 | 401 (380–427)                                         | 354              | 6               |
| PD-0   | Pine glulam   | 0              | 430 (407–449)                       | 377                                                   | 5               |
| PD-90  | Pine glulam   | 90             | 448 (439–465)                       | 393                                                   | 5               |
| LVLD-0 | Spruce LVL    | 0              | 515 (505–545)                       | 451                                                   | 5               |
| LVLD-90| Spruce LVL    | 90             | 517 (492–550)                       | 453                                                   | 5               |

* Determined according to ISO13061-2 (ISO 2014)
EN383:2007 (CEN 2007). The average value of these displacements \( v \) was used as the embedment displacement:

\[
v = \frac{v_{LVDT,1} + v_{LVDT,2} + v_{LVDT,3} + v_{LVDT,4}}{4}
\]  

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

\[
v_{abs} = \frac{v_{LVDT,5} + v_{LVDT,6}}{2}
\]

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 (\( F_h,2.1 \)) 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 \( 40 \times 40 \) 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 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):

\[
M_y = \frac{F_y \cdot l_4}{4}
\]

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

![Example of compressive test of a rectangular block](image)
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 ($F_{h,2.1\text{mm}}$) 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 $F_{h,\text{rod,mean}}/F_{h,\text{dowel,mean}}$ 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.:

$$d_{ef} = 1.10 \cdot d_1$$

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.

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           | S-90        | PD-90      |
|                           | SD-0          | SD-90       |            |
|                           | LVL-0         | LVL-90      | LVLD-0     |
|                           | LVL-90        | LVLD-90     |            |
| Method: 5%-offset         |               |             |            |
| $F_{h,\text{rod,mean}}$  | 18.48         | 14.90       | 24.24      |
| CoV$_{F_h}$               | 0.14          | 0.18        | 0.06       |
| $F_{h,\text{dowel,mean}}$ | 1.13          | 1.03        | 1.17       |
| Method: 5 mm/max $f_h$    |               |             |            |
| $F_{h,\text{rod,mean}}$  | 20.82         | 18.87       | 26.66      |
| CoV$_{F_h}$               | 0.13          | 0.13        | 0.05       |
| $F_{h,\text{dowel,mean}}$ | 1.20          | 1.20        | 1.16       |

*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.

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.
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 $f_{th}$ 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, LVL-90 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 $d_{e} \approx 1.10 \cdot d_{f}$) which is in good agreement with the experimentally determined values.

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

### 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/mm²) | 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/mm²)     | 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   |
| \( f_c(N/mm²)a \)            | 24.14         | 2.45        | 27.70      | 2.67        | 27.73 | 12.31  |
| Emb. strength (Method: 5%-offset)b |           |             |            |             |       |        |
| \( f_h,mean \) (N/mm²)       | 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   |
| \( f_h(N/mm²)a \)            | 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       |             |       |        |
| \( k_{90,mean} = f_{h,0,mean}/f_{h,90,mean} \) | 1.91          | 1.63        | 1.52       |             |       |        |
| \( (f_h/f_c)_mean \)         | 0.84          | 3.37        | 0.62       | 3.12        | 0.99  | 1.60   |
| CoV \( (f_h/f_c)_mean \)     | 0.13          | 0.25        | 0.11       | 0.26        | 0.11  | 0.08   |
| \( f_h/f_c)_mean \)          | 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/mm²)       | 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   |
| \( f_h(N/mm²)a \)            | 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       |             |       |        |
| \( k_{90,mean} = f_{h,0,mean}/f_{h,90,mean} \) | 1.56          | 1.69        | 1.41       |             |       |        |
| \( (f_h/f_c)_mean \)         | 0.94          | 4.41        | 0.79       | 4.12        | 1.09  | 1.87   |
| CoV \( (f_h/f_c)_mean \)     | 0.07          | 0.22        | 0.13       | 0.25        | 0.11  | 0.07   |
| \( f_h/f_c)_mean \)          | 0.89          | 5.63        | 0.77       | 4.72        | 1.15  | 1.83   |
| Eurocode Predictions, Eq. (4) |               |             |            |             |       |        |
| \( f_h,mean \) (N/mm²)b,c    | 27.03         | 17.31       | 30.65      | 19.39       | 34.74 | 21.86  |
| \( f_h(N/mm²)c \)            | 22.16         | 15.04       | 25.89      | 14.91       | 31.11 | 19.57  |

a The characteristic values were determined assuming lognormal distribution according to EN14358:2016 (CEN 2016)
b The embedment strength was determined by use of the effective diameter, \( d_{ef} = 1.10 \cdot d_t \)
c The mean and characteristic embedment strength was determined by use of the mean and characteristic density of the series in Eq. (4), respectively.
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 bilinear 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 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 x 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...
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. $M_{y,Rk} = 4.38 \cdot 10^5$ N mm (by use of $f_u,k = 830$ N/mm² 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 $d_1 = 16.1$ mm and $d = 22.0$ 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

Figure 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 |
| $\rho - f_h,5\%$-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) |
| $f_c - f_h,5\%$-offset | 0.47 | 0.39 | 0.77 | 0.33 | 0.17 | 0.53 |
| $\rho - f_h,5\text{mm}/f_h,\text{max}$ | 0.87 (0.51) | 0.31 (0.53) | 0.47 (0.25) | 0.21 (0.23) | 0.35 (0.53) | 0.63 (0.50) |
| $f_c - f_h,5\text{mm}/f_h,\text{max}$ | 0.83 | 0.48 | 0.39 | 0.25 | 0.23 | 0.56 |

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

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

$^a$The value in parenthesis is determined without assuming a minimum coefficient of variation of 5% according to EN14358:2016 (CEN 2016).
of the density according to ISO 13061-2 (ISO 2014) was positive for all series.

- The characteristic yielding moment of threaded rods is significantly higher compared to the prediction by EN 1995-1-1 (CEN 2004). This observation may be explained by steel-hardening during the rolling of the threads, but also suggests that the expression by EN 1995-1-1 (CEN 2004) underestimates the yielding moment.

**Author contributions** The first author has written the paper, designed the experimental set-up, contributed to concept development and post-processing of experimental results and supervised the experimental work. The second author has contributed to concept development and post-processing of experimental results and has critically reviewed the manuscript. The third author has carried-out all experiments.

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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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