Proceedings of COBEM 2009
20th International Congress of Mechanical Engineering
November 15-20, 2009, Gramado, RS, Brazil

DEVELOPMENT OF A STRENGTHENING SOLUTION FOR DOWEL-TYPE CONNECTIONS BASED ON GLUED METALLIC INSERTS

Cristóvão L. Santos, clsantos@utad.pt
CITAB/Engineering Department, School of Sciences and Technology, University of Trás-os-Montes e Alto Douro
Quinta de Prados, 5001-801 Vila Real, Portugal

Abílio M. P. de Jesus, ajesus@utad.pt
Engineering Department, School of Sciences and Technology, University of Trás-os-Montes e Alto Douro
Quinta de Prados, 5001-801 Vila Real, Portugal
UCVE, IDMEC – Pólo FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

José J.L. Morais, jmorais@utad.pt
CITAB/Engineering Department, School of Sciences and Technology, University of Trás-os-Montes e Alto Douro
Quinta de Prados, 5001-801 Vila Real, Portugal

Nuno J.P. Santos, n_j_p_santos@hotmail.com
Engineering Department, School of Sciences and Technology, University of Trás-os-Montes e Alto Douro
Quinta de Prados, 5001-801 Vila Real, Portugal

Abstract. *This paper presents a study concerning the development of a reinforcing technique for dowel-type wood connections. The proposed technique is based on the application of steel inserts, glued to the holes of the timber members. This technique is demonstrated using the Portuguese pine wood, since it is one of the species with larger implantation in Portugal. Two distinct epoxy adhesives are investigated. The experimental program included embedding tests, carried out according to EN 383 standard, with and without reinforcement, and covering parallel and perpendicular-to-grain loadings. A total of six series were tested: three according the radial direction and three according the longitudinal direction. For each direction, one series without reinforcement and two series with reinforcements (two distinct adhesives) were tested. 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 solution (ex: higher embedding strength and foundation modulus) and allow the selection of the best adhesive. Furthermore, this paper proposes the assessment of the reinforcing solution based on Finite Element Analysis. 3D finite element models of the tests carried in the experimental program are built and used to compare the stress distributions between the reinforced and unreinforced solutions, illustrating the beneficial effects of the reinforcement.*

***Keywords**: Dowel-type connections, Timber, Pine Wood, Reinforcing Solution, Finite Element Method*

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 (Itany and Faherty, 1984). 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 (Soltis and Wilkinson, 1987)(CEN, 2004) the calculation of mechanical timber joints is based upon the Johansen's yield model (YM) (Johansen, 1949). The YM presents some important limitations (Patton-Mallory *et al.*, 1997a): only predicts the ultimate loads associated to ductile failure modes; brittle failure modes (e.g. shearing out, splitting perpendicular to grain) are not foreseen; the connection stiffness or the load-slip relation are not predicted; hole clearance and friction between members are neglected. Furthermore, the YM is directly applied to single fastener joints. The strength of multiple fastener joints is usually predicted affecting the strength of single fastener joints by a group action factor. Although the fundamental concepts remain unchanged over the years, the YM has suffered several revisions supported by an extensive testing. Those experimental works mainly addressed the influence of geometric parameters of single dowel joints (end distance, member thickness, bolt diameter, dowel-hole clearance) (Soltis and Wilkinson, 1987) or multiple dowel joints (row and dowel spacing, number of dowels and dowel rows) (Moss, 1997)(Anderson, 2001).

The referred shortcomings of the YM have been addressed by several alternative analytical and numerical models. They can be divided into 2D and 3D models. Among the 2D models are the non-linear beam on foundation models (Patton-Mallory *et al.*, 1997a) (Moss, 1997) and the plane FE models (Patton-Mallory *et al.*, 1997a) (Chen *et al.*, 2003) (Racher and Bocquet, 2005) (Kharouf *et al.*, 2003). Although these models have produced a significant improvement in the description of the mechanical behaviour of dowel-type joints, they still exhibit some drawbacks. For example, a beam on foundation model can account for tension perpendicular-to-grain stresses; however other stresses that can lead to brittle failure are neglected. The 2D FE models assume uniform stresses across the wood member. In reality, stresses are not uniform, as in the case of a joint where the bolt yields in bending. Thus, 3D models seem to be the right choice for a proper modelling of the mechanical behaviour of dowel-type joints. Few 3D FE models for dowel-type joints exist. Patton Mallory *et al*. (1997b) developed a 3D FE model of a single-dowel joint, assuming nonlinear elasticity for compression parallel to grain and shear; linear elastic behaviour was assumed for all other stress-strain relationships, including all normal stresses in tension. This material model allows a good description of the experimental load-slip curves. However, it results in poor estimates of the state of stress and failure strength. Moses and Prion (2003) also proposed a 3D FE model for a single-dowel joint, modelling wood by means of the Hill's plasticity theory. For multiple-dowel joints, almost no reference to comprehensive 3D FE models can be found in literature.

The reinforcement of dowel-type joints aiming the improvement of the mechanical performance of the joints is a challenging research topic. Several reinforcing techniques have been proposed to improve the stiffness, strength and ductility characteristics of the joints (e.g. resign injected dowels, expanded tube joints, shear plate connectors, glued composites such as FGRP) (Rodd and Leijten, 2003) (Davis and Claisse, 2001) (Claisse and Davis, 1998). The performance of these reinforcing techniques has been demonstrated essentially by experimental work. There is a lack of analytical or numerical models for these reinforced wood joints.

A new reinforcing solution, based on bonded metallic inserts has been developed for high performance composites materials (Camanho *et al*., 2005) (Camanho and Lambert, 2006). 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 standard (CEN, 1993). 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. Finite element models of the embedding tests are also proposed, allowing the comparison of the stress fields between the unreinforced and reinforced solutions.

2. EXPERIMENTAL PROGRAM

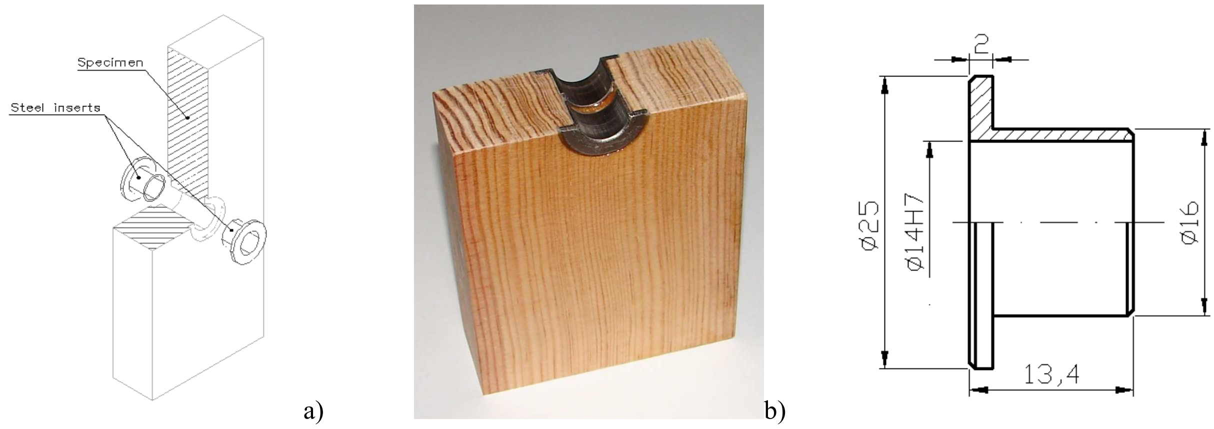
A reinforcing technique consisting on the application of metallic inserts into the holes of the wood members to connect, using a structural adhesive is proposed in this work. It is expected that this technique contributes to the stress concentration reduction in wood in the vicinity of the holes, beneficiating the strength of the connection. An experimental program is proposed in this paper to demonstrate the efficiency of the new reinforcing technique for dowel-type connections. In particular, series of compressive embedding tests are carried out, according the EN 383 standard procedures (CEN, 1993), in both longitudinal and radial directions. Both reinforced and unreinforced series are tested, for comparison purposes. Also, two alternative structural adhesives are investigated.

2.1. Experimental details

The reinforcing technique proposed in the paper is illustrated in Fig. 1. It consists on the application of two steel inserts into pre-drilled holes performed on the wood members, one at each side of the member. The insert is glued to wood using a resin. Figure 1a) illustrates the assembly process of the inserts. Figure 1b) illustrates a section view of a reinforced member. Figure 1c) 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.

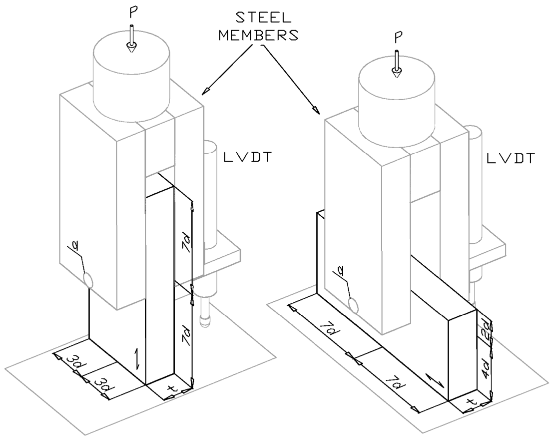
In order to assess the performance of the proposed reinforcing technique, embedding tests of wood member of Maritime Pine (*Pinus Pinaster* Ait.) were carried out, according the EN 383 standard. Both parallel and perpendicular-to-grain (radial) compressive embedding tests were carried out, as illustrated in Fig. 2. The nominal diameter of the dowel was chosen equal do 14 mm and the member's thickness equal to 30 mm. The dimensions of the members are proportional to the diameter of the dowel (see Fig. 2) as proposed in the EN 383 standard.

Six series of tests were prepared as described on Tab. 1: four 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 reinforced series, half were obtained using the HILTI® RE500 adhesive (A) and the other half using the ARALDITE® 2011 adhesive (B). Table 1 includes the density of each series and the crosshead displacement rates used in tests 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%.



a) b) c)

Figure 1. Reinforcing technique based on the application of metallic inserts: a) assembly process; b) section view of a reinforcing member; c) geometry and dimensions of the metallic insert (dimension in mm).



a) b)

Figure 2. Schematic representation of the embedding tests according the EN383 standard: a) longitudinal compression; b) radial compression.

Table 1. Summary of the test series.

Series	**Nº of Specimens**	**Density** Mean (kg/m^3)	St. Dev. (kg/m^3)	Coef. Of Variation (%)	**Displacement rate** (mm/min)
LC_NR$^{(1)}$	24	570.1	38.3	6.7	0.3
RC_NR$^{(1)}$	24	550.1	49.0	8.9	1.0
LC_R_A$^{(2)}$	12	626.8	31.0	4.9	0.3
RC_R_A$^{(2)}$	12	615.4	29.5	4.8	1.0
LC_R_B$^{(3)}$	11	633.6	32.1	5.1	0.3
RC_R_B$^{(3)}$	12	646.7	37.0	5.7	1.0

$^{(1)}$: 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

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 Fig. 2). The LVDT used in the experimental program is from the Applied Measurements® with reference AML/EU ± 10-S10 (measurement range of ±10 mm). The data was acquired by means of a SPIDER® 8-30 system. Respecting the EN 383 standard, a loading-unloading-reloading procedure was adopted: firstly specimens were loaded until 40% of the maximum estimated load (F_{est}), and the crosshead position held during 30s; after this stage, specimens are unloaded until 0.1Fest and the crosshead position again maintained along more 30s; finally, specimens are reloaded until failure.

2.2. Experimental results and discussion

Figure 3 illustrates the load-displacement curves obtained for the six embedding test series. Displacements correspond to the LVDT records. While the longitudinal compression tests exhibited a typical ultimate load, the radial compression tests exhibited a monotonically increasing loading, beyond the proportional limit. Based on the analysis of Fig. 3 it is possible to establish typical load-displacement curves for the embedding tests, as depicted on Fig. 4. Figure 4a corresponds to the longitudinal compression tests and defines an ultimate load (F_u) as well as an initial stiffness (k_1). Figure 4b, corresponding to the radial compression tests, illustrates a load-displacement record by two line segments with distinct slopes (k_1 and k_2). Since it is not possible to define an ultimate load, a load beyond the proportional limit range ($F_{0.05d}$) is adopted, corresponding to a residual displacement of 5% the diameter of the dowel (Santos *et al.*, 2009). The previous referred parameters can be normalised, dividing their values by the projected area of the hole, resulting the embedding strength (f_h) and foundation modulus (K_i):

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

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

where: d is the diameter of the dowel, t the thickness of the specimen, F the ultimate load (F_u) or the load beyond the proportional limit range ($F_{0.05d}$) and k_i the initial or elastic (k_1) or final stiffness (k_2). Table 2 summarises the global values of the embedding strength and foundation modulus measured for each test series. The f_h and K_1 values are significantly higher in the longitudinal compression series than in radial compression series. Comparing the reinforced solutions with the unreinforced ones, gains in the ranges of 52-56% and 80-90% are observed in the embedding strength as a consequence of the application of the metallic insert, for the longitudinal and radial directions, respectively. Regarding the elastic foundation modulus, K_1, increases in the ranges of 35-45% and 81-101% were observed, respectively, for the longitudinal and radial directions. It is clear that the benefit of the reinforcement is significantly higher for the perpendicular-to-grain directions, rather than for the parallel-to-grain directions, attenuating the high anisotropy of the strength properties of the wood. After yielding, the reinforced specimens, loaded according the radial direction, suffer a higher reduction in the foundation modulus than observed in the unreinforced specimens. The lower K_2 values resulted from the reinforced specimens cannot be considered a truly handicap of the proposed reinforcing solution, since the reinforcing solution increases effectively the yield loads. The load-displacement curves resulted from radial compression series shows a globally monotonic increasing load after yielding; however the reinforced specimens present some local loading drops, corresponding to cracks initiation.

A global analysis of the results presented in Tab. 2 shows that adhesive A – the HILTI® RE500 – produces the better results. Only one exception is observed for the embedding strength in the parallel-to-grain direction: specimens with metallic inserts glued with ARALDITE® 2011 produced slightly higher results. However, this result can be justified by the slightly higher density of the LC_R_B series.

The previous conclusions were based on average values of the properties of each series. However, since each series shows distinct averages densities, it is convenient to perform the comparisons between properties, taking into account the effects of the variations in densities. Figures 5, 6 and 7 show the variation of the strength properties (embedding strength and foundation modulus) with the density. The analysis of the figures shows that embedding strengths in the longitudinal direction are significantly higher for the reinforced specimens. For the radial compression, only the reinforcing solution based on adhesive A (HILTI® RE500) is significantly higher. The elastic foundation modulus of the reinforced specimens is also significantly higher than values obtained for the unreinforced specimens. Results of the Figs. 5, 6 and 7 show that adhesive A performs better than adhesive B, for both embedding strength and elastic foundation modulus.

3. NUMERICAL ANALYSIS

This section briefly presents some numerical results from finite element (FE) models. Finite element models were built, for the reinforced and unreinforced test series, under longitudinal and radial compression, using the commercial FE code, ANSYS® (SAS, 2009). Three dimensional (3D) FE models were proposed, using 20-node hexahedra elements. Only one quarter of the specimen was modelled, taking into account the two existing planes of symmetry. The FE model includes the steel dowel. Figure 8 illustrates the typical FE meshes used in the analysis. A surface-to-surface contact strategy is adopted with flexible-to-flexible behaviour in order to model the load transfer between the dowel and the wood member. For the unreinforced models, the contact is established directly between the steel dowel and the wood; for the reinforced specimens, the contact is established between the steel dowel and the metallic insert. The models for the reinforced specimens included a uniform 0.2 mm thick adhesive layer, between the metallic insert and the wood. Materials were assumed elastic: wood as orthotropic, steel and adhesives as isotropic. Due to the contact, the problem becomes non-linear, requiring an incremental analysis. The unreinforced FE model was already presented in a previous paper by the authors (Santos *et al*., 2009), where more details about the numerical modelling can be found. The elastic properties of the wood used in the experimental work – the *Pinus Pinaster* Ait. species – can be found in Santos *et al*. (2009). The elastic properties of the adhesive were obtained from Campilho *et al*. (2008). Campilho *et al*. (2009) have used E=3.4GPa and ν=0.35 to model ARALDITE® 2011, which is an epoxy resin. Since the HILTI® RE500 is also an epoxy resin, the same properties were adopted. For the dowel and steel insert, E=210 GPa and ν=0.3 was used. The radial clearances between the dowels and the holes were assumed equal to 0.15 mm, for the unreinforced series and 0.1 mm, for the reinforced series. The dowel was assumed with fixed ends (nodes fixed until 1 mm to the side faces of specimens).

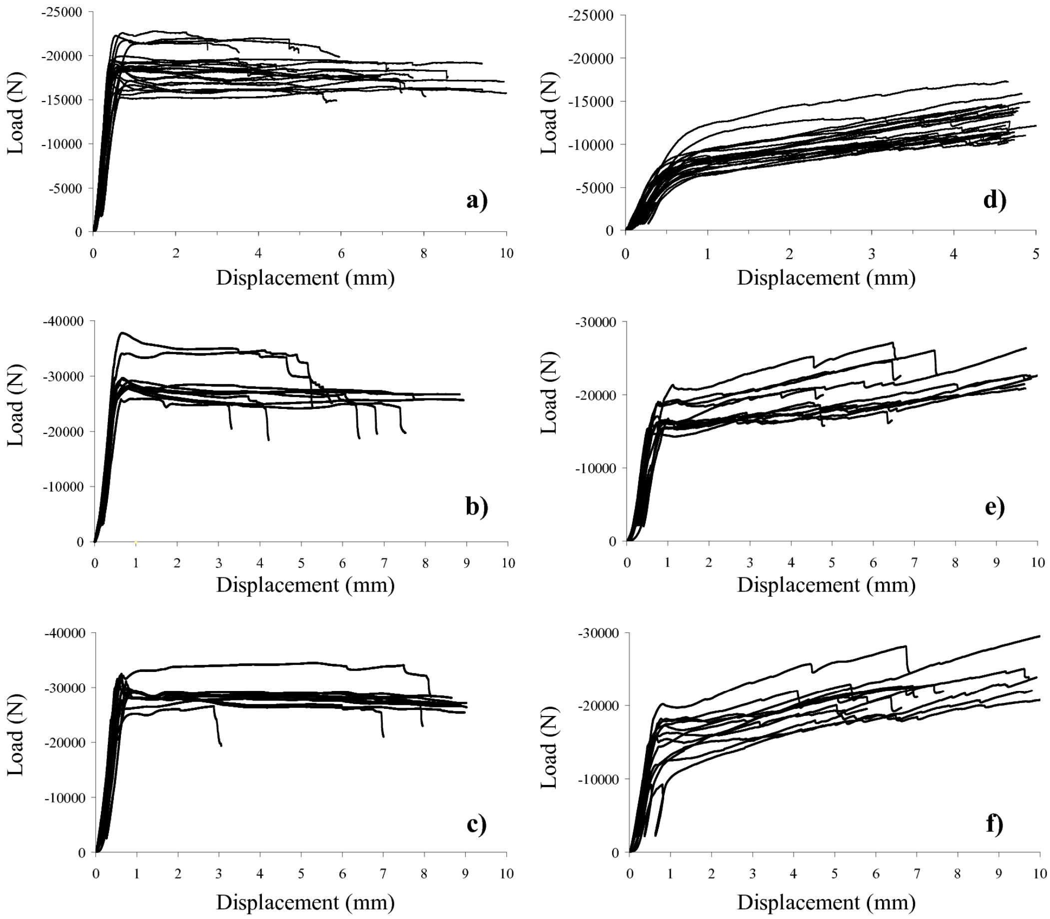


Figure 3. Experimental load-displacement curves obtained for the test series: (a) LC_NR series; (b) LC_R_A series; (c) LC_R_B series; (d) RC_NR series; (e) RC_R_A series and (f) RC_R_B series.

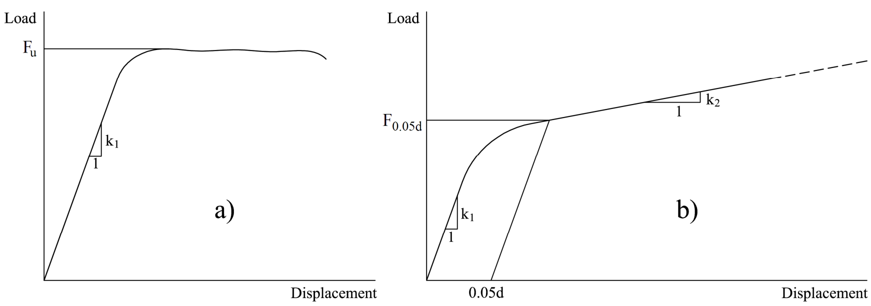


Figure 4. Typical load-displacement curves: (a) longitudinal compression; (b) radial compression.

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	-	-	-	-
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

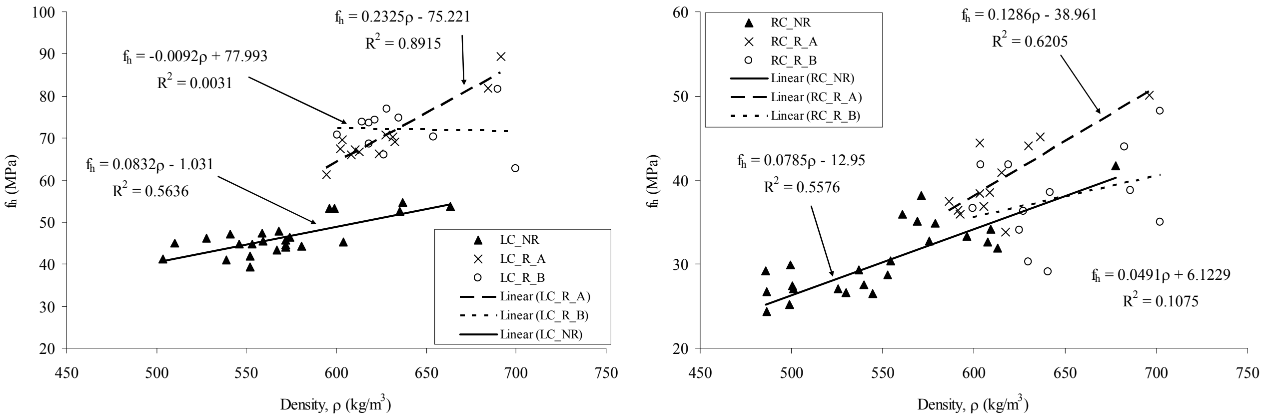


Figure 5. Evolution of the embedding strength with density for unreinforced and reinforced wood members: (left) longitudinal compression tests; (right) radial compression tests.

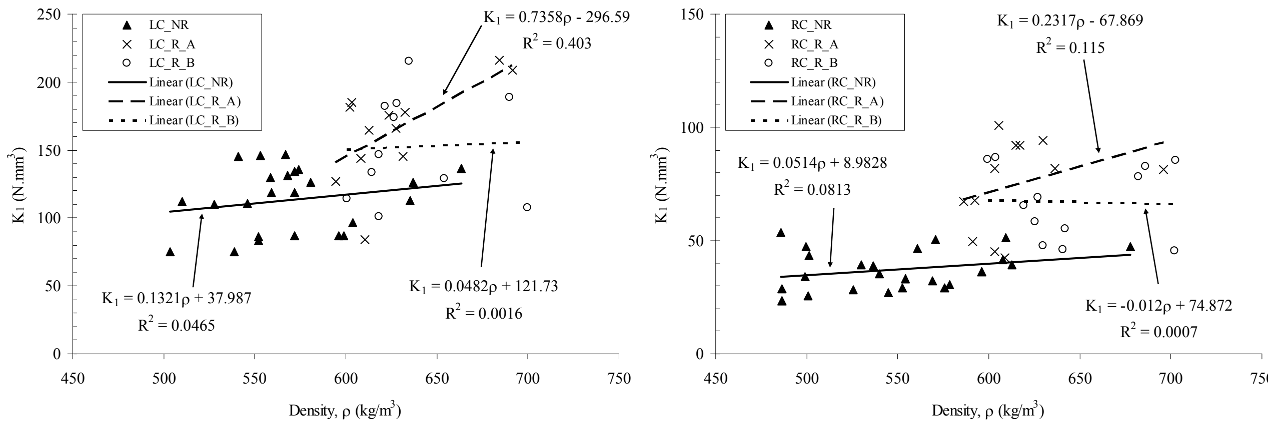


Figure 6. Evolution of the foundation modulus K_1 with density for unreinforced and reinforced wood members: (left) longitudinal compression tests; (right) radial compression tests.

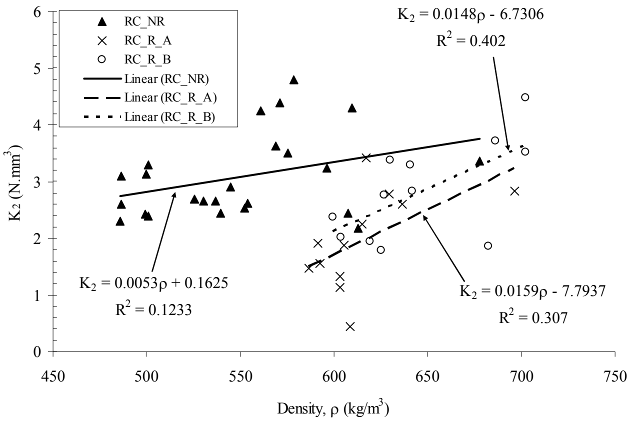


Figure 7. Evolution of the foundation modulus K_2 with density for unreinforced and reinforced wood members under radial compression.

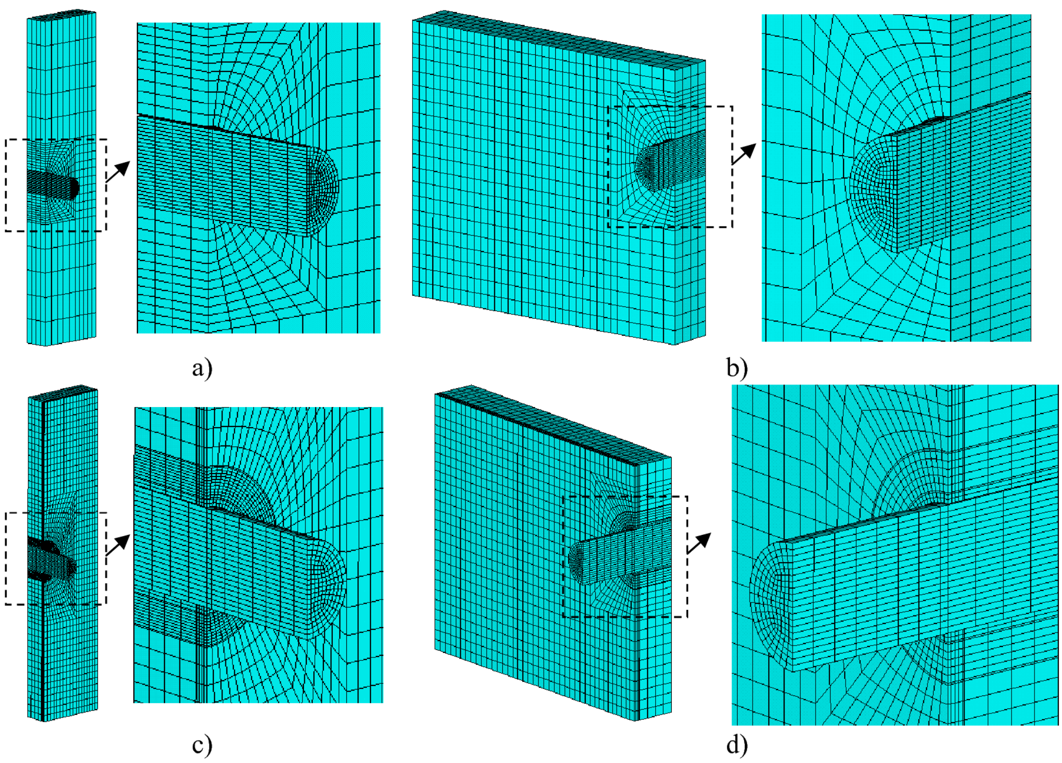


Figure 8. Finite element meshes used to model the embedding tests: (a) LC_NR series; (b) RC_NR series; (c) LC_R series and (d) RC_R series.

The contact model is governed by an important number of parameters, the normal contact stiffness parameter (FKN), the maximum penetration factor (FTOLN), the friction model and the contact algorithm being the most relevant. The definition of a contact pair requires the designation of the target (meshed with TARGE170 elements) and contact (meshed with CONTA174 elements) surfaces (SAS, 2009). For the analyses carried out in this work, the Augmented Lagrange contact algorithm was used (SAS, 2009). The augmented Lagrange method requires the definition of normal and tangential contact stiffnesses. The amount of penetration between contact and target surfaces depends on the normal stiffness. Higher stiffness values decrease the amount of penetration, but can lead to ill-conditioning of the global stiffness matrix and to convergence difficulties. Lower stiffness values can lead to a certain amount of penetration and produce an inaccurate solution. Ideally, a high stiffness is required to reduce the penetration to an acceptably small value; however, excessive high stiffness values must be avoided since they can lead to convergence difficulties. On effect, a stiffness relationship between two bodies must be established for contact to occur. Without contact stiffness, bodies will pass through one another. The relationship is generated through an 'elastic spring' that is put between the two bodies. The amount of penetration, or incompatibility, between the two bodies is dependent on the stiffness. Ideally, there should be no penetration, but this implies infinite stiffness, which will lead to numerical instabilities. The value of contact stiffness that is computed by ANSYS, depends on the relative stiffness of the bodies in contact (bulk modulus of contacted element) existing the possibility of scaling this stiffness through the FKN factor, also called normal penalty stiffness factor. The usual factor range is from 0.01–1.0, with a default of 1.0. The default value is appropriate for bulk deformation. Another relevant contact parameter to be used in conjunction with the augmented Lagrange method is FTOLN. FTOLN is a tolerance factor to be applied in the direction of the surface normal. The range for this factor is less than 1.0 (usually less than 0.2), with a default of 0.1, and is based on the depth of the underlying solid element. This factor is used to determine if penetration compatibility is satisfied. Contact compatibility is fulfilled if penetration is within an allowable tolerance (FTOLN times the depth of underlying elements). For all other contact parameters not mentioned here, default values were adopted (SAS, 2009). The basic Coulomb friction model was used.

Table 3 presents the results of the numerical analysis, specifically the elastic foundation modulus, K_1, for each test series and for several contact parameters, namely the FKN and FTOLN. Furthermore, the friction coefficient effect is assessed for the reinforced series. The first conclusion is that the friction coefficient has as marginal effect on the elastic foundation modulus, for the reinforced series. The same conclusion was also referred by Santos *et al.* (2009) concerning the unreinforced series. The numerical results obtained with the reinforced series (steel-to-steel contact) were less sensitive to the FKN and FTOLN parameters than the unreinforced series (steel-to-wood contact). For the unreinforced series, it is possible to model the experimental elastic foundation modulus, tuning the FKN and FTLON parameters within the usual ranges (SAS, 2009); conversely, it was not possible to achieve the experimental elastic foundation modulus, for the reinforced series, by changing the FKN and FTOLN parameters within the usual range. The elastic foundation modulus is overestimated for reinforced series: steel-to-steel contact cases. Some plausible explanations for the foundation modulus overestimation are the boundary conditions applied to the dowel, the extension of the metallic insert effectively modelled and the ideal interfaces assumption between materials. On effect, the dowel was modelled with both ends fully-fixed which is an extreme condition, being responsible for the stiffness increase. In practice, the boundary conditions should fit between the fully-fixed and simply supported conditions. The models included an integral metallic insert with an extension equal to the thickness of the specimens. In practice, the metallic insert is divided into two halves with total extension lower than the real thickness of the specimens. Finally, ideal steel-adhesive and adhesive-wood interfaces were considered, which corresponds to a 100% efficient joining process.

Although the elastic foundation modulus overestimation, a comparison of the elastic foundation modulus between the reinforced and unreinforced series, for a reference set of contact parameters (ANSYS defaults: FKN=1.0; FTOLN=0.1), reveals gains of 69% and 81%, respectively on longitudinal and radial directions. The experimental values of the gains are within the ranges 35-45% and 81-101%, respectively for the longitudinal and radial directions. Accordingly, the numerical models point out gains of the same order of magnitude than resulted from experimental tests. The ratio between the numerical longitudinal and radial elastic foundation modulus, for the reinforced series, is approximately equal to 2.44, against 2.23 obtained in the experimental tests.

Figure 9 illustrates the stress fields obtained with the FE models, using the default contact parameters, for an imposed displacement of 0.1 mm, applied to both dowel ends. Stresses in wood are plotted for the unreinforced and reinforced members. For the LC series the σ_L and τ_{RL} stresses are plotted. These stresses are directly responsible for the failure mechanics observed experimentally. For the RC series, the σ_R stresses are plotted. It is possible to conclude that for the same imposed displacements, stresses are lower in the reinforced series, which is consistent with the higher strength of the reinforced solutions. This effect is due to the stress redistribution promoted by the metallic insert. For example, the τ_{RL} stresses decrease about 23% for the LC series, with the application of the reinforcement, which increases the resistance to shear-splitting cracking.

Table 3. Numerical values of the elastic foundation modulus.

Reinforced Series								Unreinforced Series							
Longitudinal Compression				Radial Compression				Longitudinal Compression				Radial Compression			
FKN	FTOLN	μ	K_1 [N/mm^3]	FKN	FTOLN	μ	K_1 [N/mm^3]	FKN	FTOLN	μ	K_1 [N/mm^3]	FKN	FTOLN	μ	K_1 [N/mm^3]
0.01	0.01	0.6	459.9	0.01	0.01	0.6	183.5	0.1	0.05	0.5	162.2	0.1	0.05	0.5	103.9
0.1	0.01	0.6	469.0	0.1	0.01	0.6	194.3	**1**	**0.1**	**0.5**	**286.8**	**1**	**0.1**	**0.5**	**110.2**
1	0.01	0.6	485.5	1	0.01	0.6	199.3	0.1	0.1	0.5	157.4	0.1	0.1	0.5	103.9
0.01	0.1	0.6	380.5	0.01	0.1	0.6	172.9	0.08	0.1	0.5	126.5	0.01	0.1	0.5	67.7
0.1	0.1	0.6	468.7	0.1	0.1	0.6	194.3	0.06	0.1	0.5	92.6	0.008	0.1	0.5	61.8
1	**0.1**	**0.6**	**485.5**	**1**	**0.1**	**0.6**	**199.3**	0.01	0.1	0.5	21.1	0.006	0.1	0.5	53.9
0.01	0.01	0	460.1	0.01	0.01	0	183.9	0.01	0.2	0.5	21.1	0.005	0.1	0.5	49
0.1	0.01	0	468.8	0.1	0.01	0	194.3					0.01	0.2	0.5	67.7
1	0.01	0	485.1	1	0.01	0	199.2								
0.01	0.1	0	380.1	0.01	0.1	0	172.9								
0.1	0.1	0	468.6	0.1	0.1	0	194.3								
1	0.1	0	485.1	1	0.1	0	199.2								

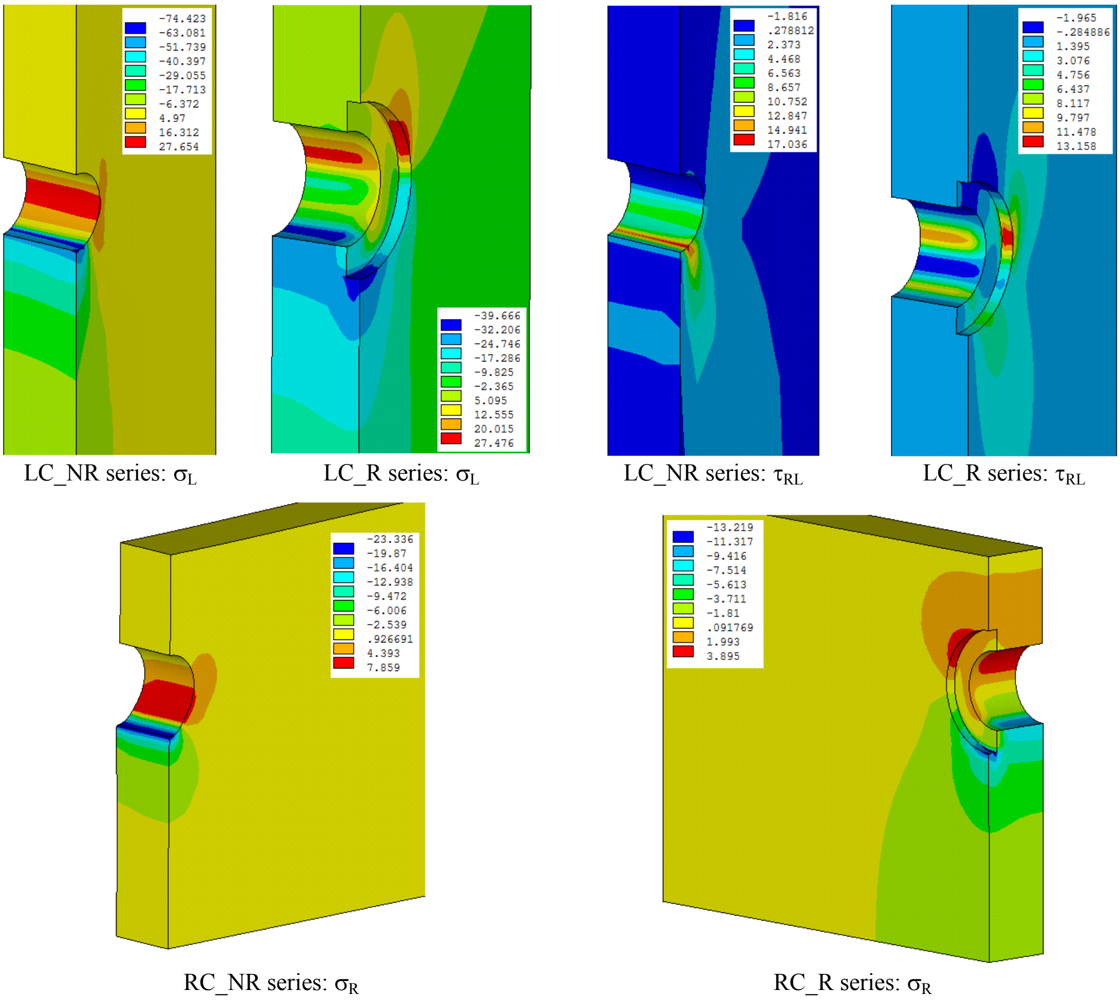


Figure 9. Stress distributions in wood, for specimens loaded with a displacement of 0.1 mm applied at dowel ends (FKN=1.0, FTOLN=0.1) (values in MPa).

4. CONCLUSIONS

A reinforced solution for dowel-type wood connections was proposed, based on the application of metallic inserts into the holes of the wood members to be joined. The efficiency of the proposed reinforcement was demonstrated through an experimental program consisting on embedding tests, carried out according the EN 383 standard. Both the embedding strength and elastic foundation modulus increase for the reinforced solutions. The proposed strengthening is more effective for the radial loading, which corresponds to the weakest direction. Two alternative epoxy adhesives were tested, 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.

Three dimensional finite element models of the unreinforced and reinforced test specimens were built to assess the reinforcement effects. These models included the contact effect between the dowel and wood/insert surfaces. Despite the absolute values of the elastic foundation modulus were overestimated, the proposed models gave a clear idea of the reinforcement effects, namely the increase in the elastic foundation modulus and the reduction in local stresses in wood, due to stress redistributions, around holes, for the reinforced solutions.

5. REFERENCES

Soviero, P.A.O. and Lavagna, L.G.M.,1997, “A Numerical Model for Thin Airfoils in Unsteady Motion”, RBCM- J. of the Brazilian Soc. Mechanical Sciences, Vol.19, No. 3, pp. 332-340.

Anderson, G.T., 2001, “Experimental Investigation of Group Action Factor For Bolted Wood Connections,” Master Thesis, Virginia Polytechnic Institute and State University.

Camanho, P.P., Tavares, C.M.L, Oliveira, R., Marques, A.T., Ferreira, A.J.M., 2005, “Increasing the efficiency of composite single-shear lap joints using bonded inserts”, Composites Part B - Engineering, Vol. 36, pp. 372-83.

Camanho, P.P., Lambert, M., 2006, “A design methodology for mechanically fastened joints in laminated composite materials”, Composites Science and Technology, Vol. 66, No. 15, pp. 3004-3020

Campilho, R.D.S.G., de Moura, M.F.S.F., Domingues, J.J.M.S., 2008, “Modelação Numérica de Reparações por Sobreposição Simples e Dupla em Materiais Compósitos”, Revista da Associação Portuguesa de Análise Experimental de Tensões - Mecânica Experimental, Vol. 15, pp. 103-116.

Chen, C.J., Lee, T.L., Jeng, D.S., 2003, “Finite element modelling for the mechanical behaviour of dowel-type timber joints,” Computures and Structures, Vol. 81, pp. 2731-2738.

Claisse, P.A., Davis, T.J., 1998, “High performance jointing systems for timber,” Construction and Building Materials, Vol. 12, pp. 415-25.

Davis, T.J., Claisse, P.A., 2001, “Resin-injected dowel joints in glulam and structural timber composites,” Construction and Building Matererials, Vol. 15, pp. 157-67.

European Committee for Standardization, 1993, “EN383: Timber Structures. Test Methods. Determination of Embedding Strength and Foundation Values for Dowel Type Fasteners. European Standard”, Brussels.

European Committee for Standardization, 2004, “EN 1995-1-1 Design of timber structures. Part 1-1: General rules and rules for buildings,” CEN-TC250, Brussels.

Itany, R.Y. and Faherty, K.F., 1984, “Structural wood research, state-of-the-art and research needs,” Proceedings of the Workshop, Milwaukee, WI, Oct. 5-6, 1983. ASCE, New York, 210 pp.

Johansen, K.W., 1949, “Theory of timber connections,” International Association for Bridge and Structural Engineering: IABSE Journal, Vol. 9, pp. 249 – 262.

Kharouf, N., McClure, G., Smith, I., 2003, “Elasto-plastic modelling of wood bolted connections,” Computers and Structures, Vol. 81, pp. 747-54.

Moses, D.M., Prion, H.G.L., 2003, “A three-dimensional model for bolted connections in wood,” Canadian Journal of Civil Engineering, Vol. 30, pp. 555-567.

Moss, P.J., 1997, “Multiple-bolted joints in wood members. A literature review”, General Technical Report FPL-GTR-97, Forest Products Laboratory – USDA, Madison, WI, USA.

Patton-Mallory, M., Pellicane, P.J., Smith, F.W., 1997a, “Modelling bolted connections in wood: review,” Journal of Structural Engineering, Vol. 123, No. 8. pp. 1054-1062.

Patton-Mallory, M., Cramer, S.M., Smith, F.W., Pellicane, P.J., 1997b, “Nonlinear material models for analysis of bolted wood connections,” Journal of Structural Engineering, Vol. 123, No. 8, pp. 1063-1070.

Racher, P., Bocquet, J.F., 2005, “Non-linear analysis of dowelled timber connections: a new approach for embedding modelling,” Electronic Journal of Structural Engineering, Vol. 5, pp. 1-9.

Rodd, P.D., Leijten, A.J.M., 2003, “High-performance dowel-type joints for timber structures,” Progress in Structural Engineering and Materials, Vol. 5, pp. 77-99.

Santos, C.L., de Jesus, A.M.P., Morais, J.J.L., Lousada, J.L.P.C., 2009, “A Comparison Between the EN 383 and ASTM D5764 Test Methods for Dowel-Bearing Strength Assessment ofWood: Experimental and Numerical Investigations”, Strain, in press (doi: 10.1111/j.1475-1305.2008.00570.x).

SAS - Swanson Analysis Systems Inc., 2005, Version 10.0, ANSYS. Swanson Analysis Systems Inc., Houston.

Soltis, L.A., Wilkinson, T.L., 1987, “Bolted-Connection Design,” General Technical Report FPL-GTR-54, Forest Products Laboratory – USDA, Madison, WI, USA.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.