BEARING PROPERTIES OF PORTUGUESE PINE WOOD BENEATH A LATERALLY LOADED DOWEL

C.L. SANTOS*, A.M.P. de JESUS**, J.J.L. MORAIS*, J.L.P.C. LOUSADA***

*CITAB/Department of Engineering, **Department of Engineering, ***Department of Forestry Science
University of Trás-os-Montes and Alto Douro
Quinta de Prados, 5001-801 Vila Real
clsantos@utad.pt

ABSTRACT: The pine wood (Pinus pinaster Ait.) is one of the species with larger implantation in Portugal. Its use for structural applications requires an adequate knowledge of its mechanical behaviour. In particular, for designing doweled joints, it is essential to know the bearing properties beneath the dowel. This paper reports a comprehensive experimental program aiming the determination of the bearing properties of the Portuguese pine wood. The embedding strength is evaluated in longitudinal and radial directions according two alternative standards, namely the ASTM D 5764 and EN 383 standards. Results are compared with empirical relations proposed in design codes of practice (e.g. EC5). Also, foundation moduli are evaluated in both directions according both standards. The experimental work also includes the test of a single dowel double shear wood connection. Additionally, some elastic strength properties are evaluated from small specimens of clear wood in order to better characterize the mechanical behaviour of the wood species.

Keywords: Pinus pinaster Ait., Dowel-type Connection, Embedding Strength, Foundation Modulus, EN 383, ASTM D 5764.

RESUMO: O pinheiro (Pinus pinaster Ait.) é uma das espécies com maior implantação em Portugal. A sua utilização para aplicações estruturais requer um conhecimento adequado do seu comportamento mecânico. Em particular, para o projecto de ligações do tipo cavilha é essencial conhecer as propriedades de resistência ao esmagamento localizado. Este trabalho consiste num extenso programa experimental com vista à determinação destas propriedades, usando madeira de pinho Português. A resistência ao esmagamento localizado é avaliada nas direcções longitudinal e radial, segundo duas normas alternativas, nomeadamente a ASTM D 5764 e EN 383. Os resultados são comparados com as relações empíricas propostas em códigos de projecto actuais (ex: EC5). O módulo de fundação também é avaliado nas duas direcções, segundo ambas as normas. O trabalho experimental inclui ainda uma série de ensaios de uma ligação de corte duplo e cavilha única. Algumas propriedades elásticas e de resistência da madeira limpa foram aferidas com base em ensaios, a fim de melhor caracterizar o comportamento mecânico da espécie Pinus pinaster Ait.

Palavras chave: Pinus pinaster Ait., Ligação tipo Cavilha, Resistência ao Esmagamento, Módulo de Fundação, EN 383, ASTM D 5764.

1. INTRODUCTION

Connections are frequently the critical locations of wood structures, being responsible for the reduction of continuity and the global structural strength, requiring oversized structural elements. About 80% of failures observed in wood structures are due to connections [1]. Dowell-type wood connections are the most common connections applied in wood structures. The singularity of this type of wood connections is associated to the combination of very distinct materials – wood and steel – and to the high anisotropy of wood. The knowledge of the mechanical behaviour of these dowel type connections (e.g. load-slip relation, stress distribution, ultimate strength and failure modes) is of primordial importance for their rational application. This complex behaviour is governed by several geometric, material and load parameters (e.g. wood species, dowel diameter, end and edge distances, space between connectors, number of connecters, clearance, friction and load configuration). According to design codes of current practice [2-3], the design of dowel type wood connections has been based on the European Yield Model proposed by Johansen [4]. This model has an empirical basis and assumes an elastic-perfect plastic behaviour, for both wood and dowel. It also considers that embedding strength is a material propriety. Generally, in order to verify the influence the previously referred parameters, a number of tests are required for assessing the embedding strength. These embedding tests are standardized such as in the EN 383 standard [5] or ASTM D 5764 [6].

This paper presents results of a comprehensive experimental program aiming the characterization of the embedding strength of the Portuguese pine wood (Pinus pinaster Ait. species). This data is essential for the design of dowel-type wood connections. The Portuguese pine wood is one of the species with larger implantation in Portugal. The use of this wood for structural applications has been disregarded due to several reasons, such as low quality of this wood, cultural and lack of data about its mechanical behaviour.

The paper starts to describe the elastic properties of the Portuguese pine wood, based on data available in the literature together with some verifications carried out by authors, through longitudinal tensile and compressive tests of small specimens of clear wood. Then, results of embedding tests carried out according the EN 383 [5] or ASTM D 5764 [6] standards are presented for the longitudinal and radial directions of the wood. Specifically the embedding strength and foundation modulus are evaluated. Finally, results of tensile tests of a double-shear single-dowel wood connection, carried out according the recommendations of the EN26891 standard [7], are illustrated. The whole load-slip behaviour of the joint is illustrated until failure. In particular, the initial joint slip modulus, the ultimate strength and the ductility are evaluated and compared with corresponding values given by the EC 5 [3].

2. CLEAR WOOD TEST RESULTS

This section describes the elastic and strength properties of the Portuguese pine wood, through tests of small specimens of clear wood. The elastic and strength properties of the Portuguese pine wood presented in this section were previously identified in references [8-11]. Tables 1 and 2 summarize the elastic and strength properties, namely: modulus of elasticity (E_L, E_T, E_R), Poisson ratios (ν_{RT}, ν_{TL}, ν_{LR}); shear modulus (G_{RT}, G_{TL}, G_{LR}); tensile strength stresses (σ_L, σ_T, σ_R) and shear strength stresses (τ_{RT}, τ_{TL}, τ_{LR}).

Table 1. Elastic and strength properties of the Pinus pinaster Ait. species [8-11].

	Average Value	Coef. Of Var. (%)
E_L (GPa)	15.1	6.8
E_T (GPa)	1.01	14.4
E_R (GPa)	1.91	7.9
ν_{RT}	0.586	7.6
ν_{TL}	0.051	22.1
ν_{LR}	0.471	8.3
σ_L (MPa)	97.5	9.8
σ_T (MPa)	7.93	5.5
σ_R (MPa)	4.20	11.0

The shear properties were evaluated according three distinct test procedures, namely off-axis, arcan and iosipescu tests. In this work, a few elastic and strength properties were verified based on compressive and tensile tests of clear wood specimens. Figure 1 illustrates the stress-strain curves resulted from the tensile and compressive tests carried out in the longitudinal direction of wood. From this data some elastic and strength properties were derived as included in Table 3. They closely agree with the elastic and strength properties published in literature [8-11] for the wood considered in this research. The tensile strength is higher than compressive strength, being the tensile strength in the same order of magnitude of corresponding value presented in Table 1. Strengths presented in Table 1 were derived under tension conditions.

Table 2. Elastic and strength shear properties of the Pinus pinaster Ait. species [8-11].

		Aver. Value	Coef. Var. (%)		Aver. Value	Coef. Var. (%)
Off-axis	G_{LR} (GPa)	1.11	7.0	τ_{LR} (MPa)	14.1	12.1
	G_{LT} (GPa)	1.04	8.1	τ_{LT} (MPa)	14.0	9.5
	G_{RT} (GPa)	0.16	7.1	τ_{RT} (MPa)	2.39	8.8
Arcan	G_{LR} (GPa)	1.45	6.5	τ_{LR} (MPa)	15.1	10.6
	G_{LT} (GPa)	1.20	5.7	τ_{LT} (MPa)	15.9	7.2
	G_{RT} (GPa)	0.25	19.8	τ_{RT} (MPa)	4.54	12.1
Iosipescu	G_{LR} (GPa)	1.41	10.3	τ_{LR} (MPa)	15.9	15.2
	G_{LT} (GPa)	1.22	8.4	τ_{LT} (MPa)	15.9	8.4
	G_{RT} (GPa)	0.29	16.2	τ_{RT} (MPa)	4.35	19.2

3. EMBEDDING TESTS RESULTS

This paper presents results of embedding tests carried out according the EN 383 and ASTM D 5764 standards. Figure 2 gives a schematic overview of all types of tests carried out. Compression test series were performed in both longitudinal and radial directions; a single tensile test series was also executed. All experiments were instrumented with LVTD's (model AML/EU±10-S10 from Applied Measurements®). A nominal diameter of the dowel (d) equal to 14 mm was selected; the dimensions of the specimens were defined proportionally, according to the standards (see Fig. 2). Table 3 summarizes the embedding test series. Figure 3 shows the load-displacement curves for the compressive embedding tests. Figure 4 shows the load-displacement curves for the tensile embedding tests.

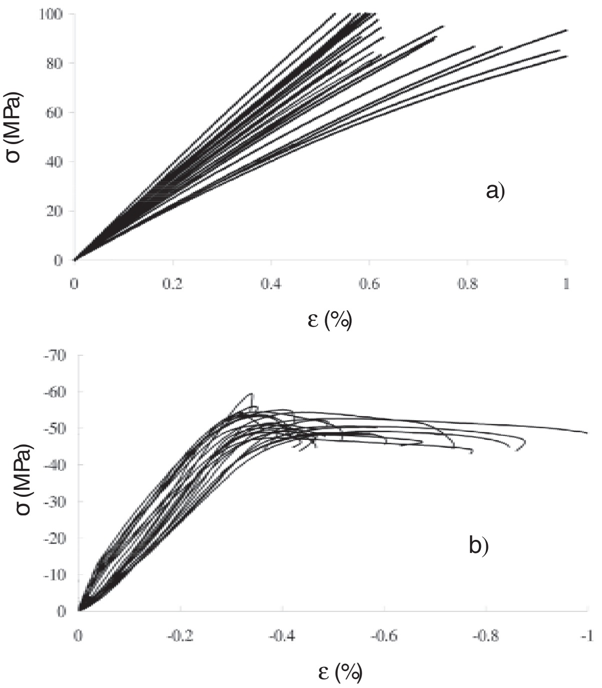

Fig. 1. Stress-strain curves obtained for (a) tensile and (b) compressive tests carried out in the longitudinal direction of wood.

Table 3. Elastic and strength properties of the Pinus pinaster Ait. species measured using parallel-to-grain tensile and compressive tests [8-11].

		Average Value	Coef. Of Var. (%)
Tensile Tests	**E_L (GPa)**	14.7	18.6
	ν_{LR}	0.47	18.9
	σ_L (MPa)	93.7	12.2
	ρ (kg/m^3)	634.8	6.6
Compressive Tests	**E_L (GPa)**	16.0	14
	ν_{LR}	0.44	28.0
	σ_L (MPa)	51.9	5.4
	ρ (kg/m^3)	646.4	3.5

The EN 383 standard suggests a loading procedure consisting on an initial loading until 40% of the estimated failure load. The load is maintained at that level during 60 s followed by an unloading until 10% of the estimated failure load. The load is held during more 60 s, after which a reloading until failure should be carried out. According the ASTM D 5764 standard, the displacement should be applied monotonically until failure. The embedding tests in the longitudinal direction exhibited a well defined ultimate load. For the embedding tests in the radial direction, after a yield load, the load increases continuously due to wood densification.

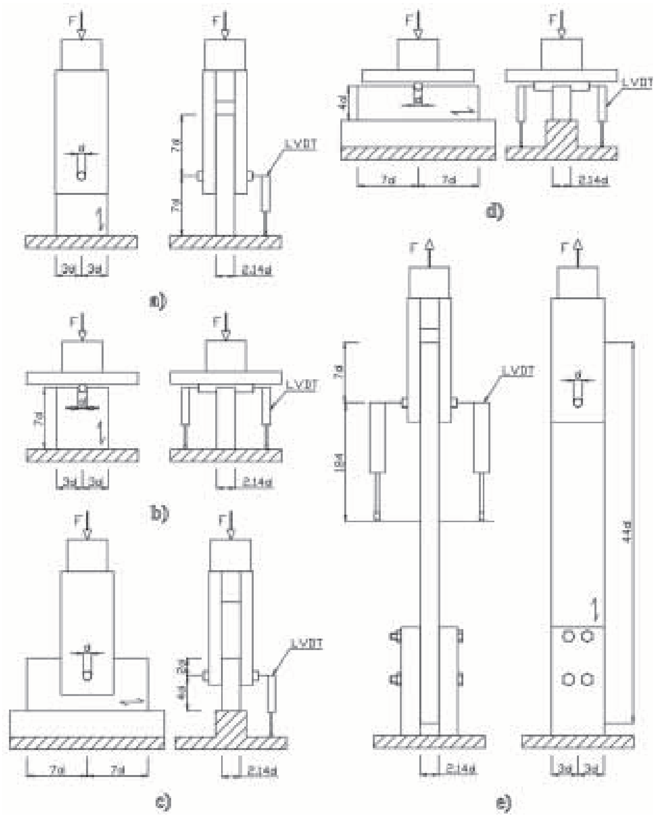

Fig. 2. Embedding tests: a) longitudinal compression according to EN 383 standard; b) longitudinal compression according to the ASTM D 5764 standard; c) radial compression according to EN 383 standard; d) radial compression according to ASTM D 5764 standard; e) longitudinal tensile test according to the EN 383 standard.

Table 4. Embedding test series.

Series	N.º of specimens	Displac. rate [mm/min]	Density (kg/m^3)	
			Aver.	Std. Dev.
Longitudinal Compression (EN 383) – LC1	24	0.3	570.1	38.3
Longitudinal Compression (ASTM D 5764) LC2	26	0.3	584.0	56.2
Longitudinal Tensile (EN 383) – LT1	26	0.5	573.2	49.8
Radial Compression (EN 383) – RC1	24	1.0	550.1	49.0
Radial Compression (ASTM D 5764) RC2	26	1.0	615.5	55.3

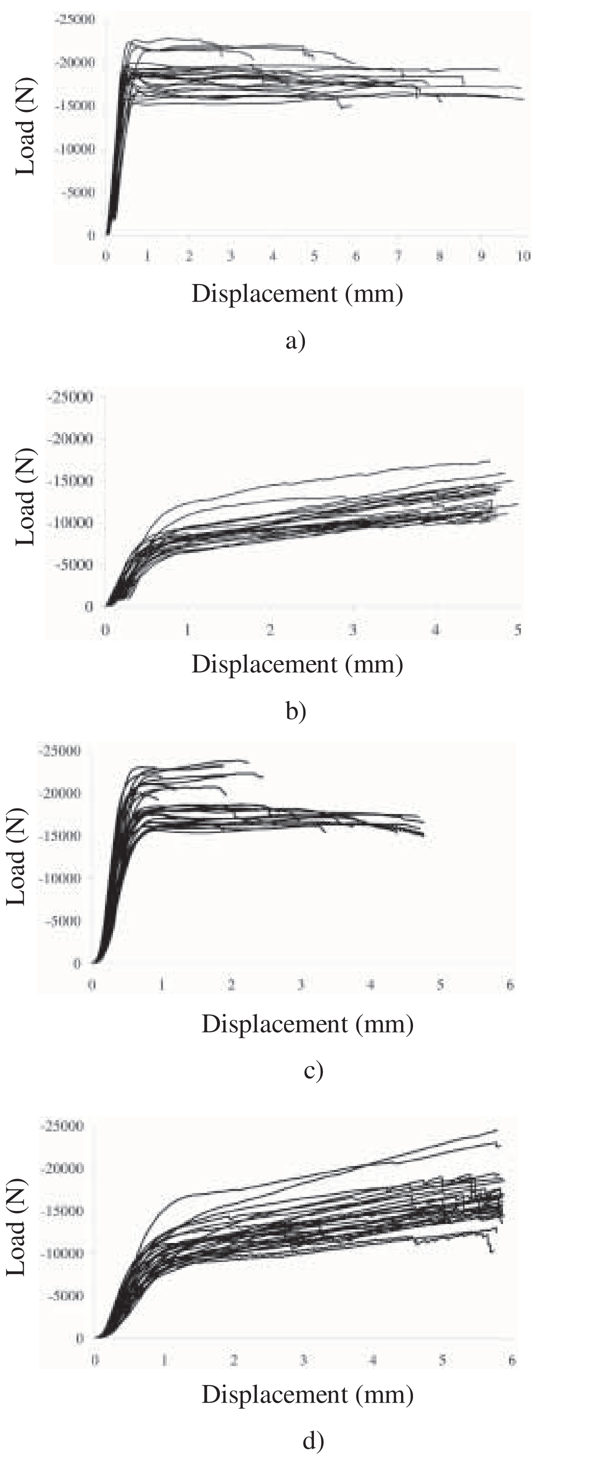

Fig. 3. Load-displacement curves. EN 383 standard: a) longitudinal compression; b) radial compression. ASTM D 5764 standard: c) longitudinal compression; d) radial compression.

For these latter cases, the ultimate load is defined as the load for which a residual embedding displacement of 5% of the dowel diameter is observed. Base of these ultimate loads, the embedding strength, f_h, was evaluated. For the tests carried out according the EN 383 standard, two stiffness vales were evaluated, being the first one the slope of the initial load-displacement curve until 40% of the estimated failure load; the second stiffness value corresponds to the average slope of the unloading/ elastic reloading curves. Furthermore, for the radial compression tests a third stiffness value is defined based on the load-displacement curve after the yield point. Since the ASTM D 5764 standard uses a monotonic increasing displacement, only one stiffness value is evaluated for the elastic range. Again, for the radial compression tests, a second stiffness value is proposed for the pos-yielding behaviour. These stiffness values are converted into foundation modulus, K, dividing their values by the diameter of the dowel and thickness of the wood specimens.

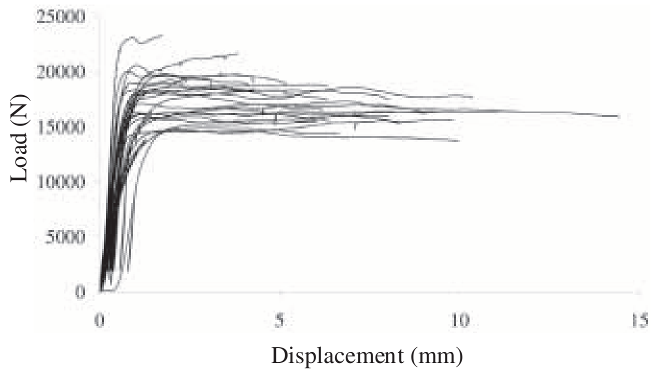

Fig. 4. Load-displacement curves resulted from tensile embedding tests carried according the EN 383 standard.

Table 5 shows the average results of the embedding tests, namely the embedding strength and foundation modulus. The embedding strength and foundation modulus in the longitudinal direction are higher than in radial direction, as expected due to the anisotropy of the wood. The EN 383 and ASTM D 5764 standards give very similar embedding strength results for the compression tests in longitudinal direction. However, for radial compression tests, the ASTM D 5764 standard gives higher embedding strength values. The longitudinal tensile and compression tests carried out according the EN 383 standard results distinct embedding strength and foundation modulus results.

Table 5. Average values of the embedding test results.

		LC1	**RC1**	**LC2**	**RC2**	**LT1**
f_h (MPa)	**Aver.**	46.4	21.1	46.2	28.6	42.8
	St. Dev.	4.2	3.6	5.8	5.2	5.3
K_1 (N/mm^3)	**Aver.**	100.0	40.1	120.9	36.0	61.3
	St. Dev.	20.6	12.1	21.4	8.8	17.3
K_2 (N/mm^3)	**Aver.**	129.2	53.5	-	-	101.0
	St. Dev.	21.0	10.1	**-**	**-**	10.3
K_3 (N/mm^3)	**Aver.**	-	3.1	-	3.5	-
	St. Dev.	-	0.7	-	1.0	-

An analysis of the embedding data revealed a significant correlation between embedding strength and density, which is consistent with EC 5 procedures. For the foundation modulus, no significant correlation was found with density. Figure 5 represents the embedding strength data as a function of the wood density. Figure 5a) illustrates the embedding strength in the longitudinal direction obtained according to the EN 383 and ASTM D 5764 procedures.

Figure 5b) represents the embedding strength in the radial direction obtained according to the EN 383 and ASTM D 5764 procedures. Finally, Fig. 5c) compares the embedding strengths in the longitudinal direction between tensile and compression tests (EN 383 standard). For each test series, a linear regression analysis is performed, resulting significant determination coefficients (R^2>0.47).

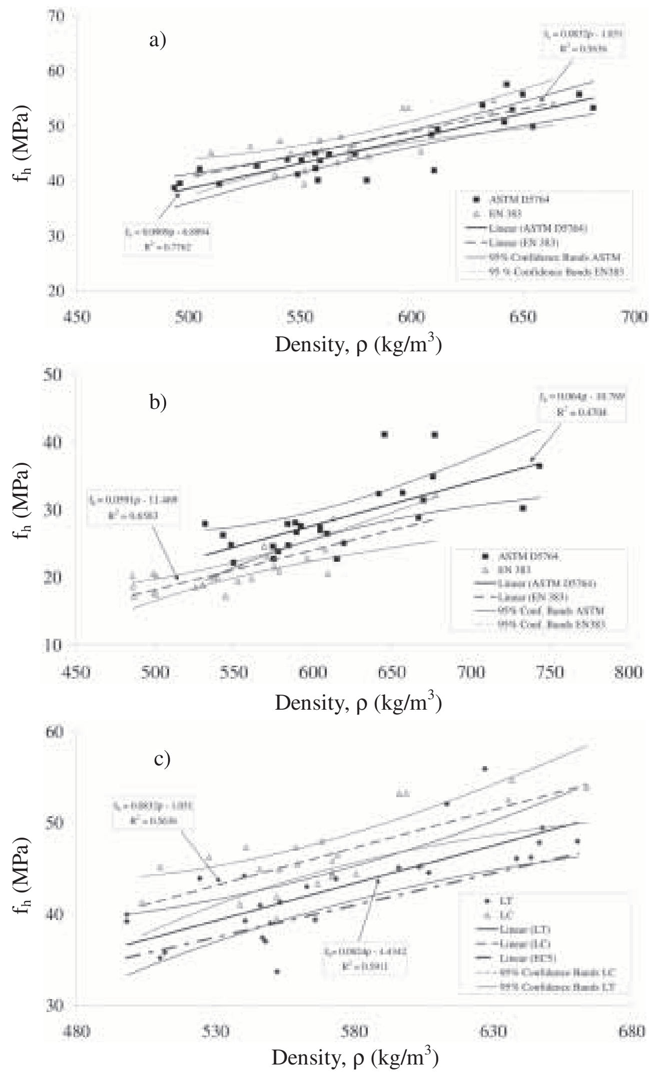

Fig. 5. Embedding strength data as a function of the wood density: a) longitudinal compression data; b) radial compression data; c) EN 383 longitudinal compression and tensile data.

Also 95% confidence bands are included in the figures. A comparison supported on linear regression lines and proposed confidence bands shows that the tensile and compression embedding tests, performed according the EN 383 standard, produce distinct embedding strengths, being the tensile embedding strength the lowest. In what concerns the compression tests, both standards produce very similar results for the longitudinal direction; for the radial direction the confidence bands superposition is relatively small. A comparison between experimental correlations and the EC5 proposal are also carried out in Fig. 5c). The EC5 does not distinguish the embedding strength from tensile or compression tests; it underestimates both embedding strength values being conservative as would be expected. However, if this comparison is made taking into account the 95% confidence bands, the EC5 values are only significantly different from the LT values for densities above 540 kg/m^3. Both experimental regression lines and EC5 relation show the same trends.

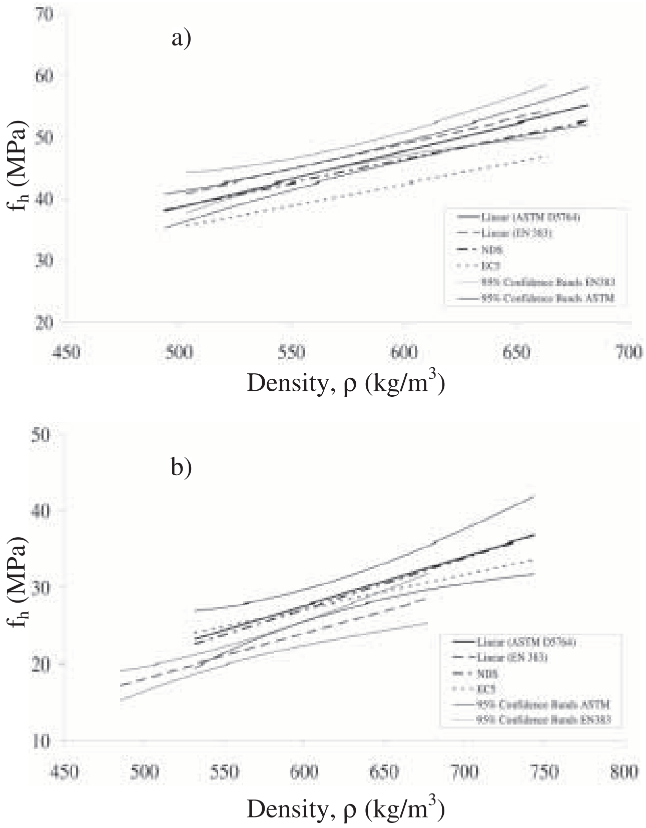

Fig. 6. Comparison between experimental embedding strength data and code based procedures: a) longitudinal compression data; b) radial compression data.

Figure 6 presents a comparison between the experimental embedding strength data and the predictions made using the EC5 [3] and NDS [12] procedures. While the NDS proposes very satisfactory results, the EC5 is inconsistent, since the latter is conservative for the longitudinal compression tests and is unsafe for the radial compression tests.

4. CONNECTION TESTS RESULTS

This paper also presents results of a test series of single-dowel double-shear wood connection, carried out according to the EN 26891 standard [7]. Figure 7a) gives a schematic illustration of the testing apparatus. Figure 7b) represents the load-slip curves obtained with 25 specimens. All tests were carried out with under a controlled displacement rate of 0.3 mm/min. The average density of wood is 617.8±20.9 kg/m^3. The EN 26891 standard suggests the same loading procedure as the EN 383 standard. The dowel diameter was 14 mm and the dimensions of the connection were defined proportionally as specified in Fig. 7a).

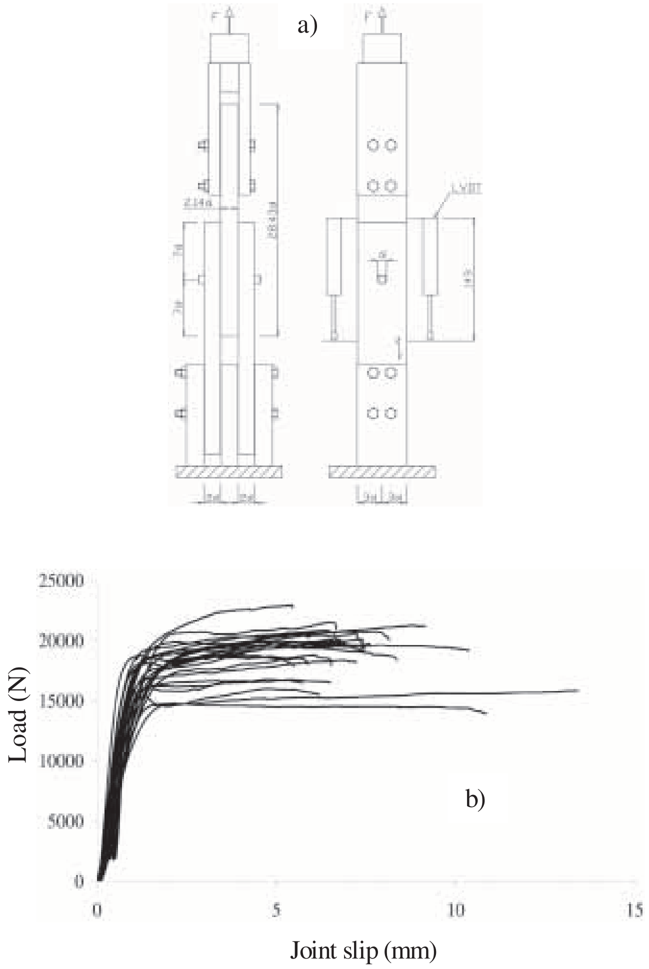

Fig. 7. Single-dowel double-shear wood connection: a) schematic overview of the test; b) load-slip curves.

In Fig. 8 the experimental ultimate loads of the connection are plotted. A linear regression line is plotted together with 95% confidence bands. The experimental data reveals important scatter around the average trend. Based on embedding strength relations, proposed in Fig. 5, the ultimate loads of the tested joint are evaluated. Only embedding test results from parallel-to-grain loading, carried out according EN 383 standard, were used in the joint assessment. Both estimations and experimental ultimate loads are compared in Fig. 8. Taking into account the average trend, the EC5 still is a safe option. However, if the 95% confidence bands are considered, the EC5 is no longer safe for densities above 640 kg/m^3. Clearly the longitudinal compression data are not well suited for the joint failure load estimation; the longitudinal tensile data seems to be a more appropriate choice, even though the different slopes observed.

The slip of the joint at failure presented the average value of 7.32 mm with a standard deviation of 1.96 mm. The average stiffness of the joint measured for the first loading stage was 22196.0 ± 5224.2 N/mm. For the unloading/reloading stages an average elastic stiffness of 39954.7 ± 3663.7 N/mm was measured.

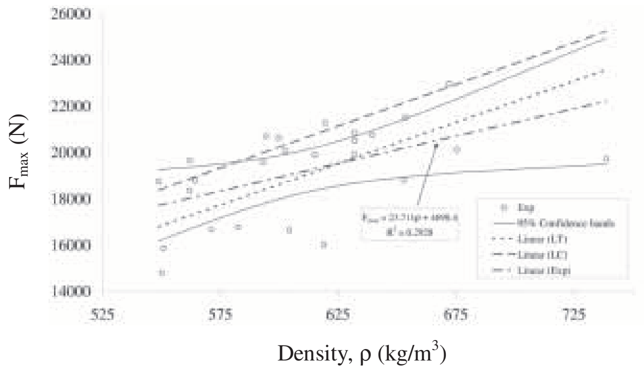

Fig. 8. Ultimate loads of a single-dowel double-shear wood connection.

5. CONCLUSIONS

This paper reported experimental work about the mechanical behaviour of the Portuguese pine wood (Pinus pinaster Ait. species). In particular, the embedding strength beneath a laterally loaded dowel is presented, for the longitudinal and radial directions, according two alternative standardized procedures. The following main conclusions are addressed:

- The embedding strength in the longitudinal direction is significantly higher than in radial direction;
- The embedding strength determined in compression is higher than in tension;
- The EN 383 standard gives about the same results as the ASTM D 5764 standard for compressive embedding tests in the longitudinal direction; for embedding tests in the radial direction some differences in results were found;
- A significant correlation between embedding strength and density was found;
- NDS procedures produce more consistent predictions of the embedding strength than the EC5 procedures.

This study referred elastic and strength properties of the Portuguese pine wood using data available in literature. Some tests performed in this study confirmed the adequacy of the published data.

Finally, strength data from a series of tests of a single-dowel double-shear joint was presented. Attempts to predict the failure load of the joint, using both standardized procedures and the embedding strength data derived in this work, was carried out. It was verified that the embedding test data derived under tensile loading is the most appropriate for assessing the tested joint; significant differences can be found if compressive embedding test data is used in the joint assessment. The EC5 procedures resulted in conservative predictions as expected.

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