STRENGTHENING OF WOODEN BEAMS WITH FRP MATERIALS

C. Bernardini 1, L. Credali 2 and G. Pistone 1

1 Department of Geotechnical and Structural Engineering, Architecture, Turin Politecnico, Italy
2 Ardea Progetti e Sistemi, Casalecchio sul Reno, Bologna, Italy

ABSTRACT

This paper illustrates the results of a study conducted at the Structural Engineering Laboratory of the Turin Politecnico on the possibility of using composite materials for the restoration and strengthening of wooden structures of historic interest, a very large field of application, in Italy.

In particular, the investigation focuses on the possibility of using FRP materials – unidirectional glass fibre and carbon fibre fabrics and carbon laminates – to repair the lesions caused by bending in wooden structures. By determining the elastic modulus of each beam in bending, it proves possible to identify the real contribution of the individual devices by comparing the conditions of the beams before and after the repair.

The strengthening devices tested were of two kinds:

• with the FRP reinforcement glued to the wood over its entire length,
• with the FRP reinforcement glued to small zones, as needed for anchoring it in place and ensuring its continuity.

The separation between the wood and the FRP reinforcement is prompted by the need to enable both materials to preserve their own properties.

Some of these devices conform to the suggestions given in the CNR guidelines, others will be developed to propose alternatives to the current intervention modalities.

KEYWORDS

FRP, wood, beams, reinforcement, bending, shear.

INTRODUCTION

For several years now the use of FRP as a strengthening materials for use in structures of historic interest has become widespread in Italy. After an initial use in the field of reinforced concrete, in fact, it was deemed worthwhile to test out the use of FRP in historic structures, which in Italy account for a large proportion of the man-made heritage.

Accordingly, testing campaigns were undertaken to assess the viability of these materials in the restoration and strengthening of masonry and wood structure. The investigation described in this paper analyses the possibility of using FRP – in particular, unidirectional carbon fibre fabrics, carbon fibre laminates and carbon bars – to strengthen wooden structures subject to bending and shear.

The testing campaign was conducted initially on 15 beams in silver fir wood (Abies alba), of structural size (400 cm long, with a cross-sectional area measuring 15 x 21 cm), obtained from a sawmill, and continues in the second stage on 40 more wooden beams the same size.

The research program was comprised of the following stages:

- Characterisation of the wood used, through bending tests designed to determine its elastic modulus and failure load;
- Bending tests on the beams, strengthened successively with different devices according to the guidelines proposed by the CNR.

The tests conducted on structures of historic interest assessed the effectiveness for restoration purposes both of the devices with the FRP reinforcement glued to the beam over its entire length and those with the reinforcement glued only to the zones needed for anchoring it, while keeping the two materials (wood and FRP) independent of one another over the remaining length of the reinforcement.

"Knowing that absolute reversibility is not possible, these innovative technologies ensure a high degree of non-invasiveness, curability and removability of the interventions and, above all, permit the permanence and the..."
structural functionality of the construction in normal serviceability conditions.” (A. Di Tommaso, 1999)

Also in the light of this type of statement, it was deemed worthwhile to ascertain the applicability of this method to wood, a material totally different from reinforced concrete, brickwork and stone, fields in which the use of composites is becoming common practice. Wood, in fact, remains a “live”, organic material, whose behaviour is deeply affected by the surrounding environment (humidity, temperature, biotic aggressions), unlike composites, which are inorganic materials and, as such, react in a totally different manner to these factors.

CHARACTERISATION OF THE WOOD

Choice of Materials

By construction woods it is meant any wood suitable for the construction of bearing structures in buildings and building works in general. They can be distinguished into resinous and non resinous woods, or conifer woods and woods from broad-leaved trees (Giordano, 1999).

Reference Standards

According to the applicable standards the main physical-mechanical characteristics must be determined through tests performed on small specimens. At present, however, it is deemed preferable to carry out the tests on full size test pieces.

The main physical and mechanical characteristics of the wood for structural use are determined through laboratory tests, according to international standard ISO 8375 of 1985, “Timber structures – Solid timber in structural sizes - Determination of some physical and mechanical properties” which is also the basis for standard EN 408, which extends its applicability to round elements and glued laminated timber.

As for the determination of strength and the elastic modulus, the reference sections are sections 8 and 11.

Bending Tests

For the elastic modulus in bending, the reference standard is UNI EN 408 (January 1995).

According to this standard, the length of the test piece must be at least 19 times the height of the section (in our case, the original size of the beams was: 150x210 mm cross sectional area and 4000 mm length, the minimum length required by the standard being 3990 mm).

The test piece must be subjected to bending in a symmetrical manner, by resting it on two supports spaced apart at a distance corresponding to at least 18 times the height of the test piece, as can be seen in Figure 1 (in our case, the distance between the supports was 3780 mm). The load was applied at a constant rate (without exceeding a displacement rate of 0.003 times the height in mm/s). The maximum load must not exceed the limit of proportionality and, in any event, must not damage the part.

\[
E_m = \frac{a l_1^2 (F_2 - F_1)}{16I (w_2 - w_1)} = \frac{3al_1^2 (F_2 - F_1)}{4bh^3 (w_2 - w_1)}
\]

(1)

where \(F_2 - F_1\) is a load increment over the straight portion of the load-deformation curve in Newtons; \(w_2 - w_1\) is the deformation increment corresponding to \(F_2 - F_1\), in mm; \(I\) is the moment of inertia, in mm\(^4\); \(l_1\) is the distance between two transducers placed at the centre of the beam (corresponding to 5 times the height of the section); a
is the distance between the support and the nearest loading point.

Results of the Characterisation Process

The tests performed to determine the elastic modulus of the wood used were designed to characterise the material in an accurate manner. Wooden elements, especially if they are of structural size, are affected by the presence of defects of different sorts (knots, misalignments of the fibres …), which, together with other variables such as humidity or temperature alter their behaviour and hence their elastic modulus. Having determined the initial characteristics of each beam, it proved possible to compare them with those of the beam after the repair and hence to assess the actual contribution of the reinforcing device: without an accurate characterisation, the contribution of the reinforcement would probably have been underestimated.

REINFORCING DEVICES

CNR Guidelines

In July 2005, a Commission set up by the CNR (National Council of Research) to express opinions on the technical regulations on building constructions set forth in Preliminary studies for the drafting of Instructions for static strengthening interventions on wooden structures through the use of fibre-reinforced composites (DT201/2005), which followed the document issued in 2004 on r.c. and masonry structures (DT200/2004) and, together with a subsequent document on metal structures (DT202/2005), provided guidelines for the practising designers on how to use FRP materials. Hence, within the framework of the testing campaign, it was decided to study the devices suggested in these guidelines in order to assess their performance and the areas in which they could be best applied, in accordance with the aims set forth in the document. As specified in the Preliminary studies, in fact, the guidelines published so far are only indicative and should be viewed as a first step towards the production of design instructions that will be defined when the theoretical and experimental studies underway at international level will have offered a more extensive overview of the state of the art. Document DT201/2005 is about fibre-reinforced composites (FRP) bonded to structural wood, for use in the strengthening of existing structures.

Reinforcing Wood with FRP According to DT201/2005

The document by the CNR underscores how the characteristics of the two materials (wood and FRP) are in some respects complementary. The dishomogeneity of wood, in fact, is mitigated by the synergetic action of the fibre reinforced composite. This effect was verified by the authors during the initial stage of the testing campaign (Bernardini, Canavesio, Credali, Pistone, 2004) that revealed how the presence of the laminate at the tension zone of the beam compensated for defects such as knots or breaks in the fibres due to misalignments, and recreated the continuity damaged by the defects. Despite these favourable aspects we should not disregard some applicability limits that the instructions bring to our attention. The different reactions of the two materials with varying humidity and temperature levels, the different fire behaviours, the problems associated with the bonding of the two materials require more in-depth investigations in terms of basic research and applied research. The approach that is adopted most widely at present is that of improvement-oriented interventions, where improvement means either the recovery of performance capabilities in a damaged, or deteriorated, element (rehabilitation) or the enhancement of the performance of an undamaged element (e.g., in structural upgrade).

Prerequisites for the use of FRP Reinforcement

A fundamental prerequisite for the applicability of the reinforcement is accessibility. However, it is not always possible to find the ideal conditions whereby a structure can be restored to safety conditions and the element can be removed to be subjected to direct non destructive tests and the application of the reinforcement. When planning the application of a reinforcement of this kind, it is necessary to take into account engineering factors (geometric characteristics of the structure and the reinforcement, characteristics of the materials…), as well as whether or not the reinforcement will be visible, the compatibility between the materials, and economic considerations.

Recommendations on Testing Procedures

Before examining the different types of reinforcement that can be applied to wooden elements, it should be noted that the instructions recommend limiting the use of filling in shrinkage cracks and the use of bonded bars to close the cracks, as these methods might cause undesired stresses in the wood.
Moreover, it is good practice not to use reinforcing systems that over time might generate mechanical or biological degeneration phenomena in the wood. It is also necessary to permit the exchange of moisture with the external environment.

Based on the foregoing considerations it was deemed worthwhile to explore the possibility of using systems enabling the two materials to adapt to temperature and moisture variations independently, as opposed to full length bonding.

The reinforcement of structural elements in wood is designed to supplement the ductile behaviour of such elements – which can be improved by forcing the ratio between ultimate tensile strength and ultimate compressive strength – with higher ultimate strength. This result can be achieved by improving the behaviour of the tension zone so as to permit a plastic behaviour in the compression zone. This amounts to taking full advantage of the material properties, resulting in higher ductility at collapse.

It should also be noted that the adhesive used for the bonding of wood in structural applications should be characterised by high shear strength, good compatibility with different wood species and curability in terms of thermo-hygrometric cycles as a function of the service class envisaged. The characteristics of the primer and the resin used are given in the table below (Table 1).

<table>
<thead>
<tr>
<th>Primer - resin</th>
<th>Primer LC – 201</th>
<th>Resin LC - 202</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardener</td>
<td>Hardener LC – 201</td>
<td>Hardener LC - 202</td>
</tr>
<tr>
<td>Catalysis resin weight ratio</td>
<td>2:1</td>
<td>2:1</td>
</tr>
<tr>
<td>Freezing time at 20° C</td>
<td>50 - 60 minutes</td>
<td>50 - 60 minutes</td>
</tr>
<tr>
<td>Hardening time</td>
<td>150 - 180 minutes</td>
<td>180 - 210 minutes</td>
</tr>
<tr>
<td>Complete hardening time</td>
<td>14 - 18 hours</td>
<td>14 - 18 hours</td>
</tr>
</tbody>
</table>

**BONDING BETWEEN FRP AND WOOD**

A significant factor in the success of a reinforcing device is the efficacy of the connection between the wood and the FRP (as is the case with all the materials to which these devices are applied). Accordingly, before proceeding with the strengthening process it is necessary to make sure that the element has been duly checked and prepared. The surface must be prepared so as to create the appropriate conditions for a strong grip of the adhesive. In some instances it is useful to start by applying a primer that enhances the compatibility between the adhesive and the wood (especially when working on high density woods).

The effectiveness of bonding by means of adhesives can be assessed from the conditions of the reinforcement at failure: it can be rated as satisfactory if an appreciable quantities of fibres remain stuck to the wood.

The instructions advise against the exclusive use of mechanical fasteners, in view of the characteristics of composites, which are very poor, both in the presence of concentrated loads and in the presence of forces arranged at an angle relative to the orientation of the fibres. However, these mechanical fasteners can be used to improve the ultimate limit state behaviour of glued connections and to secure the connection.

In our case, however, no mechanical fasteners, such as screws or rivets were used (tested in the first campaign), in order to focus on different methods that use carbon bars to improve the adhesion of the fabrics or the laminates.

**BENDING REINFORCEMENT**

Beams may need strengthening for different reasons, as mentioned before (e.g., an increase in the loads applied due to changes in the intended use of a structure, adaptation to new safety regulations, a decrease in the resisting section due to deterioration phenomena …).

Reinforcing the tension zone proves particularly useful, as pointed out above, to improve the plastic behaviour (and hence the ductility) of an element. This can be accomplished provided that the wood has an elasto-plastic behaviour in compression and that its ultimate strain in tension is lower than that in compression.

The first stage of the campaign included tests on 15 beams fitted with different types of reinforcement. Some beams were reinforced with fabric, or laminate, glued directly to the wood (either full length or only to the anchoring zone), others were fitted with a special reinforcing device, now patented under the name of Ardwood®, consisting of a small beam, in fibreglass or carbon fibre reinforced wood, which is placed at the compression zone and is made integral with the original beam by means of self-tapping screws. In Figure 2 we can see schemes illustrating the different types of reinforcement in bending that are being assessed in the course of the second stage of the testing campaign.
The devices were applied according to the instructions that advise against the use of external laminates other than by ensuring the stability of the device not only by gluing but also with the aid of mechanical fasteners. In addition to having a confining effect, the application of a laminate makes it possible to double the size of the bonding surface, thereby greatly attenuating possible delamination phenomena. On the other hand, an external reinforcement obtained by means of fabric laminate or glued laminates makes it possible to eliminate or at least reduce the effects of defects in the wood.

Additional tests are currently underway on a device evaluated during the previous testing campaign (Figure 3) and patented under the name of Ardwood® by Ardea Progetti e Sistemi, so as to obtain further data on the applicability of this system.

Finally the tests are designed to assess the contribution of the mechanical fasteners used both with this device and with those that use laminates glued to the tension zone.

**RESULTS AND DISCUSSIONS**

Let us now examine some of the most significant results obtained during the first stage of the testing campaign (Table 2).

To this end, comparative charts are given below for the different devices tested during the first stage. As can be seen from the chart in Figure 4, beam 15 is the one where the ultimate load reached was lowest, but deformation level up to failure virtually coincided with the level observed in beam 6. It should be noted that the latter was reinforced solely with a small beam wrapped in fibreglass, without any reinforcement at the tension zone. Also comparable, in terms of deformation, are the results obtained from beam 4 (small beam wrapped in fibreglass and carbon fibre reinforcement at the tension zone) and from beam 15 (reinforced with a carbon fibre beam, without reinforcement at the tension zone).

Ultimately, beam 13 displayed the best behaviour in terms of load level, while in terms of deformation, the best results were recorded for beam 9, that was not stiffened by the presence of the reinforcement at the tension zone, as was the case, instead, with beam 13.

**Table 2 - Results**

<table>
<thead>
<tr>
<th>Beam</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-modulus at 40 kN (N/mm²)</td>
<td>8900</td>
<td>8500</td>
<td>7700</td>
<td>6700</td>
<td>9700</td>
<td>6900</td>
<td>8800</td>
<td>8100</td>
<td>8100</td>
<td>8300</td>
<td>8300</td>
<td>6800</td>
<td>8400</td>
<td>6600</td>
<td>7500</td>
</tr>
<tr>
<td>Deformation at 40 kN before the reinforcement (mm)</td>
<td>33</td>
<td>35</td>
<td>33*</td>
<td>43*</td>
<td>30</td>
<td>43</td>
<td>34</td>
<td>37</td>
<td>37</td>
<td>36</td>
<td>36</td>
<td>43*</td>
<td>35</td>
<td>45</td>
<td>36*</td>
</tr>
<tr>
<td>E-modulus at 40 kN (N/mm²) with the</td>
<td>7500</td>
<td>8500</td>
<td>17600</td>
<td>7500</td>
<td>10000</td>
<td>2200</td>
<td>10000</td>
<td>10700</td>
<td>11100</td>
<td>4100</td>
<td>21400</td>
<td>7500</td>
<td>16700</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Deformation at 40 kN with the reinforcement (mm)

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>40</th>
<th>35</th>
<th>17</th>
<th>40*</th>
<th>30</th>
<th>42*</th>
<th>30</th>
<th>28</th>
<th>27</th>
<th>55*</th>
<th>14</th>
<th>40</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced with CFRP laminates (lower surface), not glued</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforced with unidirectional CFRP fibres, not glued</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforced with unidirectional CFRP fibres, glued</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforced with unidirectional CFRP fibres (lower surface) and GFRP fibres (upper surface)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforced with Arwood®</td>
<td>X</td>
<td>X</td>
<td>X*</td>
<td>X*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrapped in unidirectional CFRP fibres, not glued</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1* cross-section had been reduced to accommodate the reinforcement
2* cross-section had been reduced to accommodate the reinforcement
3* at 34 kN the beam failed
4* at 38 kN the beam failed
5* beam damaged by notching
6* beam not reinforced with FRP
7* 12 kN beam was damaged
8* 12 kN beam failed
9* 30 kN beam failed
10* beam not reinforced with FRP
11* beam damaged
12* 39 kN beam failed
13* 30 kN beam failed
14* 36 kN beam was damaged
15* 36 kN beam was damaged

![Deformation Chart](image)

**Figure 4. Comparative view of the devices tested**

The charts plotted for the same beams before the application of the reinforcements are compared in Figure 5. As can be seen, the only beam that displayed a noticeable deformation (in addition to the onset of a crack) was beam 15, which was seen to profit to a considerable extent from the reinforcement, but, not having been reinforced at the tension zone, failed under a rather low load.
Beams 6, 10 and 13 had displayed a virtually identical behaviour at the characterisation stage, but their behaviour after the application of the reinforcement differed as a function of type of reinforcement adopted.

![Figure 5. Comparison of the beams before the application of the reinforcements](image-url)

Up to a certain point, beams 6 and 10 displayed a rather similar behaviour even after the application of the reinforcement, and this seems to confirm that the presence of wrapped reinforcement on the small beam (i.e., in the compression zone) has little influence on the benefits obtainable in terms of loading capacity, yet, it should be noted that beam 6, being affected by the presence of a knot in the tension zone, was unable to have a linear behaviour like beam 10, whose behaviour was virtually linear up to failure. Moreover, the type of failure observed in this beam does not seem to be really brittle, as FRP failure actually is, and it almost seems “ductile” (if we may use this term, in an improper acceptation). This “ductility” cannot be ascribed to the reinforcement, whose failure, as mentioned above, takes place in a brittle fashion, nor can it be ascribed to the wood, but rather stems from the combination of these two materials, where the reinforcement enables the wood to have a plastic behaviour.

Following these initial results and based on the draft recommendations issued by the CNR in 2005, we have prepared the second stage of the campaign which is now underway. The aim of the second stage is obtain more significant results by testing, on a greater number of beams, a few special devices, such as the Ardwood® system and some of the devices proposed in the DT201/2005 as described in the previous paragraphs. Furthermore, some beams are tested with only the connectors applied in order to assess the importance of the latter within the reinforcing system and hence gain a better understanding of functioning and failure mechanisms.

In this second stage, a modelling method is also being fine-tuned (using the ANSYS code), as a further aid in the design of FRP reinforcements for wooden beams.

**CONCLUSIONS**

The use of FRP in the rehabilitation of wooden structures seems to open up new opportunities. The devices used during the first stage of the testing campaign proved effective in both configurations, i.e., glued over their entire length and glued only in the anchoring zones.

These initial test results cannot be rated as significant from a strictly scientific viewpoint: the tests were performed on items having drastically different characteristics and, rather than providing definitive answers they were designed to explore several possibilities and define guidelines for further, more extensive campaigns, such as the one currently underway.

The conclusions set forth in this document therefore are meant solely to indicate possible ways to use these innovative materials, that indubitably have great potential, even in the rehabilitation of wooden structure. The opportunity offered by the tests was to assess the feasibility of using FRP composites in the rehabilitation of a material as different as wood, instead of ruling out this possibility a priori.

Precisely for this reason, no specific gluing modalities were chosen from the start, and the advantages and drawbacks of both full length and partial bonding were investigated, resulting in interesting indications which can be studied further. Gluing the reinforcement over its entire length is able to compensate the deficiencies of...
wooden elements containing defects and therefore seems more effective; the reinforcement begins to collaborate with the wooden beam from the start and avoids the formation of cracks at critical points, enabling the beam to work as in the case of flawless wood. The results obtained seem to indicate that the wood is working and the (fibreglass or carbon fibre) reinforcement steps in only at the points where wood is inefficacious due to the presence of the defects associated with the nature of this material.

This type of intervention is irreversible – though it can be removed with minimal damages to the material – and it combines two materials having different behaviours: over time, this might give rise to problems of incompatibility.

The use of reinforcements anchored only to the end zones, instead, appears interesting in view of the ductile behaviour engendered in the material, even though, in the cases examined, the improvement in loading capacity observed was modest. Partial gluing proved highly effective, not only in view of the greater reversibility of the intervention, but also in that it enabled the two different materials to remain independent: since both materials can move relative to one another, fibre elongation and deformation can take place without undergoing brittle failure, which otherwise would occur soon enough under the loads involved.

The tests showed that FRP composites lend themselves to many applications in the structural rehabilitation of wooden elements, even though it will take a “creative” approach to identify the most appropriate modalities. Further studies on gluing modalities and different types of device, such as those envisaged for the second stage of the research, will provide a better understanding of the possible uses of FRP reinforcements in the strengthening of wooden structures.

ACKNOWLEDGMENTS

The authors wish to thank Ardea Progetti e Sistemi for the financial contribution and the support provided in terms of knowledge. A special thanks also goes to the technicians of the Testing Laboratory of the Department of Structural and Geotechnical Engineering of the Turin Politecnico.

REFERENCES

A. Di Tommaso, STRUTTURE IN COMPOSITO. Tecnologie, applicazioni e verifiche sperimentali. Rinforzo dell’edilizia storica con F.R.P.-materials, 26th Conference of ATE Associazione Tecnologi per l’Edilizia and DIS Politecnico di Milano, in collaboration with AICO, Milan, 21 June 1999


Giordano G. (1999), Tecnic della costruzioni in legno, Biblioteca Tecnica Hoepli, V edizione, Ulrico Hoepli Editore, Milan


A. Di Tommaso, STRUTTURE IN COMPOSITO. Tecnologie, applicazioni e verifiche sperimentali. Rinforzo dell’edilizia storica con F.R.P.-materials, 26th Conference of ATE Associazione Tecnologi per l’Edilizia and DIS Politecnico di Milano, in collaboration with AICO, Milan, 21 June 1999


APFIS 2007 304