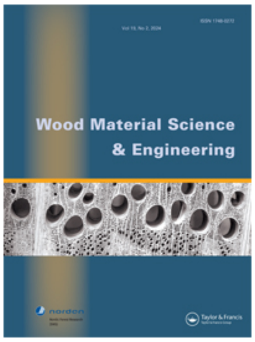

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Influence of test methodology on the characterization of the parallel-to-grain timber embedment strength and foundation modulus of dowels

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ABSTRACT

A reliable determination of the embedment strength and foundation modulus of timber elements is critical for the design and safety assessment of joints in timber structures. However, the existence of various test configurations for characterising the embedding properties of large diameter steel fasteners in timber elements poses challenges in directly comparing and utilising available test data. This paper aims to provide an insight into the influence of embedment property test methods, comparing experimental results from different test setups within the guidelines of the EN 383 and ASTM D 5764-97a standards for European softwood species, Scots pine wood (*Pinus sylvestris*) and Norway spruce (*Picea abies*). In addition to the test guidelines, the thickness of the specimen and the application of the load was evaluated within the protocols. A comprehensive statistical analysis was performed to identify statistically significant differences between the groups evaluated. The results of the analysis revealed disagreement between the standards in the evaluation of the strength of the embedding, highlighting the potential bias inserted by the experimental setup and protocol. Furthermore, it was proven that the thickness of the specimens influences both the embedding strength and the foundation modulus of the wood species tested. Finally, no distinctions were observed between tensile and compressive loading within the guidelines of the EN 383 standard.

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Embedment strength; foundation modulus; dowelled connections; test methods

1. Introduction

The embedment strength is of utmost importance in dowel-type timber connections since they affect the joint's load-bearing capacity and failure mode. This property is often determined through empirical expressions proposed in the literature. The European standard (Eurocode 5 – EC5) (Standard EN 1995-1-1 2014) introduces a formula that correlates the dowel diameter and timber density with the embedment strength along the grain direction. The expression is originated from the studies performed by Whale and Smith (1989, 1986) and Whale *et al.* (1987, 1986), who conducted embedment tests mainly on European softwoods and some tropical hardwoods. On the other hand, the American Wood Council NDS (Standard NDS 2015) proposes an expression that relies solely on timber density, based on the results of the embedment test obtained by Wilkinson (1991) for American softwoods. However, because these empirical expressions are generalised, their reliability is compromised for determining the embedment strength of different wood species.

According to the investigation of Glišović *et al.* (2012), the Eurocode 5 expression presented good results for some European softwood species, however, there are some deviations for timber species with higher densities ($\rho \geq 500\,\mathrm{kg/m^3}$). Hübner (2008) evaluated the Eurocode 5 expression for ash wood (*Fraxinus excelsior L.*), a European hardwood, and concluded that 93% of the experimental results are larger than the normative estimation. Branco *et al.* (2016) conducted embedment tests on Maritime pine (*Pinus pinaster*), a European softwood, and Iroko (*Milícia excelsa*), an African hardwood. They concluded that the Eurocode 5 expression yielded satisfactory results for Maritime pine, while slightly underestimating the embedment strength of Iroko. Similar findings were reported by Santos *et al.* (2015) regarding Maritime pine. Sandhaas *et al.* (2013) performed embedment tests with five different wood species among which, three tropical hardwoods, and concluded that the Eurocode 5 embedment strength equation penalised wood species with higher densities, while simultaneously overestimating the embedment strength of species with lower densities. This statement is supported by the work of Leijten *et al.* (2004), which involves a considerable amount of experimental data, including (Whale and Smith 1989, Sawata and Yasumura 2002). Sandhaas *et al.* (2013) discussed that the embedment strength did not vary with the dowel diameter, and therefore the formula suggested in Eurocode 5 can be simplified by dismissing the dowel diameter. Various alternative expressions have been examined through experimental analyses involving different wood species (Ehlbeck 1992, Leijten *et al.* 2004, Jumaat *et al.*

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2006, Franke and Quenneville 2010). Additionally, the influence of other parameters in the embedment strength has been investigated, such as the grain orientation (Schoenmakers *et al.* 2010, Schweigler *et al.* 2016), moisture content (Rammer and Winistorfer 2001), steel hardness (Yurrita and Cabrero 2018), dowel surface conditions (Xu *et al.* 2021, 2022), among others.

In contrast to the extensive literature on embedment strength, there is relatively limited research available regarding the embedment foundation modulus, as pointed by Schweigler *et al.* (2019). This could be related that commonly used analytical design methods (such as the European Yield Model - Johansen 1949) only take the embedment strength for the the estimation of the maximum capacity of mechanical connections. Nonetheless, the complete slip-curve is essential for accurately describing the non-linear behaviour of the dowel embedment into wood members. The latter can serve as input of non-linear numerical models that can be included in the current design of timber structures (Bader *et al.* 2016, Schweigler *et al.* 2018a), as well as the assessment of progressive collapse and seismic performance of multi-storey timber buildings that involve sophisticated models (e.g. Rodrigues *et al.* 2018, Voulpiotis *et al.* 2021, 2022). In this specific subject, Foschi (1974), Richard and Abbott (1975) and Yee and Melchers (1986) proposed analytical models that can be calibrated to experimental results through regression functions, which take into account parameters such as the foundation modulus, in the linear elastic and elastoplastic range, as discussed in Schweigler *et al.* (2018b).

The embedment foundation modulus property commonly presents an increasing scattering when compared to the embedment strength. This can be regarded to the sensitivity of stiffness determination from tests (Schweigler *et al.* 2019, Franke and Magnière 2014, Xu *et al.* 2022). Van Blokland *et al.* (2021) highlighted the disparity between local displacement (LVDTs) and cross-head displacements of the testing machine, indicating that global displacements are larger than local ones for the same load level. As a result, the foundation modulus differs, measuring displacement locally results in a higher foundation modulus as other parts of the test setup are precluded from deformation.

The embedment test protocols provided by the American standard, ASTM D 5764-97a (Standard D5764-9a 2007), and the European standard, EN 383 (Standard EN 383 2007), are frequently used to experimentally determine the embedment strength properties of distinct wooden species around the world (Sawata and Yasumura 2002, Franke and Quenneville 2009, Molina *et al.* 2020, Ottenhaus *et al.* 2022). ASTM D 5764-97a (Standard D5764-9a 2007) and EN 383 (Standard EN 383 2007) standards differ in their test specimen requirements and the basis for determining embedment strength. ASTM D 5764-97a allows for both half-hole and full-hole test specimens and calculates the embedment strength based on the yield load. In contrast, EN 383 only permits a full-hole test specimen and determines the embedment strength based on the ultimate load capacity within 5 mm deformation. Additionally, the two standards specify different dowel load conditions. EN 383 allows loading on the dowel's ends, while ASTM D 5764-97a prescribes a uniform load along the length of the dowel. As a result, in the EN 383 test method, the dowel is more prone to bend than in the ASTM D 5764-97a, as reported in Santos *et al.* (2010). To avoid the deformation of the dowel, EN 383 limits the specimen thickness up to 4 times the dowel diameter.

The standards also differ in terms of the loading protocol. While ASTM D 5764-97a proposes a displacement-controlled procedure until failure, EN 383 includes a load control additional cycle that ranges from 40% of the estimated load-carrying capacity (F_{est}) and 10% of this value. This cycle is included to obtain the unloading and re-loading foundation modulus, based on the work of Whale and Smith (1989). Nonetheless, the authors stated that the inclusion of this additional cycle might lead to slightly conservative embedment values.

The variations in test protocols and specimen dimensions pose challenges in conducting a direct and straightforward comparison between the available test data, raising the question of which one provides a more accurate description of the embedment behaviour in timber connections. Thus, this paper aims to evaluate the influence of test methods on the embedment properties of large diameter smooth steel dowels in solid timber, comparing experimental results from different test setups within the guidelines of ASTM D 5764-97a and EN 383. The influence of the thickness of the specimens, as well as the load application are investigated. The properties obtained from the experimental campaign conducted are also compared to available expressions proposed by normative.

2. Materials and methods

2.1. Embedment tests

The experimental investigation had the following objectives: (1) evaluate the influence of specimen thickness on the embedment properties of timber specimens obtained following the guidelines ASTM D 5764-97a, given that no upper bound of member thickness is recommended by the standard; (2) address the disparities in the embedment properties of timber specimens obtained according to ASTM D 5764-97a half-hole and EN 383 full-hole test setup; and (3) assess the differences between compressive and tensile loading embedment tests performed according to EN 383.

Two European softwoods were used in the experimental campaign, namely Scots pine (*Pinus sylvestris*) to address objectives 1 and 2 and Spruce (*Picea abies*) for objective 3. An overview of the tests conducted, dimension, species, number of specimens (n), mean and standard deviation values for oven-dry density ($\rho_{dry,m}$), moisture content (MC), and equivalent density at 12% equilibrium moisture content ($\rho_{12,m}$) are presented in Table 1.

The specimens for this study were cut to size and conditioned in an environmental chamber at a temperature of 20 degrees Celsius and 65% relative humidity before testing, as recommended by ASTM D 5764-97a and EN 383. An 8 mm diameter hole was created in each Scots pine specimen to accommodate a steel dowel, while a 12 mm diameter hole

Table 1. Overview of conducted tests and basic specimens properties.

Standard	Loading	d [mm]	t [mm]	w [mm]	a_3 [mm]	n [no.]	Species	$\rho_{dry,m}$ [kg/m^3]	MC [%]	$\rho_{12,m}$ [kg/m^3]
ASTM D 5764-97a	C	8	20	95	80	50	Scots pine	494 ± 43	12.5 ± 1.0	553 ± 49
			25			52		495 ± 58	12.1 ± 0.4	557 ± 66
			30			45		511 ± 49	11.7 ± 0.8	572 ± 44
			35			60		497 ± 51	12.0 ± 0.6	558 ± 58
EN 383	C	8	20	65	80	48	Scots pine	472 ± 49	11.1 ± 0.8	534 ± 57
	C	12	20	72	84	25	Spruce	376 ± 27	10.5 ± 0.4	419 ± 30
	T				100			384 ± 30	10.0 ± 0.4	428 ± 34

was used for Spruce specimens. The selection of specimens for the study was carried out using a random sampling approach, ensuring a representative mix of characteristics. It is noteworthy that the wood around the dowel hole was intentionally kept knot-free, although other parts of the specimen could potentially contain knots.

The test setup is presented in Figure 1 for ASTM D 5764-97a and Figure 2(a,b) for EN 383 in tension and compression, respectively, where d is the fastener diameter, t is the thickness of the specimen, w its width and a_3 the end-distance between the dowel and the loaded edge.

The half-hole specimens were loaded in displacement control at a constant rate of 0.02 mm/s following ASTM D 5764-97a guidelines. A hydraulic actuator equipped with a 25 kN load cell and a displacement range of 200 mm was used. The joint slip was measured with a linear variable differential transformer (LVDT) fixed at the steel loading block. The tests were concluded either when the embedment reached half of the fastener diameter (d) or when a 20% reduction in peak load was observed.

The test protocol following EN 383 guidelines consisted of five different branches. Initially, the full-hole specimens were loaded in load control until reaching 40% of the estimated maximum load (F_{est}), which was then maintained for 30 s. Subsequently, the load was reduced to 10% of F_{est} and held constant for another 30 s. The test was then switched to displacement control and continued until either when a 20% reduction in peak load was reached or when the actuator displacement reached a 5 mm threshold. For specimens tested with a dowel diameter of 8 mm, the force control rate was set at 0.013 kN/s, and the displacement control rate was 0.02 mm/s. For specimens with a dowel diameter of 12 mm, the force control rate was 0.025 kN/s, and the displacement control rate was 0.025 mm/s. Joint slip was measured using two LVDTs fixed on opposite sides of the connection, diagonally across the central timber member.

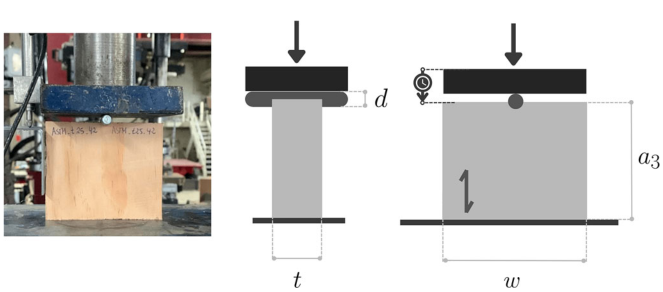

Figure 1. Test setup according to the ASTM D 5764-97a standard.

2.2. Quantification of properties

The embedment parameters retrieved from the recorded load-displacement curves for ASTM D 5764-97a and EN 383 protocols are shown in Figure 3(a,b), respectively. These standards diverge in their definition of the embedment strength, given that EN 383 bases its calculation on the ultimate load capacity, while ASTM D 5764-97a states that embedment strength corresponds to the stress retrieved from the yield load. The latter is obtained by the intersection between the offset line, which is parallel to the linear elastic range, shifted by a deformation

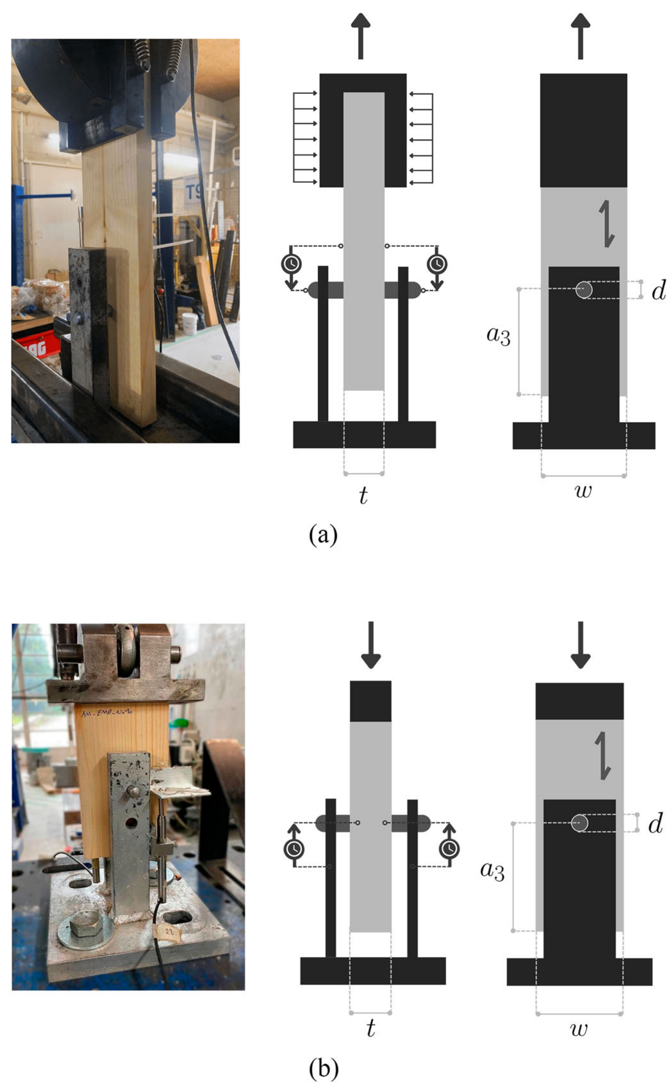

Figure 2. Test setup according to the EN 383 standard for both loading conditions: (a) loading in tension (T), and (b) loading in compression (C).

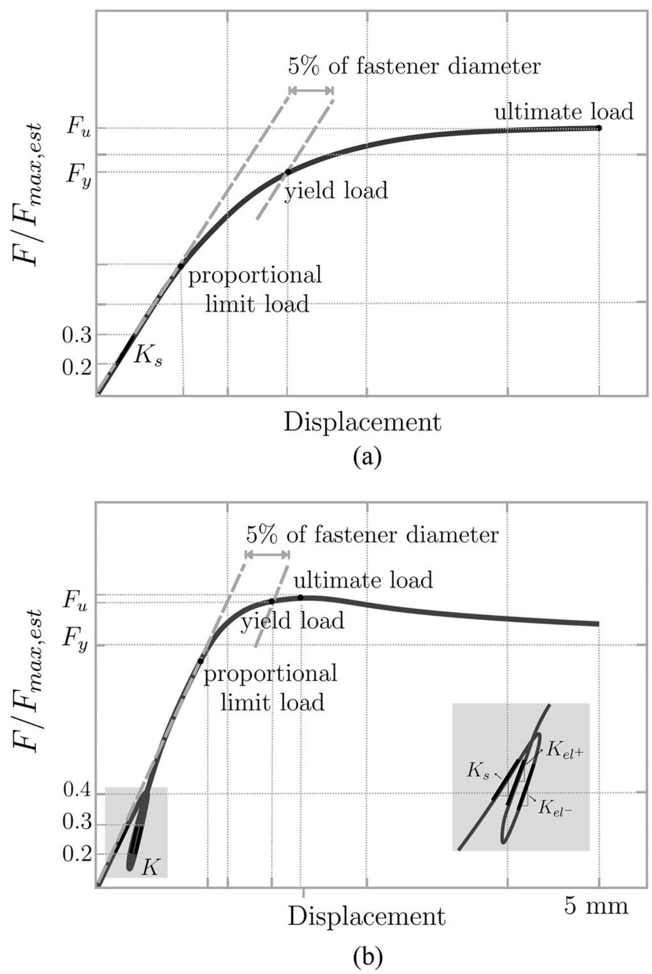

Figure 3. Embedment parameters determined from the load-displacement curves (based on Van Blokland *et al.* 2021): (a) the ASTM D 5764-97a standard, and (b) the EN 383 standard.

equal to 5% of the fastener diameter (d) and the load-deformation curve. The ultimate embedment strength ($f_{h,u}$) and the yield embedment strength ($f_{h,y}$) can be calculated according to Equations (1) and (2), respectively.

$$f_{h,u} = \frac{F_{\text{max}}}{d \cdot t} \tag{1}$$

$$f_{h,y} = \frac{F_{\text{yield}}}{d \cdot t} \tag{2}$$

Although ASTM D 5764-97a does not refer 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. In contrast, EN 383 specifies that K_s should be calculated based on the portion of the load-displacement curve between 10% and 40% of the ultimate load. However, various researchers have employed different load-displacement curve segments to calculate the parameter K_s. In their study, Nguyen *et al.* (2020) determined K_s using a linear regression within the range of 15% to 40% of the ultimate load. Meanwhile, Xu *et al.* (2022) followed the recommendation of EN 383, considering the segment between 10% and 40% of the ultimate load.

Within the EN 383 protocol, two additional stiffness properties are derived, corresponding to an additional prescribed load cycle. These properties specifically pertain to the slopes observed during the unloading phase (K_{e-}) and the reloading phase (K_{e+}). In the study conducted by Van Blokland *et al.* (2021), they identified non-linearity in the later portion of the unloading phase, occurring between 10% and 20% of the maximum estimated force ($F_{\text{max,est}}$) in their experiments. Consequently, to mitigate this non-linearity, they chose to use load levels ranging from 20% to 30% of $F_{\text{max,est}}$ to determine K_{e-}. Consistently, this same range was adopted for calculating both K_s and K_{e+}.

In alignment, to guarantee a linear range to estimate the foundation modulus, this study opted for the range between 20% and 30% for the EN 383 experiments. Although the ASTM D 5764-97a does not include the additional loading cycle, the elastic foundation modulus (K_s) was also obtained between 20% and 30% of the ultimate load to avoid any biases in the comparison of K_s between standards.

2.3. Normative embedment strength prediction formula

As discussed earlier, EN 383 and ASTM D 5764-97a differ in their definition of embedment strength (yield vs. ultimate). This difference is reflected in the empirical expressions proposed by Eurocode 5 (Standard BS EN 1995-1-1 2014) and NDS (Standard NDS 2015). The Eurocode 5 expression relates the ultimate embedment strength in the direction of the grain to the dowel diameter and timber density at 12% equilibrium moisture content (ρ_{12}) (see Equation (3)):

$$f_{h,u,m} = 0.082(1 - 0.01d)\rho_{12,m} \tag{3}$$

The expression originated from the studies performed by Whale and Smith (1989, 1986) and Whale *et al.* (1987, 1986), who conducted embedment tests mainly on European softwoods (with a density range of 400 to 500 kg/m^3) and some tropical hardwoods (with a density range of 700 to 1000 kg/m^3) following the full-hole test setup as in EN 383. The NDS, on the other hand, proposes an expression that relies solely on the timber oven-dry density for predicting embedment strength (see Equation (4)):

$$f_{h,y,m} = 0.07725\rho_{\text{dry},m} \tag{4}$$

This expression was derived for yield strength using the 5% offset method and embedment test results for American softwoods (with a density range of 360 to 590 kg/m^3) conducted by Wilkinson (1991) using the same half-hole test setup as in ASTM D 5764-97a.

The validity of the strength predictions was assessed by comparing the mean values of the yield and ultimate embedment strength obtained from the experimental campaign with the normative prediction models presented. The results of this comparison are further elaborated in the subsequent sections.

2.4. Statistical analysis

The adopted analysis utilised the statistical tool IBM SPSS Software (IBM, Armonk, United States) and the Scipy statistical library in Python. A significance level of 0.05 was chosen for all analyses. Data normality was assessed using the Shapiro-Wilk test, and homoscedasticity was checked using the Levene test. To compare embedment properties across various thicknesses in accordance with ASTM D 5764-97a, a one-way Bonferroni analysis of variance (ANOVA) was conducted. Due to deviations from normality in the data, bootstrapping procedures (1000 resamplings; 95% CI, bias-corrected and accelerated – BCa) were employed to enhance result reliability (Haukoos and Lewis 2005).

Statistical significance was determined for comparisons involving different test protocols (ASTM D 5764-97a vs. EN 383) and compressive vs. tensile procedures within EN 383 via independent t-tests. Data was confirmed to be normally distributed with homogeneous variances by the Shapiro-Wilk and Levene tests.

To explore correlations between various study parameters, Spearman's correlation coefficient was used (Spearman 1961). This non-parametric measure allows to examine associations between parameters, regardless of their distribution.

3. Results and discussion

3.1. Influence of thickness within ASTM D5764-97a protocol

This section focuses on to examine the impact of specimen thickness on embedment properties. Notably, the most substantial variations resulting from changes in thickness were observed in embedment strength. In the analysis of variance for both $f_{h,y}$ and $f_{h,u}$, highly significant p-values ($p < 0.001$) were obtained.

A subsequent post-hoc Bonferroni analysis identified that the significant differences stemmed from the group with a thickness of 35 mm (4.4d). This observation is also supported by a visual comparison of the mean load-displacement curves presented in Figure 4 and the distribution of $f_{h,y}$ shown in Figure 5. It is important to emphasise that the Bonferroni analysis highlighted a significant difference (p-value = 0.009) in the density for the 30 mm thickness group compared to the others (as shown in Table 1). Consequently, this particular group should be excluded from the analysis concerning the influence of thickness due to its lack of representativeness.

The results emphasises the importance of conducting a comprehensive investigation into the correlation between member thickness (t) and embedment strength (f_h). This is particularly relevant since commonly utilised reference cross-sections of timber elements in timber connections have thicknesses greater than 40 mm.

In Figure 6, the plot of $f_{h,u}$ over the oven-dry density, ρ_{dry}, including the correlation equation and R^2 is presented.

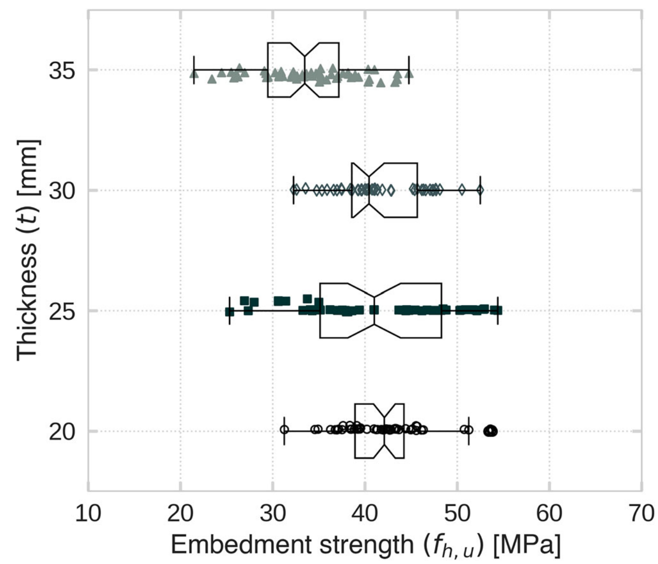

Figure 5. Embedment strength for different member thicknesses according to the ASTM D 5764-97a standard for a dowel of 8 mm.

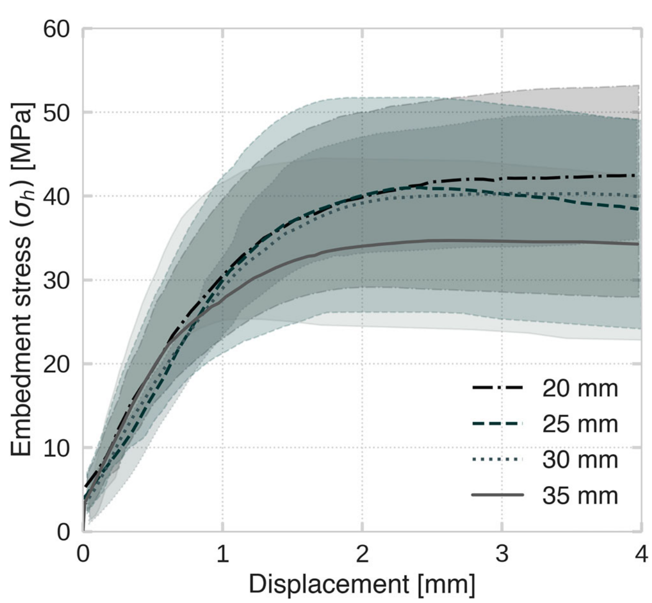

Figure 4. Mean stress-displacement curves for specimens tested according to the ASTM D 5764-97a standard for a dowel of 8 mm varying the thickness (t).

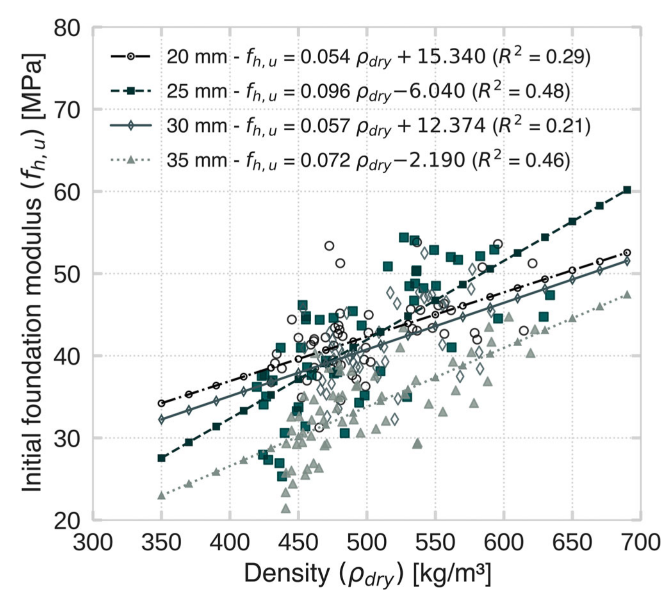

Figure 6. Scatter plot of oven-dry density versus embedment strength for specimens tested according to the ASTM D 5764-97a standard for a dowel of 8 mm.

Groups of thickness equal to 25 mm and 35 mm showed a greater fit, whereas group of 30 mm presented the lowest R^2. It is worth noting that the group with a thickness of 30 mm had a smaller sample size than the other groups, which may have contributed to the lower R^2. As expected, the scatter of data is reflected in the correlation coefficient, shown in Table 2. The strongest correlation between $f_{h,u}$ and ρ_{dry} was found for groups of thickness equal to 25 mm and 35 mm. Nonetheless, even the smallest correlation coefficient (group of 30 mm) still represents a statistically significant relationship between the variables.

No significant difference was found in terms of the mean values for the initial foundation modulus with the variation of member thickness (see Figure 7). However, in terms of the correlation with timber oven-dry density, all the groups displayed similar behaviour, exhibiting a statistically significant relationship (see Figure 8).

Table 2. Correlation of embedment parameters for different member thickness according to the ASTM D 5764-97a standard for a dowel of 8 mm.

	ρ_{dry}	$f_{h,y}$	$f_{h,u}$	K_s
(a) thickness of 20 mm				
ρ_{dry}	1	–	–	–
$f_{h,y}$	0.597	1	–	–
$f_{h,u}$	0.539	0.924	1	–
K_s	0.702	0.792	0.735	1
(b) thickness of 25 mm				
ρ_{dry}	1	–	–	–
$f_{h,y}$	0.710	1	–	–
$f_{h,u}$	0.736	0.975	1	–
K_s	0.446	0.375	0.348	1
(c) thickness of 30 mm				
ρ_{dry}	1	–	–	–
$f_{h,y}$	0.553	1	–	–
$f_{h,u}$	0.425	0.760	1	–
K_s	0.394	0.640	0.463	1
(d) thickness of 35 mm				
ρ_{dry}	1	–	–	–
$f_{h,y}$	0.481	1	–	–
$f_{h,u}$	0.634	0.708	1	–
K_s	0.366	0.778	0.556	1

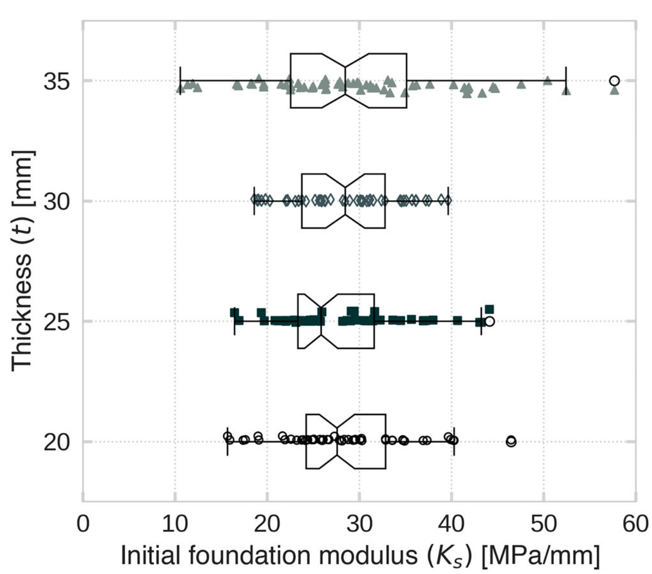

Figure 7. Initial foundation modulus for different member thickness according to the ASTM D 5764-97a standard for a dowel of 8 mm.

Finally, the predicted embedment strength according to both NDS (Equation (4) – based on oven-dry density) and Eurocode 5 (Equation (3) – based on density at 12% equilibrium moisture conntent) are compared to the experimental yield (Figure 9) and ultimate (Figure 10) embedment strength, respectively.

Although an adequate fitting was found for $f_{h,y}$ with the NDS equation in groups of 20 mm, 25 mm, and 30 mm, the values obtained for group 35 mm were overestimated by the expression. One possible explanation for this is the higher slenderness ratio of the specimens in this group (t/d = 4.375), which is outside the range of the experiments used to fit the prediction equation (between 1.5 and 3) (Wilkinson 1991).

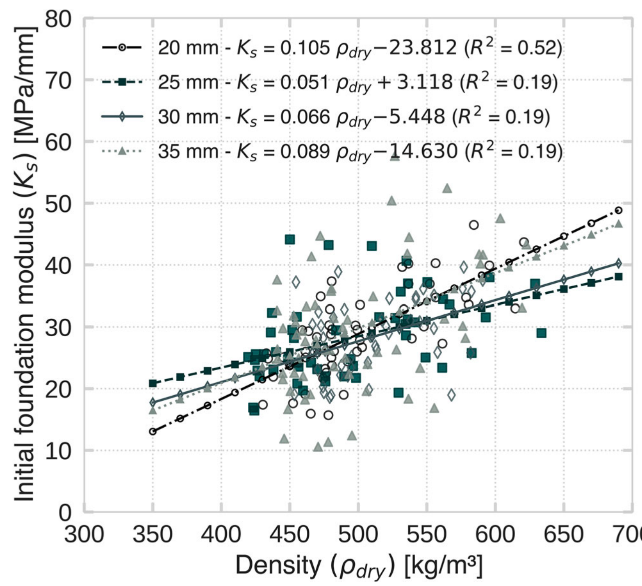

Figure 8. Scatter plot of oven-dry density versus initial foundation modulus for specimens tested according to the ASTM D 5764-97a standard for a dowel of 8 mm.

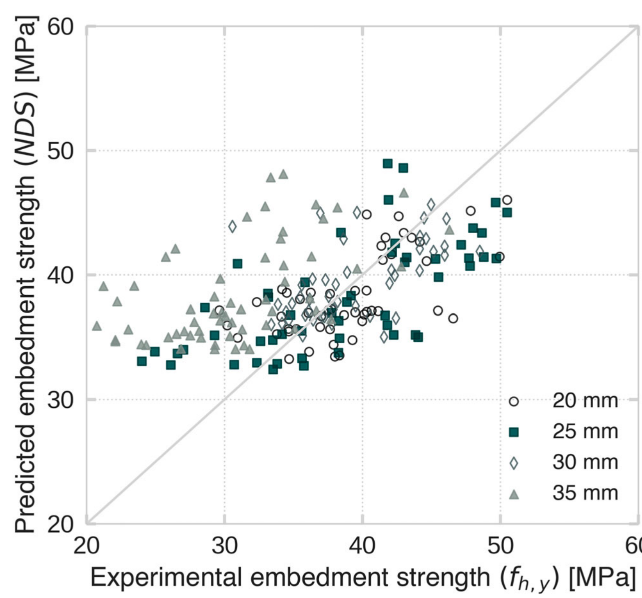

Figure 9. Comparison between experimental $f_{h,y}$ and NDS prediction model for specimens tested according to the ASTM D 5764-97a standard for a dowel of 8 mm and varying member thickness.

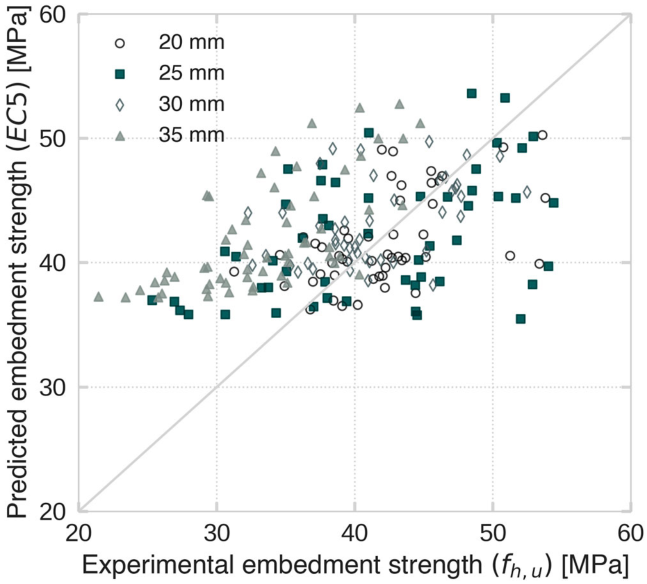

Figure 10. Comparison between experimental $f_{h,u}$ and EC5 prediction model for specimens tested according to the ASTM D 5764-97a standard for a dowel of 8 mm and varying member thickness.

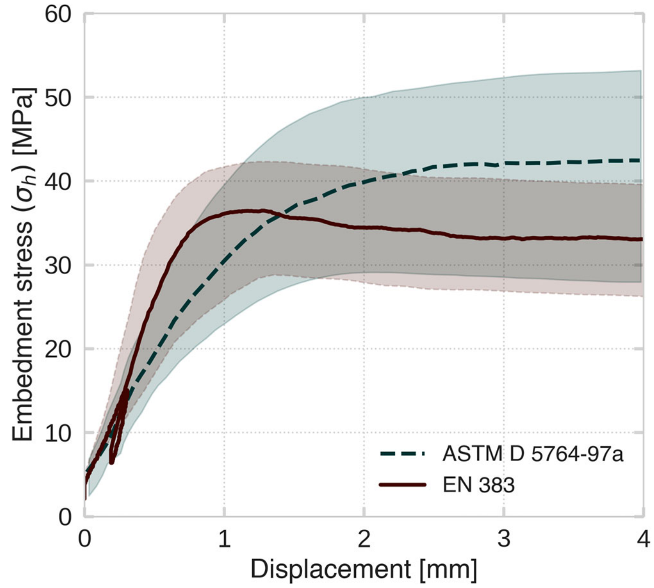

Figure 11. Mean stress-displacement curves according to the ASTM D 5764-97a and the EN 383 standards for a dowel of 8 mm and timber specimen 20 mm thick.

Furthermore, upon comparing the embedment strength results for groups with thicknesses of 20 mm, 25 mm, and 35 mm (with no statistically significant differences in mean density), it was noted that the mean yield embedment strength $f_{h,y}$ for the 35 mm group was significantly smaller than that for the other two groups. This observation aligns with the outcomes presented in Figure 9). It is very difficult to identify the origin of the observed phenomenon of decreasing embedment strength with increased timber thickness. Nonetheless, it could be linked to the larger area available for the distribution of embedment stress and the higher probability of a non-uniform loading distribution due to imperfections in the manufacturing process. It is essential to underscore that this study provides only preliminary insights, and further investigation is paramount. To explore this phenomenon more reliably, a broader experimental campaign, complemented by thorough numerical analyses, should be conducted.

The Eurocode 5 equation behaved poorly for all the groups. The primary reason for this is likely to be given to the fact that the Eurocode 5 equation was predicted based on experimental results performed according to EN 383. In contrast, the evaluations presented here are based on experimental results following the ASTM D 5764-97a standard. This discrepancy suggests potential variability introduced by the differing test setups. In the following section, a more detailed comparison of the ASTM D 5764-97a and EN 383 test protocols will be presented.

3.2. Comparison between test standards: ASTM D 5764-97a vs. EN 383

The comparison between test standards is presented for the mean slip curves according to both ASTM D 5764-97a and EN 383 in Figure 11. A significant difference (p−value < 0.001) was found, according to the independent t-test, for all the embedment properties (namely embedment strength and foundation modulus). 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. It is worth mentioning that the p-value found between oven-dry densities was 0.02 and 0.08 for the equivalent densities at 12% equilibrium moisture content. The group from EN 383 presented a mean value 4.5% and 3.4% higher than the one from ASTM D 5764-97a for $\rho_{dry,m}$ and $\rho_{12,m}$, respectively. Additionally, it is noteworthy that the width between specimens varied, as depicted in Table 1. The impact of width was not explicitly assessed in this study; however, given that the requirements regarding the specimen width given in EN 383 and ASTM are fulfilled, it is reasonable to expect a minimal influence on embedment stress. The selected widths are considered sufficient to absorb the stresses arising from dowel embedment effectively.

The distribution of the ultimate embedment strength, $f_{h,u}$, and its relationship with timber oven-dry density, is presented in Figures 12 and 13, respectively.

The statistical analysis conducted showed that the $f_{h,u}$ obtained from the ASTM D 5764-97a curve is 18.7% higher than the one obtained from EN 383. The difference decreases to 9.9% when comparing $f_{h,y}$ from ASTM D 5764-97a with $f_{h,u}$ from EN 383, taking into account the variation in the definition for estimating embedment strength as per the standards (refer to Section 2.2).

In their study, Franke and Magnière (2014), conducted comprehensive embedment tests on Spruce using full-hole tests according to EN 383 and both half-hole and full-hole tests according to ASTM D 5764-97a, all with a dowel diameter of 12 mm. Loading was applied according to the procedure used in the EN 383 standard to all test series. Consistent with the present study, the results showed that the EN 383 method yielded the lowest strength, followed by ASTM full-hole tests. The ASTM half-hole specimens exhibited the highest strength, measuring approximately 30% higher than the EN 383 results.

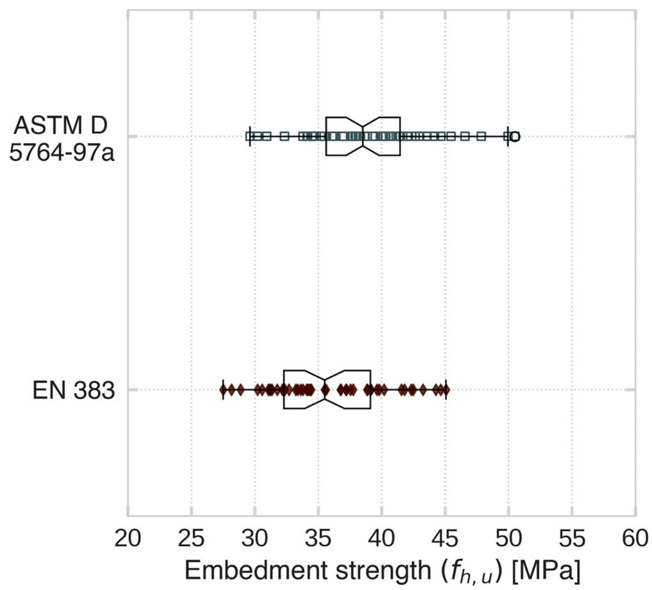

Figure 12. Embedment strength according to the ASTM D 5764-97a and the EN 383 standards for a dowel of 8 mm and timber specimen 20 mm thick.

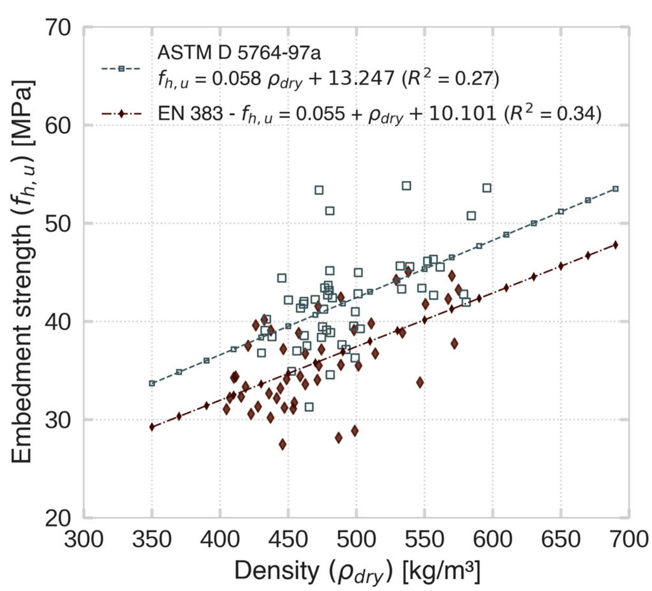

Figure 13. Scatter plot of oven-dry density versus embedment strength for specimens tested according to the ASTM D 5764-97a and the EN 383 standards for a dowel of 8 mm and timber specimen 20 mm thick.

Van Blokland *et al.* (2021) compared the test setup between the investigated standards for Spruce with a dowel diameter of 10 mm, also following the loading protocol of EN 383. The authors conclude that the test specimen configuration (half-hole or full-hole), has a relatively small and not statistically significant effect on the embedment strength. Nonetheless, they argue that despite no significant difference being found, embedment strength was around 7% higher for half-hole specimens.

Ottenhaus *et al.* (2022) compared the half-hole test setup from ASTM D 5764-97a with the tensile full-hole specimen from EN 383 on Australian softwoods Radiata Pine and Southern Pine with dowel diameters of 12.7 mm and 16 mm. All samples were subjected to preloading according to the recommendations of EN 383. The comparison showed that little difference was found between half-hole and full-hole samples. In fact, the embedment strength was around 6% lower than full-hole specimens, differing from previous studies where half-hole specimens showed higher values for the embedment strength. Similar behaviour was found by Wang *et al.* (2023), who investigated, among other parameters, the influence of half-hole and full-hole test setups on the embedment strength of birch plywood for a dowel diameter of 12 mmm. Notwithstanding, Santos *et al.* (2010) performed a comparison for Maritime Pine with a dowel diameter of 14 mm by changing both the specimen configuration and the loading protocol. The results showed no significant difference for both K_s and f_h.

Based on these findings, it is likely that the difference observed between the two standards is related to both the loading protocol and specimen configuration (half-hole and full-hole). As noted by Whale and Smith (1989), an additional cycle in the loading protocol may lead to more conservative (lower) embedment strength values. The comparison with the literature also indicates that the variability of test methods is also dependent on the wood species evaluated and the dowel diameter.

In terms of the initial foundation modulus, K_s, the EN 383 protocol yielded a mean value 39.7% bigger than the one obtained from ASTM D 5764-97a. This result differs from investigations found in the literature between test configuration, half-hole vs. full-hole specimens. While no significant difference was found between half-hole and full-hole specimens in Santos *et al.* (2010) and Ottenhaus *et al.* (2022), other studies have found significantly higher values for the half-hole test setup (Franke and Magnière 2014, Van Blokland *et al.* 2021, Wang *et al.* 2023).

The distribution of K_s can be found in Figure 14. Moreover, the relationship of K_s with ρ_{dry} is plotted in Figure 15. One can note that the values obtained from EN 383 present a very low correlation with the timber oven-dry density, differing from ASTM D 5764-97a results, in addition to the increase in the scatter (see also Table 3).

Interpreting these results is challenging due to the numerous potential influencing factors involved. One important distinction between the results presented in this study and those discussed in the literature relates to the loading protocol. The initial load cycle, as per EN 383, is performed under load control until the unloading stage, while the loading protocol in ASTM D 5764-97a follows a displacement control under monotonic load. In this study, this difference was accounted for in the experiments, whereas the aforementioned studies adhered to the loading protocol outlined in EN 383. Nonetheless, as pointed out by Schweigler *et al.* (2023), the measuring of the foundation modulus is very sensitive and might be subjected to uncertainties resulting from other factors such inaccuracies of the specimen preparation, dowel hole drilling, test setup, and displacement measurement.

Finally, the predicted embedment strength according to NDS and EC5 are compared with the respective experimental yield (as shown in Figure 16) and ultimate embedment

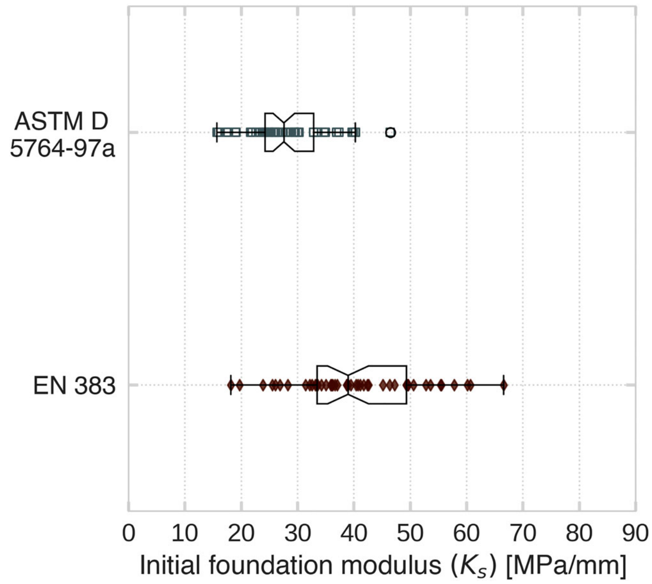

Figure 14. Initial foundation modulus according to the ASTM D 5764-97a and the EN 383 standards for a dowel of 8 mm and timber specimen 20 mm thick.

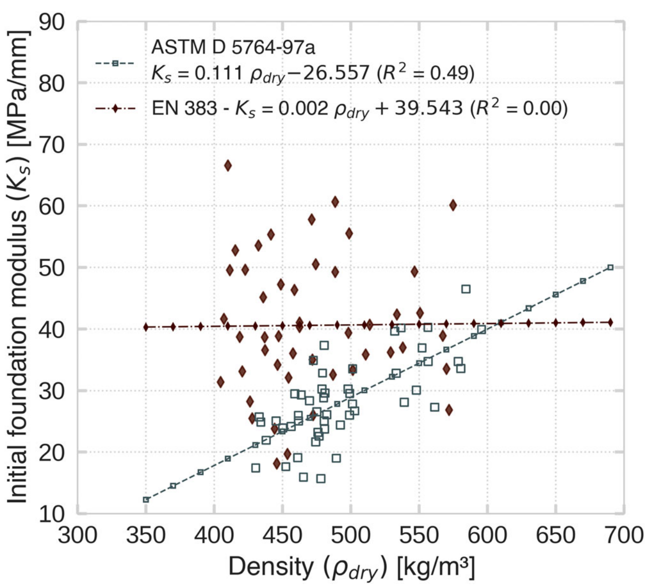

Figure 15. Scatter plot of oven-dry density versus initial foundation modulus for specimens tested according to the ASTM D 5764-97a and the EN 383 standards for a dowel of 8 mm and timber specimen 20 mm thick.

Table 3. Correlation of embedment parameters for a dowel of 8 mm and timber specimen 20 mm thick tested according to the EN 383 standard.

	ρ_{dry}	$f_{h,y}$	$f_{h,u}$	K_s
ρ_{dry}	1	–	–	–
$f_{h,y}$	0.521	1	–	–
$f_{h,u}$	0.496	0.907	1	–
K_s	-0.120	-0.128	-0.022	1

strength (Figure 17). It is emphasised herein that the evaluation of the NDS expression incorporates the oven-dry density (ρ_{dry}), while for the EC5 expression, the density at 12% equilibrium moisture content (ρ_{12}) is considered (see Equations (3) and (4)).

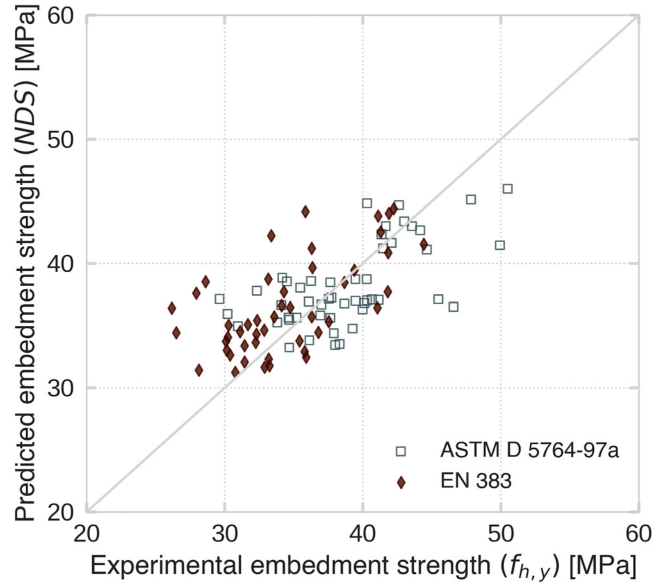

Figure 16. Comparison between experimental $f_{h,y}$ and NDS prediction model for specimens tested according to the ASTM D 5764-97a and the EN 383 standards for a dowel of 8 mm and timber specimen 20 mm thick.

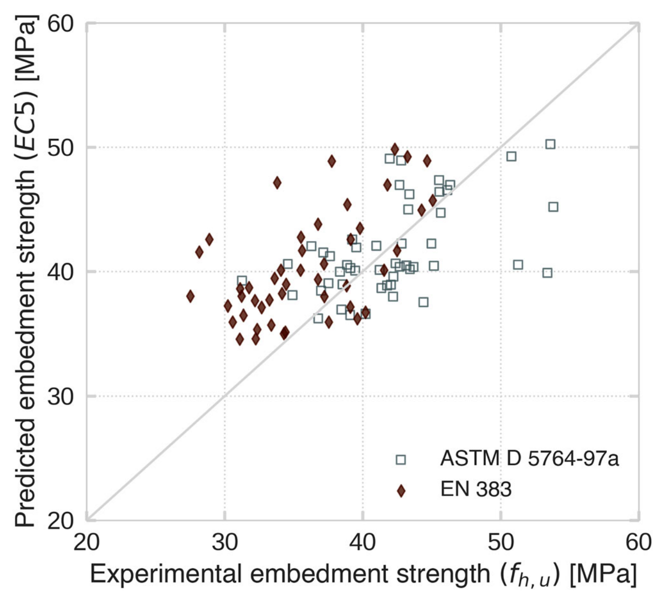

Figure 17. Comparison between experimental $f_{h,u}$ and EC5 prediction model for specimens tested according to the ASTM D 5764-97a and the EN 383 standards for a dowel of 8 mm and timber specimen 20 mm thick.

Regarding $f_{h,y}$, the NDS formula performed well for the results obtained according to ASTM D 5764-97a, but mainly overestimated those obtained according to EN 383. This is expected, as the prediction formula was fitted using data obtained from ASTM D 5764-97a, and a statistically significant difference was found between this and the results obtained from EN 383 in this study.

With respect to $f_{h,u}$, the application of the EC5 formula resulted in an overestimation of values derived from EN 383. It demonstrated an improved performance for the results obtained from ASTM D 5764-97, though still unsatisfactory mainly due to the sparsity of the data, that cannot be capture by the normative expression.

3.3. Comparison between compressive and tensile loading within EN 383

The main difference between compressive and tensile loading embedment tests lies in the specimen boundary conditions. While the loaded-end edge in compressive load is continuously supported, for the tensile setup, it is free, resulting in different loading distributions within the specimen. Additionally, in the compression test, frictional forces arise on the bearing surface of the test specimen counteracting the forces perpendicular to the grain developed due to the wedge effect. Conversely, in tension tests, specimens might be more susceptible to splitting.

Ehlbeck (1992) performed embedment tests for both softwood and hardwood in tensile and compressive loading and achieved higher embedment strength for loading in tension. The authors mention a tendency of early splitting of specimens under a compression load, but this can be explained by the small end distance adopted (3*d*) for this group. Sandhaas *et al.* (2013) investigated the contribution of friction forces in compressive embedment tests by the insertion of a teflon strip between the load-transferring steel plate and the timber specimen. No statistically significant difference was observed. Wydler (2023) performed tensile and compressive embedment tests with Spruce laminated veneer lumber (LVL) for a dowel diameter of 10 mm and the only difference found was a higher deformation capacity for specimens loaded in compression.

In regard to the foundation modulus (K_s), none of the mentioned studies have made any reference to the influence of the loading method on it. This property has received significantly less research attention when compared to embedment strength. However, it is noteworthy that in Wydler (2023), mean values for both tensile and compressive tests are provided. Interestingly, for compressive loading, K_s is found to be 28% greater than for tensile loading. It's important to point out that the tensile group consisted of only 5 specimens, while the compressive group included 12 specimens.

In the present study, to avoid premature splitting, specimens intended for tension loading were manufactured with a larger end-distance of 8.3*d*, while those for compressive loading adhered to the recommendations outlined in EN 383 of 7*d*. In both setups, only about 10% of the specimens failed between displacement of 4 mm and 5 mm, where the mean ultimate displacement capacity was 10.4 mm for tensile and 10.1 mm for the compressive loading specimens. The stress-displacement curves from embedment tests conducted under both compressive and tensile loading parallel-to-the-grain are depicted in Figure 18. A 7% higher mean value of K_s and 3%

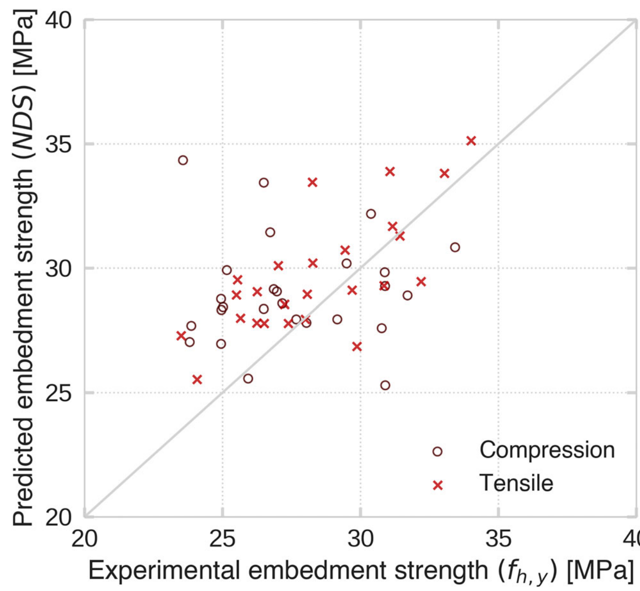

Figure 19. Comparison between experimental $f_{h,y}$ and NDS prediction model for specimens tested according to the EN 383 standard for a dowel of 12 mm and timber specimen 20 mm thick.

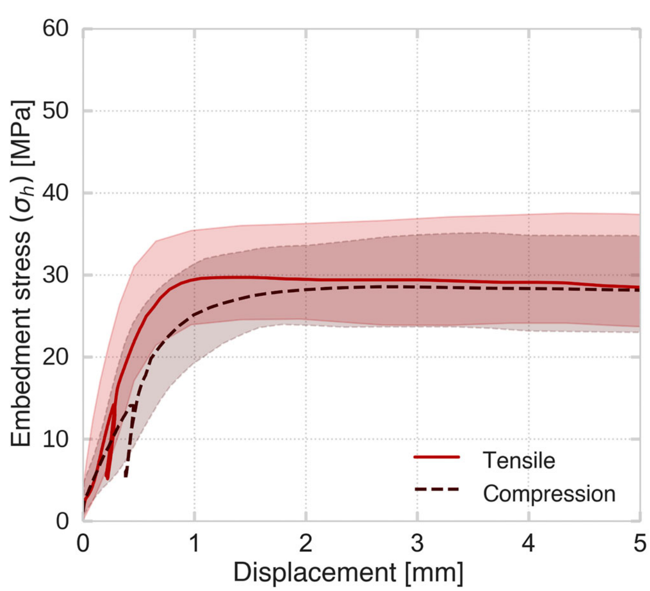

Figure 18. Mean stress-displacement curves according to the EN 383 standard for a dowel of 12 mm and spruce timber specimen 20 mm thick for loading in tension and compression.

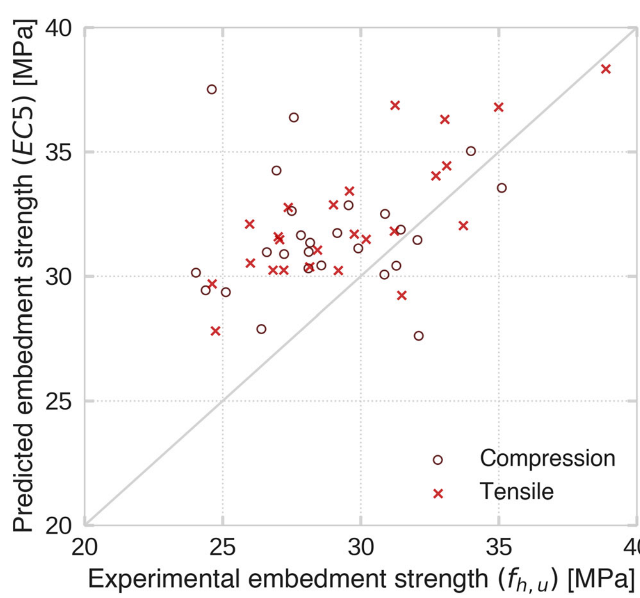

Figure 20. Comparison between experimental $f_{h,u}$ and EC5 prediction model for specimens tested according to the EN 383 standard for a dowel of 12 mm and timber specimen 20 mm thick.

Table 4. Summary of test results (mean ± standard deviation values).

Standard	Loading	d [mm]	t [mm]	$f_{h,y}$ [MPa]	$f_{h,u}$ [MPa]	K_s [MPa/mm]	K_{el-} [MPa/mm]	K_{el+} [MPa/mm]
ASTM D 5764-97a	C	8	20	38.9 ± 4.7	42.1 ± 4.8	28.3 ± 6.8	–	–
			25	38.5 ± 7.1	41.4 ± 7.8	28.2 ± 6.7	–	–
			30	39.3 ± 4.3	41.4 ± 4.8	28.4 ± 6.1	–	–
			35	30.8 ± 5.5	33.6 ± 5.4	29.6 ± 10.4	–	–
EN 383	C	8	20	34.4 ± 4.5	35.9 ± 4.6	40.6 ± 11.0	62.6 ± 5.6	73.3 ± 10.9
	C	12	20	27.5 ± 2.8	28.7 ± 2.9	29.9 ± 7.0	57.1 ± 6.5	59.9 ± 11.7
	T			28.4 ± 2.8	29.7 ± 3.4	32.2 ± 7.7	57.5 ± 3.9	52.7 ± 3.8

higher value of $f_{h,u}$ was found for the tension setup compared to the compression setup, which were proved to be not statistically significant according to the independent t-test.

In addition, embedment strength results from both the tensile and compression setups are compared with predictions from NDS and Eurocode 5, as seen in Figures 19 and 20. For the evaluation of the NDS expression, the yield embedment strength ($f_{h,y}$) obtained from the experimental campaign was utilised. Meanwhile, for the comparison with Eurocode 5, the ultimate embedment strength was adopted ($f_{h,u}$). Both expressions, however, led to an overestimation of the experimental values obtained.

In conclusion, Table 4 provides a comprehensive overview of the test results discussed in the preceding sections.

4. Conclusions

This paper presents an experimental study focussed on testing methods and setup for determining two crucial properties of dowel embedment behavior in timber elements: embedment strength and foundation modulus. The research primarily explores the impact of specimen thickness within the framework of ASTM D 5764-97a and assesses the influence of the test protocol on the quantification of parallel-to-grain timber embedment strength and foundation modulus. Furthermore, the research involves the comparison between the ASTM D 5764-97a and the EN 383 standards, allowing for a comprehensive assessment of the test protocol's effects. Finally, the paper includes a comparison of loading application methods (tensile and compressive) within the scope of EN 383.

In the investigation conducted following ASTM D 5764-97a, the findings revealed a significant impact ($p-\text{value} < 0.001$) of thickness on embedment strength (both yield – $f_{h,y}$ and ultimate – $f_{h,u}$) for specimens with a thickness of 35 mm (4.4d) when compared to those with 20 mm (2.5d) and 25 mm (3.1d). The mean values of $f_{h,y}$ and $f_{h,u}$ were around 20% and 14% lower for the 35 mm group. However, no discernible difference was observed in the initial foundation modulus (K_s). This outcome underscores the necessity for a more comprehensive examination of the relationship between member thickness and embedment strength, particularly in light of the common use of timber elements with thicknesses exceeding 40 mm in timber connections. To further validate this trend, an expanded experimental campaign involving various wood species should be undertaken. In this endeavour, the half-hole specimen should be used to avoid dowel bending.

The analysis comparing test protocols (ASTM D 5764-97a vs. EN 383) yielded noteworthy differences in both $f_{h,y}$ and $f_{h,u}$, as well as in K_s. The mean embedment strength values of $f_{h,y}$ and $f_{h,u}$ were respectively 12% and 15% bigger for the ASTM D 5764-97a group. With respect to the foundation modulus, K_s was 30% bigger for the EN 383 group. It is important to note that these results partly diverged from findings in the existing literature for different wood species. This disparity may suggest that the variability in test methods is not only influenced by the choice of test protocol but also by factors such as the wood species under evaluation, dowel diameter, specimen size, and potentially other variables. These contrasting outcomes underscore the need for a more comprehensive understanding of the influence of these factors in determining embedment properties and foundation modulus in timber connections.

Within the guideliness of EN 383, no statistical significant difference was found regarding tensile vs. compressive loading for neither properties.

With respect to the EC5 embedment strength prediction expression, the results from experiments tested according EN 383 were overestimated, while the ones from ASTM D 5764-97a were underestimated. NDS expression, on the other hand, performed well for the results from ASTM D 5764-97a but generally overestimated the ones from EN 383.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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