World Conference on Timber Engineering Oslo 2023

INFLUENCE OF DENSITY AND PREDRILL IN THE EMBEDMENT STRENGTH OF TWO HARDWOOD SPECIES

Gonzalo Cabrera[1], Gonzalo Moltini[2], Vanesa Baño*[3]

ABSTRACT: The embedment strength is a key parameter in the design of timber connections with metal fasteners. It can be determined by the equations given by Eurocode 5 from the density value. Since those equations were mainly developed for softwood species, the objective of this work is to evaluate the influence of the density in the embedment strength of two high- and low-density hardwood species (beech – *Fagus sylvatica*- and poplar – *Populus x euroamericana*-, respectively) in the parallel- and perpendicular-to-grain direction. Four different experimental test configurations were carried out according to EN 383 for each species using a 5-mm nominal diameter and considering the influence of predrilling in the wood specimens. Results showed a good correlation between density and embedment strength for all the test types. In addition, predrilling showed no significant influence on the value of embedment strength, contrary to what is considered in the equations provided by the current version of the structural design codes. Both, current and new equations proposed by the new draft of Eurocode underestimate the values of embedment strength in both species, thus being on the safe side for the structural design of connections.

KEYWORDS: Embedment strength, density, predrilling, hardwood species, beech, poplar.

1 INTRODUCTION

Timber has been consolidated as a common material in short and large-span ceilings and roofs, and the current tendency is leaning toward mid- and high-rise buildings, where cross-laminated timber panels (CLT) become a key product in the design. In a bibliometric analysis of the research trends related to CLT between 2006 and 2018, the seismic performance of the structures and behaviour of connections resulted in the most relevant topics [1]. In structural design, the good execution and design of connections are vital for adequate behavior and stability of the structure.

Design codes of timber connections are based on the "European Yield Model" proposed by Johansen, whose equations for defining the strength capacity and stiffness of connections depend on the embedment strength of the wood and the yield moment of the fastener. Eurocode 5 [2], currently under review, regulates timber structural design in Europe; however, the Spanish Building Technical Code -CTE- [3] is mandatory in Spain for building design. The CTE got the connections design equations from EC5, but without taking into consideration the rope effect ($F_{ax,Rk}$). In both cases, the equations to determine embedment strength are based on experimental results and fit mostly for softwood species [4,5].

Several authors have studied the embedment strength in solid timber and Engineered Wood Products (EWPs) of softwood and/or hardwood species in different directions with respect to the grain and with different types and geometries of connectors, although most of the studies involve nails, bolts, or dowels, and not screws. For designing connections with smooth shank screws with a diameter greater than 6 mm, EC5 and CTE refer to bolts' equations. Otherwise, the requirements for nails apply. In the latest consolidated draft of Eurocode 5 (prEC5) [6] new equations are included for the specific case of screws in solid structural timber and to cover connections in other EWPs.

The current equations provided by the design codes to determine timber embedment strength are derived from two studies, Whale and Smith [7] and Ehlbeck and Werner [8], which included tests in both softwood and hardwood species. Nonetheless, the number of tests performed in softwood species was considerably higher than in hardwood ones. More studies were performed in the coming years, and some of them such as Sawata and Yasamura [9], Sandhaas et al. [10], and Yurrita et al. [5]found results not aligned with the equations proposed by previous works. In addition, Hubner [11], Sosa Zitto et al. [12], and Franke and Magniere [4], reached the conclusion that the current equations should be reviewed when considering hardwood species, and some of them proposed modifications to the equations based on their results. Since timber´s physical and mechanical properties depend not only on species but also on origin, it becomes necessary to know these parameters for the hardwood species from Spain.

[1] Gonzalo Cabrera, MEng Student, Cesefor, Spain, and Universidad Politécnica de Madrid (UPM), Spain, gonzalo.cabrera@cesefor.com
[2] Gonzalo Moltini, PhD Student, Cesefor, Spain, and Universidad Politécnica de Madrid (UPM), Spain, gonzalo.moltini@cesefor.com
[3] *Vanesa Baño, Dr. Forest Eng., Innovawood, Belgium, and Cesefor, Spain, vanesa.bano@innovawood.eu

https://doi.org/10.52202/069179-0183

The experimental methods that are more extensively used to determine the embedment strength are the ones from the European standard EN 383:2007[13], the American standard ASTM D 5764-97a [14], and the International Standard ISO 10984-2:2009 [15]. These methods have differences from each other, regarding test method, test setup, sample sizes, loading procedures, and evaluation methods. The most important difference is the determination of the maximum load, F_{max}, which leads to different results depending on the method and, therefore, to the difficulty of comparison.

Hardwood species currently visually- [16,17] or machine-graded [18] in Spain for structural use are southern blue gum (*Eucalyptus globulus*), shining gum (*Eucalyptus nitens*), and sweet chestnut (*Castanea sativa*). Since there are not yet harmonized European standards for the manufacturing of EWPs from hardwood species, some Spanish timber industries have obtained the European Technical Assessment (ETA) to commercialize specific certified products, such as glulam beams from oak by Grupo Gámiz and sweet chestnut by Sierolam, or Parallel Strand Lumber (PSL) from poplar by Tabsal.

The increasing demand for wood is leading the industry to look for alternative species for structural uses, both fast-growing with lower mechanical properties, such as poplar, and slow-growing with higher mechanical properties, such as beech. The rotation of poplar varies between 9 years in the south of Spain and up to 18 years in the north, depending not only on the origin but also on the subspecies and hybrid, and in 2016 the cuts represented 1.6% of the total cuts and 3.1% of hardwoods in Spain [19]. Characteristic values of the structural properties of the 18-year-old *Populus x euroamericana, hybrid I-214*, from the North of Spain were $f_{m,k} = 36.5$ N/mm^2, $E_{0,m} = 7746$ N/mm^2, and $\rho_k = 338$ kg/m^3 [20], which fit with the strength class C14 of EN 338:2016 [21]. The values of modulus of elasticity increased to 8800 N/mm^2 for the same hybrid from Central Spain (Guadalajara) [19] and to 9907 N/mm^2 for Portuguese poplar (*Populus alba* and *Populus nigra*) [22], showing in all the cases structural properties like softwood species. Until 2003, poplar was included in the Spanish timber grading standard [16], but it was removed due to the lack of updated data on new species and hybrids. The rotation of beech varies between 90 and 100 years old approximately [23], and occupies 2% of the total forest extension in Spain [24]. Sawmills classify solid wood in two qualities based on the wood color, first quality with white color destined for aesthetic, and second quality with red color and not industrial uses. In other countries of Europe, it is of interest for structural use due to its high mechanical properties [25–27], which reach the strength class D40 ($f_{m,k} = 40$ N/mm^2, $E_{0,m} = 13$ kN/mm^2, $\rho_k = 550$ kg/m^3) in Germany, Switzerland, and Austria [28,29] and D50 ($f_{m,k} = 50$ N/mm^2, $E_{0,m} = 14$ kN/mm^2, $\rho_k = 620$ kg/m^3) in France [27].

Previous experimental studies in these species [30], using 9 mm diameter screws and 12 mm diameter bolts (Fig. 1), showed that current equations of EC5 overestimated perpendicular to grain embedment strength. However, the equation proposed in prEC5 for screws fitted best perpendicular-to-grain embedment strength and underestimated the parallel-to-grain one.

This work aims to study the influence of the density in the embedment strength of poplar and beech from Spain in the parallel- and perpendicular-to-grain direction using a 5 mm diameter screw and considering the influence of predrilling.

2 EXPERIMENTAL CAMPAIGN

An experimental campaign was carried out to determine the embedment strength of two different low- and high-density hardwood species from Spain, poplar, and beech, in two different directions with respect to grain, parallel and perpendicular, using the following screw provided by Rothoblaas®: 5 mm diameter and 50 mm long screw (LBS550), Fig. 1. Specimens of poplar were between 12 and 15 years old, graded as ME-1 according to UNE 56.544:2003, and beech was around 90 years old classified as first quality according to the aesthetic criteria of the sawmill. Specimens were obtained from different boards and then conditioned until constant mass under conditions of relative humidity (65 ± 5) % and temperature (20 ± 2) °C, in a humidity chamber Memmert HCP240, before and after placing the fasteners (Fig. 2).

Figure 1: *5 mm ø screw, 9 mm ø screw, and 12 mm ø bolt provided by Rothoblaas®*

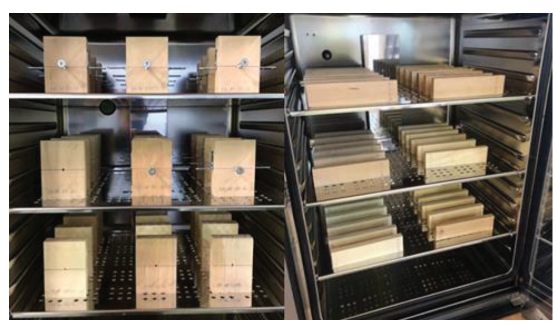

Figure 2: *Conditioning of the test specimens*

Four different test types were carried out for each species, following the specifications of EN 383:2007 [13], as summarized in Table 1, depending on the grain direction, and the predrilling of the wood. Since both CTE and EC5 propose a different formulation of the timber embedment

https://doi.org/10.52202/069179-0183

strength for each case (Eq. 1 and 2), specimens with and without a predrilled hole were tested.

Without predrilled hole:

$$f_{h,k} = 0.082\,\rho_k\,d - 0.3\;(N/mm^2) \qquad (1)$$

With predrilled hole:

$$f_{h,k} = 0.082\,(1 - 0.01\,d)\,\rho_k\;(N/mm^2) \qquad (2)$$

where, $f_{h,k}$ is the characteristic timber embedment strength, ρ_k is the characteristic timber density (kg/m³), and d is the nail (or screw) diameter (mm).

Table 1: *Test types per species*

	Test	N	Mean MC (%)	ϕ (mm)	Pre-drill	Cross-section (mm^3)	Grain direct.
Poplar	T1	9	12.0 (5%)	5	No	17 × 50	∥
	T2	10	12.0 (5%)	5	No	17 × 50	⊥
	T3	10	11.8 (5%)	5	3 mm	17 × 50	∥
	T4	10	11.6 (5%)	5	3 mm	17 × 50	⊥
Beech	T1	7	12.5 (5%)	5	No	17 × 50	∥
	T2	10	12.1 (7%)	5	No	17 × 50	⊥
	T3	9	12.1 (5%)	5	3 mm	17 × 50	∥
	T4	9	12.2 (5%)	5	3 mm	17 × 50	⊥

* Note: MC is the moisture content and the coefficient of variation, CoV, is presented between ( ), and ϕ is the diameter of the screw.

2.1 METHODOLOGY

The specimens were tested in compression through a loading steel device, as shown in Figure 3. Figures 4 and 5 show the experimental tests in parallel- and perpendicular-to-grain compression in poplar and beech, respectively. The loading procedure was defined in terms of the maximum estimated load $F_{max,est}$ for each test. It consisted of two cycles: a preload cycle up to $0{,}4F_{max,est}$, and a final loading until failure. The loading procedure is presented in Figure 6. After testing, a slice of the specimen was extracted to determine its density and moisture content according to EN 13183-1:2002 [31]. Density was later adjusted to a reference moisture content of 12 %.

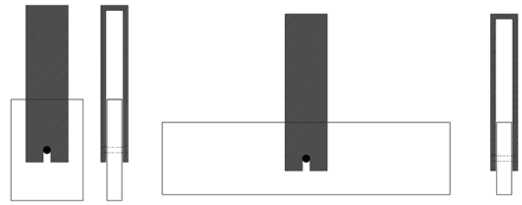

Figure 3: *Parallel- (left) and perpendicular-to-grain (right) tests*

Figure 4: *Experimental tests T1 (left) and T2 (right) performed in poplar.*

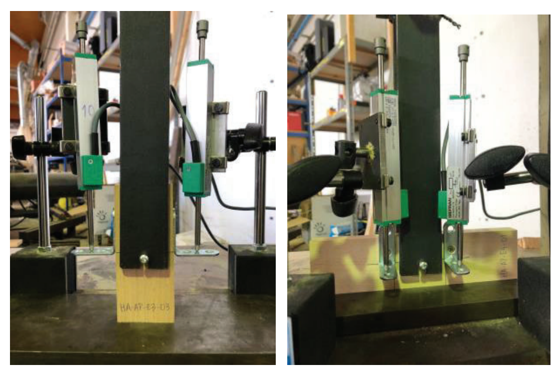

Figure 5: *Experimental tests T3 (left) and T4 (right) performed in beech.*

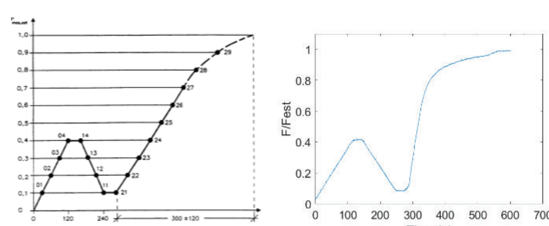

Figure 6: *Loading procedure provided by EN 383 (left) and experimental loading procedure (right)*

3 RESULTS AND DISCUSSION

3.1 LOAD-DISPLACEMENT CURVES

Load-displacement curves of both species tested in the parallel- and perpendicular-to-grain direction, with and without predrilling, are shown in Figures 7-10.

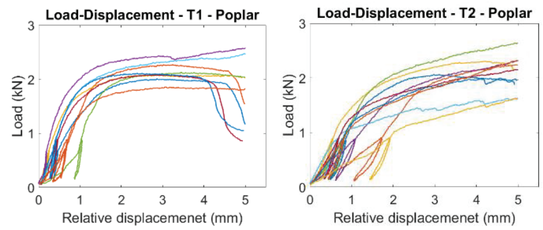

Figure 7: *Load–displacement curves of poplar without predrilling*

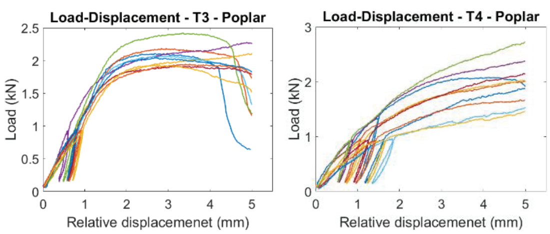

Figure 8: *Load–displacement curves of poplar with predrilling*

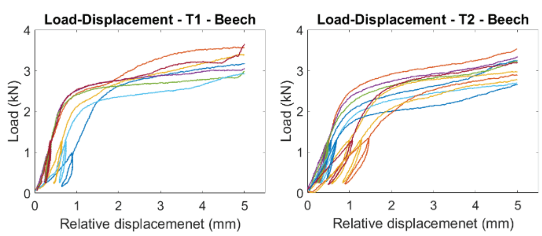

Figure 9: *Load–displacement curves of beech without predrilling*

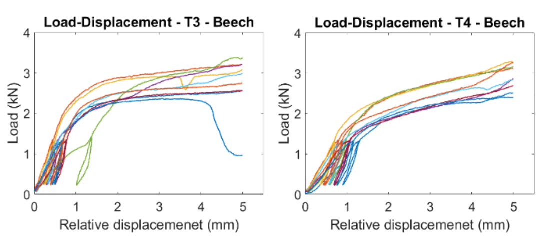

Figure 10: *Load–displacement curves of poplar with predrilling*

As expected, and observed previously by Cabrera et al. [30], beech presents higher values of embedment strength than poplar, and a difference in behavior is observed when comparing parallel- with perpendicular-to-grain tests. A plateau in the diagram is observed after the yield point in the parallel-to-grain tests, while the load increases with relative displacement in the perpendicular-to-grain tests, showing a hardening behavior of wood, but lower than that observed for greater fastener diameters.

Figures 11 and 12 show the comparison of the load–displacement diagrams of tests with and without predrilled holes within the same species. Load–displacement diagram of a particular test specimen representative of the mean behavior of the sample was selected in each case. Through this comparison, it can be directly observed that there are no important differences in behavior due to the execution of the predrilled hole. The shape of the curves in general terms are similar within the same test type for each species.

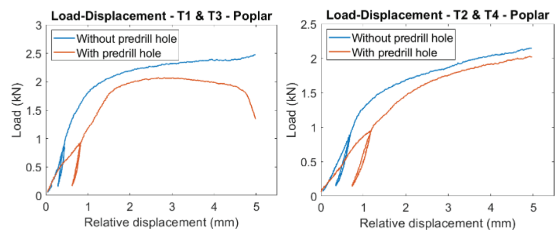

Figure 11: *Load-displacement diagram of poplar with and without predrilling in parallel and perpendicular to the grain tests*

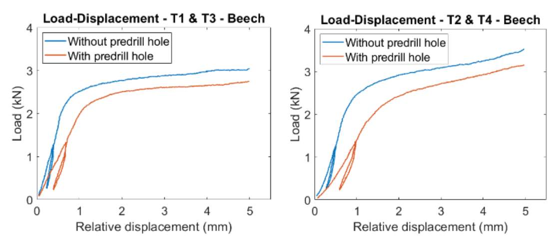

Figure 12: *Load-displacement diagram of beech with and without predrilling in parallel and perpendicular to the grain tests.*

3.2 EMBEDMENT STRENGTH

The embedment strength f_h was determined according to Equation (3), and characteristic values were obtained according to EN 14358:2016 [32] assuming a lognormal distribution.

$$f_h = \frac{F_{max}}{dt} \tag{3}$$

where F_{max} is the maximum load; d is the effective diameter of the screw, taken as 1.1 times the thread root diameter, which resulted in 3.3 mm for LBS550 screws; and t is the thickness of the test specimen.

Results from Cabrera et al. [30] showed that the method provided by EN 383 for the determination of embedment strength could overestimate that value for the perpendicular-to-grain direction. So, the embedment strength obtained from EN 383 was compared with that obtained from ASTM D 5764-97a and EN 408:2010 [33] according to the following criteria:

https://doi.org/10.52202/069179-0183

(i) F_{max} corresponding to a relative displacement of the fastener of 5 mm, or the maximum force in case it was reached at a lower deformation, as specified in EN 383.
(ii) F_{max} as the yield point defined in the load-deformation diagram by a straight line parallel to the elastic slope offset by deformation of 5% of the fastener diameter, as it is defined in ASTM D 5764-97a.
(iii) F_{max} determined according to the method defined in the EN 408 for the perpendicular-to-grain compression strength, like that described in (ii) but with a straight line offset by 0.01 h_t, where h_t is the loaded length, i.e., the distance below the fastener.
Results of mean and characteristic values of embedment strength -obtained from EN 383- and density, with their coefficient of variation, are presented in Table 2 for both species.

Table 2: *Results of the experimental tests according to EN 383*

	Poplar				Beech			
Test	f_{h_m} (N/mm^2)	$f_{h,k}$ (N/mm^2)	ρ_m (kg/m^3)	ρ_k (kg/m^3)	f_{h_m} (N/mm^2)	$f_{h,k}$ (N/mm^2)	ρ_m (kg/m^3)	ρ_k (kg/m^3)
T1	38.3 (11%)	30.6	414 (18%)	253	57.8 (9%)	46.9	670 (11%)	503
T2	37.6 (15%)	26.9	419 (19%)	252	54.6 (9%)	44.9	645 (7%)	549
T3	37.1 (8%)	31.6	424 (21%)	241	52.1 (12%)	39.8	692 (12%)	519
T4	35.1 (20%)	23.0	420 (21%)	239	51.8 (11%)	40.6	685 (10%)	542

Note: The value between brackets shows the coefficient of variation (%); ρ_k is the density adjusted to 12% of moisture content according to EN 384

Figures 13 and 14 show the characteristic values of the embedment strength depending on the standard method for both species and the four test types.
In poplar, experimental values obtained through the three different methods are more even between each other for the two parallel-to-grain tests performed than for the perpendicular-to-grain ones (Fig. 13). Values of perpendicular-to-grain embedment strength evaluated according to EN 383 standard were higher compared with those of the other two methods, especially in tests without predrilling (T2). In addition, perpendicular-to-grain embedment strength is rather lower than parallel-to-grain one, contrary to what the standard states according to its equations.

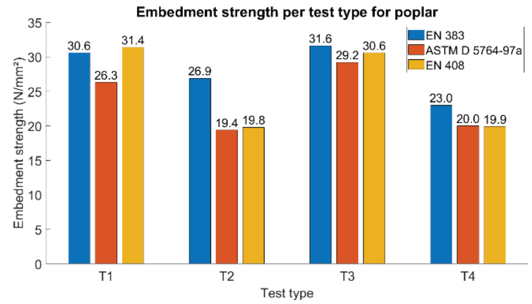

Figure 13: *Experimental characteristic values of embedment strength depending on the standard and test type in poplar.*

In beech (Fig. 14), higher values of embedment strength are obtained according to the EN 383 method for both with and without predrilling and parallel- and perpendicular-to-grain tests, with significant differences with respect to the other methods according to an ANOVA analysis. The small diameter of the screw and the cross-section of the wood specimen could lead to evaluate the embedment strength before the yield point of the load-displacement diagram for the ASTM and EN 408 methods, which could result in an underestimation of the embedment strength parallel to the grain.

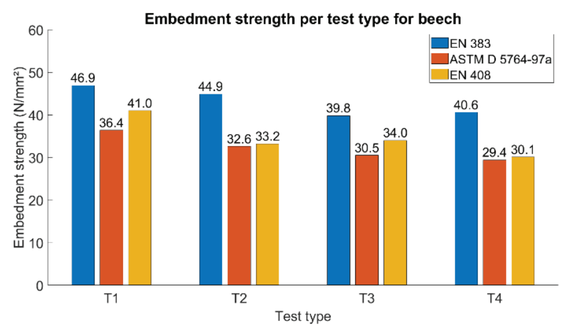

Figure 14: *Experimental characteristic values of embedment strength depending on the standard and test type in beech.*

3.3 FAILURE MODE

Most of the specimens from T1 to T4 tests showed a failure mode that combines the timber embedment with plastic deformation of the screw (Fig. 15), which differs from the failure mode of the fasteners with greater diameter, in which the plastic deformation of the fastener did not occur [30]. As in the case of the greater diameter of fasteners, a combination of embedment and splitting was observed in the perpendicular-to-grain tests especially performed in poplar.

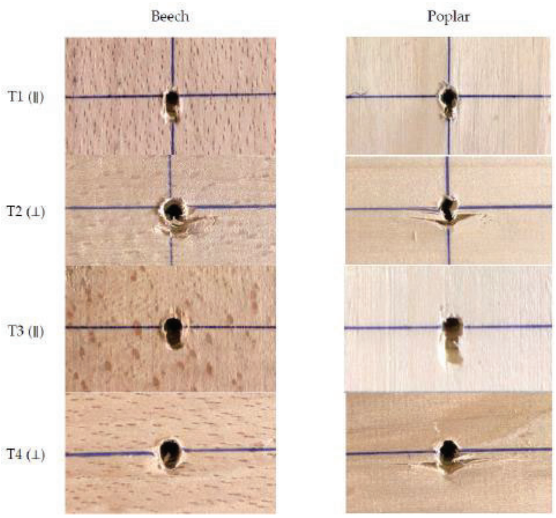

Figure 15: *Failure modes*

3.4 COMPARISON WITH THE THEORETICAL VALUES OF THE DESIGN CODES

For comparing experimental values with theoretical ones, the experimental values obtained according to the method of the EN 383 standard will be considered because of the two main reasons that follow. The first is that experimental values of embedment strength obtained according to the methods of ASTM D 5764-97a and EN 408 tend to underestimate embedment strength since as it was mentioned before, the small diameter of the fastener and geometry of test specimens lead to obtaining a failure point located before the yielding phase of the load-displacement diagram, which does not make any sense. The second reason is that the correlation obtained between density and embedment strength according to the methods of ASTM D 5764-97a and EN 408 was much lower than the one obtained with the results of the EN 383 standard.
Thus, the experimental values of the embedment strength obtained from EN 383 were compared with those obtained from the equations provided by the EC5 and prEC5. The equations that are applicable for each studied case depend on the existence or not of a predrilled hole as a determining factor in the embedment strength according to EC5, but not according to prEC5, which proposes only one equation for both cases, but considers the influence of the angle between the fastener axis and the grain direction, as shown in Table 3. Neither EC5 nor prEC5 considers load-to-grain angle as a determining factor for obtaining embedment strength.
Results are shown in Figures 16 and 17 and the ratios between theoretical values obtained from EC5 and prEC5 and the experimental values are presented in Table 4. It is not clear that a predrilled hole in the wood improves the embedment strength, as EC5 considers, resulting in an underestimation of embedment strength for the studied cases T1 and T2.

Table 3: *Equations provided by EC5 and prEC5 to determine the embedment strength of small-diameter screws.*

Test		Equation of EC5	Equation of prEC5
Nails without predrilling (EC5)	T1 (∥)	$f_{h,k} = 0.082\rho_k d^{-0.3}$	$f_{h,k} = \frac{0.019\rho_k^{1.24}d^{-0.3}}{2.5\cos^2\varepsilon + \sin^2\varepsilon}$
Screws (prEC5)	T2 (⊥)		
Nails without predrilling (EC5)	T3 (∥)	$f_{h,k} = 0.082(1 - 0.01d)\rho_k$	
Screws (prEC5)	T4 (⊥)		

ε is the angle between the fastener axis and the grain direction. $\varepsilon = 90°$ for all tests.

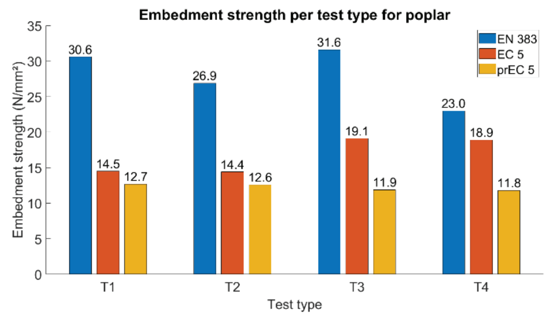

Figure 16: Experimental *vs. theoretical characteristic embedment strength in poplar*

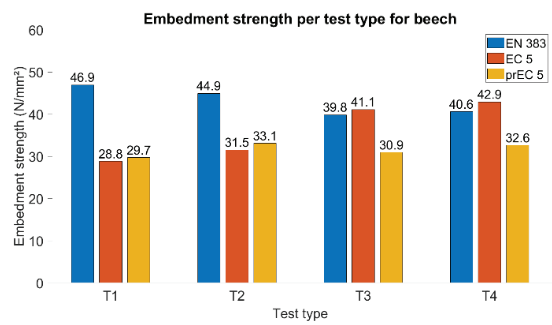

Figure 17: Experimental *vs. theoretical characteristic embedment strength in beech*

Table 4: *Ratios between theoretical and experimental values of embedment strength*

Test	Poplar		Beech	
	$\frac{f_{h,k\_EC5}}{f_{h,k\_exp}}$ (N/mm²)	$\frac{f_{h,k\_prEC5}}{f_{h,k\_exp}}$ (N/mm²)	$\frac{f_{h,k\_EC5}}{f_{h,k\_exp}}$ (N/mm²)	$\frac{f_{h,k\_prEC5}}{f_{h,k\_exp}}$ (N/mm²)
T1	0.47	0.41	0.61	0.63
T2	0.54	0.47	0.70	0.74
T3	0.60	0.38	1.03	0.78
T4	0.83	0.51	1.06	0.80

Results show that the execution of a predrill in the wood does not have a significant influence on the embedment strength for screws of 5 mm of diameter for both species according to an ANOVA analysis with a confidence level of 95%, which was also stated by Sosa Zitto et al. [12]and differs from the current EC5 approach. In addition, the equations provided by the EC5 underestimate the

https://doi.org/10.52202/069179-0183

experimental values for both parallel- and perpendicular-to-grain embedment strength of poplar. When it comes to beech, it is observed that EC5 equations predict appropriately the embedment strength in wood specimens with predrilling and underestimate embedment strength for the cases without predrilling. In terms of structural design, equations could lead to oversizing, but in any case are on the safe side.

New equations proposed by prEC5 showed similar values to those obtained from EC5 without predrilling, which implies that they also underestimate the embedment strength for both species with small-diameter screws.

In addition, no significant influence of the load-to-grain direction was observed for all the studied cases according to an ANOVA analysis with a confidence level of 95%, which goes along with the fact that the formulations proposed are independent of the load-to-grain angle.

3.5 CORRELATION BETWEEN DENSITY AND EMBEDMENT STRENGTH

The correlation between experimental embedment strength and density adjusted to 12% of MC was studied for both species and the different tests performed. Results are presented in Figures 17 and 18.

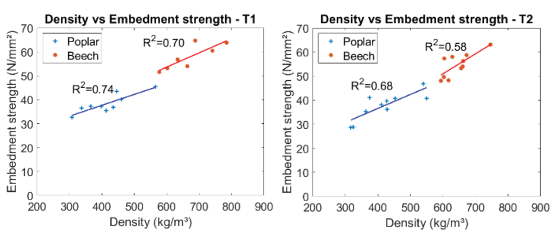

Figure 17: *Correlation between density (ρ_{12}) and embedment strength ($f_{h,exp}$) for wood specimens without predrilling.*

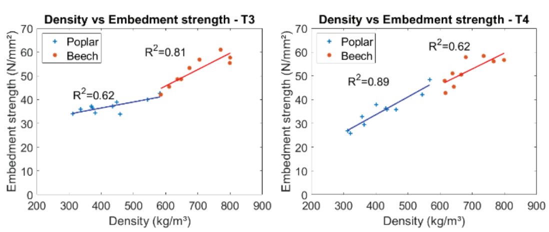

Figure 18: *Correlation between density (ρ_{12}) and embedment strength ($f_{h,exp}$) for wood specimens with predrilling.*

The correlation coefficient between density and embedment strength was higher than 0.62 for all the cases, except for beech without predrilling compression perpendicular to the grain (R^2=0.58) which indicates that density is a good predictor of embedment strength for these species.

4 CONCLUSIONS

Beech showed higher values of embedment strength than poplar for all the cases studied. Embedment failure was observed in parallel-to-grain tests, while a combined failure of embedment and splitting took place in some of the perpendicular-to-grain tests, especially in poplar.

When testing nails or screws with small diameters, the method provided by ASTM D 5764-97a or the one proposed based on EN 408, could lead to underestimation of embedment strength, thus being not appropriate.

Results showed that there is no significant influence of the predrilled hole in the embedment strength of the species studied with the small-diameter screw tested, contrary to what EC5 considers, thus penalizing embedment strength for the case without predrilled holes. New equations provided by prEC5 showed similar values to those obtained from EC5 without predrilling, therefore, a better prediction of embedment strength is obtained in the cases studied if the equation for nails with predrilled holes of EC5 is used in every case.

In addition, results also showed that there is no significant influence of the load-to-grain direction in the embedment strength for the studied cases, a fact that is aligned with the current proposal of EC5.

Density becomes a good predictor of embedment strength for these species and screws studied.

ACKNOWLEDGEMENT

Research project CCTT3/20/SO/0001 funded by the ERD through Junta de Castilla y León, and EUFORE HE No.101081788 by the European Union

REFERENCES

1. Abejón, R.; Moya, L. Cross-Laminated Timber: Perspectives from a Bibliometric Analysis (2006–2018). *Wood Mater Sci Eng* **2022**, *17*, 429–450, doi:10.1080/17480272.2021.1955295.
2. CEN EN 1995-1-1: Eurocode 5: Design of Timber Structures - Part 1-1: General - Common Rules and Rules for Buildings 2004.
3. Ministerio de Fomento Código Técnico de La Edificación Documento BásicoSE-M Seguridad Estructural Madera 2019.
4. Franke, S.; Magnière, N. The Embedment Failure of European Beech Compared to Spruce Wood and Standards. In Proceedings of the Materials and Joints in Timber Structures; Aicher Simon and Reinhardt, H.-W. and G.H., Ed.; Springer Netherlands: Dordrecht, 2014; pp. 221–229.
5. Yurrita, M. New Criteria for the Determination of the Parallel-to-Grain Embedment Strength of Wood. *Constr Build Mater* **2018**, *173*, 238–250.
6. CEN PrEN 1995-1-1:20XX; Design of Timber Structures-Common Rules and Rules for Buildings-Part 1-1: General 2021.
7. Whale, L.R.J.; Smith, I. The Derivation of Design Clauses for Nailed and Bolted Joints in Eurocode 5. *CIB-W18 Meeting 19* **1986**, *1*, 446–472.
8. Ehlbeck, J.; Werner, H. Softwood and Hardwood Embedding Strength for Dowel-Type Fasteners. *CIB-W18 Meeting 25* **1992**, 555–568.

9. Sawata, K.; Yasumura, M. Determination of Embedding Strength of Wood for Dowel-Type Fasteners. *Wood Science* **2002**, *48*, 138–146.
10. Sandhaas, C.; Ravenshorst, G.J.P.; Blass, H.J.; van de Kuilen, J.W.G. Embedment Tests Parallel-to-Grain and Ductility Aspects Using Various Wood Species. *European Journal of Wood and Wood Products* **2013**, *71*, 599–608, doi:10.1007/s00107-013-0718-z.
11. Hübner, U. Embedding Strength of European Hardwoods. *CIB-W18 Meeting 41* **2008**, 203–219.
12. Sosa Zitto, M.A.; Köhler, J.; Piter, J.C. Embedding Strength in Joints of Fast-Growing Argentinean Eucalyptus Grandis with Dowel-Type Fasteners. Analysis According to the Criterion Adopted by European Standards. *European Journal of Wood and Wood Products* **2011**, *70*, 433–440, doi:10.1007/s00107-011-0572-9.
13. CEN EN 383: Timber Structures-Test Methods-Determination of Embedment Strength and Foundation Values for Dowel Type Fasteners 2007.
14. ASTM ASTM D 5764-97a: Standard Test Method for Evaluating Dowel-Bearing Strength of Wood and Wood-Based Products 2002.
15. ISO ISO 10984-2:2009 Timber Structures — Dowel-Type Fasteners — Part 2: Determination of Embedding Strength 2020.
16. AENOR UNE 56544 - Clasificación Visual de La Madera Aserrada Para Uso Estructural. Madera de Coníferas 2022.
17. AENOR UNE 56546 - Clasificación Visual de La Madera Aserrada Para Uso Estructural. Madera de Frondosas 2022.
18. CEN EN 14081-2:2019. Timber Structures. Strength Graded Structural Timber with Rectangular Cross-Section. Part 2: Machine Grading; Additional Requirements for Type Testing. Brussels, Belgium 2018.
19. Gallego, A.; Ripoll, M.A.; Timbolmas, C.; Rescalvo, F.; Suarez, E.; Valverde, I.; Rodríguez, M.; Navarro, F.B.; Merlo, E. Modulus of Elasticity of I-214 Young Poplar Wood from Standing Trees to Sawn Timber: Influence of the Age and Stand Density. *European Journal of Wood and Wood Products* **2021**, *79*, 1225–1239, doi:10.1007/s00107-021-01675-5.
20. Basterra, L.A.; Acuña, L.; Casado, M.; López, G.; Bueno, A. Strength Testing of Poplar Duo Beams, Populus x Euramericana (Dode) Guinier Cv. I-214, with Fibre Reinforcement. *Constr Build Mater* **2012**, *36*, 90–96, doi:10.1016/j.conbuildmat.2012.05.001.
21. AENOR UNE-EN 338:2016 - Madera Estructural. Clases Resistentes. 2016.
22. Monteiro, S.; Martins, C.; Dias, A.; Cruz, H. Mechanical Characterization of Clear Wood from Portuguese Poplar. *Bioresources* **2019**, *14*, 9677–9685, doi:10.15376/biores.14.4.9677-9685.
23. García-Robredo, F. Effect of Species Complementarity on Financial Return in Mixed Stands of European Beech and Scots Pine in Northern Spain. *Forests* **2018**, *9*, doi:10.3390/f9090559.
24. MITECO *Anuario de Estadística Forestal 2019*; Ministerio para la Transición Ecológica y el Reto Demográfico: Madrid, Spain, 2021; ISBN 9788418508493.
25. Hu, W.; Wan, H.; Guan, H. Size Effect on the Elastic Mechanical Properties of Beech and Its Application in Finite Element Analysis of Wood Structures. *Forests* **2019**, *10*, doi:10.3390/f10090783.
26. Brunetti, M.; Nocetti, M.; Pizzo, B.; Aminti, G.; Cremonini, C.; Negro, F.; Zanuttini, R.; Romagnoli, M.; Mugnozza, G.S.; Biologici, S.; et al. Glued Structural Products Made of Beech Wood: Quality of the Raw Material and Gluing Issues. In Proceedings of the International Scientific Conference on Hardwood Processing; 2019.
27. Lanvin, J.D.; Reuling, D.; Legrand, G. French Beech-a New Opportunity in Wood Housing. In Proceedings of the 7th - International Scientific Conference on Hardwood Processing; 2019; pp. 129–137.
28. CEN EN 1912 Structural Timber - Strength Classes - Assignment of Visual Grades and Species 2012.
29. Kovryga, A.; Stapel, P.; van de Kuilen, J.W.G. Mechanical Properties and Their Interrelationships for Medium-Density European Hardwoods, Focusing on Ash and Beech. *Wood Mater Sci Eng* **2020**, *15*, 289–302, doi:10.1080/17480272.2019.1596158.
30. Cabrera, G.; Moltini, G.; Baño, V. Embedment Strength of Low- and Medium-Density Hardwood Species from Spain. *Forests* **2022**, *13*, 1154, doi:10.3390/f13081154.
31. CEN EN 13183-1:2002. Moisture Content of a Piece of Sawn Timber - Part 1: Determination by Oven Dry Method 2002.
32. CEN EN 14358: Timber Structures - Calculation and Verification of Characteristic Values 2016.
33. CEN EN 408:2011+A1: Timber Structures - Structural Timber and Glued Laminated Timber - Determination of Some Physical and Mechanical Properties 2019.

 https://doi.org/10.52202/069179-0183