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EMBEDMENT TEST OF WOOD FOR DOWEL-TYPE FASTENERS

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ABSTRACT

The mechanical performances of timber joints are particularly important for timber engineers involved in the design of timber structures. Embedding properties are thought to be of great importance for any dowel-type timber joints since they affect the load-bearing capacity, stiffness and failure mode of the joint. This paper specifies a comprehensive experimental program, whose aim is to determine the embedding properties of the species with lager implantation in Serbia. The embedding strength and foundation moduli are determined in longitudinal direction according to EN 383 standard. The experimental embedding strength results are compared with those empirical relations proposed in design codes of practice (Eurocode 5). In addition, compressive strength parallel to the grain is evaluated from small specimens of clear wood so as to characterize the embedding strength of the wood species better.

KEYWORDS: Compressive strength, dowel, embedding strength, foundation modulus, wood density.

INTRODUCTION

The dowel-type fasteners (bolt, nail, dowel) are one of the most popular types of joints in timber construction since they are easy to use, relatively cheap and available everywhere. In order to apply dowel-type joints efficiently the key thing is to understand their mechanical behaviour when undergoing the load (e.g. load-slip relation, stress distributions, ultimate strength and failure modes). The mechanical behaviour of wooden joints is a complex problem governed by a number of geometric, material and loading parameters (e.g. wood species, fastener diameter, end distances, edge distances, spacing, number of fasteners, fastener/hole clearances, friction and loading configuration) (Santos et al. 2010).

According to design codes of current practice, the design of dowel-type timber connections has been based on the European Yield Model proposed by Johansen (1949). In this model, the load-bearing behaviour of the dowel-type fasteners mainly depends on the geometry, plastic moment of the fastener and the embedding properties of the wood. The embedment behaviour is related to the capability of the wood to support the forces applied by rigid body with a circular section.

The importance of embedding properties in timber connection design has drawn considerable attention from researchers across the world (Zhou and Guan 2006). Although historical embedding strength and stiffness can be deduced from a number of studies with different approaches and employing different testing procedures, two broad groups of studies, one carried out in Europe and the other in North America, can be singled out as the primary source of embedment data, which were used in drawing up codes of practice for joint design based on Johansen's theory. In Europe, Whale and Smith (1986a, b, 1989) and Ehlbeck and Werner (1992) made a mayor contribution in terms of determining the embedding strength of deciduous and coniferous wood species and other wood based products. The studies conducted were very comprehensive and involved 1549 embedment tests using seven nail diameters and four bolt diameters with four softwood species, six tropical hardwood and two European hardwood species encompassing a broad range of densities. Results of these works are reflected in the European Standard for determining embedding strength, EN 383 (1993) and in the Eurocode 5 (EC5) timber design code. Dowel-bearing strength values in the NDS and LRFD are based on research conduced by Wilkinson (1991). It involved a total of 379 specimens using five bolt diameters, three nail diameters with four softwood and three hardwood species. Rammer (1999) augmented Wilkinson's work by testing two Guatemalan hardwoods and thereby providing data for the density range which had not been considered in the original study. Current American standard procedures for embedment tests are set out in ASTM D5764-97a (2002). Recent experimental research was performed by Davis and Claisse (2000), Sawata and Yasumura (2002), Awaludin et al. (2007), Hubner et al. (2008), Sandhaas et al. (2010) and Santos et al. (2010).

The purpose of this research was to determine the dowel embedding properties of several wood species groups typical of those used in timber construction in Serbia, namely Pine (*Pinus silvestris* L.), Spruce (*Picea abies* Karst.) and Oak (*Quercus robur* L.). These species represent the softwood and hardwood. The experimental program consists of embedding tests along the longitudinal (parallel-to-grain) direction, meaning that recommendations from the EN 383 (1993) standard have been abided. These embedding tests allow the determination of the whole load-displacement curve until failure as well as the verification of the failure modes. Based on these records, the embedding strength, the initial and elastic foundation modulus were evaluated. The experimental embedding strength results are used so as to verify the empirical formulations proposed in literature. Finally, estimating the embedding strength from the compressive strength of wood was suggested by comparing the embedding test results with those of compressive tests.

MATERIAL AND METHODS

Embedding tests were conducted on solid timber of Pine and Oak, and glulam of Spruce (Fig. 1). Glulam was formed by bonding three timber laminations with grain running essentially in parallel and produced as horizontal glued laminated timber or vertical glued laminated timber. All test were performed with a d = 12 mm steel dowel. According to EN 383 (1993) standard, the test specimen dimensions were 180 mm (14*d*) long, 75 mm (6*d*) wide and 30 mm (1.5*d* - 4*d*) thick. The specimen thickness t = 30 mm was suitable to ensure that for the doweled joints the t/d ratio was sufficiently low (2.5) to minimize the effect of fastener bending and producing the desired embedment response in wood. The thickness direction was chosen to correspond to the wood radial direction. The specimens were conditioned to a constant mass in an environment with a temperature 20 ± 2°C and a relative humidity of 65±5 %. Tab. 1 summarizes general information about the test series, namely the number of specimens, densities and moisture contents. Densities were assessed by whole volumes and masses of the specimens.

Fig. 1: Embedment test series: Oak – solid timber (OK), Pine – solid timber (PN), Spruce –vertical glulam (SP-V), Spruce – horizontal glulam (SP-H).

Tab. 1: Summary of the embedment tests.

Test series	Wood species	Number of specimens	Density ($kg.m^{-3}$)		Moisture content (%)
			Mean	CoV (%)	
PN	Pine	25	528.4	5.05	10.7
SP-H	Spruce	25	478.9	2.16	11.2
SP-V	Spruce	25	489.8	2.84	11.3
OK	Oak	25	718.8	3.00	12.2

The dowel type fastener consisted of a dowel made of short pieces of steel reinforcement bars. Yield strength of f_y = 540 $N.mm^{-2}$ and a tensile strength of f_u = 631 $N.mm^{-2}$ both resulted from tension tests. The hole for the dowel was formed after the climatisation by wood drill with a box column drill with the nominal diameter of the dowel. It is important to highlight the fact that the drilled holes varied for different types of wood (Dias 2005). In the Spruce test specimens it was not possible to drill a really tight fitting hole. There was always a certain clearance and part of the fibers were not cut, but just crushed, leading to imperfect surfaces and damages in the surrounding fibers. In the specimens made of Oak, the hole was much more perfect and all the fibers were perfectly cut, leading to very smooth surfaces. The hole surface of the specimens with Pine resembled that of Oak but not as perfectly smooth. This phenomenon is shown in Fig. 2, where examples are given of holes in the test specimens of the three wood species.

The embedment test was performed as a symmetrical double-shear joint test, using rigid steel side members and a wood or wood-based material centre member. The centre member constitutes the test specimen. The test apparatus is designed so that movement of the connector in the side members is negligible and so that the connector acts as a rigid body undergoing displacement in the direction of loading.

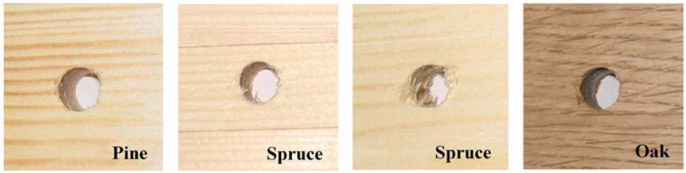

Fig. 2: Holes drilled in Pine, Spruce and Oak.

The clearance provided between the specimen and the steel plate was adjusted and reduced to its minimum to ensure no contact (less than 1 mm) for each specimen. It should be noted that these clearances represent a compromise between the need to minimize frictional interactions between the joint members and the need to minimize connector bending deformations.

The compression load was applied on an UTM-100 (Servo-hydraulic Universal Testing Machine - IPC Global), rated to 100 kN load capacity, with a maximum error less than 1 %. In order to distribute the force applied at top of timber element, tick steel plate was used for entire area. Embedment of the dowel into the wood was measured by using two inductive transducers (LVDTs, 0-10 mm, IPC Global). Aluminum angle plates were screwed to the side of the timber specimen at the centre line level of the dowel hole to measure the movement of the timber at this level. This movement was judged to be equal to that of the displacement of the fastener into the timber specimen. The experimental arrangement and positioning of LVDTs is shown in Fig. 3. The measurements were recorded by data acquisition equipment (IMACS, IPC Global) every 0.1 second. Displacements were measured to an accuracy of ± 0.01 mm. During the test, the load-embedment curve was drawn based on the current data measurement and wood splitting was observed visually.

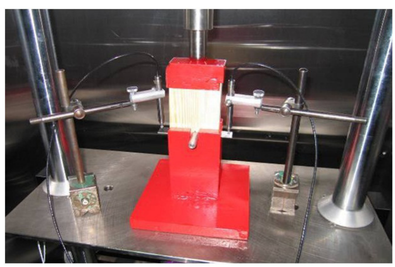

Fig. 3: Embedment test set-up.

The tests were conducted in accordance with EN 383 (1993). This involves a multi-stage loading regime, the key elements of which are: Initial loading to 40 % of estimated maximum load (F_{est}), approximately the working load, of the joint; removal of load to 10 % of F_{est} and finally loading to failure. The test was performed with load control up to 70 % of F_{est} and from that point, with displacement control. The estimated maximum loads were based on the results of the preliminary tests. The embedment tests were stopped when the embedding displacement was 5 mm or when crack reached the end of the timber.

In addition to the embedding tests, quasi-static compressive tests of small specimens of clear wood were carried out in the longitudinal direction of wood. The compressive tests were carried out according to the EN 408 (1995) standard. The compressive specimen used in the experiments has a prismatic shape with a rectangular 30x30 mm cross section and a length of 180 mm. The wood used in these tests was cut from the specimens used for the embedding tests. A total of 48 specimens (12 specimens in each test series) were tested. These tests were also performed in the same testing machine used in the embedding tests using a constant rate of loading-head movement. Compressive tests were terminated after the maximum load was attained.

RESULTS AND DISCUSSION

Embedding strength and foundation modulus

Fig. 4 presents the load-displacement curve with the ultimate load closest to the mean value, for each one of four test series studied. Displacements correspond to the average of the two LVDTs records.

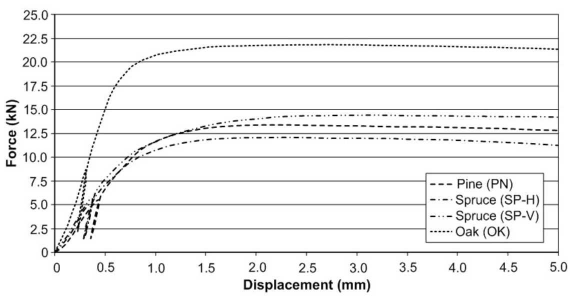

Fig. 4: Load-displacement curves for the embedment tests.

The following parameters were obtained from the load-displacement response:

- F_{max}, the maximum load in kN achieved by the joint, and corresponding displacement in mm;
- k_s, the stiffness of the joint in $kN.mm^{-1}$, determined from analysis of the load-displacement curve until 40 % of the estimated maximum load;
- k_e, the stiffness of the joint in $kN.mm^{-1}$, determined from analysis of the load-displacement curve during the reloading stage 10 % to 40 % of the estimated maximum load.

The previous referred parameters are normalised, dividing their value by projected area of hole, showing the embedding strength (f_h) and foundation modulus (K_s, K_e):

$$f_h = \frac{F_{max}}{d \cdot t} \quad \left(\mathrm{N.mm^{-2}}\right) \tag{1}$$

$$K_s = \frac{k_s}{d \cdot t} \quad \left(\mathrm{N.mm^{-3}}\right) \tag{2}$$

$$K_e = \frac{k_e}{d \cdot t} \quad \left(\text{N.mm}^{-3}\right) \tag{3}$$

where: d - the diameter of the dowel (12 mm),
t - the thickness of test specimen (30 mm).

Tab. 2 summarizes the global values of the embedding strength and foundation modulus measured for each test series.

Tab. 2: Summary of experimental results from the embedment tests.

Test series	f_h (N.mm^{-2})		K_s (N.mm^{-3})		K_e (N.mm^{-3})		Number of failures caused by splitting
	Mean	CoV (%)	Mean	CoV (%)	Mean	CoV (%)	
PN	38.00	8.08	44.91	37.35	133.67	10.24	9
SP-H	34.34	3.49	48.79	30.40	128.86	9.34	5
SP-V	41.46	5.34	49.30	27.77	139.48	9.19	3
OK	59.62	4.23	101.98	24.97	200.22	14.57	2

f_h, embedding strength; K_s, initial foundation modulus; K_e, elastic foundation modulus

The behaviour was plastic for all the wood species, the exception were the specimens that failed due to splitting in the wood. The embedding load showed a linear increase up to the yielding of wood and was almost constant after yielding regardless of the increase in displacement. The maximum load is usually reached within 2-4 mm displacement. Most of Spruce and Pine test specimens showed an initial displacement caused by the hole clearance.

The different failure modes observed in the several embedding testseries are illustrated in Fig. 5. In general, bearing and shear splitting failures are observed. The failure starts with fibers crushing beneath the dowel, being the load in a plateau around the maximum load. After some amounts of deformation, the final failure occurs due to the formation of one or two shear splitting cracks, leading to an important decrease in the load. Sometimes these cracks were initiated in an existing defect, which, in a majority of the cases, was a drying fissure. In many of the other tests, cracks were also formed under the fastener, but did not increase enough to cause failure or even have an evident influence on load-displacement behaviour.

The high-tensile steel dowels were generally unaffected, confirming the desired embedment response, although the three strongest Oak specimens did cause noticeable permanent deformation. None of the glulam specimens failed at the glue line, the transverse splitting occurred in the adjacent wood.

The results observed in the embedding test with solid and glulam timber with similar density were comparable. The mean values of the embedding strength, f_h, obtained for Pine (PN) and Spruce (SP-H, SP-V) are 38.00, 34.34 and 41.46 N.mm^{-2}, respectively. It was found that SP-V specimens with a smaller density have a higher embedding strength than PN specimens.

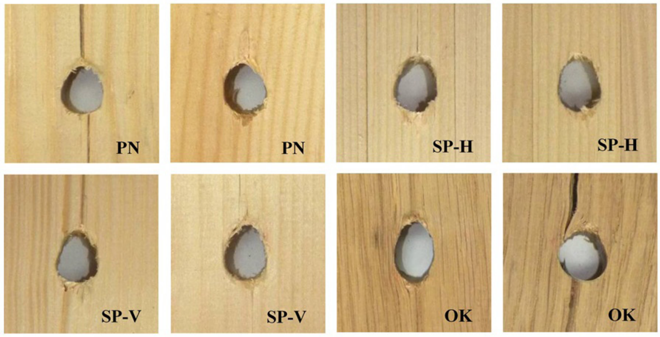

Fig. 5: Typical failure modes observed in the different embedment test series.

The results observed in the embedding test with solid and glulam timber with similar density were comparable. The mean values of the embedding strength, f_h, obtained for Pine (PN) and Spruce (SP-H, SP-V) are 38.00, 34.34 and 41.46 N.mm^{-2}, respectively. It was found that SP-V specimens with a smaller density have a higher embedding strength than PN specimens. It can be concluded that the vertical glue line had a determinable effect on joint strength and stiffness. The mean value obtained for Oak, 59.62 N.mm^{-2}, is different from Pine and Spruce. The high density of these specimens would suggest a higher strength and this is confirmed. The coefficient of variation from the embedding strength is low and it varies from a minimum of 0.04 for glulam of Spruce to a maximum of 0.08 for solid timber of Pine. This relatively low coefficient of variation probably occurs due to the natural wood samples used in this experiment, which were carefully selected; more so than would be the case in stress-graded timber for construction.

A similar analysis is made for the foundation moduli. The mean values of initial fundamental modulus, K_s, for Pine (PN) and Spruce (SP-H, SP-V) are 44.91, 48.79 and 49.30 N.mm^{-3}, respectively, while value obtained for Oak (OK) is 101.98 N.mm^{-3}. When considering this parameter, the difference between the test with Oak and other species (Pine and Spruce) is much greater than for the embedding strength. The different behaviour might be explained by the anatomical structure of softwood and hardwood species. The values found for elastic foundation modulus, K_e, are much higher and scatter smaller when compared to the initial fundamental modulus, K_s. This may indicate that there are other parameters, apart from the density, with an important influence on the foundation modulus. One of them is probably the perfection of the hole and the quality of the hole surface (Dias 2005). On embedment tests, hole clearance affects the initial measurements and also a hole surface that is not smooth influences the measurements at the beginning of the load-displacement curve. During the embedment test, as the load increases, the area around the fastener is completely changed and importance of these parameters becomes negligible. The coefficient of variation obtained for the initial foundation modulus varied between 0.25 and 0.37. This is higher when compared to the variation of the same parameter for the embedding strength.

The experimental values of the embedding strength and initial foundation modulus plotted against the density for all tested series are presented in Fig. 6 and Fig. 7. Also, linear regression lines are included as well as the linear regression parameters. Both dowel embedding strength and stiffness were positively affected by the density. The correlation between the embedment properties and wood density was assessed. A significant correlation was found for embedding strength (R^2 = 0.85) and medium correlation was found for initial foundation modulus (R^2 =

0.55). This means that the density is an important factor for embedding properties, but not the only one.

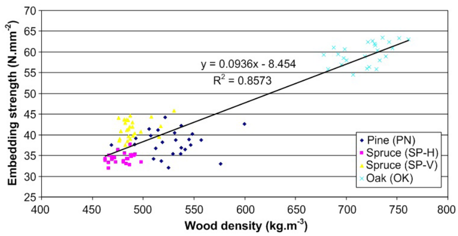

Fig. 6: Embedding strength results obtained in the tests against the density of wood.

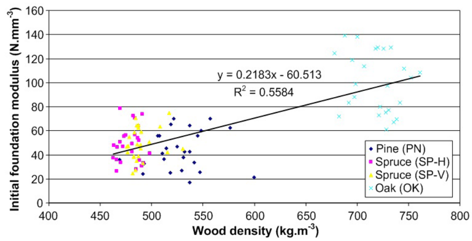

Fig. 7: Initial foundation modulus results obtained in the tests against the density of wood.

Prediction of embedding strength

The embedding strength of wood can be estimated through empirical formulations available in literature. These relations express a dependency of the embedding strength with wood density as well as a dependency with the diameter of the dowel and the load orientation, in relation to the wood grain direction. The following relation has been suggested by Eurocode 5 for the longitudinal direction:

$$f_{h,0} = 0.082\ (1\text{-}0.01d)\ \rho \tag{4}$$

where: $f_{h,0}$ - the embedding strength in the wood grain direction expressed in $N.mm^{-2}$,
d - the diameter of the dowel in mm and ρ is the density of wood in $kg.m^{-3}$.

The NDS proposes the following expression:

$$f_{h,0} = 0.07725\ \rho \tag{5}$$

where: $f_{h,0}$ - the embedding strength in the wood grain direction expressed in $N.mm^{-2}$,
ρ - the density of wood in $kg.m^{-3}$.

Note that NDS expression is only a function of the density of wood material and is not a function of the dowel size.

Leijten and Köhler (2004) evaluated embedment tests parallel to the grain in a probabilistic framework to enable reliability analyses. Based on multiple linear regression analyses they defined constants that fit the data bases best. In case of dowels, the following relationships for coniferous and deciduous wood species are suggested:

$$f_{h,0} = 0.097\ \rho^{1.07}\ d^{-0.25} \quad \text{for coniferous species} \tag{6}$$
$$f_{h,0} = 0.087\ \rho^{1.09}\ d^{-0.25} \quad \text{for deciduous species} \tag{7}$$

where: $f_{h,0}$ - the embedding strength in the wood grain direction expressed in $N.mm^{-2}$,
d - the diameter of the dowel in mm and ρ is the density of wood in $kg.m^{-3}$.

Embedding strength estimated by empirical equations and obtained from the experiment is compared in Tab. 3 and Fig. 8. Although these empirical equations were derived from test results of different wood species, specimen dimensions and test configurations, their embedding strengths were within close approximation to one another. Fig. 8 shows that the estimated embedding strength given by NDS was higher than that given by EC5. This discrepancy corresponded to the difference of test methods. While the experimental results for solid timber of softwoods species meet the EC5 equation, there are some deviations for solid timber with high densities. This finding was supported by the fact that the calculation of embedding strength according to EC5 is based on substantial and fundamental experiences with softwoods and tropical hardwoods but includes only small number embedding tests with two European hardwood species (Hübner et al. 2008). For practical use, some modifications or restrictions are probably required when the empirical equation given by EC5 is used for hardwood species. Oak, which has been tested, displays realistic values by using Leijten and Köhler‘s embedding strength formula (Eq. 7). The EC5 does not make a distinguish between the embedding strength of horizontal and vertical glulam; it underestimates embedding strength values for vertical glulam as expected.

Tab. 3: Estimated and experimental embedding strength (N.mm^{-2}).

Test series	Eurocode 5 (Eq. 4)	NDS (Eq. 5)	Lejten & Köhler (Eq. 6 or 7)	Experiment	
				Mean	Range
PN	38.12	40.80	42.70	38.00	32.06-44.27
SP-H	34.56	36.99	38.44	34.34	31.96-37.69
SP-V	35.37	37.86	39.41	41.46	37.61-45.83
OK	51.87	55.53	60.74	59.62	54.57-63.50

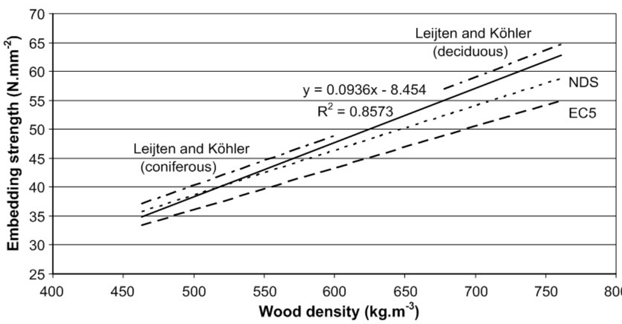

Fig. 8: Comparison between the experimental results and the empirical formulations for the embedding strength.

Relation between embedding strength and compressive strength

Compressive strength parallel to the grain was evaluated with maximum stress according to EN 408 (1995) standard. Fig. 9 illustrates four typical specimens after testing.

The embedding strength is closely related to the more straight forward compressive strength parameters of wood, but it is of course influenced by the uneven stress distribution below the fasteners. Since embedding strength and ultimate compression strength both measure wood resistance to crushing, it would follow that they should be positively correlated. This belief is verified by comparing dowel embedding strength and ultimate compression strength obtained from this experimental investigation. Fig. 10 shows the linear regression derived from all the test series. Analysis indicated a good correlation, with R^2 = 0.74.

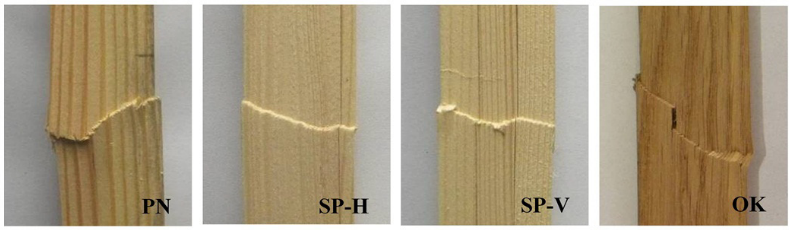

Fig. 9: Typical failure modes observed in the different compression tests.

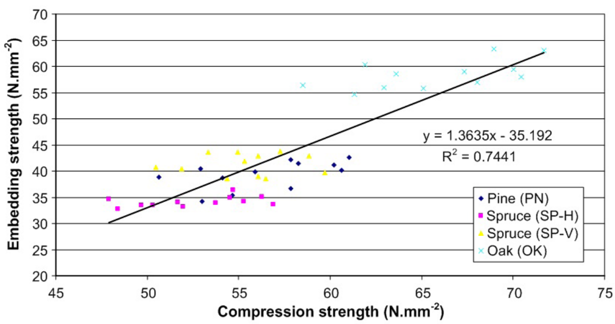

Fig. 10: Embedding strength test results against the compression strength test results.

Tab. 4: Ratio of embedding strength to compression strength.

Test series	Ratio of f_h/f_c	CoV (%)
PN	0.68	10.49
SP-H	0.64	5.21
SP-V	0.75	6.72
OK	0.89	8.34

f_h, embedding strength; f_c, compression strength

Tab. 4 presents data from all test series that result in a ratio of embedding strength to ultimate compression strength in the 65 % to 70 % range for softwood specimens, which compares favorably with ratios from studies discussed by Rammer and Winistorfer (2001). However, as shown in Tab. 4, this ratio increases to approximately 90 % for hardwood.

CONCLUSIONS

Different wood species exhibit different behaviour under embedment. Knowing more about this behaviour will help to improve knowledge and prediction quality of the mechanical behaviour of timber connections.

This paper presented results of embedment tests parallel to the grain with different wood species (Pine, Spruce and Oak) and dowel-type fasteners carried out according to the EN 383 standard. For all test series the load-displacement curves show a typical linear and full plastic branch. The failure modes observed for the embedding tests corresponded to the local bearing and to the shear splitting. Results demonstrated that both embedding strength and foundation modulus of the softwood species are significantly lower than those corresponding values of hardwood species, as expected due to the wood density. Also, doweled connections in glulam appear to give strength and stiffness properties at least comparable to a solid timber of similar density.

Empirical equations to determine the embedding strength of wood were proposed based on the experimental data. However, because these empirical equations were derived from test results of different wood species, specimen dimensions and test configurations, trials to validate the equations are consequently required. The relationship between the experimental values of density and embedding strength meet the EC5 for the softwood species. However, for the hardwood species, the EC5 underestimates the embedding strength.

Finally, additional tests verified previous research, which had shown that parallel to the grain dowel embedding strength is positively correlated with ultimate parallel to the grain compression strength.

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