Glued laminated timber beams repair.

Master’s Degree Extended Abstract

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1. INTRODUCTION

Glued laminated timber elements are regularly used in construction. Their fabrication method allows the possibility to obtain beams with a wide range of sizes and shapes. However, these elements are susceptible to the occurrence of delamination due to fabrication errors such as an inadequate surface preparation of the lamellas (before collage) or incorrect glue amount used to bond the lamellas amongst other errors or bad design of the structure (loads, class services).

The delamination of glued laminated timber beams decreases the load-carrying capacity of the beams, as well as their modulus of elasticity causing bigger deformations. This problem leads to an early failure of the glued laminated timber beams, being necessary to repair the structure. As the removal of timber elements is a very costly and time consuming option, on-site repair is a much more desirable approach towards rehabilitating the structure.

Previous studies have developed numerous techniques using self-tapping screw amongst other connections with metal fasteners, plates, and new materials – Glass fiber-reinforced polymers (GFRP) and Carbon fiber-reinforced polymers (CFRP) – to reduce costs and develop faster and simpler techniques.

The main objective of this dissertation is to evaluate the effectiveness of a fast, simple and non-intrusive on-site repair of glued laminated beams with delamination, previously tested to failure. The repair in this dissertation was executed using self-tapping stainless steel screws applied vertically to the beams, with plywood plates.

2. MATERIALS AND METHODS

2.1. Experimental program

A total of 21 industrial produced beams with 3,090m x 0,175m x 0,095m were tested, presenting intentionally various kinds of delamination: i) 3 beams without any type of delamination called reference beams or "A" beams (A1 to A3); ii) 6 beams with “short” delamination reaching the totality of the cross-section glue lines in the edges of the beam with a 0,320m length value, called “B” beams (B1 to B6); iii) 6 beams with “long” delamination reaching the totality of the cross-section glue lines in the edges of the beam with a 0,720m length value, called “C” beams (C1 to C6); iv) 6 beams with delamination on all the glue lines reaching 2/3 of the cross-section width, in the whole length of the beam. The beams used in this experimental project were produced using cluster pine (Pinus pinaster, Ait.), with a moisture content of 14%, composed by 5 lamellas with a thickness of 3,5cm. Fig. 1 shows a scheme of the beams geometry, and Fig. 2 and Fig. 3 shows the delamination on beams “B/C” and “D” respectively. The experimental project involved the following beams: A1, A2, A3, B1, B3, B6, C1, C2, C3 and D1 to D6 (D3, D4 and D5 not repaired because these beams were used in another experiment).
In order to achieve the proposed objectives, it was used the following experimental program: first the beams were submitted to a 4 point bending test, applying symmetric loads, in accordance with the European standard EN 408:2004 [1]; after the bending tests the beams were repaired according to the type of failure (shear or bending failure); then the repaired beams were submitted again to a 4 point bending test. The materials used in the beams repair were the following: self-tapping steel screws HBS10160 and HBS10240 provided by “Rothoblaas” illustrated in Fig. 4, and Okoumé plywood plates with 2,392m x 0,095m x 0,027m, provided by “JULAR Madeiras”.

| L (m)  | 3,090 |
| b (m)  | 0,095 |
| h (m)  | 0,175 |

**Figure 1. Beams geometry and dimensions**

**Figure 2. Delamination scheme of "B" and "C" beams (delaminations marked as thick black lines)**

**Figure 3. Delamination scheme of “D” beams (delaminations marked as thick black lines)**
2.2. Beams industrial fabric

The beams used were manufactured in a specialized fabric and montage of glued laminated timber company, following the general proceedings in wood selection, surface preparation, collage, cramping pressure and curing [2, 3]. The collage of the lamellas was performed with a Melamine-Urea-Formaldehyde glue named “KOMARTEX M” provided by “Colquímica”. This glue was also used in the fabric of the finger-joints.

To simulate real delamination in the glue lines tape was palces between the lamellas before they were glued together in order to prevent the adhesion between the lamellas ensuring the desired shape and dimension for the delamination with a natural proceeding instead using saw blades (introduces tension). This procedures was previously tested in laboratory,

The beams were manufactures with a greater length that the desired one, allowing after the fabric of the beams to cut out about 20cm of the edges, rejecting the beam ends where is more difficult to assure an uniform cramping pressure. Fig. 5 shows the presence of tape between the lamellas in a tested beam (D6).

![Figure 4. Self-tapping screws HBS10240 (up) and HBS10160 (down)](image)

![Figure 5. Presence of tape between lamellas](image)
2.3. Bending tests

As written before, all the beams were submitted to a 4 point bending test performed at LNEC as described in the standard EN 408:2004 [1], using six Linear Variable Differential Transformers (LVDTs) on the load application points, on the supports and two in the middle point on the beam (Figures 7 and 8). The equipment used was the following: load application machine of “SHIMADZU CORPORATION”, model AG-IS; six LVDTs; and a DataLogger of the “RDP” brand.
2.4. Repair Design

The beams’ repair design was performed and calculated so that the failure force of the repaired beams was equal to the average failure force obtained in the “A” beams (45kN). It was decided to apply the same repair method to all the beams, with just slight adjustments on the position of the reinforcement, according to the type of failure occurred. Fig. 9 shows the failures obtained in the tested beams, where the blue lines represent the failure lines, the black lines represent delamination, and the dark brown lines represent the glue lines.

![Figure 9. Failures occurred](image)

The repair method consisted in using the screws to transmit shear stresses, and the plywood plates centred in the lamellas’ failure zone to transmit tensile stresses caused by bending forces. Only screws were applied in the beams D1 and D3 due to shear failure (horizontal splits). The plywood plated should be necessary only in the central third of the beams where there are greater bending forces. However, given that the anchorage length of the plywood plates in some cases created the overlap of the two methods, it was decided to use the same screws, applied as in the shear repair, to fix the plywood plates to the beam.

It was chosen to insert the screw perpendicular to the lamellas, instead of inserting them at an angle (which creates a better repair), using pre-drilling, because this method is easier to apply in on-site repairs to a high density wood such as in this case.
2.4.1. Shear stresses transmission

The values used in the calculations are shown in Fig. 10, measures during the tests.

The shear failure repair was performed with the HBS10160 self-tapping screws with the characteristics presented in table 1. It was used a design force value \( F = 45\text{kN} \), resulting in a shear force of 22.5kN.

Table 1. HBS10160 self-tapping screws characteristics

<table>
<thead>
<tr>
<th>Parafusos HBS10160</th>
<th>( F_{u,k} ) (MPa)</th>
<th>1000.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>d1 (mm)</td>
<td>10.00</td>
<td></td>
</tr>
<tr>
<td>d2 (mm)</td>
<td>6.40</td>
<td></td>
</tr>
<tr>
<td>ds (mm)</td>
<td>7.00</td>
<td></td>
</tr>
</tbody>
</table>

Where \( F_{u,k} \) is the characteristic tensile strength of the screw; \( d1 \) is the outer thread diameter, \( d2 \) is the inner thread diameter; and \( ds \) is the smooth shank diameter.

It was assumed that the bond was performed by the screws connecting two halves of the beam cross-section, whereby it was applied the equations (8.6) in the chapter 8.2.2. of the Eurocode 5 [6]. In the following expressions \( t_i \) is the timber or board thickness or penetration depth, with \( i \) either 1 or 2; \( f_{h,i,k} \) is the characteristic embedment strength in timber member \( i \); \( M_{y,R,k} \) is the characteristic screw yield moment; \( F_{ax,Rk} \) is the characteristic axial withdrawal capacity of the screw. \( F_{v,Rk} \) is the characteristic load-carrying capacity per shear plane per screw, which will correspond to the first type of failure to occur (equation 1).

According to the section 8.7.1. of the Eurocode 5 [6], in (1) the value of the diameter \( d \) of the screw to use in the calculations shall be an effective diameter \( d_{ef} = 1.1 \times d2 = 7.04\text{mm} \). The diameter of the screws is larger than 6mm so it is possible to use the same rules applicable to bolted connections (section 8.5.1. of the EC5 [6]). In this case \( \alpha = 0^\circ \) (angle formed between the applied strength and the grain direction).
f_{h,0,k} is the characteristic embedment strength parallel to grain and f_{u,k} is the characteristic tensile strength of the screws.

\[ f_{h,0,k} = 0,082(1 - 0,01d_{ef}) \times 600 = 45,74 \text{ MPa} \]  

(2)

\[ M_{y,Rk} = 0,3 \times f_{u,k} \times d_{ef}^{2,6} = 0,3 \times 1000 \times 7,04^{2,6} = 47952 \text{ Nmm} \]  

(3)

Since the screws have a total length of 160mm, the thicknesses to consider in the calculations are the following: \( t_1 = 87,50 \text{mm} \) and \( t_2 = 72,50 \text{mm} \), corresponding to the “elements” connected to the head of screw and the tip of the threaded part of the screw respectively. \( \beta \) is the ratio between the embedment strength of the members:

\[ \beta = \frac{f_{h,2,k}}{f_{h,1,k}} \]  

(4)

Since the screws have a total length of 160mm, the thicknesses to use in the calculations are the following: \( t_1 = 81,50 \text{mm} \) and \( t_2 = 72,50 \text{mm} \) corresponding to the “elements” connected to the head and to the tip of the threaded part of the screw respectively. And since those “elements” made of the same material \( \beta = 1 \).

\[ F_{v,Rk} = \min \left\{ \begin{array}{l} (a)23,34 \\
(b)28,17 \\
(c)10,75 + 100\% \times 10,75 = 21,50 \\
(d)8,85 + 100\% \times 8,85 = 17,70 \\
(e)10,43 + 100\% \times 10,43 = 20,86 \\
(f)6,39 + 100\% \times 6,39 = 12,78 \end{array} \right\} \]  

(5)

Which results in \( F_{v,Rk} = 12,78 \text{ kN} \)

With this value, the next step consisted in calculating the spacing between screws to use on the beams. \( \tau \) is the maximum shear stress and \( F_c \) the resulting force from the shear stresses.
\[ \tau = \left( \frac{F}{2} \right) \times \frac{3}{2} \times \frac{1}{b \times h} = 2.03 \text{ MPa} \quad (6) \]

\[ F_c = \tau \times b = 192.86 \text{ kN} \quad (7) \]

\[ \#\text{Parafusos por metro} = \frac{F_c}{F_{v,\text{Rk}}} \times b = 15.09 \cong 15 \quad (8) \]

For a better distribution, it was decided to place the screws in 2 rows, as displayed in Fig. 11.

![Figure 11. Scheme of the screws spacing](image)

### 2.4.2. Tensile stresses transmission

To the bending moment in the middle of the beam (21.60 kN), it is obtained the following associated force \( F_M \):

\[ \sigma_M = \frac{M}{w} = 44.55 \text{ MPa} \quad (9) \]

with

\[ w = \frac{bh^2}{6} \quad (10) \]

\[ F_M = \frac{1}{2} \times \sigma_M \times \frac{h}{2} \times b = 185.14 \text{ kN} \quad (11) \]

To make the bending stresses transmission, it was decided to use two plywood plates and the HBS10240 self-tapping screw (in the plywood zones) with the same characteristics as the screws used in the shear stresses transmission, just with a bigger length. Fig 12 illustrates the scheme of a bending failure repair in the A1 and C1 beams, to help understand the location of the plywood plates.

(Legend: blue – HBS10240; Gray – HBS10160; orange – Plywood plate; brown – Beam)

![Figure 12. C1 and A1 repair schemes](image)

In these zones the connection was assumed to be a central wood element (beam) connected by the screws to other two elements (plywood plates), applying the equations (8.7) of the Eurocode 5 [6] (double shear) where the index 1 corresponds to the plywood plates, and index 2 to the beam.
Where: \( t_1 = 27\text{mm}, t_2 = 175\text{mm} \) and \( d = d_{ef} = 7.04\text{mm} \). According to the catalog of the Okoumé Plywood used: \( \rho_k = 600\text{ kg/m}^3 \)

\[
f_{h,1,k} = 0.11(1 - 1.01d_{ef}) \times \rho_k = 61.35\text{ MPa}
\]

Resulting in \( \beta = 0.741 \)

And then:

\[
F_{v,Rk} = \min \begin{cases} 
  \frac{f_{h,1,k}}{2 + \beta} \left[ 2\beta(1 + \beta) + \frac{4\beta(2 + \beta)f_{x,Rk}}{f_{h,1,k}d^2} \right] + \frac{F_{x,Rk}}{4} \\
  1.15 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2M_{y,Rk}f_{h,1,k}d} + \frac{F_{x,Rk}}{4} 
\end{cases} 
\]

Considering double shear and two rows of screws, applying the correction factor recommended in the Eurocode 5 [6] to take into account the efficiency loss of using multiple screws in a row, there must be used a minimum number of 10 screws per row on the plywood plates, on each side of the connection. The spacing between the screws used in the plywood was the same used in the shear failure repair.

### 3. RESULTS

#### 3.1. Initial tests

The table 2 shows the average results (per type of beam) obtained in the initial bending tests. The deformation \( \delta \) correspondent to the failure is the displacement obtained by the testing machine, being this value just a qualitative number to use in comparisons. The other values were calculated through the intersection of the LVDTs data and the testing machine data, resulting in real numbers (quantitative and qualitative value). The legend of the following tables is:

- \( F_{rot} \) is the load-carrying capacity of the beam;
- \( E_{m,g} \) is the global modulus of elasticity in bending;
- \( \sigma_{rot} \) is tensile stress in the lowest fibre of the beam in mid-section correspondent to failure;
- \( T_{rot} \) is maximum shear stress in the supports zone correspondent to failure.
Table 2. Average results obtained in the initial bending tests

<table>
<thead>
<tr>
<th>Vigas</th>
<th>$F_{rot}$ (kN)</th>
<th>$\delta$ (mm)</th>
<th>$E_{m,g}$ (MPa)</th>
<th>$\sigma_{rot}$ (MPa)</th>
<th>$\tau_{rot}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>46.53</td>
<td>49.05</td>
<td>12633</td>
<td>46.18</td>
<td>2.10</td>
</tr>
<tr>
<td>B</td>
<td>22.03</td>
<td>27.09</td>
<td>11140</td>
<td>21.82</td>
<td>0.99</td>
</tr>
<tr>
<td>C</td>
<td>9.84</td>
<td>34.33</td>
<td>3825</td>
<td>11.12</td>
<td>0.51</td>
</tr>
<tr>
<td>D</td>
<td>43.24</td>
<td>42.43</td>
<td>13370</td>
<td>42.82</td>
<td>1.95</td>
</tr>
</tbody>
</table>

These results confirm that delamination reaching the totality of the cross-section glue lines in the edges of the beam (beams “B” and “C”) affected the mechanical performance of the beams (strength and elasticity) more as the delamination length of the delamination. The results obtained in the “A” and “D” beams are very similar showing that in this case the delamination in the “D” beams doesn’t affect its performance because there are straight beams where the design values are conditioned by bending stresses.

### 3.2. Tests after repair

Table 3 show the average results (per type of beam) obtained in the bending tests after the repairs.

Table 3. Average results obtained in the bending tests after the repairs

<table>
<thead>
<tr>
<th>Vigas</th>
<th>$F_{rot}$ (kN)</th>
<th>$\delta$ (mm)</th>
<th>$E_{m,g}$ (MPa)</th>
<th>$\sigma_{rot}$ (MPa)</th>
<th>$\tau_{rot}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>36.83</td>
<td>49.07</td>
<td>10368</td>
<td>26.73</td>
<td>1.41</td>
</tr>
<tr>
<td>B</td>
<td>38.12</td>
<td>75.94</td>
<td>7753</td>
<td>37.74</td>
<td>1.72</td>
</tr>
<tr>
<td>C</td>
<td>24.48</td>
<td>79.18</td>
<td>4651</td>
<td>24.23</td>
<td>1.10</td>
</tr>
<tr>
<td>D</td>
<td>37.15</td>
<td>55.99</td>
<td>9538</td>
<td>36.78</td>
<td>1.68</td>
</tr>
</tbody>
</table>

### 3.3. Results analysis

To help analysing the effectiveness of the repairs, it is presented in table 4 the recovery of the mechanical properties of the beams through a percentage of the quotient of the values obtained before and after the repairs.

Table 4. Average recovery of the mechanical properties

<table>
<thead>
<tr>
<th>Vigas</th>
<th>$F_{rot}$ (%)</th>
<th>$\delta$ (%)</th>
<th>$E_{m,g}$ (%)</th>
<th>$\sigma_{rot}$ (%)</th>
<th>$\tau_{rot}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>80%</td>
<td>100%</td>
<td>81%</td>
<td>57%</td>
<td>67%</td>
</tr>
<tr>
<td>B</td>
<td>182%</td>
<td>304%</td>
<td>70%</td>
<td>182%</td>
<td>182%</td>
</tr>
<tr>
<td>C</td>
<td>251%</td>
<td>230%</td>
<td>122%</td>
<td>220%</td>
<td>220%</td>
</tr>
<tr>
<td>D</td>
<td>87%</td>
<td>142%</td>
<td>65%</td>
<td>87%</td>
<td>87%</td>
</tr>
</tbody>
</table>

Here is possible to verify that the repair was much more effective on the “B” and “C” beams, recovering and improving its initial results and characteristics, although the repair’s effects are much more effective in the bending strength (and ductility) rather than in the elasticity. In beams “A” and “D”
the recovery of both strength and elasticity are very similar in both type of beams, where the bending strength recovery was very effective (80% and 87% for beams “A” and “D” respectively).

4. DISCUSSION AND CONCLUSIONS

Based on the obtained results it is possible to conclude that with the repair method used in this experimental work it is possible to recover the bending strength of the beams after their collapse, especially in beams with delamination in the edges reaching the totality of the cross-section glue lines. It was verified that the effectiveness of the repair was higher the lower deterioration suffered by the beam in caused by tensile failure of the lowest lamellas. Also, the repair method used was more effective recovering the shear stresses transmission capacity than recovering the tensile stresses transmission capacity. The results also show that it wasn’t possible to recover the original elasticity of the beams as shown in figure 13 illustrating the graphics obtained in the bending tests before and after repair of the beams D1 and D2.

The elasticity recovery would have been probably higher if the screws were to be introduces in pairs at an angle to the delamination direction. That was not possible to do, because it is a method of a hard technical execution on-site with cluster pine with a relatively high density.
5. References

[1] EN 408:2004 - Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties


