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WOOD BEAM REPAIRING WITH CARBON–EPOXY COMPOSITES

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ABSTRACT

Wood damaged beams submitted to bending loads were repaired using carbon-epoxy patches. The effect of patch thickness as well as adhesive filleting were both studied experimentally and numerically. The objective was to verify the influence of these aspects on the strength and failure of the repaired structural components. Cohesive zone modeling considering mixed-mode (I+II) loading was carried out to simulate the observed experimental behavior. It was concluded that repair can successful recover the original bearing capacity, although patch thickness and adhesive filleting did not reveal a significant gain on strength.

INTRODUCTION

Structural applications of wood have recently been increasing owing to its ecological and economical advantages. In fact, wood is a renewable and very efficient material in which concerns its production, processing and use. Therefore, the development of appropriate repair methodologies arises as a fundamental research topic. Effectively, under service conditions wood damage can be induced by overloading, moisture fluctuations, fire, decay fungi, insects attack or even the strengthening motivated by alteration of functioning or security norms.

A contemporary procedure for wood repair consists in using artificial composite patches, as is the case of glass-epoxy (Triantafillou 1988, Radford 2002) or carbon-epoxy laminates (Triantafillou 1988, Premrov 2004, Pirvu 2004). Different strategies of repair and strengthening have been executed, depending on the accessibility of the structural component, structural requests, esthetical aspects and costs. In the case of tensile or compression reinforcement of beams these strategies consist of bonding laminate plates directly applied on beam surfaces or embedded on surfaces (Pirvu 2004), or bonding of strips or rods inserted on the beam (Radford 2002). In the case of shear reinforcement of beams two techniques have been used: bonding of plates on the lateral surfaces (Triantafillou 1988) or the insertion of bonding rods on the beam transversal direction (Radford 2002, Lorenzis 2005).

The focus of this work is to investigate the influence of bonded repairs of wood damaged structures using carbon-epoxy composites. Wood damaged beams were submitted to four-point bending (Fig. 1) in order to access the influence of different types of repair on the stiffness and strength.

EXPERIMENTS

Fig. 1 shows a schematic representation of the experimental setup used in the mechanical test. The chosen dimensions were defined as being representative of typical characterization studies involving wood (de Moura 2008, Silva 2007). *Pinus pinaster* Ait. was used in this

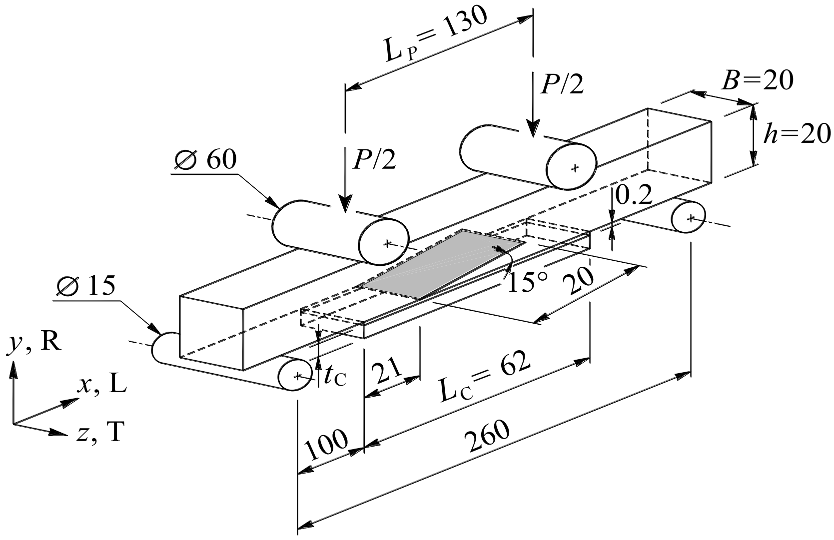

Fig. 1. Repaired beam under four-point bending.
Wood axis: L – Longitudinal; R – Radial; T – Tangential.

work as the testing material. Wood moisture content was found in the interval 11-13% once conditioned at 20°C and 65 RH until equilibrium has been reached. Wood was machined sufficiently far from the stem pith in order to get specimens of mature wood and less affected by annual rings curvature. A total number of 25 specimens were machined from a single wood log and stabilised at laboratory conditions before the experiments. The selected pre-crack angle (15°) intends to simulate severe grain misalignment in wood beams, which defines natural paths prone to crack propagation and it was executed using a circular band saw (1 mm thick).

Unidirectional composite laminates (Texipreg HS 160 RM from SEAL®) were produced from high strength carbon pre-preg according to the manufacturer recommendations, using a hot-plate press. Patches were cut from laminated plates with two different thicknesses (0.6 and 2.0 mm) and bonded onto the beam damaged region, using SIKADUR 30 adhesive from Sika®. This adhesive presents a glass transition temperature of 62°C which is adequate for typical timber applications. Surfaces were methodically cleaned and sandpapered (180-grit) to improve bonding quality, preventing spurious failure at the interfaces (adhesive/composite and adhesive/wood).

The four-point-bending tests were performed using a mechanical spindle-driven tension-compression machine (INSTRON 1125) under displacement control. A 5 kN load-cell was installed and the crosshead displacement rate was set to 0.3 mm/min. A Spider® 8 (HBM) data acquisition system was used to register the load displacement curve (i.e., the P-δ curve), with a frequency of 5 Hz. A two-point assembly device with rotating cylindrical contact surfaces was used in the mechanical tests, inducing equal reactions in the beam supports.

COHESIVE ZONE MODELING

Damage initiation and propagation in repaired beams was simulated by means of a cohesive mixed-mode damage model. This model permits establishing a linear softening relationship between stresses and relative displacements (Fig. 2).

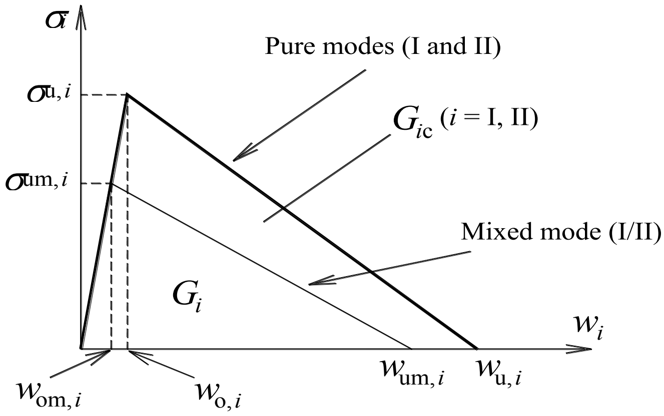

Fig. 2. Pure (I or II) and mixed-mode (I/II) bilinear cohesive zone model.

According to pure-mode model, the local strength $\sigma_{u,i}$ (i=I, II) as well as the energy release rate G_{ic} (area of the triangle corresponding to pure-mode model) have to be known *a priori*. Damage onset occurs when $\sigma_{u,i}$ is attained, and its evolution depends on a damage parameter which is a function of relative displacements w_i. Therefore, complete failure at a point occurs when the relative displacement attains $w_{u,i}$, which is obtained equating the triangle area to G_{ic}.

Since structures under general loading usually behave under mixed-mode, an extension of pure-mode model is provided. The mixed-mode law (I+II) is based on a quadratic stress criterion to deal with damage initiation,

$$\begin{aligned} &\left(\frac{\sigma_{\mathrm{I}}}{\sigma_{\mathrm{u,I}}}\right)^2 + \left(\frac{\sigma_{\mathrm{II}}}{\sigma_{\mathrm{u,II}}}\right)^2 = 1 \quad \text{if } \sigma_{\mathrm{I}} \geq 0 \\ &\sigma_{\mathrm{II}} = \sigma_{\mathrm{u,II}} \qquad\qquad\qquad \text{if } \sigma_{\mathrm{I}} \leq 0 \end{aligned} \tag{1}$$

assuming that normal compressive stresses do not induce damage. A linear energetic criterion is used to simulate crack propagation,

$$\frac{G_{\mathrm{I}}}{G_{\mathrm{Ic}}} + \frac{G_{\mathrm{II}}}{G_{\mathrm{IIc}}} = 1 \tag{2}$$

According to this criterion, the total failure under mixed-mode occurs when the energies dissipated in each mode satisfy Eq. (2). Using the relationships between stresses and relative displacements ($\sigma_I = k_i w_i$, with k_i representing the interfacial stiffness) and between energies and stresses and relative displacements (G_i=$\sigma_i w_i$/2), both Eqs. (1) and (2) can be defined as a function of the squared equivalent relative displacement (i.e., w_m^2), which means that they are compatible. More details about this issue are provided in de Morais et al. 2003.

NUMERICAL MODEL

The numerical model was developed using 8-node solid plane-stress elements from ABAQUS® software and 6-node interface finite elements (FE) previously developed (Gonçalves 2003) including a cohesive mixed-mode I+II damage model. The FE-mesh was refined in the critical regions to better simulate the non-linear phenomena due to damage development (Fig. 3). The experimental praxis has shown that several different crack paths

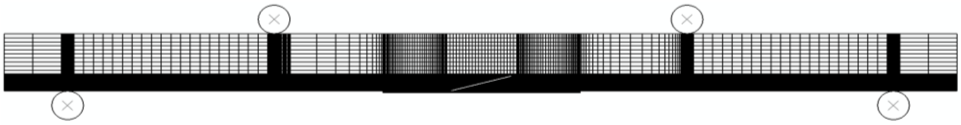

Fig. 3. Mesh used in the finite element analysis

should be considered in the numerical model to simulate the reality. Bearing this in mind, cohesive zone elements with different properties were disposed in the model. Thus, two options were considered for wood failure: (a) crack parallel to wood grain and (b) crack perpendicular to grain. In addition, interlaminar failure in the unidirectional composite patch and cohesive failure in the adhesive simulating patch debonding were taken into account.

Mechanical properties of wood (*Pinus pinaster* Ait.) and unidirectional (UD) carbon-epoxy composite used in the numerical modeling were determined in previous works (Tables 1-4). The elastic properties of the structural adhesive (E = 11200 MPa and ν = 0.3) and strength (Table 5) (SIKADUR 30, from Sika®) were provided by the manufacturer.

Table 1 – Elastic properties of *Pinus pinaster* Ait. (Dourado 2010, de Moura 2009, Xavier 2004)

E_L (GPa)	E_R (GPa)	ν_{LR}	G_{RL} (GPa)
12.5	1.9	0.47	1.12

Table 2 – Cohesive parameters of *Pinus pinaster* Ait. (Silva 2007, Campilho 2010, Dourado 2008)

Propagation System	G_{Ic} (N/mm)	G_{IIc} (N/mm)	$\sigma_{u,I}$ (MPa)	$\sigma_{u,II}$ (MPa)
RL	0.26	0.91	5.34	9.27
LR	25.0	1.2	97.5	16.0

Table 3 – Elastic properties of UD carbon-epoxy (de Morais 2003)

E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12} (GPa)
150	11	0.25	6

Table 4 – Cohesive parameters of UD carbon-epoxy (de Morais 2003)

G_{Ic} (N/mm)	G_{IIc} (N/mm)	$\sigma_{u,I}$ (MPa)	$\sigma_{u,II}$ (MPa)
0.31	0.63	40	40

Table 5 – Damage parameters of SIKADUR 30 structural adhesive (Sika®)

G_{Ic} (N/mm)	G_{IIc} (N/mm)	$\sigma_{u,I}$ (MPa)	$\sigma_{u,II}$ (MPa)
0.35	1.10	30	18

RESULTS

Five different cases were experimentally tested under four-point bending: unrepaired, thick patch (2 mm), thick patch with fillet, thin patch (0.6 mm), thin patch with fillet (Fig. 4). The patches were bonded to the damaged beams (Fig. 5) using the structural adhesive SIKADUR 30 (from Sika®). The stiffness and strength of the different studied cases were experimentally evaluated (Fig. 6). Subsequently, numerical simulations considering cohesive mixed-mode damage model I+II (de Moura, 2010) were performed accounting for several different possibilities to crack growth. In these analyses the cohesive properties were determined previously by means of fracture tests (Table 2), applying the Double Cantilever Beam for pure mode I and the End Loaded Split for the mode II (de Moura 2008, Silva 2007). In all cases failure paths were correctly captured by the numerical simulations.

The experiments allow observing that an increase of 62% in the ultimate load P_u is achieved when a thick patch is used to perform the beam repair (difference between the two first columns in Fig. 6). Besides, an increase of 38% (on average) was measured in the initial stiffness.

In order to reduce the stress concentration effect an adhesive fillet of 30° (Fig. 4b) was chosen in a new series of tests for the patch thickness t_C = 2.0 mm. As observed in Fig. 6 this solution did not provide a visible increase in the ultimate load (3rd column), when compared to an unfilled patch with the same thickness.

Another approach had to do with the study of the influence of the patch thickness, considering t_C = 0.6 mm. Though affected by scatter, the experiments revealed an increase of 13% in the ultimate load, compared with the thick patch, i.e., t_C = 2.0 mm (see Fig. 6: 2nd and 4th columns).

(a) (b)

Fig. 4. Geometry of the repaired solutions: (a) unfilleted and (b) filleted patches

Fig. 5. Failure path of a repaired beam with thick patch

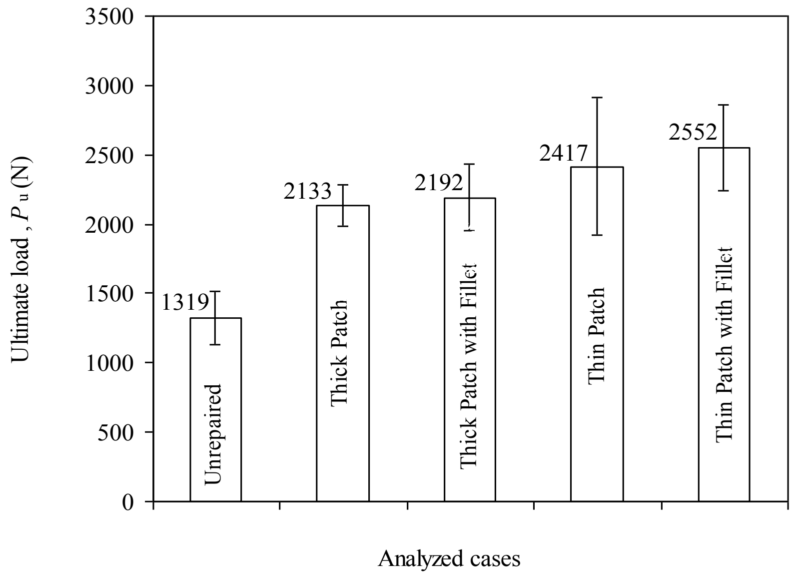

Fig. 6. Experimental mean values of strength

In a like manner as for the thick patch, the influence of the adhesive fillet on the ultimate load was analyzed (t_C = 0.6 mm). Once a comparison is made with the thick patch, the experiments have demonstrated that a more pronounced gain in strength is obtained when the adhesive fillet solution is implemented (fillet angle is kept at 30°).

A possible reason for the these results is explained by the observed mismatch stiffness that exists between the adhesive and carbon-epoxy leading to the development of important tensile stresses at the boundary between the two materials.

Additionally, the values of strength and stiffness of repaired beams were accurately predicted by the numerical model (Fig. 7 and 8), which reveals the good performance of the developed methodology. More details about the obtained results may be found in Dourado, 2012.

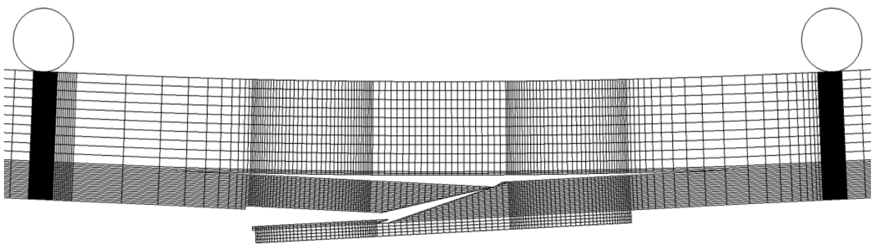

Fig. 7. Repaired beams under four-point bending

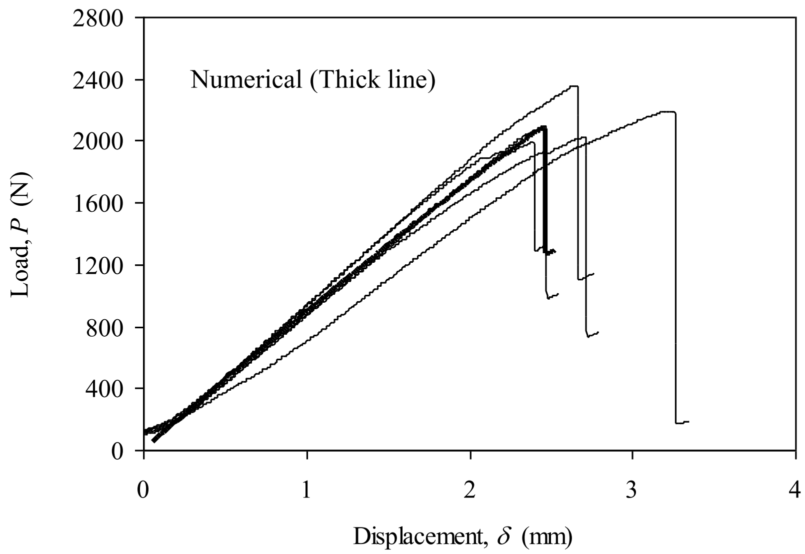

Fig. 8. Numerical and experimental P-δ curves for repaired beam using thick patch

CONCLUSIONS

The repair of damaged wood beams by carbon-epoxy patch bonding was studied both experimentally and numerically. Four-point bending tests were chosen, since wood beams are typically under bending in real structural applications. The bonding repair with a thick patch revealed a significant increase on the ultimate load and specimen stiffness, compared with the non-reinforced solution. A cohesive zone modeling considering mixed-mode (I+II) loading was carried out to simulate the observed experimental behavior. An adhesive fillet was considered with the objective to reduce stress concentration effects at the bonding singularity. A more pronounced gain in strength has been attained when a thinner patch was used considering an adhesive fillet with the same geometry. This result was explained by the detected mismatch stiffness that exists between the adhesive and carbon-epoxy. A good agreement was obtained for load-displacement curves as well as for the failure paths in tested solutions.

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