COMPARISON OF DIFFERENT STRENGTHENING SOLUTIONS FOR GLUED-LAMINATED WOOD BEAMS OF PINE WOOD

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Abstract. *The pine wood, Pinus pinaster, is the species with larger implantation in Portugal. However, this wood has little acceptance for structural applications due to its general low quality. The concept of glued-laminated wood (glulam) is widely used since it allows the manufacturing of structural components, namely beams with large dimensions, variable curvatures and enhanced mechanical behavior. The application of this concept to the Pinus pinaster wood, results in an improvement of the mechanical properties of the solid wood. However, the strengthening of the glued-laminated pine wood still is desirable and is the subject of this work. Two reinforced glued-laminated wood beams are proposed and assessed. The first is based on a concept of laminated wood composite with fiber glass; the second is based on the application of pultruded lamellas glued to the most stressed tensile region of the glued-laminated beams. In order to demonstrate the potential of the proposed strengthening solutions, a comparison between their mechanical behaviors and the mechanical behaviors of the conventional glued-laminated and solid beams are performed. Static load-deflection curves, an equivalent modulus of elasticity, the ultimate strains and stresses at rupture are determined using 3-point quasi-static bending tests. In general, it is demonstrated the beneficial effect of the proposed strengthening solutions both in terms of resistance and ductility.*

Keywords: *Pine Wood, Glued-Laminated Beams, Strengthening, Quasi-static behavior, 3-point bending*

1. INTRODUCTION

The pine wood, *Pinus pinaster*, is the species with larger implantation in Portugal. However, this wood has little acceptance for structural applications due to its general low quality (e.g. high density of defects, presence of knots, inadequate dimensions. Applications with *Pinus pinaster* are usually restricted to those concerning transformation industries, such as furniture, pallets, posts, boxes, particleboards, etc.

Generally, the structural applications of wood are performed using the concept of engineered wood products which basically correspond to structural composites. Some of the major engineered wood products are the glued-laminated timber, parallel strand lumber, laminated strand lumber, laminated veneer lumber and thick oriented strand board/rimboard (Lam, 2001). The mechanical and physical properties of these products depend on the interaction relationships between the quality of the resource, the manufacturing process and the applications. In general, their mechanical properties are more uniform compared with solid timber. Hence, higher allowable properties are available in engineering design.

The concept of glued-laminated wood (glulam) is widely used since it allows the manufacturing of structural components (e.g. beams) with large dimensions, variable curvatures and enhanced mechanical properties. The application of this concept to the *Pinus pinaster* wood, results in an improvement of the mechanical properties of the solid wood. However, the mechanical performance of the glued-laminated *Pinus pinaster* still is lower than the mechanical performance of other laminates produced with better quality woods, such as the *Picea abies*.

Thus, the subject of this work is the development of new engineered woods products. The first is based on a concept of laminated wood composite with fiber glass; the second is based on the application of pultruded lamellas glued to the most stressed tensile region of the glued-laminated beams. For both products laminated wood, built from *Pinus pinaster* wood lamellas glued together with phormaldehyde/phenol-resorcinol adhesive, was used.

In order to demonstrate the potential of the proposed reinforced material, the comparison between mechanical properties of the laminated wood composite with fiber glass and pultruded lamellas glued to the most stressed region of the glued-laminated beams are carried out. This comparison also includes the mechanical properties of the conventional laminated and solid beams.

The mechanical resistance of the investigated materials is characterized using 3-point quasi-static bending tests. The static load-deflection curves, the modulus of elasticity and the ultimate strain and stress at rupture are determined.

In general, the mechanical properties obtained for pultruded lamellas glued to the most stressed tensile region of the glued-laminated beams are better than properties obtained for laminated wood composite with fiber glass. On the other hand, the mechanical properties of laminated wood are better than mechanical properties of solid wood. The scatter obtained in data for the laminated wood is reduced, in comparison to the solid wood. The introduction of the reinforcement on laminates results in enhanced mechanical properties, in comparison to conventional laminates, illustrating the potential of these new material concepts.

2. ORTHOTROPIC NATURE OF WOOD

Wood may be described as an orthotropic material. It has unique and independent mechanical properties in the directions of three mutually perpendicular axes (see Fig. 1): longitudinal (L), radial (R) and tangential (T). The longitudinal axis is parallel to fiber (grain); the radial axis is normal to the growth rings (perpendicular to the grain in the radial direction); and the tangential axis is perpendicular to the grain but tangent to the growth rings. Nine independent constants are needed to describe the elastic behavior of wood: three elasticity modulus (E_L, E_R, E_T), three shear modulus (G_{LR}, G_{LT}, G_{RT}) and three Poisson's ratios (ν_{LR}, ν_{LT}, ν_{RT}).

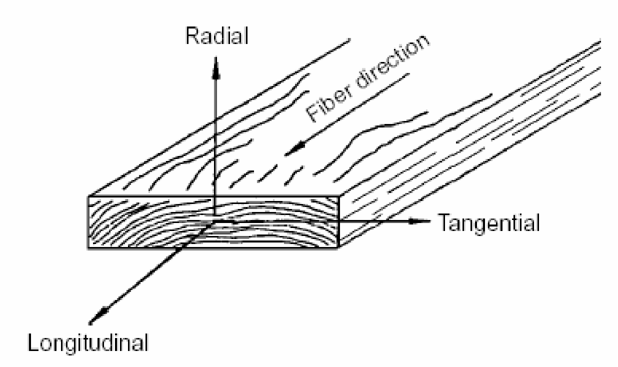


Figure 1. Principal axes of wood defined with respect to grain direction and growth rings (FPL, 1999).

This work only includes bending tests of small beams that were produced with the longitudinal direction or grain direction oriented parallel to the length (axis) of the beams. Thus, only one elastic property can be measured: the longitudinal modulus of elasticity, E_L. The other two modulus of elasticity are, in general, about one order of magnitude below the longitudinal modulus of elasticity (FPL, 1999). The bending tests were carried out until complete rupture of specimens which allowed the evaluation of some strength properties of wood in the grain or longitudinal direction.

3. EXPERIMENTAL DETAILS

In order to illustrate the mechanical performance and potential of the new concept of material, an experimental program was carried out. The experimental program included quasi-static 3-point bending tests of relative small beams. Solid and laminated wood, including the new concept of laminated wood composite with fiber glass and the application of pultruded lamellas glued to the most stressed tensile region of the glued-laminated beams, were considered which resulted in a total of 6 series of specimens. Each series was composed of 10 specimens which results in a total of 60 specimens. Table 1 summarizes the tested series.

Table 1. Series of specimens used in the experimental program.

Series	Tested specimens	Wood	Construction solution
MPP	MPP_01-MPP_10	*Pinus pinaster*	Solid wood
LPP	LPP_01-LPP_10	*Pinus pinaster*	Laminated wood
LPPF1	LPPF1_01- LPPF1_10	*Pinus pinaster*	Laminated wood with a unique composite layer
LPPF2	LPPF2_01- LPPF2_10	*Pinus pinaster*	Laminated wood with two composite layers
LPPRH	LPPRH_01- LPPR2_10	*Pinus pinaster*	Laminated wood with horizontal pultruded lamellas
LPPRV	LPPRV_01- LPPRV_10	*Pinus pinaster*	Laminated wood with vertical pultruded lamellas

3.1. Preparation of the specimens

The wood used in the production of the specimens was air-dried in order to achieve a moisture content of about 12%, which is appropriated for use in an environment with a relative humidity ranging from 40% to 70% (Denig *et al.*, 2000). The overall nominal dimensions of the specimens are: length (L) equal to 760 mm, width (b) equal to 50 mm and thickness (h) equal to 50 mm. These dimensions were adopted from the ASTM D143 standard (ASTM, 1997) since they are well suited for the available testing apparatus. This standard is proposed for testing small clear specimens of timber. However, this work applied it for testing specimens of structural timber and glued laminated timber. The structural timber and glued laminated timber exhibits several types of defects that can influence the test results, specially the strength properties. Also the dimensions of the specimens of structural timber and glued laminated timber can influence the measured strength properties, since larger volumes of material likely include more defects. Thus, the absolute values of the properties reported in this paper should be used with care, since they may not represent the characteristic values for the testing woods. The main goal of the paper is to present a comparative analysis between the mechanical performances of different beam products, using the same testing conditions.

The solid specimens were sawn in order their longitudinal axis being parallel to grain. The laminated specimens were produced through the superposition of five wood layers with a thickness of 5 mm each. A phenol-resorcinol/phormaldehyde adhesive was used to bond the wood layers. One of the new concepts of reinforced laminated wood was produced through the introduction of composite layers in tensile between the interfaces of wood layers. The composite material resulted from the junction of roving of E glass with phenol-resorcinol/phormaldeyde resin. The adhesion between the composite and wood layers was carried out simultaneously with the cure of the composite layer. The other concept of reinforced laminated wood was produced through the introduction of pultruded lamellas glued to the most stressed tensile region of the glued-laminated beams in horizontal and vertical position.

Figure 2 illustrates the overall dimensions of the manufactured beams and the concept of laminated and reinforced beams with composite layers and pultruded lamellas.

The glass filament winding was direct roving (2400tex) with filaments of 24 μm of diameter. This material has good mechanical properties as well facilities resin penetration. The glass filament presents a Young's modulus of about 74 GPa which is about ten times the longitudinal (fiber direction) Young's modulus of the studied wood. The pultruded material has a Young's modulus is about 40 GPa and 400 MPa of tensile strength.

Four different series of reinforced beams were produced: the first series (LPPF1) was produced with a unique composite layer obtained with two E glass rovings; the second series (LPPF2) was produced with two composite layers obtained with three E glass rovings in each layer; the third series (LPPRH) was produced with laminated wood and horizontal pultruded lamellas and the fourth series (LPPRV) was reinforced with vertical pultruded lamellas (see Fig.2).

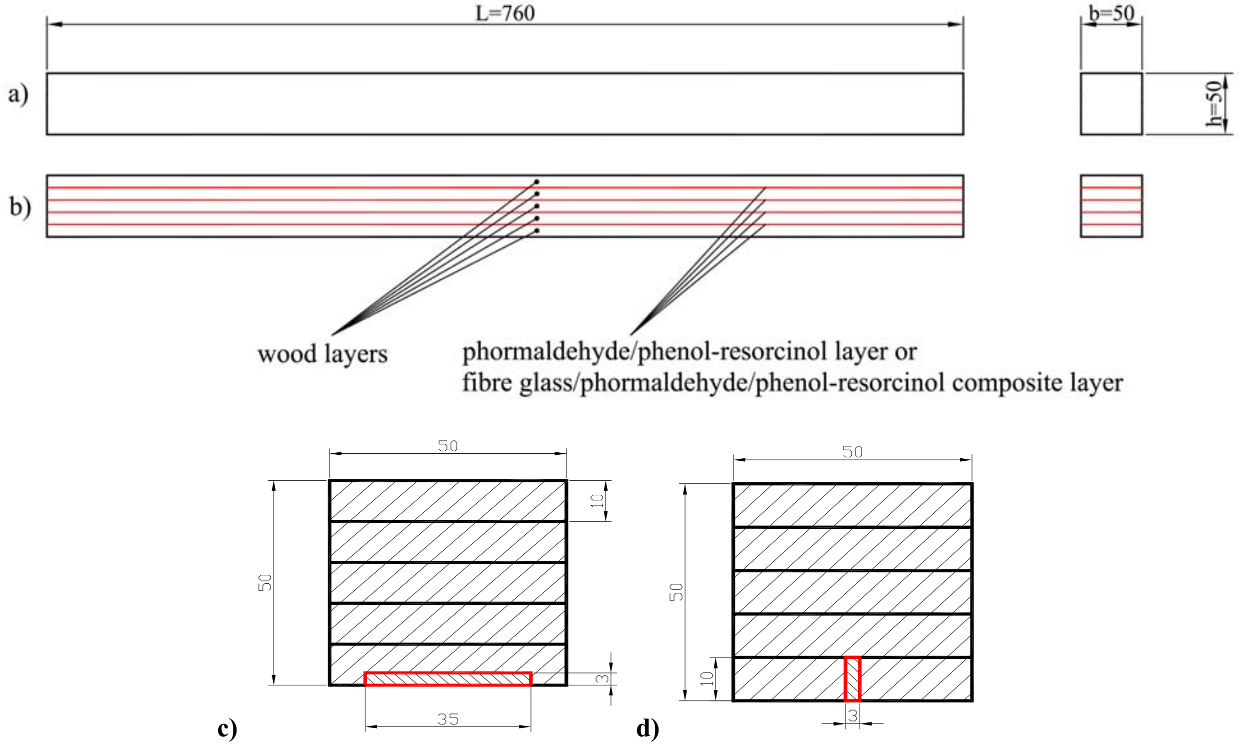


Figure 2. Beam-type specimen configurations: a) solid beams (MPP); b) laminated beams reinforced with fiber glass (LPPF1 and LPPF2); c) laminated beams reinforced with horizontal pultruded lamellas (LPPH); d) laminated beams reinforced with vertical pultruded lamellas (LPPV).

All laminates were produced at room temperature under a pressure of about 1 MPa. The pressure was maintained over a period of at least 24 hours. The tests of the beams were carried at least 36 hours after the gluing process was initiated. The layers of wood used in the manufacturing of the laminated and reinforced beams were disposed randomly, without any special care with the distribution of the defects. The mean density of the *Pinus pinaster* wood is about 550kg/m^3 at 12% moisture content

3.2. Test methodology

An Instron machine, model 1125, with a Syntech/MTS control system and rated to 100kN, was used to test the beam specimens using a 3-point quasi-static bending test configuration. The beams spans were chosen to be equal to 710 mm, as specified in the ASTM D143 standard (ASTM, 1997). Tests were carried out under midspan displacement control, characterized by a displacement rate of approximately 1.35 mm/min. The specimens were supported on two sliding supports and a hardwood/high radius load applier was used. Both load and midspan displacement were recorded during the test. The tests were conducted until the complete ruptures of the beams were observed.

4. STRUCTURAL ANALYSIS EQUATIONS

The load-deflection information derived from the 3-Point bending tests can be analyzed using formulae for structural analysis. In this case, formulae for beams under bending loads are used. The deflection of straight beams that are elastically stressed and have a constant cross section throughout their length is given by (FPL, 1999):

$$\delta = \frac{k_b F a^3}{EI} + \frac{k_s F a}{GA'} \tag{1}$$

where: δ is the midspan deflection; F is the total beam load acting perpendicular to beam neutral axis; a is the beam span; k_b and k_s are constants dependent upon beam loading, support conditions, and location of point whose deflection is to be calculated; I is the moment of inertia of beam cross section; A' is a modified area of beam cross section; E is the beam modulus of elasticity; G is the shear modulus. In the present study, beams have the grain direction parallel to their longitudinal axis, thus $E = E_L$. The shear modulus, G, can be defined as G_{LT}, for beams with flat-grained vertical faces, and as G_{LR} for beams with edge-grained vertical faces. For a concentrated load applied at midspan of a beam with both ends simply supported the constants k_b and k_s assume the following values:

$$\begin{cases} k_b = 1/48 \\ k_s = 1/4 \end{cases} \tag{2}$$

In the equation (1) the term $\frac{k_b F a^3}{EI}$ represents the bending deflection effect and the term $\frac{k_s F a}{GA'}$ the shear deflection effect. In this analysis the shear deflection effect is neglected. This assumption is according to the Euler-Bernoulli hypothesis. The error introduced in the analysis is reduced as the ratio a/h increases. In the proposed tests $a/h \cong 14.2$. In this case the modulus of elasticity should be increased by 10% in order to be corrected for shear deflection (FPL, 1999). Neglecting shear effects, equation (1) can be simplified in order to express the modulus of elasticity, in grain direction, as a function of midspan deflection and load. Introduction the equation for the moment of inertia of a rectangular beam cross section, results:

$$E_L = \frac{a^3}{4bh^3} \frac{F}{\delta} \tag{3}$$

The best fit of equation (3) to the linear range of load-deflection curves gives the modulus of elasticity. The previous equation is applicable for beams made from one material. For beams made from several distinct materials, equation (3) can also be applied. In this case, equation (3) gives the modulus of elasticity of an equivalent homogeneous material that presents the same load-deflection curves than those observed for beams composed of distinct materials.

The stress due to the bending moment, for a simply supported pin-ended beam, is a maximum at midspan and at top and bottom faces. While the concave edge is compressed, the convex edge is under tension. The maximum bending stress, function of load, is given by:

$$\sigma_L = \frac{3Fa}{2bh^2} \tag{4}$$

Assuming linear elastic behavior, the respective maximum strain can be expressed using the of Hooke's law and assuming a uniaxial stress state in the grain direction:

$$\varepsilon_L = \frac{\sigma_L}{E_L} = \frac{6h\delta}{a^2} \tag{5}$$

Although equations (4) and (5) are valid for linear elastic behavior, they are also used beyond the limits of Hooke's law. When using these equations beyond elastic limit stresses and strains can be considered as pseudo-stresses and pseudo-strains, respectively.

Introduction, in equation(4), the ultimate load at rupture results an ultimate pseudo-stress which is usually called the modulus of rupture (FPL, 1999). Introduction the ultimate deflection at rupture in equation (5) results an ultimate pseudo-strain at rupture.

For the beams reinforced with pultruded material, an equivalent Young´s modulus is estimated, using classical beam theory. Assuming a perfect adhesion between wood and pultruded material, the same radius of curvature is expected, given by:

$$\frac{1}{R} = \frac{M_f}{EI} \tag{6}$$

where E represents the equivalent Young´s modulus, R the radius of curvature, I the moment of inertia of the cross section of the specimen and M_f the bending moment. This is an important equation in the determination of the deflection of beams. For cross section presented in Fig. 3, constituted by two different materials, the radius of curvature is given by the equation:

$$\frac{1}{R} = \frac{M_f}{E_1 I_1 + E_2 I_2} \tag{7}$$

where E_1, E_2, I_1 *and* I_2 are the de Young's modulus and the inertial moments of the materials 1 and 2. The elimination of $1/R$ from Eqs. (6) and (7) results the equivalent Young's modulus:

$$E_{eq} = \frac{E_1 I_1 + E_2 I_2}{I} \tag{8}$$

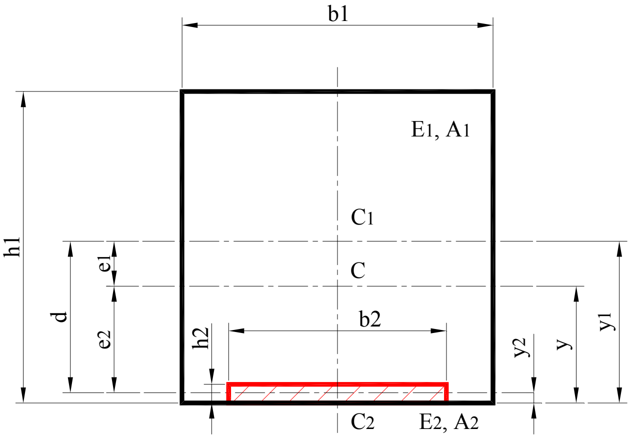


Figure 3. Cross section of the specimens reinforced by pultruded lamellas (LPPRH).

To determine the moments of inertia of each material in relation to the neutral axis it's necessary to determine the position of the neutral axis of the specimen. For such, it's necessary to determine the centroid section of the wood and composite material. Then, it is possible to calculate the distances e_1 and e_2, representing the distances from the centroidal axis to the neutral axis of each material, as is illustrated in Fig. 3. Equations (9) and (10) allow the determination of e_1 and e_2 (Lima 2004):

$$e_1 = \frac{E_2 A_2}{E_1 A_1 + E_2 A_2} \tag{9}$$

$$e_2 = d - e_1 \tag{10}$$

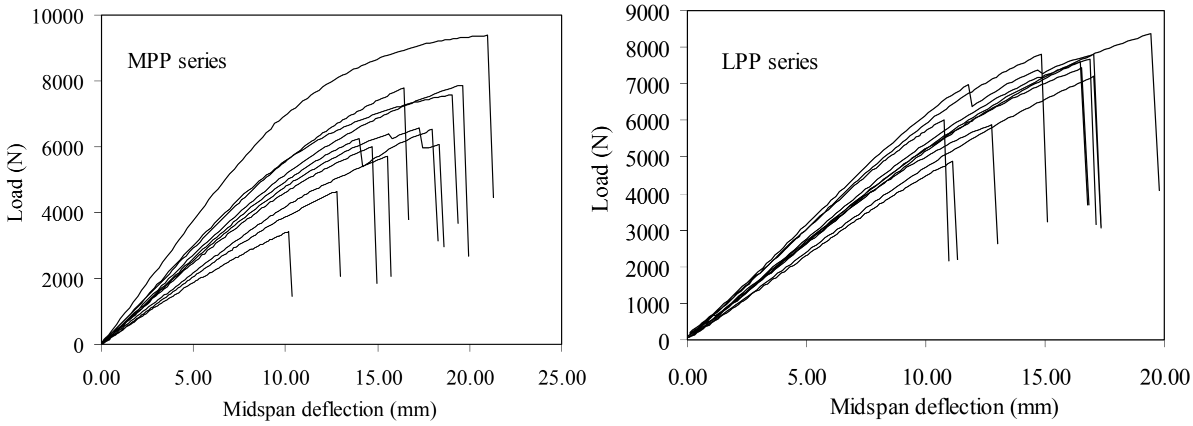
A similar treatment can be presented for the beams reinforced with vertical pultruded lamellas.

5. EXPERIMENTAL RESULTS

The direct results obtained from the bending tests are the load *versus* midspan deflection curves. Figure 4 a) and 4 b) presents the curves obtained for solid and glued-laminated beams. Each graph includes 10 curves corresponding to the specimens tested in each series. The analysis of the results denotes an important scatter in curves. The variability in properties of wood is common, because wood is a natural material and trees are subjected to many constantly changing influences such as moisture, soil conditions, and growing space, even in clear material. Specimens were prepared from current quality wood. This wood, unlike the clear wood, contains small knots, cross grain, and other kind of heterogeneities. The mechanical behavior of the laminated wood, (LPP), presented a little scatter due the undoing of defects.

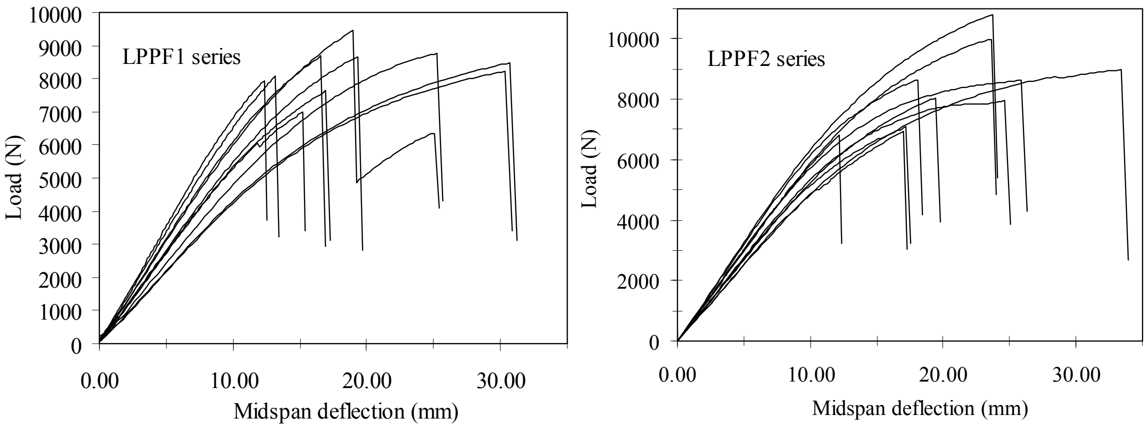
Figure 5 a) and 5 b) presents the load *versus* midspan deflection curves obtained for the laminated beams reinforced with roving of fiber glass. The introduction of reinforcement did not result in a significant reduction in the scatter. In fact, the more stressed layers drove the rupture process of the reinforced beams still which are wood layers and not fibers. Also, the scatter observed in curves obtained for the reinforced beams can be considered as a result of the combination of two main contributions: the quality of solid wood used in the production of the layers and the quality of the composite interfaces layers. The tests of the reinforced beams, produced with two composite layers, demonstrated an increase in the scatter when compared with the results obtained for the reinforced beams produced with only one composite layer. The increase of the number of composite interfaces can reduce de general quality of the product, if the quality of the composite interfaces is not satisfactory due to deficient gluing process. In fact, some failures of reinforced laminated beams were characterized by some delaminations along the fiber layers, between the wood layers, which were not observed for the glue laminated beams.

The behavior of the laminated wood reinforced with pultruded lamellas are presented in Fig. 6 a) and 6 b). The LPPRH series exhibits the greater scatter. This behavior can be explained by the heterogeneities and some problems in the gluing process between the materials



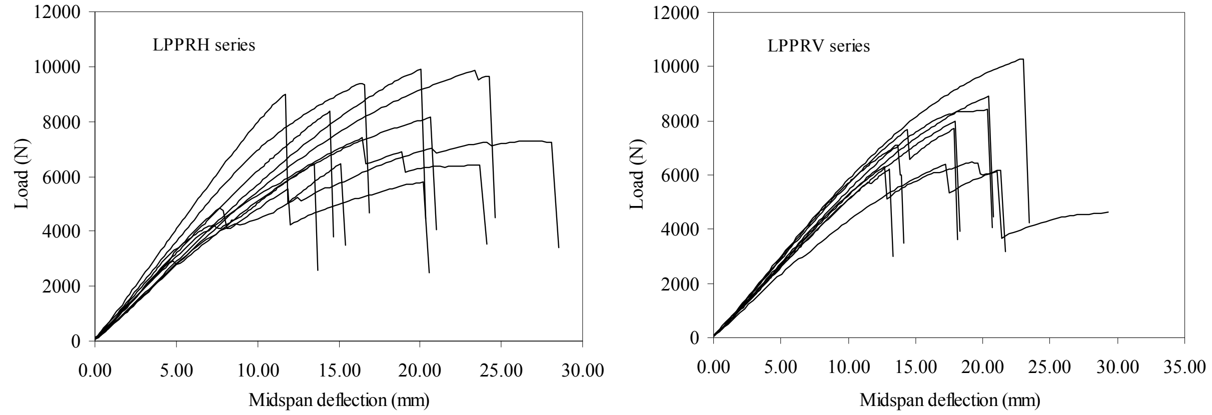
a) **b)**

Figure 4. Load *versus* midspan deflection curves obtained for solid and glued-laminated specimens: a) Specimens of solid wood - MPP series; b) Specimens of laminated wood - LPP series.



a) b)

Figure 5. Load *versus* midspan deflection curves obtained for the reinforced laminated specimens: a) Laminated wood with a unique composite layer - LPPF1 series; b) Laminated wood with two composite layers - LPPF2 series.



a) b)

Figure 6. Load *versus* midspan deflection curves obtained for laminated specimens reinforced with pultruded lamellas: a) horizontal pultruded lamellas – LPPRH series; b) vertical pultruded lamellas LPPRV series.

5.1. Analysis of results

Table 2 summarizes the mean and standard deviations of the ultimate load, the modulus of rupture, the ultimate strain and the modulus of elasticity obtained for the 6 series of tested specimens. These properties correspond to the grain or fiber direction. Figure 7 allows the comparison of mean and standard deviations of the modulus of rupture and Young's modulus for the tested series of specimens.

Table 2. Mean and standard deviations of strength properties obtained for the 6 series of tested specimens.

Series		*Ultimate load (N)*	*Modulus of rupture (MPa)*	*Ultimate strain (%)*	*Modulus of elasticity (MPa)*
MPP	**Mean**	**6544.80**	**56.30**	**1.0**	**7677.38**
	St. Deviation	1722.10	15.00	0.2	1589.82
LPP	**Mean**	**7069.60**	**59.8**	**0.9**	**7801.74**
	St. Deviation	1100.50	10.4	0.2	934.91
LPPF1	**Mean**	**8295.3**	**63.70**	**1.3**	**7611.61**
	St. Deviation	686.8	5.7	0.4	1206.22
LPPF2	**Mean**	**8387.8**	**64.3**	**1.4**	**7049.70**
	St. Deviation	1309.0	9.5	0.4	651.35
LPPRH	**Mean**	**8156.7**	**79.2**	**1.0**	**11212.98**
	St. Deviation	1410.9	14.1	0.3	1310.77
LPPRV	**Mean**	**7729**	**74.9**	**1.0**	**9420,14**
	St. Deviation	1346.2	13.2	0.2	713.8

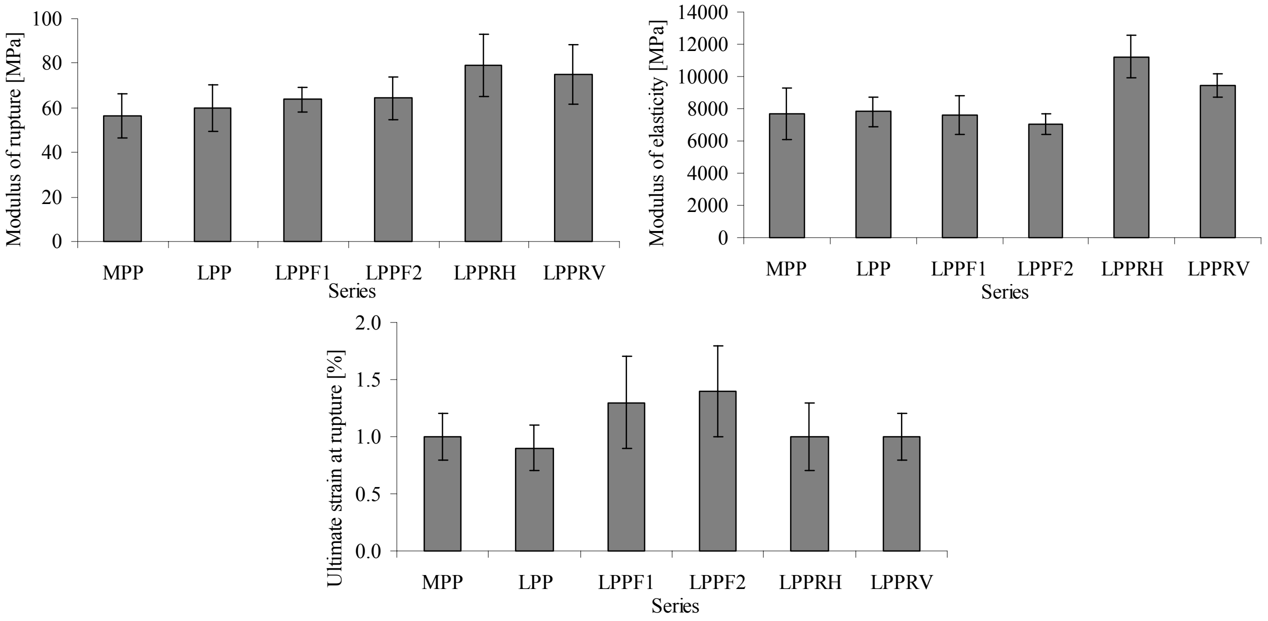


Figure 7. Comparison of the mean values and standard deviations of the modulus of rupture, modulus of elasticity and ultimate strain at rupture.

The results from the solid wood beams were the ones that presented the lowest mechanical properties, as expected. This behavior can be explained because, unlike the clear wood, the applied solid wood contains small knots, cross grain, and other kind of heterogeneities. By the other side, for the laminated wood without reinforcement it is observed a scatter reduction with better mechanical properties than observed for the solid wood beams, due to defects undoing. The specimens strengthened with fiber glass presented better mechanical properties than the specimens with no reinforcement. However, a clear tendency in the scatter variation was not verified.

Comparing the specimens with one and two layers of reinforcement of fiber glass rovings, no significant improvements in the mechanical behavior is verified and an increase in the properties scatter is visible with the increase in the number of layers of reinforcement.

For the specimens reinforced with pultruded lamellas an increase in the strength properties was verified when compared with beams reinforced with fiber glass rovings: about 20 % in modulus of rupture and of about 40 % in the modulus of elasticity.

Comparing the specimens reinforced with horizontal and vertical pultruded lamellas a decrease of the mechanical properties was verified with the vertical reinforcement. Based on Eq. (8) it is possible to estimate an equivalent Young's modulus for comparison with the experimental values. Assuming a Young's modulus for the solid wood, E_1=7 677 MPa, (Fabela e Fundo, 2004) and for the pultruded material E_2= 40 000 MPa results and equivalent Young's modulus for the laminate beams reinforced with horizontal pultruded lamellas E_{eq}=10 813 MPa. Similarly, for beams reinforced with vertical pultruded lamellas the equivalent Young's modulus is E_{eq}=8 037 MPa. These results are confirmed by the experimental values.

6. CONCLUDING REMARKS

An overall analysis of the experimental results reveals that, for the laminated and reinforced laminated beams have a greater static strength (greater modulus of rupture) than the solid wood beams. The scatter in the properties measured for the laminated and reinforced laminated beams is lower than scatter measured for the solid wood beams. The lamination of wood can act as a homogenization process which can contribute for the scatter reduction and also for an increase in the mean values of the strength properties. This effect is more pronounced if the material presents a high level of heterogeneities, which is the case of the *Pinus pinaster*.

The laminated wood with composite and with horizontal and vertical of pultruded materials exhibits higher modulus of rupture than solid and glued-laminated beams. Also the proposed laminated wood composite exhibits higher ductility at failure than the other beam solutions. The second solution of laminated wood composite, with two layers of composite material, yields the same modulus of rupture of the first solution of laminated wood composite, with only one layer of composite material. A slightly increase in the scatter of the modulus of rupture is observed for the second solution of composite material. Thus, the second solution is not satisfactory, since it uses three times more fiber. The laminated wood reinforced with horizontal and vertical pultruded lamellas were the series that presents a higher modulus of rupture as well the modulus of elasticity.

In general, the proposed engineered wood product enhances the properties of the *Pinus pinaster* for structural applications. This solution can make the *Pinus pinaster* wood competitive with the *Picea abies* (Ribeiro *et al.*, 2004).

The results presented in this research aren't yet surprising since the enhancements in the strength properties of the *Pinus pinaster* could be considered marginal, although they suggest a way to follow.

The location of the composite layers should be optimized. One solution consists in placing the composite layers as close as possible from the outer faces of the beams. The placement of composite layers near the neutral axis of the beams it is not recommended as illustrated by the second solution of laminated wood composite, proposed in this paper. Also, the use of pultruded lamellas of composite material glued at the bottom face of the beams seems to be a better choice to consider for future investigations.

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