EXPERIMENTAL TESTS ON TIMBER-TO-CROSS LAM COMPOSITE SECTION BEAMS

Alessandra Gubana¹

ABSTRACT: Cross laminated timber panels are generally used to build walls and floor slabs of new wood houses, but they have interesting mechanical characteristics also for strengthening ancient wood floors in restoration interventions. XLam panels can be connected to timber beams to achieve stiffness upgrading and a floor diaphragm effect under seismic actions. First results of a series of tests to determine the panel shear behaviour show high shear resistance and huge potential for this use. Bending tests on timber-to-XLam composite section beams are here described. Experimental data show that an increment of bending stiffness can be achieved. This technique has the advantage to be much more reversible than the refurbishment of existing timber floors using a concrete topping with a steel mesh connected to the timber joists.

KEYWORDS: Timber-to-CrossLam Composite Section, Wood Floor Stiffness Upgrading, Floor Diaphragm

1 INTRODUCTION

Structural strengthening are often required in restoration interventions and, in ancient buildings, wood floors stiffness upgrading is very frequently necessary. Moreover if seismic resistance has to be assured to existing masonry buildings, a floor diaphragm behavior has to be achieved. The importance of an effective diaphragm action in the floors of multi-storey masonry buildings is well-known in earthquake engineering. Thanks to the diaphragm action, in fact, the floors can transfer the actions due to wind and earthquake to the lateral load resisting systems.

One of the techniques extensively used in Italy for rehabilitation of historical buildings is refurbishment of existing timber floors using a concrete topping with a steel mesh effective connected to the timber joists. This type of intervention contemporary ensures a significant floor stiffness upgrading and an effective three-dimensional behaviour of masonry buildings and therefore, it markedly improves the lateral load resistance [1, 2, 3].

In recent years other possible solutions were investigated with the aim to develop less invasive and more reversible techniques [4, 5, 6]. The attention towards preservation of cultural heritage buildings has constantly grown and new technologies, in accordance with the principles of restoration, are often preferred.

At the same time, advanced plate-like glued timber composite elements, as cross laminated timber (XLam), were developed by glue-lam timber factories. They are commonly used as walls and slabs in the construction of new timber buildings.

In retrofitting and rehabilitation intervention on wood floors in ancient buildings, XLam panels can be used as a wood topping, mechanically connected to the beams, so as to create a timber-to-timber composite section. The panels are stiff enough in their plane to give the floor also a diaphragm effect.

Few theoretical researches and experimental tests on XLam panels structural behaviour are disposable in literature, as they are a recent technology [7]. First results of experimental tests on the shear behaviour of cross laminated panels are presented in [10]. The test data show huge potential for the use as floor diaphragms. Moreover the use of timber topping is much more favourable, because the seismic floor action intensity is less than in the case of concrete topping, as timber mass is relatively inferior.

In the present paper the use of XLam panels mechanically connected to timber joists to upgrade their bending stiffness is investigated [11] and the results of a first series of bending tests on timber-to-XLam composite section beams are presented.

2 TIMBER-TO-CROSSLAM SECTIONS

Timber-to-XLam composite section beams can be used as in strengthening intervention on existing timber joists as in new timber floors.

The composite section is made by connecting XLam panels to the joists with mechanical fasteners. In old structures the planks over the joists can be left in situ and the XLam panels can be placed on them and fastened.

¹ Alessandra Gubana, Dipartimento di Ingegneria Civile e Architettura, University of Udine, via delle Scienze 206, 33100 Udine, Italy. Email: alessandra.gubana@uniud.it
The flexural behaviour can be described by composite section theory [12], it depends on the fastener stiffness and it is intermediate between the two ideal limit conditions of null stiffness, which means free slip between the beam and the panel, and infinite stiffness, which means no slip at all and the validity of the principle of plane section conservation after bending.

2.1 CROSSLAM PANELS

The XLam panels connected to the timber beams in the experimental tests here described were made of 3 layers of boards of 20 mm height, so as to reach 60 mm section height. The total height of the panel was chosen with reference to structural restoration intervention, where it is important not to vary much the existing floor levels of the building.

The external layers have the boards in the direction of the maximum length of the panel, while the layer inside has the boards in the perpendicular direction. The planks are 200 mm large.

The requested length of the panel is reached by finger joints between the boards.

The panels are made of spruce wood.

Several tests had been performed before on 4 layers panels of 120 mm height, at reference moisture content, to check the principal mechanical characteristics of XLam panels and the shear strength [10].

The results described in the following demonstrate that XLam panels have great potential to be used as floor diaphragms, as they show good medium values of shear resistance.

The timber of the layers was classified as GL24C, after EN 1194 [13]. The tests were conducted following the indications of EN 408 [14], EN 1194 and EN 789 [15] for compression and tension perpendicular and parallel to the grain.

Medium values of the mechanical characteristics were evaluated on at least 9-10 samples for each test and they are reported in Table 1.

<table>
<thead>
<tr>
<th>Strength (MPa)</th>
<th>Elasticity Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression ⊥ to the grain</td>
<td>$\sigma_{c,90}=3.23$</td>
</tr>
<tr>
<td>Tension ⊥ to the grain</td>
<td>$\sigma_{t,90}=1.49$</td>
</tr>
<tr>
<td>Compression // to the grain</td>
<td>$\sigma_{c,0}=4.1$</td>
</tr>
<tr>
<td>Tension // to the grain</td>
<td>$\sigma_{t,0}=28.9$</td>
</tr>
</tbody>
</table>

In Figure 1 a sample under compression test and a sample under tension test are visible.

The shear capacity of the XLam panels was tested on 20 samples. In each test a couple of panels was stressed up to collapse under shear forces by a properly designed rig.

The rig is a steel frame made by two lateral beams and two transversal beams (Figure 2). The aim of the rig design was to reach a constant shear stress distribution on the lateral sections.

A central beam is free to move longitudinally in the centre of the frame. In each test two panels, one on the right and one on the left of the central beam, are stressed at the same time. The panels lateral sections are constrained to the lateral and the central longitudinal beams. The jackets are placed at the two ends of the central movable beam, where there is a proper contrast.

The transmission of the shear forces to the panels is reached by a distributed series of connectors.

A particular device was designed to optimize the test preparation and to make easy the collocation of the panels inside the rig.

The experimental results are reported in Table 2. The medium value of the shear resistance results equal to 3.19 MPa and in any case it is always greater than 3.06 MPa.
The elasticity modulus values are more variable, but this is expectable as the global deformation of the panel is influenced by the local deformation at the parallel shank interface, which is not glued. Also for this reason the values obtained are significantly less with respect to an ideal gross wood section. In any case these values are much better with respect to a traditional wood floor with only nailed planks on the top over the joists.

Table 2: Shear mechanical characteristics of XLam panels

<table>
<thead>
<tr>
<th>Couple of panels</th>
<th>Maximum Shear Strength (MPa)</th>
<th>Shear Elasticity Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.29</td>
<td>302</td>
</tr>
<tr>
<td>B</td>
<td>3.22</td>
<td>253</td>
</tr>
<tr>
<td>C</td>
<td>3.14</td>
<td>277</td>
</tr>
<tr>
<td>D</td>
<td>3.29</td>
<td>261</td>
</tr>
<tr>
<td>E</td>
<td>3.33</td>
<td>270</td>
</tr>
<tr>
<td>F</td>
<td>3.15</td>
<td>244</td>
</tr>
<tr>
<td>G</td>
<td>3.06</td>
<td>250</td>
</tr>
<tr>
<td>H</td>
<td>3.22</td>
<td>476</td>
</tr>
<tr>
<td>I</td>
<td>3.08</td>
<td>200</td>
</tr>
<tr>
<td>L</td>
<td>3.21</td>
<td>451</td>
</tr>
</tbody>
</table>

The collapsed panels showed an unexpected ductility, as it is possible to note in Figure 2, where the shear stress \( \tau \) to the shear deformation \( \gamma \) relationship is represented for the B couple of panels. The ductile behaviour of the panels is due to the fact that the rupture is generally not simultaneous in all the shanks, it happens shank after shank with great deformation of the collapsing panel.

Figure 2: Shear stress-shear deformation experimental relationship

Two couples of panels were subjected also to cyclic tests and the experimental \( \tau-\gamma \) relationships for one panel of couple L are described in Figure 3. The behaviour is not so fragile and dissipation cycles are recognizable. These results confirm the great potential of XLam panels to be used as timber diaphragm under seismic actions.

Figure 3: Shear stress-shear deformation cycles

In Figure 4 it is possible to note the great deformation of the panel after the collapse and the cracks crossing different layers.

Figure 4: A cross section of a panel after collapse

2.2 TIMBER BEAMS

Glulam beams GL24h of red spruce wood were used in the experimental tests. The beams had a rectangular section of 140 mm width and 160 mm height. The principal mechanical characteristics are summarized in Table 3.

Table 3: Mechanical characteristics of glulam beams

<table>
<thead>
<tr>
<th></th>
<th>MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Strength ( f_{m,k} )</td>
<td>24.0</td>
</tr>
<tr>
<td>Tension Strength ( f_{t,k} )</td>
<td>16.5</td>
</tr>
<tr>
<td>Elasticity Modulus ( E_{c,0,m} )</td>
<td>11600</td>
</tr>
</tbody>
</table>

2.3 TIMBER-TO-XLAM COMPOSITE SECTION BEAMS

The beams and the XLam panels were fastened together by steel dowels inserted in predrilled holes. In Figure 5 XLam panels, beams and dowels are reproduced before fastening, while in Figure 6 the
timber-to-XLam section beams after their set up are illustrated.

Figure 5: XLam panel, beam, dowels

Figure 6: Timber-to-XLam composite section beams

The bending stiffness limit values were evaluated for the composite beam section. The lowest limit refers to null connection stiffness, which means free slip between the beam and the panel, while the highest limit refers to an ideal infinite connection stiffness, which means no slip at all and conservation of plane section after bending.

In the calculation only the external layers of the XLam panel were computed, as they are stressed in the grain direction, while the internal layers contribution was omitted, as they are stressed perpendicularly to the grain.

With reference to the symbols used in Figure 7, in case of free slip, the composite section bending stiffness $EJ_0$ can be calculated with the following equation:

$$EJ_0 = E_T J_T + E_P J_P$$  \hspace{1cm} (1)

where $E_T$ = timber beam elastic modulus, $E_P$ = XLam elastic modulus, $J_T$ = moment of inertia of the gross timber section, $J_P$ = moment of inertia of the XLam panel which depends on the number of layers with the grain oriented in the stress direction.

In the ideal case of absence of slip at the interface, the bending stiffness $EJ_\infty$ can be evaluated with the equation:

$$EJ_\infty = \sum_i E_i J_i + E_T A_T a_T^2 + E_P A_P a_P^2$$  \hspace{1cm} (2)

where $E_i J_i$ = panel and timber beam flexural rigidity, $A_T$ = area of the timber beam cross section, $a_T$ = distance of the beam centroid from the ideal centre of the composite section, $A_P$ = area of the XLam panel, $a_P$ = distance of the panel centroid from the ideal centre of the composite section, and, as previously, $E_T$ = timber beam elasticity modulus, $E_P$ = XLam elasticity modulus.

Figure 7: Timber-to-XLam composite section

The geometry of the tested beam cross section is indicated in Figure 8. With reference to the specified dimensions, it results $EJ_0 = 6.60 \times 10^{11}$ Nmm$^2$ and $EJ_\infty = 2.18 \times 10^{12}$ Nmm$^2$.

Figure 8: Timber-to-XLam composite cross section of the tested beams

Steel dowels of 16 mm diameter and 140 mm length were used as fasteners. They crossed the XLam panel and so they were inserted for 80 mm length into predrilled holes along the timber beam. The dowel spacing varied as indicated in Figure 9, with a lower distance of 100 mm near the supports where shear stress is greater.

Figure 9: Dowel spacing along the beam

3 EXPERIMENTAL BENDING TESTS

Bending tests on 6 timber-to-XLam composite section beams were carried out by means of an hydraulic servo controlled system on a proper rig.
The beams were loaded over 2 points at a distance corresponding to 1/3 of the beam length. The increasing of the load was checked by displacement control. At the beginning of each test wood moisture content was surveyed by means of an electric hygrometer. The data acquisition was automatically carried out. The instrumentation consisted of 10 potential transducers of 1/1000 mm precision, set up as indicated in Figure 10, in order to monitor the vertical deflection in the middle of the beam (T9 and T10* transducers, one on the front and one on the back side of the beam), the rotation (T5 and T6 near the left support and T7 and T8 near the right support) and the slip at interface near the supports (T1 on the front face and T2* on the back face on the left end of the beam and T3 on the front face and T4*on the back face on the right end of the beam).

**Figure 10: Monitoring device set up**

In Figure 11 one of the beams and the instrumentation set up is represented during the bending test.

**Figure 11: One of the beams and instrumentation set up during bending test**

The beam load-to-centre deflection relationships are described for all the 6 tested beams in Figure 12, where they are also compared with the theoretical elastic values in the ideal case of flexural rigidity $EJ_0$ and $EJ_\infty$, previously computed. All the curves show an increment of flexural stiffness after a deflection of 20 mm. This difference of rigidity is due to a small discrepancy of about 1 mm between the hole and the dowel diameter for set up reasons. So only when the dowels got into contact with the surrounding wood, the fasteners began to work and the bending rigidity increased. The first three samples T1, T2, T3 show a greater value of stiffness than the others, as they were made using new XLam panels, instead the samples T4, T5 and T6 were made using again the same panels, as these did not collapse and did not plastically deform during the tests.

As a matter of fact the drilled holes had become oval after the tests, due to high pressure on the contact border between the dowels and the XLam layers, so the initial free slip was more consistent for the last three beams.

**Figure 12: Load-Deflection relationships for the 6 tested beams**

In Figure 13 the XLam panel-to-timber beam slip at the two supports is reported with reference to the sample T4. Also in this case it is possible to note that there is a variation gradient of the curves after an initial slip of about 1.3 mm.

**Figure 13: Slip at the supports of beam T4**

In Figure 14 the predrilled holes of one beam are photographed after the bending test.

**Figure 14: Predrilled holes in the timber beam after the bending test**
All the collapses of the tested composite section beams happened in a fragile way, with sudden failure of the glulam beams, as it is possible to note by the curves in Figure 12 and in Figures 15, 16.

In Figure 15 one composite beam is photographed after the collapse and it is possible to note that the XLam panel is unaffected, but integer, while the timber beam is deeply cracked.

![Figure 15: A composite section beam after collapse](image)

In Figure 16 an important crack crosses the timber beam after the collapse.

![Figure 16: Failure cracks in the timber beam](image)

For all the tested beams the maximum values of the load and the corresponding deflection are reported in Table 4, while in Table 5 the maximum slips and the maximum rotations at the two supports are reported.

### Table 4: Maximum values of load and deflection

<table>
<thead>
<tr>
<th>Beam</th>
<th>Max Load kN</th>
<th>Max Deflection mm</th>
<th>Moisture content %</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>53.0</td>
<td>66.7</td>
<td>10.0</td>
</tr>
<tr>
<td>T2</td>
<td>43.1</td>
<td>50.3</td>
<td>9.8</td>
</tr>
<tr>
<td>T3</td>
<td>46.0</td>
<td>68.0</td>
<td>10.2</td>
</tr>
<tr>
<td>T4</td>
<td>50.8</td>
<td>83.8</td>
<td>10.9</td>
</tr>
<tr>
<td>T5</td>
<td>41.9</td>
<td>53.3</td>
<td>10.5</td>
</tr>
<tr>
<td>T6</td>
<td>47.2</td>
<td>63.7</td>
<td>11.0</td>
</tr>
</tbody>
</table>

### Table 5: Maximum values of load, rotation and slip at the left and right supports

<table>
<thead>
<tr>
<th>Beam</th>
<th>Max Load kN</th>
<th>Left Rotation rad</th>
<th>Right Rotation rad</th>
<th>Left Slip mm</th>
<th>Right Slip mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>53.0</td>
<td>0.0518</td>
<td>0.0509</td>
<td>3.67</td>
<td>4.14</td>
</tr>
<tr>
<td>T2</td>
<td>43.1</td>
<td>0.0400</td>
<td>0.0386</td>
<td>2.90</td>
<td>2.57</td>
</tr>
<tr>
<td>T3</td>
<td>46.0</td>
<td>0.0520</td>
<td>0.0521</td>
<td>3.52</td>
<td>3.10</td>
</tr>
<tr>
<td>T4</td>
<td>50.8</td>
<td>0.0658</td>
<td>0.0647</td>
<td>5.03</td>
<td>5.37</td>
</tr>
<tr>
<td>T5</td>
<td>41.9</td>
<td>0.0409</td>
<td>0.0413</td>
<td>2.94</td>
<td>2.85</td>
</tr>
<tr>
<td>T6</td>
<td>47.2</td>
<td>0.0491</td>
<td>0.0504</td>
<td>3.54</td>
<td>3.44</td>
</tr>
</tbody>
</table>

Experimental flexural rigidity were evaluated on the basis of the acquired data, and they were compared with the theoretical values. The maximum deflection in the midspan of the beam registered during the tests is due to the concentrated loads and it can be evaluated with the following equation:

\[
f = \frac{P}{8EJ} \left( \frac{d_1^2 + d_1*d_2}{2} \frac{d_1 + d_2}{d_1 + d_2} \right) - \frac{P}{8EJ} \left( d_1 \frac{d_2^2}{2} \right)
\]

where \(f\) = deflection of the beam in the midspan, \(P\) = the total load transmitted by the hydraulic system, \(d_1\) = the distance between the load point and the support (\(d_1=1.33\) m Figure 10) and \(d_2\) = the distance among the two load points (\(d_2=1.34\) m Figure 10), \(EJ\)= flexural rigidity.

With the specified data it results:

\[
f = 1.134 \frac{P}{EJ}
\]

where, as previously, \(P\) = the total load transmitted by the hydraulic system, \(EJ\)= flexural rigidity.

In Figure 12, besides the experimental load-to-deflection relationships for the 6 tested beams, the theoretical relationships in case of complete connection and absence of connection are reported.

It is possible to note that, in the first load step, until the difference between the hole and the dowel has been overcome, the composite beam behaviour is similar to the ideal condition of connection absence, while subsequently an increment of bending stiffness can be noted, as the fasteners have began to work successfully. Flexural rigidity were evaluated, on the basis of the experimental data, with reference to the second phase of the behaviour. All the values are reported in Table 6. They were computed on the linear elastic branch between 20 and 30 kN loads. In Table 6 it is indicated also the ratio \(\rho\) between the actual rigidity of the composite section beam and the ideal situation of connection absence, and finally it is reported also the coupling coefficient \(\eta\), as it is a significant parameter to evaluate the capacity of the connection in order to limit slip between the two parts of the composite section.

The expression of the coupling coefficient \(\eta\) is defined by the following equation:
The collapse mechanism of the timber-to-XLam composite section involved the glulam beam, showing in this way the capacity of the panel to work together with the timber beam, without precluding the final capacity of the composite section.

ACKNOWLEDGEMENT
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REFERENCES


