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INFLUENCE OF TEST METHODS ON THE PARALLEL TO GRAIN EMBEDMENT STRENGTH AND FOUNDATION MODULUS CHARACTERIZATION

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ABSTRACT: Different test setups have been reported in the literature for the determination of the embedment strength in timber elements. These variances hinder a straightforward comparison between available test data. It is difficult to determine if the source of variability lies in intrinsic timber properties or is related to the test protocol used. This paper aims to provide a better insight into the influence of embedment strength test methods, comparing experimental results from different test setups within the guidelines of EN 383 and ASTM D 5764-97a for Scots pine wood (*Pinus sylvestris*) and Spruce (*Picea Abies*). A robust statistical analysis was performed to identify statistically significant differences between the groups evaluated. The analysis of the parallel to grain embedment strength showed that the results differed between standards, pointing out the potential bias inserted in the embedment properties given their evaluation method. Moreover, the thickness of the specimen tests also proved to influence the yield and ultimate embedment strength for the wood species tested.

KEYWORDS: Embedment Strength, Test methods, Dowel-type Connections, RILEM TC TPT

1 INTRODUCTION

The embedment strength, which is a property of utmost importance in dowel-type timber connections, is often determined through empirical expressions proposed in the literature. For instance, the European standard (Eurocode 5) [1] proposes an expression relating the dowel diameter and the wood density to the embedment strength, while the American Wood Council NDS [2] proposes an expression only based on the wood density. Nonetheless, because these empirical expressions are generalized, they fail to reliably predict the embedment strength for some wood species.

In that sense, alternative expressions have been studied based on experimental analysis of varying wood species [3,4]. The American standard, ASTM D 5764-97a [5], and the European standard, EN 383 [6], are the two most often used test standards for this purpose. The main difference between these standards is that ASTM D 5764-97a [5] allows for both half-hole and full-hole test specimens and bases the embedment strength on the yield load. On the other hand, EN 383 only allows for a full-hole test specimen and bases the embedment strength on the ultimate load capacity within 5 mm deformation. The two standards also reflect different dowel load conditions. Whereas the EN 383 standard loads the dowel on its ends, the ASTM D5764-97a [5] standard loads the dowel uniformly along its length. As a result, the EN 383 [6] test method is more likely to produce a bending effect than the ASTM D5764-97a [5], as reported in [7]. In terms of displacement measurement, EN 383 [6] recommends a local measure between the fastener and timber specimen, while ASTM D5764-97a [5] proposes a global measure between upper and lower support.

The standards also differ concerning the loading protocol. While ASTM 5764-97a [5] predicts a single loading cycle in displacement control, EN 383 [6] includes an additional cycle in load control of 40% of the estimated load-carrying capacity. This cycle was included to obtain the foundation modulus but at the expense of slightly conservative embedment values [8,9].

Moreover, when it comes to the thickness of the specimens, the protocols also differ. While EN 383 [6] proposes a range for the specimen thickness varying from

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1.5 up to 4 times the dowel diameter, ASTM D 5764-97a [5] only defines a minimum value (the smaller between 38 mm and two times the diameter). The European standard defines a maximum value for the thickness mainly to avoid the bending of the dowel.

The variances between test protocols and specimen dimensions described hinder a straightforward comparison between available test data. It is difficult to determine if the source of variability lies in intrinsic timber properties or is related to the test protocol used. This paper aims to provide a better insight into the influence of embedment strength test methods, comparing experimental results from different test setups within the guidelines of ASTM D 5764-97a [5] and EN 383 [6].

2 MATERIALS AND METHODS

2.1 EMBEDMENT TESTS

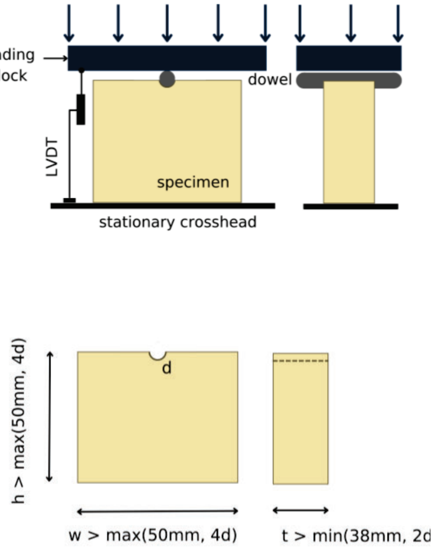
This study investigates the effect of different test setups and protocols on the embedment properties of Scots pine timber. The influence of the thickness of the specimens, as well as the test configuration (load application) are investigated within the guidelines of ASTM D 5764-97a [5] and EN 383 [6]. A total of 264 specimens of Scots pine *(Pinus sylvestris*) were tested according to both standards for a dowel diameter (*d*) of 8 mm. Their minimum dimensions are shown in Figure 1 and Figure 2, respectively.

Within the scope of ASTM D 5764-97a [5], the height (*h*) and width (*w*) of the specimens were defined as *h* = 80 mm and *w* = 95 mm. Regarding the thickness (*t*), four different groups were tested: 20 mm, 25 mm, 30 mm, and 35 mm, whereas only one group with *t* = 20 mm was considered for EN 383 [6]. The height and width for the specimens tested according to the European standard were *h* = 160 mm and *w* = 65 mm. Mean and standard deviation values of oven-dry density (ρ) and moisture content (MC), calculated from mass and volume, are presented in Table 1.

Table 1. *Basic properties of Scots pine specimens tested according to ASTM D 5764-97a [5] and EN 383 [6] for a dowel diameter of 8 mm*

Thickness [mm]	N [no.]	ρ [kg/m^3]	MC [%]
ASTM D 5764-97a [5]			
20	53	500±48	11.5±1.0
25	52	495±58	12.1±0.4
30	45	511±49	11.7±0.8
35	60	497±51	12.0±0.6
EN 383 [6]			
20	54	522±69	11.2±1.3

An additional investigation was conducted regarding the method of load application within the scope of EN 383 [6]. Two test configurations - Setup 1 and Setup 2 - were evaluated (see Figure 2) since both were founded in the literature [10,11]. The main difference between setups lies in the load application. For Setup 1 the load is applied to the timber specimen while the dowel is kept fixed. For Setup 2, the load is applied on the steel dowel while keeping the specimen fixed. Scots pine (*Pinus sylvestris*) and Spruce (*Picea abies*) were tested for dowels of diameter 12 mm for both setups. Similar, mean and standard deviation values of ρ and MC are presented in Table 2.



(a)

(b)

Figure 1: *(a) Test setup for ASTM D 5764-97a [5] and (b) corresponding specimen*

Table 2. *Basic properties of Scots pine and Spruce specimens tested according to EN 383 [6] for dowel diameter of 12 mm*

Setup [-]	Thickness [mm]	N [no.]	ρ [kg/m^3]	MC [%]
Scots pine (*Pinus sylvestris*)				
Setup 1	30	21	445±62	11.1±0.4
Setup 2	30	21	424±58	11.1±0.5
Spruce (*Picea abies*)				
Setup 1	25	23	357±45	11.5±0.7
Setup 2	25	23	365±44	11.4±0.5

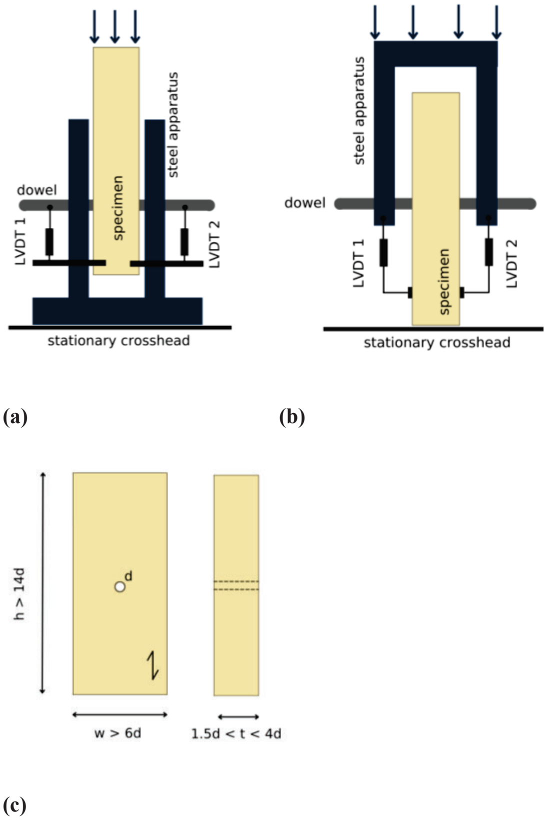


Figure 2: *Test setup for EN 383 [6] (a) Setup 1, (b) Setup 2, and (c) corresponding specimen*

The half-hole specimens tested according to ASTM D5764-97a [5] were loaded at displacement control at a constant rate of 0.02 mm/s. The test setup, presented in Figure 3, has a hydraulic actuator, equipped with a load cell of 25 kN, and a displacement range of 200 mm. To measure the joint slip, one linear variable differential transformer (LVDT) was fixed at the steel loading block. The tests were terminated at an embedment of one-half the fastener diameter or after the maximum load was reached.

The full-hole specimens tested according to EN 383 [6] were loaded into five different branches. The first part consisted of a loading branch, followed by a plateau where the load was kept constant and equal to 40% of the estimated capacity for 30 seconds. After, the load was diminished until it reached 10% of the estimated capacity and then kept constant for another 30 seconds. Thereafter, the test was performed under displacement control with a constant rate of 0.02 mm/s for specimens with dowels of 8 mm and 0.025 mm/s for dowels of 12 mm in diameter. Both loading and unloading branches were force controlled with a constant rate of 0.025 kN/s and 0.013 kN/s for dowels of 8 mm and 12 mm in diameter, respectively. The test setup, presented in Figure 4, has a hydraulic actuator, equipped with a load cell of 25 kN, and a displacement range of 200 mm. To measure the joint slip, two LVDTs were fixed on both sides of the connection. These two LVDTs were placed diagonally opposite the central timber member. The tests were terminated after the maximum load was reached or when the actuator displacement reached the threshold of 5 mm.

Figure 3: *Test setup within ASTM D 5764-97a [5]*

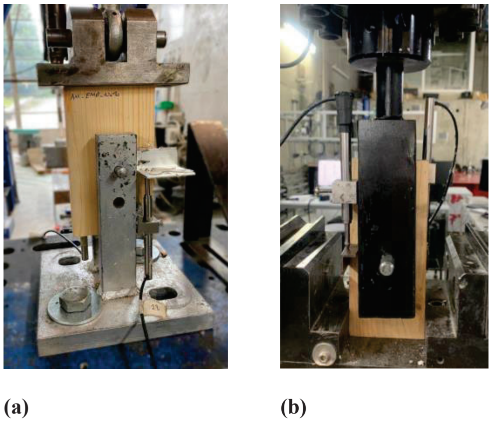


Figure 4: *Test setups within EN 383 [6] (a) setup 1, and (b) setup 2*

2.2 QUANTIFICATION OF PROPERTIES

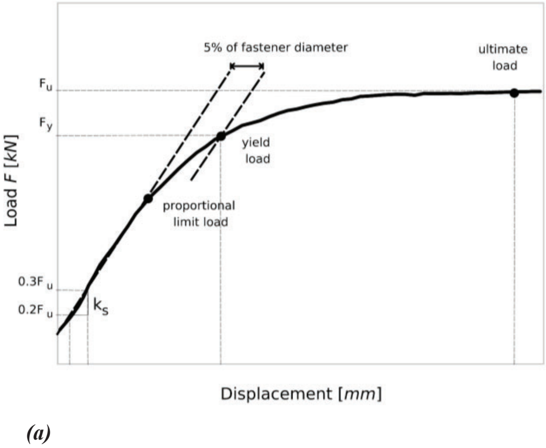
The embedment properties retrieved from the recorded load-displacement curves for ASTM D5764-97a [5] and EN 383 [6] protocols, are shown in Figures 5a and 5b, respectively. A significant difference between these standards lies in the definition itself of embedment strength. While the EN 383 [6] definition is based on the ultimate load capacity, the ASTM D5764-97a [5] standard defines the embedment strength based on the yield load. The yield load is obtained by the intersection between the offset line of the initial linear portion of the load-deformation curve by a deformation equal to 5% of the fastener diameter. Nonetheless, if the offset line and the load-deformation curve do not intersect, the yield load can be regarded as the ultimate one. The ultimate embedment strength ($f_{h,u}$) and the yield embedment strength ($f_{h,y}$) were calculated according to Equation (1) and Equation (2), respectively.

$$f_{h,u} = \frac{F_{max}}{dt} \tag{1}$$

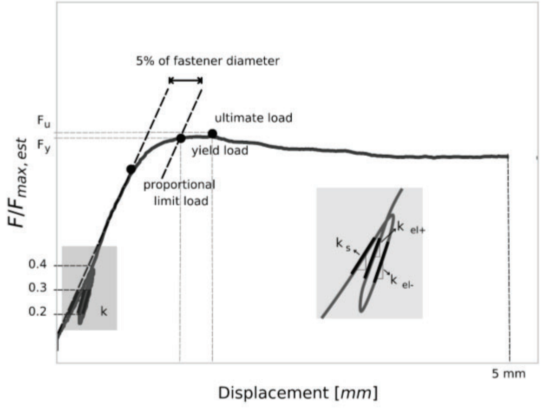
$$f_{h,y} = \frac{F_{yield}}{dt} \tag{2}$$

Although ASTM D5764-97a [5] does not make a reference to the initial or elastic foundation modulus (K_s), it can be interpreted as the slope of the initial linear portion of the load-displacement curve divided by the product of d and t. Nguyen et al. [12] computed K_s through a linear regression between 15% and 40% of the ultimate load. Xu et al. [13] considered the portion between 10% and 40% of the ultimate load, as recommended by EN 383 [6]. Santos et al. [7] only refer to the slope of the linear portion, not defining the4 range of load from which it was obtained. In this study, the portion between 20% and 30% of the ultimate load was chosen to be consistent with the approach adopted for the EN 383 [6] protocol based on the discussion of Van Blokland *et al.* [9]. The load at which the load-deformation curve deviates from a straight line fitted to its initial linear portion is known as the proportional limit load.

From the EN 383 [6] protocol, three foundation moduli were determined: the initial foundation modulus (K_s), related to the initial loading branch, and the elastic foundation modulus (K_e) related to the slopes of the unloading (K_{e-}) and reloading cycles (K_{e+}). According to Van Blokland et al. [9], non-linearity can be observed in the last part of unloading, which is between 10% and 20% of the maximum estimated force ($F_{\text{max,est}}$) in their tests. Therefore, to avoid this, the load levels between 20–30% of $F_{\text{max,est}}$ were used to obtain K_{e-}. Consistently, the same range was adopted for K_s and K_{e+}.



(a)



(b)

Figure 5: *Embedment parameters determined from the load-displacement curves for (a) ASTM D 5764-97a [5], and (b) EN 383 [6] (based on Van Blokland et al. [9])*

2.3 STATISTICAL ANALYSIS

A statistical software program (IBM SPSS Software, IBM, Armonk, United States) was used to perform the analysis with a significance level of 0.05. The normality of the data was diagnosed by the Shapiro-Wilk test and homoscedastic by the Levene test. A one-way Bonferroni analysis of variance (ANOVA) was performed to compare the embedment properties within different thicknesses tested according to ASTM D5764-97a [5]. Due to the non-normality of the data, bootstrapping procedures (1000 resamplings; 95 % CI, bias-corrected and accelerated - BCa) were implemented to obtain greater reliability of the results to correct deviations from the normality of the sample distribution and to present a 95 % CI for differences among means [14].

The statistical significance regarding the test protocol (ASTM D5764-97a [5] vs. EN 383 [6]) and setup (Setup 1 vs. Setup 2 from EN 383 [6]) was assessed via an independent t-test since data was diagnosed as normally distributed through the Shapiro-Wilk test and their variances was verified to be homogeneous by the Levene test.

3 RESULTS AND DISCUSSION

3.1 INFLUENCE OF THICKNESS WITHIN ASTM D5764-97a [5] PROTOCOL

The largest differences were found for the embedment strength, as a result of thickness. A p-value<0.001 was achieved in the analysis of variance for both $f_{h,y}$ and $f_{h,u}$. A post-hoc Bonferroni analysis indicated that the source of difference relies on the group with a thickness of 35 mm, which can also be noted by visually comparing the mean load-displacement curves shown in Figure 6 and the distribution of $f_{h,u}$ showed in Figure 7.

To ensure the representativeness of the data, a power (by mean of averages, OpenEpi) [15] was calculated for the ultimate embedment strength, comparing the high (mean

= 42.29 MPa, standard deviation = 4.9, sample size = 53, thickness = 20 mm) and low group (mean = 33.61 MPa, standard deviation = 5.4, sample size = 60, thickness = 35 mm) and power of 100 % was achieved.

It is important to highlight here that the Bonferroni analysis pointed out a significant difference (p-value = 0.009) in density for the group of thickness = 30 mm compared to the others (see also Table 1). Therefore, the group shall not be considered for the analysis regarding the thickness influence since it is not representative.

No significant difference was found for the initial foundation modulus, which can also be noted by its distribution presented in Figure 8.

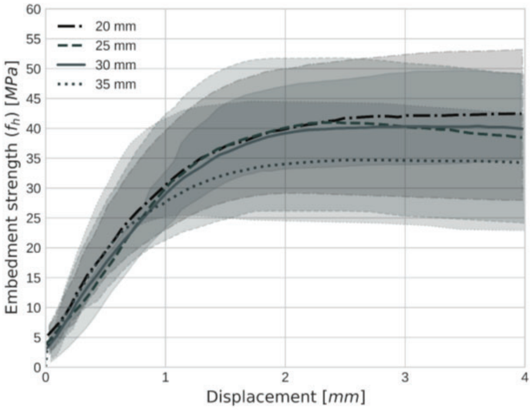


Figure 6: *Mean load-displacement curves for specimens tested according to ASTM D 5764-97a [5] for a dowel of 8 mm*

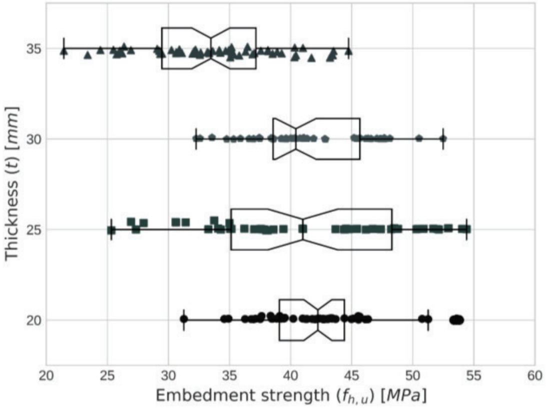


Figure 7: *Embedment strength for different member thicknesses according to ASTM D 5764-97a [5] for a dowel of 8 mm*

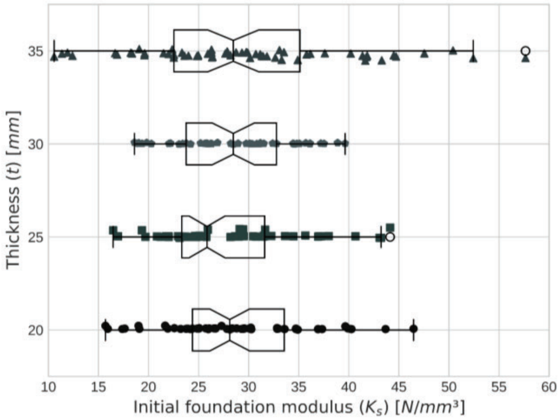


Figure 8: *Initial foundation modulus for different member thickness according to ASTM D 5764-97a [5] for a dowel of 8 mm*

The relationships between density and embedment strength ($f_{h,u}$) is presented in Figure 9.

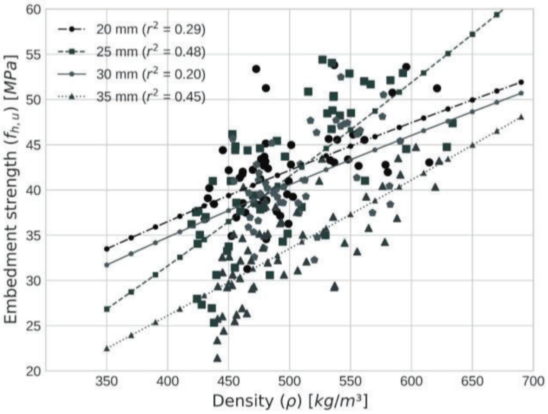


Figure 9: *Scatter plot of density versus embedment strength for specimens tested according to ASTM D 5764-97a [5] for a dowel of 8 mm*

3.2 ASTM D5764-97a vs. EN 383

A significant difference (p-value<0.001) was found, according to the independent t-test, for all the embedment properties retrieved from the load-displacement curves obtained according to ASTM D5764-97a [5] and EN 383 [6] protocols. The statistical test was also conducted to guarantee that there was no statistically significant difference in the densities of each group to avoid bias in the results.

Figure 10 shows the mean-load displacement curves according to both standards. The distribution of the ultimate embedment strength ($f_{h,u}$) and the initial foundation modulus (K_s) is presented in Figures 11 and 12, respectively. The relationships between density and embedment strength ($f_{h,u}$) is presented in Figure 13.

The analysis showed that the $f_{h,u}$ obtained from the ASTM D5764-97a [5] curve is 18.7% bigger than the one obtained from EN 383 [6]. The difference decreases to 9.9% when comparing $f_{h,y}$ from ASTM D5764-97a [5]

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with $f_{h,u}$ from EN 383 [6]. In terms of the initial foundation modulus (Ks), the EN 383 protocol yielded a value 39.7% bigger than the one obtained from ASTM D5764-97a [5].

Frankel and Magnière [11] and Van Blokland *et al.* [9] compared the test setup between the investigated standards for Spruce (*Picea abies*) with dowel diameters of 12 mm and 10 mm, respectively, and conclude that the test specimen configuration (half-hole or full-hole), has a relatively small and not statistically significant effect on the embedment strength. Both test configurations followed the loading protocol of EN 383. Nonetheless, Van Blokland *et al.* [9] argue that despite no significant difference being found, embedment strength was around 7% higher for half-hole specimens. The study also found that K_s was 80–180% higher when determined in the half-hole compared to the full-hole test setup, differing from the results found in this study. Santos et al. [7] performed a comparison for Maritime Pine (*Pinus pinaster*) with a dowel diameter of 14 mm by changing both the specimen configuration and the loading protocol. The results showed no significant difference in terms of K_s and $f_{h,u}$. This could indicate the variability of test methods is also dependent on the wood species evaluated and the dowel diameter. An additional comparison was made to infer the influence of the diameter of Scots pine (*Pinus sylvestris*) (see Figure 14) within the scope of EN 383 [6]. Specimens with the same slenderness ratio were considered for the comparison (t/d = 2.5). The largest difference was found for K_s. The specimens with a dowel diameter of 8 mm had a mean initial foundation modulus 42.3% higher than the ones with 12 mm. With respect to the embedment strength, a difference of 17.4% was found.

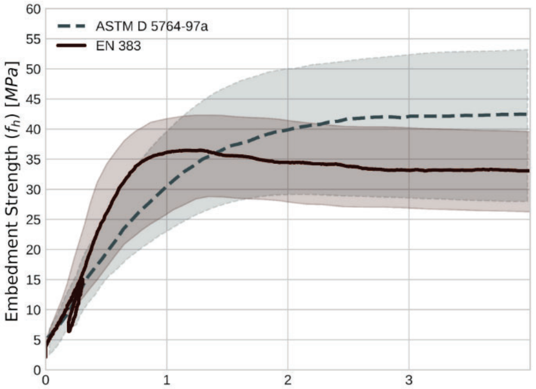

Figure 10: *Mean load-displacement curves according to ASTM D 5764-97a [5] and EN 383 [6] for a dowel of 8 mm and timber specimen 20 mm thick*

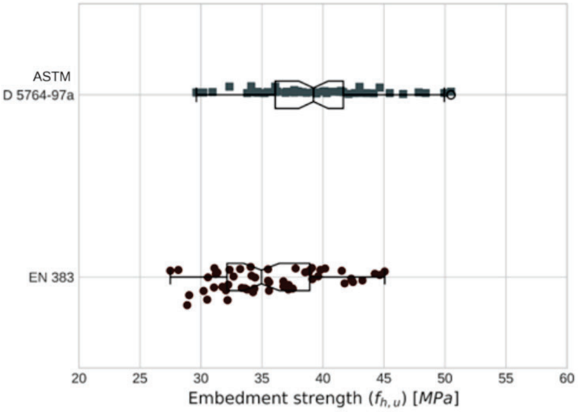

Figure 11: *Embedment strength according to ASTM D 5764-97a [5] and EN 383 [6] for a dowel of 8 mm and timber specimen 20 mm thick*

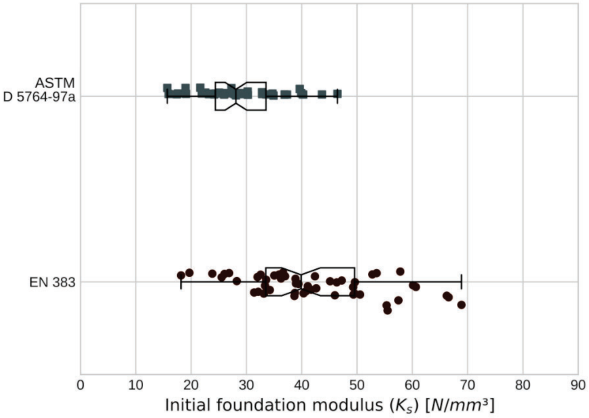

Figure 12: *Initial foundation modulus according to ASTM D 5764-97a [5] and EN 383 [6] for a dowel of 8 mm and timber specimen 20 mm thick*

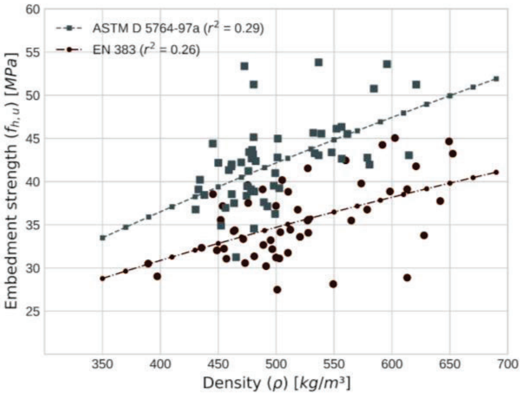

Figure 13: *Scatter plot of density versus embedment strength for specimens tested according to ASTM D [5] 5764-97a and EN 383 [6] for a dowel of 8 mm and timber specimen 20 mm thick*

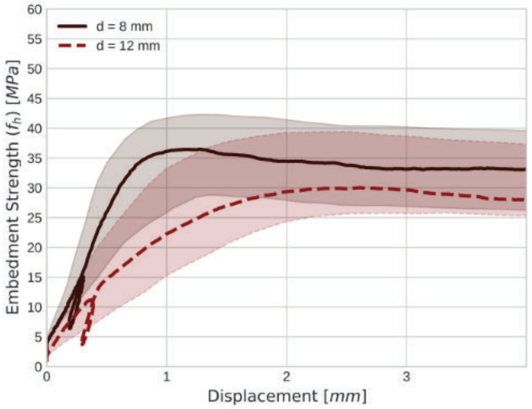

Figure 14: *Mean load-displacement curves for Scots pine (Pinus sylvestris) according to EN 383 for a dowel of 8 mm (t/d = 2.5) and 12 mm (t/d = 2.5) in diameter*

3.3 INFLUENCE OF TEST SETUP WITHIN EN 383

For the test setup within the scope of EN 383 [6] investigated in this study, no statistically significant difference was found for the embedding properties. The mean displacement curves for both wood species investigated are shown in Figures 15 and 16. This led to the conclusion that once the embedment failure is guaranteed within the experiment, that is, there was no premature splitting or bending of the dowel, the impact of the test setups evaluated is not significant to the results. This was guaranteed by following the recommendations of specimen dimensions of EN 383. A slenderness ratio (t/d) between 2 and 2.5 was adopted for the tests presented.

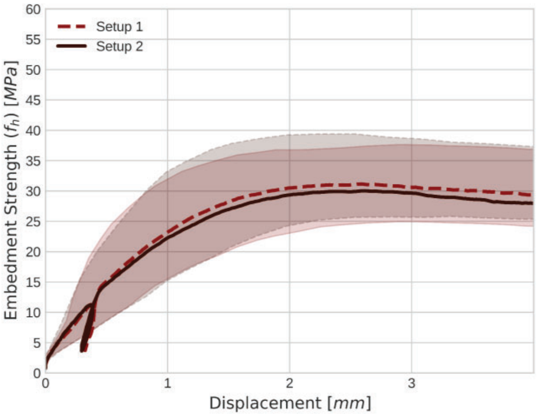

Figure 15: *Mean load-displacement curves for Scots pine (Pinus sylvestris) according to EN 383 for a dowel of 12 mm in diameter and specimens' thickness of 30 mm*

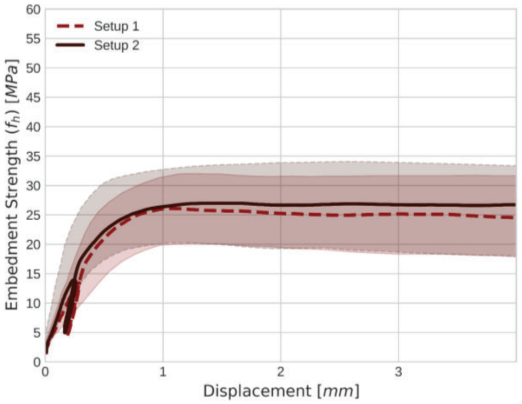

Figure 16: *Mean load-displacement curves for Spruce (Picea abies) according to EN 383 for a dowel of 12 mm in diameter and specimens' thickness of 30 mm*

4 CONCLUSIONS

This paper presents an experimental investigation related to testing methods and setup for the timber embedment strength and foundation modulus, two important properties for the connection behaviour. The investigation mainly covered the influence of specimen thickness within the scope of ASTM D5764-97a [5] and the influence of the test protocol in the quantification of the timber embedment according to the grain direction. The latter investigation was conducted by evaluating the embedment strength following both ASTM D5764-97a [5] and EN 383 [6] standards. An additional investigation was also conducted regarding the test setup (load application) of EN 383.

The results showed that the thickness had a significant impact on specimens with 35 mm (4.4*d*) compared to the ones with 20 mm (2.5*d*) and 25 mm (3.1*d*). No difference was found in the initial foundation modulus (K_s). This result points to the need for a deeper investigation regarding the influence of the member thickness on the embedment strength, especially since reference cross-sections of timber elements, commonly used in timber connections, have thicknesses greater than 40 mm. A broader experimental campaign involving other wood species, as well as a robust numerical analysis shall be conducted to confirm the trend found. For this, the half-hole specimen should be used to avoid dowel bending.

The investigation between test protocols resulted in a significant difference for both the embedment strength (yield – $f_{h,y}$ and ultimate – $f_{h,u}$) and the initial foundation modulus (K_s). The results differed from similar investigations found in the literature on different wood species. This could indicate the variability of test methods is also dependent on the wood species evaluated and the dowel diameter.

No significant difference was found in terms of the load application according to the EN 383 [6] standard.

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