REFURBISHMENT OF TRADITIONAL TIMBER FLOORS BY MEANS OF WOOD-WOOD COMPOSITE STRUCTURES ASSEMBLED WITH INCLINED SCREW CONNECTORS

Albino Angeli¹, Maurizio Piazza², Mariapaola Riggio², Roberto Tomasi²

ABSTRACT: In the present paper a refurbishment technique is reported, which couples the timber floor beams with thick timber planks, connected with a couples of crossed self tapping and full threaded screws, disposed with an inclination of 45°. The structural behaviour of the resulting timber composite structure is governed by the strength and stiffness of the connector system adopted. The research illustrated in the paper has been devoted both to investigate the mechanical properties of continuous threaded screws connectors – in order to provide a reliable engineered model to predict strength and stiffness of the joints – and to implement and validate the method through an in situ application on an existing floor. The case study was given during the restoration of the Belasi Castle (14th century) situated in north Italy, where a timber floor has been reinforced, increasing its out of plane flexural stiffness. After the intervention an in situ experimental analysis has been performed, in order to validate the proposed engineered model.

KEYWORDS: Traditional timber floors, Strengthening, Mechanical screws connections, Seismic design, Ductility

1 INTRODUCTION

Old timber floors often need strengthening and stiffening as they were designed to bear moderate loads and may suffer from excessive deflections with respect to current requirements. Moreover if seismic resistance has to be assured, the increase of floor stiffness, both in plane and out of plane, is necessary to prevent dangerous out of plane forces in the masonries, under seismic actions. In the past, the stiffening and strengthening of timber floors has been often achieved by using a reinforced concrete slab over the timber decking with a steel mesh connected to the timber joists [1]. The aim of such a slab is twofold: to form a wood-concrete composite structure, resistant to both bending moment and shear force, and to obtain a stiff diaphragm behaviour. The aforementioned technique has some shortcomings concerning mainly the increase of dead load and the need for an additional structural depth over the existing decking. Moreover, it does not meet the requirement of “reversibility”, coming from the heritage administration agencies. Indeed, Recommendations developed by international and national technical committee [e.g., 5] emphasize the use of compatible materials and reversible repair techniques. These requirements are generally met in traditional solutions, which use wood to reinforce or substitute decayed elements or parts, often coupled with mechanical connections, such as nails, bolts, screws, bands and metallic plates [e.g., 6-8]. Therefore, recently, it is raised the interest for “dry” “reversible” strengthening techniques, such as that described hereinafter, where the existing timber beams are coupled with thick timber planks, connected with crossed self tapping and full threaded screws, disposed with an inclination of 45°.

The use of screws, inserted with an angle between the screw axis and shear plane varying from 45° to 90°, has been recently proposed in different applications, in order to exploit the high resistance and stiffness of screws against withdrawal and pushing in. Timber floors refurbished with the proposed technique behave as timber composite structure, whose structural performance is governed by the strength and stiffness of the connector system adopted. Consequently, the correct modelling of the connection becomes a crucial point for a suitable design of the strengthening intervention.

The strengthening technique investigated was applied in the reported case study, characterised by low intrusion into the existing structural material and by complete reversibility of the intervention.

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2 THE STRENGTHENING TECHNIQUE

2.1 STRENGTHENING DESIGN CRITERIA

The deformability of a composite beam can be limited by controlling the composite beam span-height ratio (S/H) and the connection stiffness (K\text{ser}). Span-height ratios ranging between S/H=15\text{÷}25 usually guarantee limited mid span deflection and rotations at the supports. Connection stiffness also highly influences the deformability of the composite beam. The strengthening is therefore bound to the evaluation of the connection stiffness (K\text{ser}).

While the resistance of wood connections, made using metal elements with cylindrically shaped shanks loaded perpendicularly to the axis of the fastener, can be calculated using Johansen’s yielding theory [1] which is embedded in several European codes [10-11], no design rules are available so far in standards to predict the stiffness of inclined screws subjected to lateral load. A fundamental work was carried out by Bejtka and Blaß [12] to obtain a strength model for inclined screws subjected to shear-tension stress. Starting from the considerations of Kevarinmäki [13] on the deformability of inclined screw connectors, and on the basis of a broad experimental campaign, carried out at the laboratory of Materials and Structural Testing at the University of Trento, a specific model for the stiffness of inclined screws was developed [14], in order to characterize the slip modulus of the connection for different screws inclinations and joint configuration.

2.2 PROPOSED MODEL FOR CALCULATING THE STIFFNESS OF INCLINED SCREWS

Hereinafter the calculation model is discussed for the three configurations illustrated in Figure 1.

![Figure 1: Geometrical characteristics of the type specimen (dimensions in mm).](image1)

In the case of screws embedded in X position the relation reported in table 7.1 of Eurocode 5 is no longer capable of adequately estimating the experimental stiffness values. Consequently, the following calculation method is proposed for such cases.

Figure 2: Components of displacement on the shear plane.

The components of displacement $\delta = \overrightarrow{AA'}$ in Figure 2 with respect to the undeformed configuration of the screw shall be:

$$\delta_{\perp} = \delta \cos \alpha ; \quad \delta_{\parallel} = \delta \sin \alpha$$  \hspace{1cm} (1)

Where

- $\delta$ is the lateral displacement parallel to the shear plane;
- $\delta_{\perp}$ is the perpendicular component of displacement $\delta$ with respect to the undeformed configuration of the screw;
- $\delta_{\parallel}$ is the parallel component of displacement $\delta$ with respect to the undeformed configuration of the screw;
- $\alpha$ is the screw’s angle of inclination with respect to the normal to the shear plane.

Assuming an elastic-linear behaviour of the screw at serviceability limit state, a generic force can be expressed as $F = K \cdot u$. Consequently, the following two equations can be written:

$$F_{\perp} = K_{\perp} \delta_{\perp} ; \quad F_{\parallel} = K_{\parallel} \delta_{\parallel}$$  \hspace{1cm} (2)

where:

- $F_{\perp}$ is the elastic force acting perpendicularly to the screw’s axis;
- $F_{\parallel}$ is the elastic force acting parallel to the screw’s axis;
- $K_{\perp}$ is the shear stiffness of the inserted screws subjected to lateral load;
- $K_{\parallel}$ is the axial stiffness of the screw subjected to withdrawal load.

Figure 3: Forces acting on the shear plane.
As regards the equilibrium concept, by imposing separately the translation of the first or of the second wood element in the direction of the external load, one obtains:

\[ F_{\text{ser}} = F_{\text{ser}}^{\text{ax}}(\cos \alpha - \mu \sin \alpha) + F_{\text{ser}}^{\text{lat}}(\sin \alpha + \mu \cos \alpha) \quad (3) \]

At this point, by inserting Equations 1 and 2 in Equation 3, the following is obtained:

\[ F_{\text{ser}} = K_{\text{ser}}^{\text{ax}} \delta \cos(\cos \alpha - \mu \sin \alpha) + \ldots \]

\[ + K_{\text{ser}}^{\text{lat}} \delta \sin(\sin \alpha + \mu \cos \alpha) \quad (4) \]

Reminding that \( K_{\text{ser}} = F_{\text{ser}} / \delta \), by substituting Equation 4 in this definition, one obtains the stiffness expression valid for screws working only under shear-tension stress:

\[ K_{\text{ser}} = K_{\text{ser}}^{\text{ax}} \cos(\cos \alpha - \mu \sin \alpha) + \ldots \]

\[ + K_{\text{ser}}^{\text{lat}} \sin(\sin \alpha + \mu \cos \alpha) \quad (5) \]

When the screws are in X-position, instead, and working simultaneously one under shear-tension stress and the other under shear-compression stress, the equilibrium conditions must be written taking into account the fact that the resistant system consists of a pair of crossed screws. The resulting expression for \( K_{\text{ser}} \) of X-positioned crossed screws is similar to the previous Equation 5 but different in that the terms describing friction between wood elements disappear, then:

\[ K_{\text{ser}} = K_{\text{ser}}^{\text{ax}} \cos^2 + K_{\text{ser}}^{\text{lat}} \sin^2 \alpha \quad (6) \]

In all of the equations containing \( K_{\text{ser}}, K_{\text{ser}}^{\text{ax}}, K_{\text{ser}}^{\text{lat}} \), obviously the intent is to indicate the stiffness of a single screw, i.e. of a single resisting section.

Notice how the stiffness of a screw with an inclination \( \alpha \) with respect to the perpendicular to the shear plane is a combination between the lateral stiffness \( K_{\text{ser}}^{\text{ax}} \) and the axial stiffness \( K_{\text{ser}}^{\text{lat}} \) of the same screw. In particular, the following is true:

- when \( \alpha = 0^\circ \), \( K_{\text{ser}} = K_{\text{ser}}^{\text{ax}} \);
- when \( \alpha = 90^\circ \), \( K_{\text{ser}} = K_{\text{ser}}^{\text{lat}} \).

Thus the stiffness values associated with the limit states of a screw under pure shear stress and a screw under pure axial stress can be found.

In summary, the calculation method proposes to determine the stiffness of inclined screws, using the expression:

a) \( (5) \) for screws under shear-tension;

b) \( (6) \) for screws crossed in an X position working simultaneously one under shear-tension stress and the other under shear-compression stress.

The calculation model proposed here, applicable in principle to any type of screw as long as \( K_{\text{ser}}^{\text{ax}} \) and \( K_{\text{ser}}^{\text{lat}} \) are defined. As regards \( K_{\text{ser}}^{\text{ax}} \), the Eurocode 5 formula, (Eurocode 5, table 7.1) is proposed once more. As regards \( K_{\text{ser}}^{\text{lat}} \), according to Kevarinnäki, the following expression can be adopted, depending from the withdrawal stiffness \( K_{\text{ser,ax,1}} \) of the threaded parts of the screws anchored by a length of \( l \) into the \( i \)th wood element.

\[ K_{\text{ser}}^{\text{lat}} = \frac{1}{1/K_{\text{ser,ax,1}} + 1/K_{\text{ser,ax,2}}} \quad (7) \]

The values for \( K_{\text{ser,ax}} \) can be directly measured via a withdrawal test according to EN 1382 [15], or adopting the formulation provided in homologation certificate, if available.

2.3 EXPERIMENTAL BEHAVIOUR OF THE CONNECTION SYSTEM

Hereinafter we illustrate the experimental results of push-out tests under static monotonic load procedure carried out on timber-to-timber connections with inclined screws. Homogeneous spruce (Picea Abies) glued laminated timber of strength class GL24h were used. Density of the wood was determined experimentally, according to EN 28970 [16], resulting in \( \rho_w = 426 \text{ kg/m}^3 \) and \( \rho_k = 402 \text{ kg/m}^3 \). Self-tapping double thread screws with nominal diameter of 8.2, with different lengths (L=190 and L=220 mm) and of strength class 10.9 (\( f_{\text{uk}} = 1000 \text{ MPa} \)) were used. The main feature is that each screw has two threads of different pitch but of equal length: one for penetrating and the other for tightening (see Figure 4 and Table 1).

Figure 4: Main geometrical features of screw adopted.

Table 1: Main geometrical features of screw adopted

<table>
<thead>
<tr>
<th>Type</th>
<th>L</th>
<th>S₁=S₂</th>
<th>S₃</th>
<th>D₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1-8.2xL-190</td>
<td>190</td>
<td>80</td>
<td>30</td>
<td>8.2</td>
</tr>
<tr>
<td>D1-8.2xL-220</td>
<td>220</td>
<td>95</td>
<td>30</td>
<td>8.2</td>
</tr>
</tbody>
</table>

The samples configuration is that generally used in push-out tests as is depicted in Figure 1.

For standardization purposes, the fasteners were anchored by 15° increments. The result was screws anchored at 0°, 15°, 30° and 45° with respect to the perpendicular to the shear plane.

In the case of connections with an angle of 0° and 15°, screws with length of 190 mm were used; in the case of 30° and 45°, screws with length of 220 mm were preferred. In all cases, screw anchorage was performed so as to place the midpoint of the smooth shank of the fastener on a level with the slip plane.

Considering that, throughout the test campaign it was decided to compare the experimental results only with Eurocode 5, the instructions given in that Standard were followed (i.e. the minimum spacing values and edge distances).

The screws were placed so that, in the connection, each one featured only one shear plane.

EN 26891 [17] is the basic standard for defining the strength and deformability characteristics of connections made using mechanical fasteners. It introduces:

- \( F_{\text{max}} \), maximum load or maximum admissible load: this corresponds to the first of the two following conditions occurring during a test: actual maximum load (\( F_{\text{max},\text{ax}} \)), or load corresponding to a 15 mm slip (F15);
According to EN 26891, starting from the \( F - v \) curves, the slip modulus can be calculated:

\[
K_{\text{ser}} = \frac{0.4 \cdot F_{\text{max}} - 0.1 \cdot F_{\text{max}}}{v_{0.4} - v_{0.1}}
\]  \hspace{1cm} (8)

Figure 5 shows the average \( F - v \) curves for the different types of specimens tested. Table 2 shows the experimental stiffness values carried out according to the EN 26891 standard for inclined screws crossed in X position.

**Table 2: Mean experimental values of the stiffness of double thread screws at various inclinations with reference to the shear plane and crossed in X position (see Figure 6, lower right). Case 2+2.**

<table>
<thead>
<tr>
<th>[kN/m]</th>
<th>45°X</th>
<th>30°X</th>
<th>15°X</th>
<th>0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>2+2</td>
<td>57487</td>
<td>42175</td>
<td>28633</td>
<td>9035</td>
</tr>
</tbody>
</table>

**Figure 5: Average F-v curves for various inclinations \( \alpha \); cases 2+2, 4+4, 4+4E.**

Fig. 6 shows the performance, upon variation of the screws’ angle \( \alpha \) with respect to the perpendicular to the shear plane, of the mean experimental value for the slip modulus \( F_{\text{ser}} \) according to Equation 8 and of the theoretical stiffness values expected from the Eurocode 5 calculation method and from the innovative proposed calculation method proposed in this paper.

In the calculation model proposed, two different assumptions for the withdrawal stiffness value \( K_{\text{ser,ax,i}} \) can be adopted:

- **Double stiffness model:** considering the simultaneous pull-out of the two threaded portions of the screw from both wood element, the Equation 7 for two springs placed in series can be adopted, depending from the withdrawal stiffness \( K_{\text{ser,ax,i}} \) of both threaded parts of the screws;
- **Single stiffness model:** observing the experimental evidences of the penetration of the head of screw after failure (while the tip of the screw remained in its initial position), also for small displacements has been assumed that only one threaded segment of the screw (the head segment) pulls out, assuming in Equation 7 infinite the value of withdrawal stiffness \( K_{\text{ser,ax,i}} \) for the tip of the screw.

The observation of the experimental values achieved by the slip modulus shows that the adopted inclined screws:

- crossed in X-position (cases 45°X, 30°X, 15°X) have stiffness that increases with the angle \( \alpha \) of the screws, reaching maximum values for \( \alpha = 45^\circ \);
- the maximum value of stiffness is obtained when the screws are crossed in X-position at an angle \( \alpha = 45^\circ \) (values equivalent to about 6÷8 times those at 0°).

As regards the evaluation of the slip modulus, it is possible to conclude that:

- in case of screws crossed in X-position, the Eurocode 5 formula is entirely unsuitable because it greatly underestimates the true values of the slip modulus;
- the calculation method proposed in this paper provides a good estimate of the experimental values \( K_{\text{ser}} \) for all conditions of screw load/stress. In particular, the hypothesis of the single pull-out/withdrawal of the screw from the wood element shows perfect matching between experimental and theoretical values.

**3 IN SITU APPLICATION**

The chance to investigate the effectiveness of the proposed strengthening technique was given during the restoration of the Belasi castle (14\textsuperscript{th} century), in the Non valley (Trento) (Fig.7). In particular, the intervention was executed on a floor in the north-east wing of the castle (15\textsuperscript{th} century). The room has a trapezoidal shape; the twenty timber beams have variable reciprocal distances (99÷50 cm) and span length (6÷7.2 m).

A preliminary investigation campaign was carried out, in order to estimate current and future structural performance of the timber floor [18]. The existing timber beams (Larch and Spruce), have been classified according to the Italian Standard UNI 11119 [19] (i.e. Table 3).
On the basis of the diagnostic survey, structural restoration interventions have been proposed for the refurbishment of the floor in object.
In order to preserve, as much as possible, the integrity of the existing timber beams, interventions have been kept to the minimum level meeting structural requirements.
Due to the necessity of replacing the existing degraded decking, a complete wooden composite structure has been designed, coupling the beam with glulam planks strength class GL 24h according to EN 1194:1999 [20], 70 mm in thickness.

**Figure 7: Longitudinal vertical section, plan of the Belasi Castle and particular of the investigated floor.**

Table 3: Piecewise grading of a floor beam, according to UNI 11119:2004

<table>
<thead>
<tr>
<th>Beam portion</th>
<th>Wanes (1)</th>
<th>Checks</th>
<th>Knots (2)</th>
<th>SoG</th>
<th>Strength class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-A</td>
<td>≤1/5</td>
<td>/</td>
<td>≤1/3</td>
<td>≤10%</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>≤2/5</td>
<td></td>
<td>≤2/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-A'</td>
<td>≤1/5</td>
<td>/</td>
<td>≤1/3</td>
<td>≤10%</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>≤2/5</td>
<td></td>
<td>≤2/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A'-B</td>
<td>≤1/5</td>
<td>/</td>
<td>≤1/5</td>
<td>≤10%</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>≤2/5</td>
<td></td>
<td>≤2/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-C</td>
<td>≤1/8</td>
<td>/</td>
<td>≤1/3</td>
<td>≤10%</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>≤2/5</td>
<td></td>
<td>≤2/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-D</td>
<td>≤1/5</td>
<td>/</td>
<td>≤1/5</td>
<td>≤10%</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>≤2/5</td>
<td></td>
<td>≤2/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-E</td>
<td>≤1/8</td>
<td>/</td>
<td>≤1/5</td>
<td>=10%</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>≤2/5</td>
<td></td>
<td>≤2/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-2</td>
<td>≤1/8</td>
<td>/</td>
<td>≤1/5</td>
<td>=10%</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>≤2/5</td>
<td></td>
<td>≤2/5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Strength class of the beam II

(1) measured value= ratio of the wane length to the element height
(2) single knot: measured value= ratio of the minimal diameter to the width of the element face
(3) knots' cluster: measured value= ratio of the sum of the minimal diameters of all the knots, in a 150-mm range, to the width of the element face

The adopted connection system consists of self-tapping double thread screws, strength class 10.9 (f_u,k = 1000 MPa). The disposal of the inclined screws, X-crossed with an angle α = 45°, has been chosen on the basis of the experimental results reported in Table 2, and it is designed to contribute to the stiffness of the connection, in case of both shear-compression and shear-tension load conditions. Moreover, screws are staggered, to avoid the occurrence of splits along the fiber.
The geometric scheme of the connection system is illustrated in Figure 8.

**Figure 8: Plan and section of the composite structure and geometry of the connections system.**

The geometrical configuration of the refurbished floor is reported in Table 4.
The floor has been verified according to the Eurocode 5, assuming a permanent load of the floor of 2 kN/m² and live load of 3 kN/m².
Table 4: Geometrical data of the composite structure

<table>
<thead>
<tr>
<th></th>
<th>(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams interspace</td>
<td>0.5</td>
</tr>
<tr>
<td>Span between supports</td>
<td>7.2</td>
</tr>
<tr>
<td>Beams height</td>
<td>0.2</td>
</tr>
<tr>
<td>Beams base</td>
<td>0.15</td>
</tr>
<tr>
<td>Glulam plank base</td>
<td>0.5</td>
</tr>
<tr>
<td>Glulam plank height</td>
<td>0.08</td>
</tr>
<tr>
<td>Wooden boards</td>
<td>0.03</td>
</tr>
<tr>
<td>Min. distance between screw connections</td>
<td>0.1</td>
</tr>
<tr>
<td>Max. distance between screw connections</td>
<td>0.2</td>
</tr>
</tbody>
</table>

In order to control on site the efficiency of the new refurbishment technique, the intervention was checked, first, only on a single beam, which was tested before and after repair. For this purpose, after dismantling the decayed floorboards, a timber formwork was built on the beam, and then waterproofed with nylon sheets (Fig. 9). Mid span deflection, as well as possible settlement at the support, were monitored by means of LVDT transducers at the intrados. Two additional displacement sensors were placed to monitor contingent asymmetric deflections (Fig.10). The beam was then monotonically loaded and unloaded, pouring water, with load steps of 0.5 kN/m$^2$ and maximum load of 2kN/m$^2$.

After testing the unrepaired beam, a new floorboard portion large 500 mm was built, which rested symmetrically and solely on the test beam. The boards crossly disposed to the beam were cut in the middle, in order to avoid load transmission to not investigated lateral beams. After the execution of the intervention, the repaired portion of the floor has been tested, as it was done with the unrepaired beam. In this case, the maximum test load was 4.5 kN/m$^2$, with load steps of 0.5 kN/m$^2$.

3.1 STRUCTURAL PERFORMANCE AND VERIFICATION OF TEST RESULTS

Loading were performed at 80% of the service load. Figure 11 shows the load-deflection curves for the unrepaired and repaired beam. In Figure 11, the theoretical response of the structure, by alternatively assuming a simply supported and a fixed-fixed beam, is also shown.

Figure 9: On site bending test: loading system

Figure 10: On site bending test: displacement measurement system

Figure 11. Theoretical deflections, calculated modelling the element both as a simple-supported and as a fixed-fixed beam, compared with the experimental displacements for the cases of reinforced and unreinforced beam
The experimental results demonstrate that the technique allows significantly enhancing the stiffness of the wooden floor. The stiffness of the composite beam is more than four times as large as the stiffness of the wood beam alone. This way the deformability of the structure can be conveniently reduced.

4 CONCLUSIONS AND FUTURE WORKS

The calculation method proposed by the authors provides a good estimate of the experimental stiffness of continuous thread screws arranged in X-position. In particular, the assumption of the single pull-out/withdrawal of the screw from the wood element shows good matching between experimental and theoretical values. The adoption of the described geometrical configuration has been successfully implemented in an in situ application, showing promising results in terms of increase of the out of plane flexural stiffness of the studied existing floor. Additional advantages of the proposed technique are the low intrusion into the structural material in service and the complete reversibility of the intervention.

The future work will be devoted to the experimental validation of the proposed strengthening technique on full-scale timber elements tested in laboratory. This will allow a better control of both the material characteristics and the boundary conditions of the tested structures. A first series of experiment will be carried out on those beams of the Castle floor which have been considered severely decayed and dismantled.

Complementary, tests will be performed on new timber beams.

ACKNOWLEDGEMENT

The research was founded by the Italian ReLULIS Consortium, within the research program carried out for the Italian Agency for Emergency Management. The third Author was supported by the Provincia Autonoma di Trento, with the post-doc fellowship titled “DIGITIMBER (DIGItal technologies in TIMBER Restoration)”. The Authors wish also to thank the company Rothobraas s.r.l., for supplying the WT-T-8.2 screws and glued laminated wood, the Soprintendenza Beni architettonici P.A.T. and the SWS-Engineering S.p.A. and arch. Fabio Bartolini for having trusted and encouraged the application of the implemented technology on site. Moreover the Authors are very grateful to the former under-graduated students Marcella Rizzi and Alessandro Crosatti for the work done during the research.

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