DEVELOPMENT OF STRENGTHENING SOLUTIONS FOR DOWEL-TYPE WOOD CONNECTIONS

C.L. Santos[1], A.M.P. de Jesus[2,3], J.J.L. Morais[1], E.R.M.A. Queirós[2], A.M.V. Lima[2]

[1] CITAB/Engineering Department, School of Sciences and Technology
University of Trás-os-Montes and Alto Douro, Quinta de Prados, 5001-801 Vila Real
E-mail: clsantos@utad.pt; jmorais@utad.pt

[2] Engineering Department, School of Sciences and Technology
University of Trás-os-Montes and Alto Douro, Quinta de Prados, 5001-801 Vila Real, Portugal
E-mail: ajesus@utad.pt; edgarruben@hotmail.com; alima@utad.pt

[3] UCVE, IDMEC – Pólo FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

ABSTRACT

This paper presents a study concerning the development of reinforcing techniques for dowel-type wood connections. One of the proposed techniques is based on the application of CFRP laminates (glued with epoxy resin) in the areas surrounding the holes of the wood members. The other technique is based on the application of steel inserts, glued to the holes of the timber members. In this latter technique two distinct commercial epoxy adhesives are investigated. Both techniques are demonstrated for the maritime pine wood. The experimental program included embedding tests, carried out according to the EN 383/1993 standard, with and without reinforcement, and covering parallel and perpendicular-to-grain quasi-static loading. The proposed experimental program allowed the evaluation of the embedding strength and foundation modulus. The analysis of this information showed the improved performance of the strengthening solutions. Also, it is important to emphasize that the reinforcement based on CFRP laminates eliminated fragile failure modes in the wood members.

KEY WORDS: Dowel-type connections, Maritime Pine Wood, Reinforcing solutions, CFRP, Metallic Inserts.

1. INTRODUCTION

Joints are often the weakest points in timber structures. The loss of perfect continuity in the structure, which is caused by the presence of joints, will result in a reduction of the global strength. This implies an increase in dimensions of the assembled elements. About 80% of structural failures have their origin on connections [1]. The dowel-type connections are the main fastening technique used worldwide in timber structures. The singularity of wood joints is not only attributed to a combination of different materials, such as wood and steel, but also due to the highly anisotropic behaviour of wood. Fundamental to an efficient utilisation of dowel-type joints is the understanding of their mechanical behaviour under load (e.g. load-slip behaviour, stress distributions, ultimate strength and failure modes). The mechanical behaviour of wood 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).

According to the actual worldwide design rules [2,3], the calculation of mechanical timber joints is based upon the Johansen's yield model (YM) [4]. It only predicts the ultimate loads associated to ductile failure modes; brittle failure modes (e.g. shearing out, splitting perpendicular to grain) are not foreseen [5]. Since the YM does not allow the modelling of fragile failure modes, design codes suggest empiric minimum dimensions for joints (e.g. hole-member end distances) in order to avoid the fragile failure modes, which are undesirable for structures in service.

The reinforcement of dowel-type joints, aiming the improvement of the mechanical performance including the reduction of fragile failures, is a challenging research topic. Several reinforcing techniques have been proposed to improve the stiffness, strength and ductility characteristics of the joints (e.g. resin injected dowels, expanded tube joints, shear plate connectors, glued composites such as FGRP) [6-8].

A new reinforcing solution, based on bonded metallic inserts has been proposed for high performance composites materials [9,10]. This paper proposes the extension of this technique to dowel-type wood joints. Based on an experimental work, authors demonstrate the potential of this reinforcing technique. Embedding tests were carried out on unreinforced and reinforced series, according the procedures of the EN383/1993 standard [11]. The embedding tests were carried out on maritime pine wood (*Pinus pinaster* Ait. species) according both the parallel (longitudinal) and

perpendicular (radial) to grain directions, allowing the comparison of the embedding strength and foundation modulus.
Additionally, this paper assess an alternative reinforcing technique based on the application of Carbon Fibre Reinforced Plastic (CFRP) in the form of laminates glued with epoxy resin to the sides of wood members, surrounding the holes for insertion of the dowels. The performance of this reinforcement is demonstrates also using embedding tests according to the EN 383/1993 standard [11], along the longitudinal and radial directions of wood.

2. EXPERIMENTAL PROGRAM

A reinforcing technique consisting on the application of metallic inserts into the holes of the wood members being joined, using a structural adhesive is proposed in this work. Also, another reinforcing technique based on the application of CFRP laminates is investigated in this work. It is expected that these techniques contribute to the stress concentration reduction in wood, in the vicinity of the holes, beneficiating the strength of the connection.
An experimental program is proposed in this paper to demonstrate the efficiency of the reinforcing techniques for dowel-type connections. In particular, series of compressive embedding tests are carried out, according the EN 383/1993 standard procedures [11], in both longitudinal and radial directions. Two alternative structural adhesives were investigated in the reinforced solution based on metallic inserts. For the reinforced solution based on CFRP laminates only an adhesive is used.
The reinforcing techniques investigated in the paper are illustrated in Figure 1. The metallic inserts, used in one the proposed reinforcing technique, were introduced on pre-drilled holes carried out on the wood members, one at each side of the member. The insert is glued to wood using an epoxy resin. Figure 2 represents the geometry and dimensions of the metallic inserts. The performance of the strengthening solution is dependent on the efficiency of the adhesive. In this paper, two alternative adhesives were tested, namely the ARALDIDE® 2011 and the HILTI® RE500.
The CFRP laminates used as an alternative reinforcing technique were specifically manufactured for this investigation. It consisted on a bidirectional laminate in order to allow good performance in both radial and longitudinal wood directions. The laminate resulted from the superposition of 10 alternate lamellas of unidirectional SEAL Texipreg® HS160 RM, according to the sequence $[(0/90)_2/0]_S$. Epoxy resin was used to impregnate the lamellas. Each lamella has a thickness of 0.15mm, which gives a laminate of about 1.5 mm thick. 84x50 mm^2 CFRP laminates were glued centred in the wood members. Wood members were previously machined to accommodate the laminate in order to preserve to thickness of the member of 30 mm. Holes for dowels were drilled after curing the adhesive, using drills with high hardness tungsten finishing, to avoid damaging the CFRP laminates.
In order to assess the performance of the proposed reinforcing techniques, embedding tests of wood member of Maritime Pine (*Pinus pinaster* Ait.) were carried out, according the EN 383/1993 standard. Both parallel- (longitudinal) and perpendicular-to-grain (radial) compressive embedding tests were carried out, as illustrated in Figure 3. The nominal diameter of the dowel (*d*) was chosen equal to 14 mm and the member's thickness (*t*) equal to 30 mm. The dimensions of the members are proportional to the diameter of the dowel (see Figure 3) as proposed in the EN 383/1993 standard. Eight series of tests were prepared as described on Table 1: six reinforced series (R) and two unreinforced series (NR). Half of the series were tested under radial compression (RC) and the other half under longitudinal compression (LC). Regarding the series reinforced with metallic inserts, half were obtained using the HILTI® RE500 adhesive (A) and the other half using the ARALDITE® 2011 adhesive (B). The CFRP laminates were glued to the wood members using the Sikadur® 30 epoxy-based resin. Table 1 refers the density values of each series. The average density values range from 550.1 kg/m^3 to 646.7 kg/m^3. The displacement rates were 0.3 mm/min for the LC series and 1.0 mm/min for the RC series. The wood used in the tests was air dried until approximately a moisture content of 12%.
Tests were performed on an INSTRON® machine, model 1125, rated to 100kN, under crosshead displacement control. One linear variable differential transducer (LVDT) was used to measure the relative displacement between the dowel and the base plate (see Figure 3). The LVDT used in the experimental program is from the Applied Measurements® with reference AML/EU ± 10-S10 (measurement range of ±10mm). The data was acquired by means of a SPIDER® 8-30 system. Respecting the EN 383/1993 standard, a loading-unloading-reloading procedure was adopted: firstly specimens were loaded until 40% of the maximum estimated load (Fest), and the crosshead position held during 30s; after this stage, specimens are unloaded until $0.1F_{est}$ and the crosshead position again maintained along more 30s; finally, specimens are reloaded until failure.

Figure 1. Specimens reinforced with metallic inserts (left) and CFRP laminates (right).

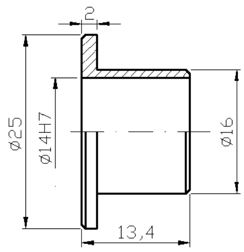

Figure 2. Geometry and dimensions of the metallic insert (dimensions in mm).

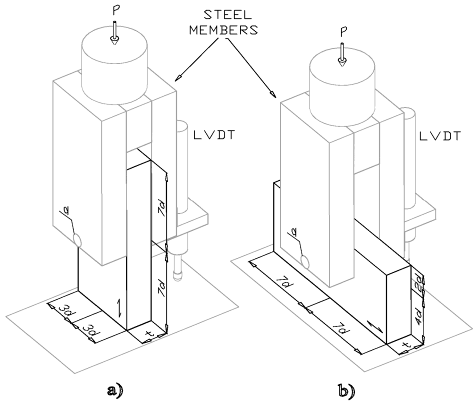

Figure 3. Schematic representation of the embedding tests according the EN383/1993 standard: a) longitudinal compression; b) radial compression.

Table 1. Summary of the test series

Series	N.º of Speci -mens	Density		
		Mean	Std. Dev.	Coef. of Var.
		Kg/m^3		%
LC_NR(1)	24	570.1	38.3	6.7
LC_R_A(2)	12	626.8	31.0	4.9
LC_R_B(3)	11	633.6	32.1	5.1
LC_R_CFRP(4)	15	595.9	48.47	8.1
RC_NR(1)	24	550.1	49.0	8.9
RC_R_A(2)	12	615.4	29.5	4.8
RC_R_B(3)	12	646.7	37.0	5.7
RC_R_CFRP(4)	15	581 .7	48.4	8.32

(1) : wood member not reinforced
(2) : wood member reinforced with glued metallic inserts - HILTI® RE500 adhesive
(3) : wood member reinforced with glued metallic inserts - ARALDITE® 2011 adhesive
(4) : wood member reinforced with CFRP laminates

3. RESULTS AND DISCUSSION

Figure 4 illustrates the load-displacement curves obtained for the four embedding test series, carried out according the longitudinal direction. Figure 5 illustrates the load-displacement curves obtained for the four embedding test series, carried out according the radial direction. Displacements in the graphs were measured using an LVDT, as illustrated in Figure 3. The LVDT gives the displacement between the end of the dowel and the base of the testing machine. Regarding the longitudinal compression tests, unreinforced series and reinforced series with metallic inserts, exhibit a maximum load plateau, which defines the ultimate load (see Figure 6a)). Typically, after some amount of deformation, at almost constant load, fragile failures occur, with a sudden load drop. For these test series, the failure load is defined as the absolute maximum load. The longitudinal test series reinforced with glued CFRP laminates, exhibits a yield plateau, after which an irregular increasing load is verified. This increasing strength is due to the beneficial effect of the CFRP laminates, which postpones the fragile failure modes. For this latter series, the failure load was considered as the load prior the first load drop at the initial yield plateau. The analysis of the load-displacement curves from the embedding tests in the radial direction shows that for the unreinforced series there is a smooth transition from the elastic to inelastic behaviours. Also, there is a monotonic load increase after yielding. In this case, the ultimate failure load was defined as the load at 0.05*d* permanent displacement (see Figure 6b)), where *d* is the dowel diameter. All the reinforced series shows a yield plateau before the load starts to increase again. This yield plateau is more pronounced for the series reinforced with glued CFRP laminates. For these reinforced test series, the failure load was defined as the first load peak appearing at the yield plateau.

Using the failure loads it was possible to establish the embedding strength, f_h, for all test series using the following formula:

$$f_h = \frac{F_{\max}}{d \cdot t} \tag{1}$$

where: F_{max} is the failure load, d is the diameter of the dowel and t is the thickness of the wood member.

Despite the embedding tests were carried out according the EN383/1993 standard, which proposes a loading path consisting on an initial load until 40% of the maximum estimated load, followed by an unloading until 10% of the maximum estimated load and a final reloading until failure, an initial stiffness was evaluated neglecting the unloading/reloading paths. The load-displacement curves (Figures 4 and 5) were edited to remove the unloading/reloading hysteresis. An initial elastic stiffness (k_1) was evaluated using the linear regression analysis applied to the linear range of the load-displacement curves, as illustrated in Figure 6. Another stiffness value (k_2) was defined for the embedding tests in the radial direction, after yielding, as defined in Figure 6b). The previous referred stiffness parameters can be normalised, dividing their values by the projected area of the hole, resulting the foundation modulus (K_i):

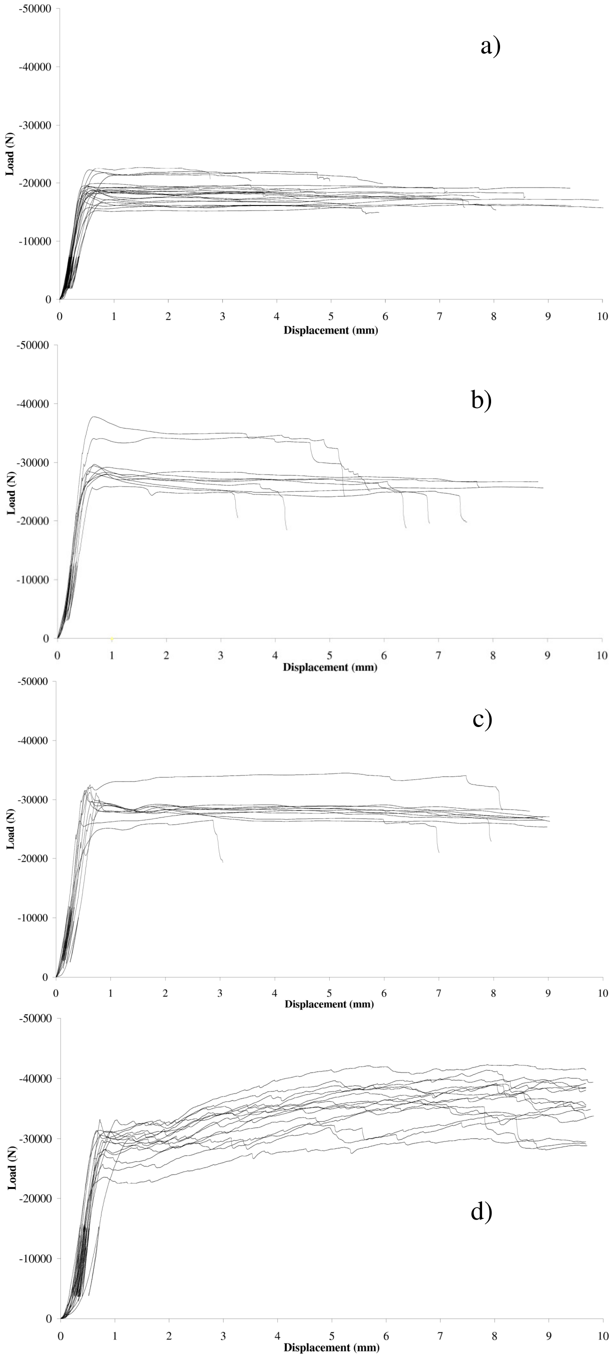

Figure 4. Experimental load-displacement curves obtained for the test series: (a) LC_NR series; (b) LC_R_A series; (c) LC_R_B series; (d) LC_R_CFRP series.

$$K_i = \frac{k_i}{d \cdot t} \tag{2}$$

where: K_i is the foundation modulus, k_i the stiffness, d is the diameter of the dowel and t if the thickness of the member.

Figures 7 and 9 illustrate the evolution of the embedding strength with the wood density, since the latter property is often used to explain variations of mechanical propertied of wood, within the same species and among species. The analysis of the figures reveals a significant gain in the embedding strengths when the reinforcements are used, even if density differences are taken into account. The correlation between the embedding strength and density is significant for both unreinforced series. For some reinforced series this trend is also observed, but there are some reinforced tested series for which no correlation between the embedding strength and density is verified.

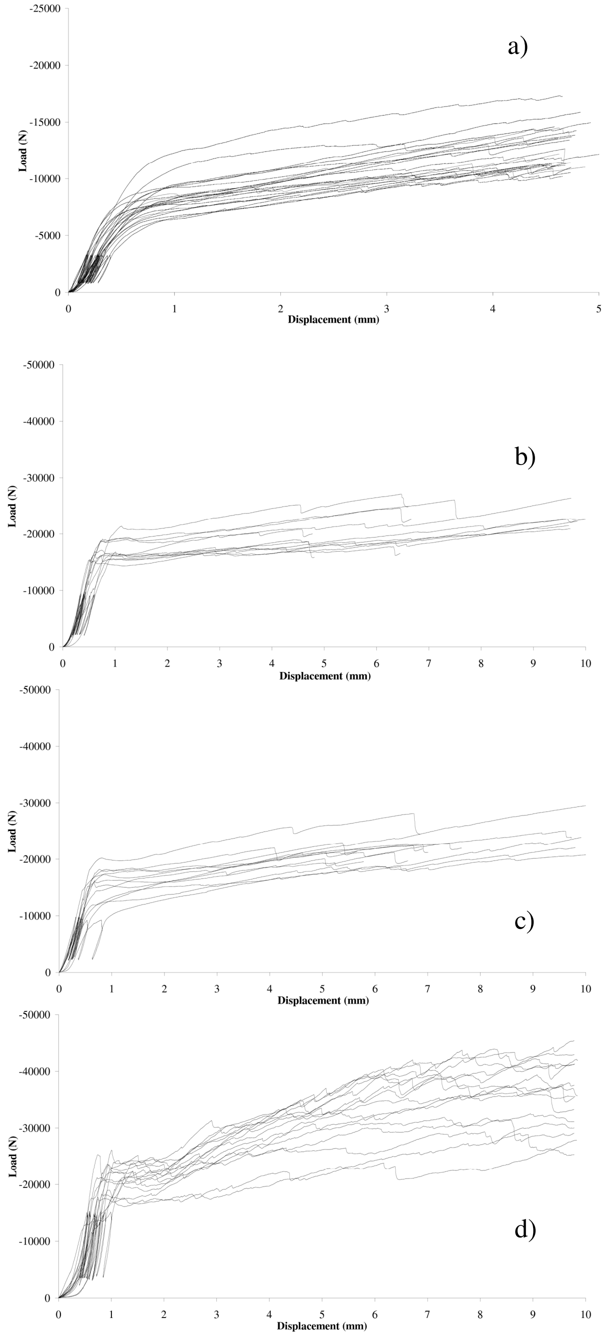

Figure 5. Experimental load-displacement curves obtained for the test series: (a) RC_NR series; (b) RC_R_A series; (c) RC_R_B series; (d) RC_R_ CFRP series.

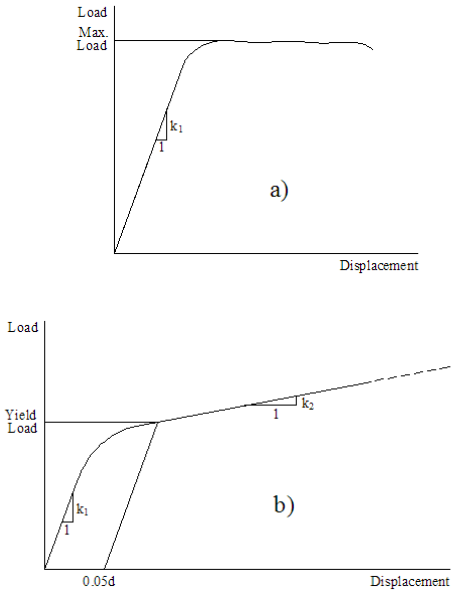

Figure 6. Typical load-displacement behaviours: a) longitudinal compression; b) radial compression.

Table 2 summarizes the average values of the embedding strength for all the testing series. It is clear a higher gain in the embedding strength for tests carried out in the radial compression. In radial direction, the use of CRFP laminates results in significant higher embedding strength when compared with the unreinforced solutions or even with the reinforced solutions with metallic inserts. However, for the longitudinal compression tests, both reinforcing techniques produce similar results. Concerning the reinforcement with metallic inserts, the use of HILTI® RE500 adhesive resulted higher embedding strength properties for the radial compression tests; for longitudinal compression tests, the use of ARALDITE® 2011 adhesive resulted in slightly higher embedding strength.

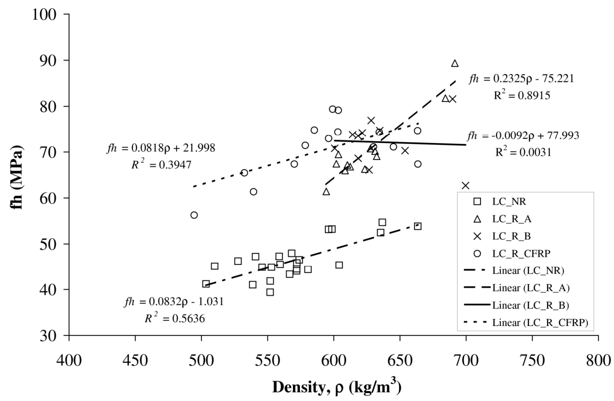

Figure 7. Evolution of the embedding strength with density for unreinforced and reinforced wood member in longitudinal compression tests.

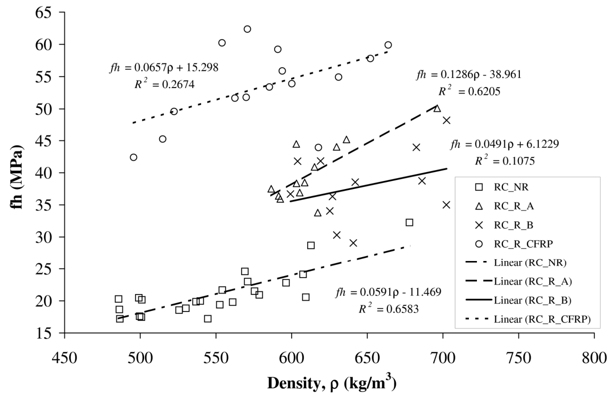

Figure 8. Evolution of the embedding strength with density for unreinforced and reinforced wood members in radial compression tests.

Average foundation moduli (K_1, K_2) are presented in Table 2 for each test series. For this parameter no general correlation was verified with density, therefore respective graphs were omitted. An increase in K_1 is observed for all reinforced solutions. Regarding K_2, only the CFRP laminates had a beneficial effect.

Table 2. Summary of the test results.

Series	f_h				K_1				K_2			
	Mean	St. Dev.	COV	Gain	Mean	St. Dev.	COV	Gain	Mean	St. Dev.	COV	Gain
	MPa		%	%	N/mm^3		%	%	N/mm^3		%	%
LC_NR	46.4	4.2	9.1	-	113.3	23.5	20.7	-	-	-	-	-
LC_R_A	70.5	7.6	10.8	51.9	164.6	36.0	21.8	45.3	-	-	-	-
LC_R_B	72.1	5.2	7.2	55.5	152.4	38.4	25.2	34.5	-	-	-	-
LC_R_CFRP	72.8	6.5	8.9	56.9	146.4	28.6	19.5	29.2				
RC_NR	21.1	3.6	0.2	-	37.2	8.8	23.7	-	3.1	0.7	22.6	-
RC_R_A	40.2	4.8	12.0	90.4	74.8	20.1	26.9	100.9	2.0	0.8	42.9	-36.6
RC_R_B	37.9	5.5	14.6	79.5	67.1	16.3	24.3	80.5	2.8	0.9	30.5	-8.7
RC_R_CFRP	53.5	6.1	11.5	153.6	97.6	31.3	32.1	162.4	4.6	1.3	29.0	48.4

The proposed reinforcing solutions have more significant effect on K_I, for radial compression, rather then for longitudinal compression embedding tests. For radial compression tests, the use of CFRP laminates resulted in the higher foundation modulus. Concerning the reinforcement with metallic inserts, the use of HILTI® RE500 adhesive always produced higher foundation modulus, for both radial and parallel-to-grain compression tests.

The use of CFRP laminates to reinforce dowel-type connections produced significant increases in both foundation modulus and embedding strength. Additionally, it fully eliminates the fragile failure modes, which are yet observed for some specimens reinforced with metallic inserts. However if costs are taken into account, the use of glue metallic inserts becomes more attractive, since CFRP laminates are generally expensive.

4. CONCLUSIONS

Two alternative reinforcing solutions for dowel-type wood connections were proposed and compared their mechanical performance under monotonic loading. The first solution consisted on the application of metallic inserts into the holes of the wood members to be joined, using an epoxy adhesive. The second solution consisted on gluing CFRP laminates on both sides of wood members.

The efficiency of the proposed reinforcements was demonstrated through an experimental program consisting on embedding tests, carried out according the EN 383/1993 standard. Both the embedding strength and elastic foundation modulus (K_I) increased for the reinforced solutions. The proposed strengthening techniques are more effective for the radial loading, which corresponds to the weakest direction. Two alternative epoxy adhesives were tested with the metallic inserts, namely the ARALDITE® 2011 and the HILTI® RE500. The HILTI® RE500 adhesive demonstrated to be the most efficient to join the steel insert to wood.

The use of CFRP laminates demonstrated to be more efficient than the use of glued metallic inserts. It resulted in higher embedding strength and elastic foundation modulus. The ductility of the joint is also beneficiated since the fragile failure modes are eliminated. The cost is the one drawback of the CFRP solution as well as its possible anaesthetic impact on wooden structures.

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