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*Article*

# Basalt FRP spike repairing of wood beams

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**Abstract:** This article describes aspects within an experimental programme aimed at improving the structural performance of cracked solid fir-wood beams repaired with Basalt Fibre Reinforced Polymer (BFRP) spikes. Fir wood is characterised by low density, low compression strength and high level of defects, is likely to distort when dried and tends to fail in tension due to the presence of cracks, knots or grain deviation. The proposed repair technique consists of the insertion of BFRP Spikes into timber beams to restore the continuity of cracked sections. The experimental campaign is dealing with the evaluation of bending strength and deformation properties of 24 timber beams. An artificially simulated cracking was produced by cutting in half and notching the wood beams. The obtained results for repaired beams have been compared which those of solid un-damaged and damaged ones and increases of beam capacity, bending strength and of modulus of elasticity and analysis of failure modes were measured and discussed. For notched beams the application of the BFRP spikes was able to restore the original bending capacity of undamaged beams, while only a small part of the original capacity was recovered for cut in half beams.

**Keywords:** softwood; basalt spikes; timber beams; bending test.

## 1. Introduction

Fir is a common softwood and a traditional construction material that has been extensively used in civil engineering for centuries. Construction made of softwood is also an important part of the infrastructure in many areas of the world: it may be can be considered as one of the oldest construction material and its widespread use, from antiquity to the present, is essentially due to its high tensile strength, low weight density, large diffusion on Earth and good workability. However softwood may be heavily affected by defects: natural defects (knots, shakes, cross grain) and defects caused during treatment of felled timber may highly reduce softwood mechanical properties and particularly tensile strength and cause high decreases in the mechanical properties.

Cracks in softwood are produced by the seasoning and changing in moisture content and are an important natural defect that mostly reduces the capacity of wood beams: as an orthotropic material wood presents different shrinkage coefficients in the tangential and radial directions and the compatibility of the deformation leads to the formation of cracks. For these reasons it is very difficult to prevent the opening of cracks and only a controlled, careful and slow seasoning may contribute to reduce their formation.

The introduction of laminated softwood (glulam) has minimized this problem for new timber construction. Dimensional changes in the length, depth and width and crack formation of structural glued laminated wood due to changes in moisture content has been highly reduced.

On the other hand there is a difficulty in achieving a reliable solution to this problem for existing timber constructions or when solid-sawn timber is used for new constructions. A controlled seasoning may minimize the formation of cracks in softwood before the implementation of the beams, but a sudden variation in temperature or air humidity can provoke the opening of cracks decades after the implementation of the beams.

Structural reinforcement and repair of timber structures is often necessary for historic timber elements in order to comply with the new standard. Existing timber beams have been commonly subjected either to reinforcement or replacement with standard methods involving the use of traditional construction materials such as metals (aluminium, steel, etc.) or modern techniques with composite materials. The need for repair and improvement is typically very high for infrastructure: over 47 % of the timber bridges in US are classified as structurally deficient in the National Bridge Inventory based on visual inspection and classification of defects [1].

In order to restore the continuity of cracked timber beams several solutions have been proposed: the use of self tapping screws as reinforcement perpendicular to the grain have been studied by Blass and Bejtka [2]. Parisi et al. [3] analysed the use of small screws (7-8 cm) to prevent splitting near the joints of timber trusses. Tampone [4] studied the use of metal brackets and several others [5-7] studied the application of metal braces. However an important limitation is that metal elements are prone to oxidation and collapse in fire as metals heat readily than the timber.

Leijten [8] has found that local steel reinforcements (screws, bolts, etc) inserted into timber members may lead to unexpected and unpredictable splitting caused by the presence of hole clearance and by the stress concentration induced by the small diameter of the screws.

The use of composite materials for reinforcement of existing timber members is not new [9-16]. Fiber-Reinforced Polymer (FRP) have proven good tensile mechanical properties. Composite materials, especially glass and carbon reinforced polymer composites (GFRP and CFRP), are being applied progressively more in structural functions not only for infrastructure or reinforcement of "modern" timber beams, but also for elements belonging to the architectural heritage. Usually, FRPs are applied where at least two of its valuable properties, e.g. high corrosion resistance and high tensile strength may be exploited at the same time. In these situations, the total costs (material, application and maintenance) of using composite materials are commensurate with traditional competitor materials such aluminium and steel or with replacement. FRPs are usually applied using epoxy adhesives inserted into pre-drilled holes, both in repair and in new-build applications. The bonded-in rod technology have been studied by Broughton and Hutchinson [17] and the conclusion that epoxy adhesives resulted in a satisfactory performance compared to acrylic, polyurethane and phenol-resorcinol adhesives with a pull-out strength increasing linearly with bondline thickness. Even if there have been considerable advancements in relation to the performance of polyurethane adhesives, he bond strengths and overall mechanical properties of epoxy adhesives are still superior.

However the varied range of composite products and the scattered mechanical characteristics of FRP elements at present available can cause serious difficulties for the engineer who approaches this problem. For this reason, choice of the strengthening layout and material should be guided by an precise analysis of the characteristics of the timber element to be repaired or reinforced in order to avoid unsuccessful interventions. The long-term durability of some FRP products needs to be studied and demonstrated [18-19].

In 2009 UN/FAO proclaimed the International Year of Natural Fibres but only very recently researchers started to study the use of natural-based FRPs for applications in Civil Engineering. The aim of all major international organisations is to promote the efficiency and sustainability of natural fibres industries and encourage suitable policy from governments. However there have been few studies to date of the use of natural fibres for reinforcement of timber structures. Borri et al. studied the use of bamboo, flax and basalt strips to enhance to capacity of timber beams [20]. De la Rosa et al. also analysed the effect of basalt strip reinforcements applied on the tension side of timber beams [21]. Recently Raftery et al. used bonded-in basalt FRP rods to strengthen and repair low-grade glued laminated timber beams [22].

This paper describes an experimental study on the use of basalt FRP (BFRP) spikes into timber beams to restore the continuity of cracked and damaged sections. The repair technique consists in the application of 95 mm long BFRP spikes inserted into diagonal holes perforated in the timber beams at centre-to-centre distance of 200 mm. An artificially simulated cracking was produced by cutting in half and notching the wood beams. Repaired and control timber beams were carried out to four-point-bending test and results in terms of bending capacity and modulus of elasticity were compared to evaluate the effectiveness of the proposed repair technique. In comparison with the use of self-tapping screws this procedure may be of interest because of the lower Young's modulus of BFRP spikes (similar the one of timber) and for lower stress concentration based on the larger dimensions of BFRP spikes.

## 2. Design of the repair technique

An efficient composite solution is achieved when an effective joint is used to connect the two artificially sectioned timber parts. An effective joint should be characterized by enough strength to transmit the shear loads developed at the interface and stiff enough to restrict the slip between the two elements. Two extreme situations of a simple supported beam are shown in Figure 1a: no connection (materials acting completely independent) and a perfect connection between the materials (full composite action). In the first case, slip occurs between the two elements resulting in two materials reacting independently to the bending loads and consequently to compressive and tensile stresses. In the second case, both elements are forced to act as a single element. The mechanical behaviour of the joint has a substantial importance for the behaviour of the composite structure and it has a direct impact on the stress pattern as well as in its deformation mode.

In this investigation eight BFRP spikes were inserted into diagonal holes (45°) drilled in the timber beams (Figures 1b and 2) at a centre-to-centre distance of 200 mm. The use of inclined spikes was chosen because several experimental and numerical studies have showed how the increase of screw inclination affords an increase of the resistance and stiffness of the joints [23-24]. No spikes were applied in the central part of the softwood beams where shearing force equal to zero. Bi-component epoxy putty was injected inside the holes before inserting the BFRP spikes to facilitate the connection between timber and reinforcement (Figure 1c). By considering that the spike and hole diameters were 6 and 0 mm, the epoxy bond thickness was approximately 0 mm.

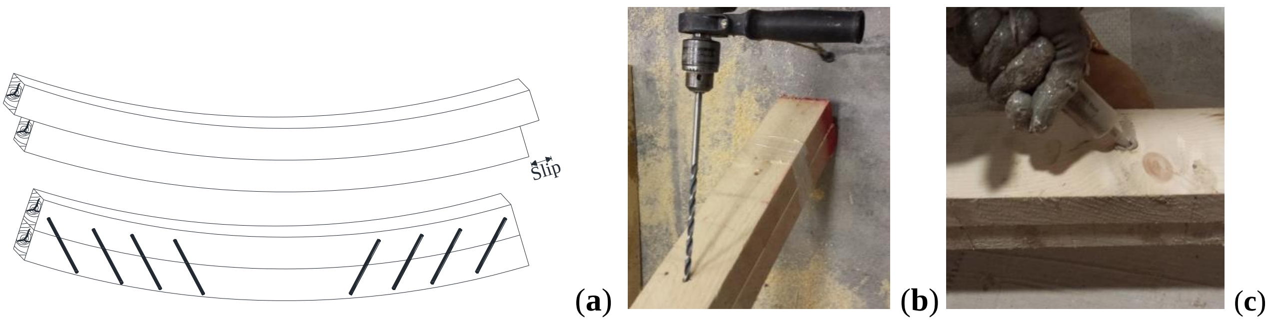



**Figure 1.** (**a**) Schematic arrangement of BFRP spikes; (**b**) Diagonal hole drilling, (**c**) Injection of epoxy putty.

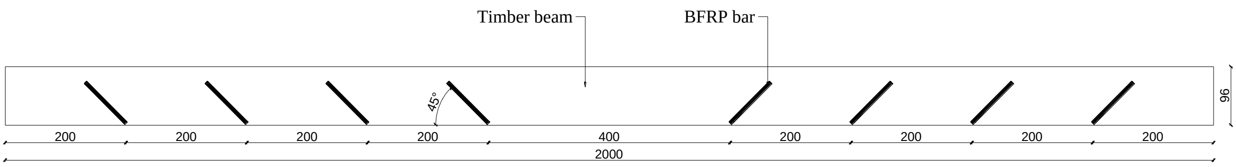



**Figure 2.** Layout of BFRP spikes (dimensions in (mm)).

In order to calculate the diameter (*d*) of the spikes (Table 1), the Johansen yielding theory [25] has been used and adapted for this purpose. The Johansen approach identifies three different failure modes for timber to timber joints with connections: in the first mode (mode A), the final load-bearing capacity is obtained when the wood yields plastically along the reinforcement (Figure 3); the second (mode B) is characterized by a combination of the embedment failure in the timber and a single yield failure in the connector. The last failure mode (mode C) occurs when is reach a combination of the embedment failure in the timber and a double yield failure in the connector.

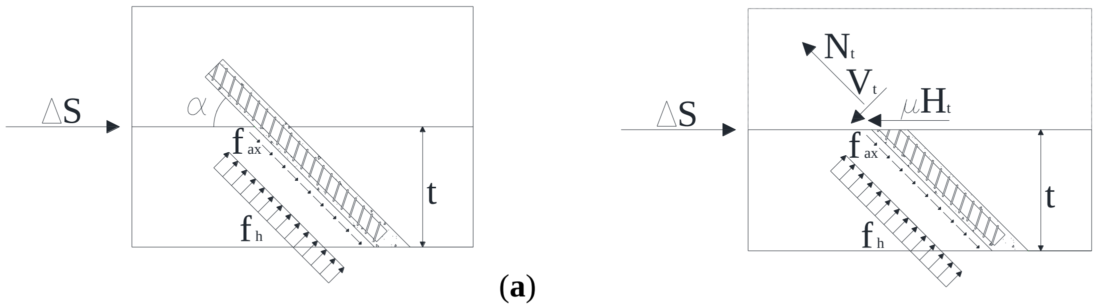



**Figure 3.** Failure mode A: (**a**) stresses in the joint; (**b**) load on the interface between the timber elements.

Due to the high mechanical characteristics of the BFRP spikes and the loads reached on the tests carried out on the control beams the design of the nominal diameter has been evaluated considering only the failure mode A. The ultimate load-bearing capacity can be calculated from internal forces (Eq. 1). The following equation is based on the equilibrium in the non-deformed state:

$$\Delta S = N_t \cos\alpha + V_t \sin\alpha + \mu H_t \tag{1}$$

where $N_t$ and $V_t$ are the axial and shear forces applied on the spike, respectively, $H_t$ is the horizontal force at the interface between the two timber elements, $\mu$ is the coefficient of friction, α is the angle of inclination of the spike with respect to the grain direction (equal to 45°) and $\Delta S$ is the slip load at the interface between the two timber parts. Assuming a perfect connection between the two parts the slip load $\Delta S$ on the length Δz (equal to 200 mm) can be evaluated as:

$$\Delta S = \frac{V_{Ed} \times S_x}{I_x} \times \Delta z \tag{2}$$

where $V_{Ed}$ is the average shearing force measured in the control specimen, $S_x$ is the first moment and $I_x$ is the second centroidal moment of the beam's section, respectively evaluated as:

$$S_x = \frac{b \times h^2}{8} \tag{3}$$

and

$$I_x = \frac{b \times h^3}{12} \tag{4}$$

where $b$ is the width and $h$ is the height of the beam's cross section.

The horizontal force is defined as:

$$H_t = N_t \sin\alpha - V_t \cos\alpha \tag{5}$$

The axial load $N_t$ on the BFRP spike can be calculated:

$$N_t = \frac{f_{ax} \times d \times t}{\sin\alpha} \tag{6}$$

where $d$ is the nominal diameter of the composite element, $t$ is the embedded length and $f_{ax}$ is the withdrawal strength of the timber, defined according to the Eurocode 5 [26] as:

$$f_{ax} = \frac{3.6 \times 10^{-3} \times \rho^{1.5}}{\sin^2 \alpha + 1.5 \times \cos^2 \alpha} \tag{7}$$

The lateral actions on the BFRP spike can be evaluated by the following equation:

$$V_t = \frac{f_h \times d \times t}{\sin \alpha} \tag{8}$$

where $f_h$ is the embedment strength for timber according with Eurocode 5 for timber with pre-drilled holes, based on a large number of embedding tests, and equal to:

$$f_h = 0.082 \times (1 - 0.01 \times d) \times \rho \tag{9}$$

Substituting Eq. (6) and (8) into the Eq. (5) and (1), the following equation is obtained:

$$\Delta S = f_{ax} \times d \times t \times (\cot \alpha + \mu) + f_h \times d \times t \times (1 - \mu \times \cot \alpha) \tag{10}$$

Assuming a coefficient of friction for the timber equal to 0.3, solving the eq. (10) the required spike's diameter is equal to 5.34 mm and according to the suitable commercial nominal diameters, 6 mm diameter spikes have been used.

## 3. Material characterization

### *3.1. Timber*

All beams were made of softwood (fir-wood). Tests were carried out on sharp-edged timber beams (Figure 4a) in fir wood (*Abies Alba*). All the timber beams had the same width (96 mm), height (96 mm) and length (2000 mm). The average weight density and moisture content were 417 kg/m$^3$ (dev. 24 kg/m$^3$) and 14.31 % (dev. 0.89 %), respectively. Moisture content was measured according to EN 13183-1: 2002 standard [27].

### *3.2. BFRP spikes*

Due to its anisotropic behaviour, seasoning of timber always causes spit opening along the grain in structural timber beams. The prime objective of seasoning is to reduce the moisture content and increase mechanical properties. BFRP spikes (Figure 4b) were used here to restore the continuity of artificially damaged timber beams.

For this purpose fir wood beams, from the same batch, were artificially damaged. Eight beams were cut in half and six beams were partially cut on both sides. Two notches (35 mm long) were made along the entire longitudinal direction.

Six 6 mm diameter spikes were tested in tension according to ASTM D3039 standard [28] and their strains recorded with a 50 mm gauge length mechanical extensometer. The average of the six coupon test values in given in Table 1. Tensile tests were first conducted to verify the ultimate strength and longitudinal Young modulus given by the producer data sheet. All spike specimens exhibited a linear elastic response and failed suddenly as expected. Test results show a tensile strength and Young's modulus of 761 MPa and 35.5 GPa, respectively.

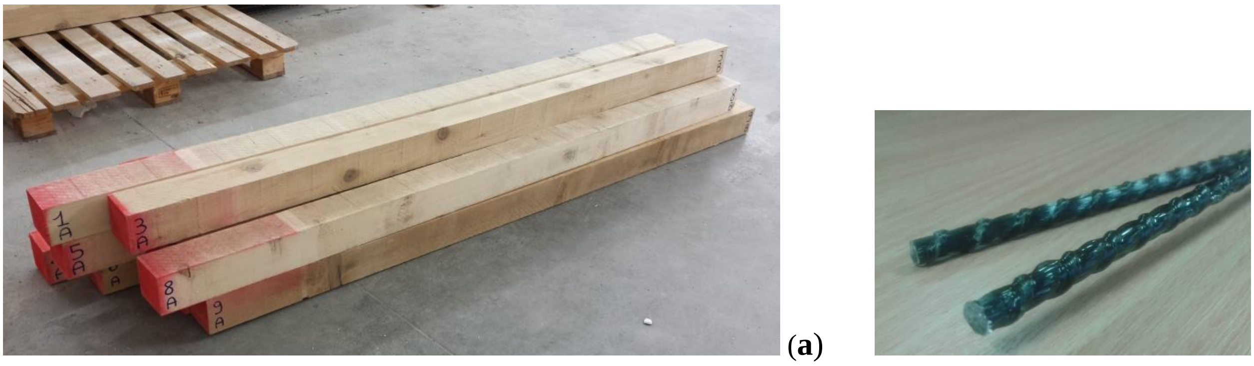

(**a**) (**b**)

**Figure 4.** (**a**) Softwood beams; (**b**) BFRP spikes.

**Table 1.** Mechanical properties of the BFRP spikes.

| **Nominal diameter (mm)** | **Weight density (kg/m$^3$)** | **Failure load (kN)** | **Tensile strength (MPa)** | **Young's Modulus (GPa)** | **Strain at failure (%)** |
|---|---|---|---|---|---|
| 6 | 0.452 | 21.5 | 761 | 36.56 | 2.08 |

*3.2. Epoxy putty*

To facilitate the connection between timber and BFRP spikes, a bi-component epoxy putty, manufactured by MAC Spa, was injected inside the pre-drilled holes. After the insertion of the spikes the epoxy system has been cured for 10 days at room temperature.

**Table 2.** Mechanical properties of the epoxy putty.

| | |
|---|---|
| Compressive strength (MPa) | 65.54 |
| (Standard deviation) (MPa) | (3.95) |
| Sample size | 5 |
| Tensile strength (MPa) | 25.21 |
| (Standard deviation) (MPa) | (2.88) |
| Sample size | 4 |
| Young's modulus (GPa) | 4.58 |
| (Standard deviation) (GPa) | (0.27) |

Mechanical characteristics of the epoxy putty were evaluated by testing 5 specimens in compression according to the ASTM D695 standard [29] and 4 specimens in tension according to the ASTM D638 standard [30]. Test results are shown in Table 2.

## 4. Test setup and test results

Five series of bending tests were performed on undamaged, damaged and repaired softwood beams (Table 3). 24 beams were subjected to the four-point-bending test, according to UNI EN 408 standard [31]. The strength tests were carried out of a span of 1728 mm and the distance between the loading heads was 576 mm. In order to decrease the local crushing of the wood, the load was applied through two 42 mm diameter solid steel cylinders. Displacement controlled loading ensued with a crosshead speed of 2 mm/min.

**Table 3.** Test matrix.

| Index | Number of beams | Timber Beam | Repair |
|---|---|---|---|
| UNS_series | 10 | - | - |
| US_series | 3 | Cut in half | - |
| UN_series | 3 | Notched | - |
| RS_series | 5 | Cut in half | BFRP spike |
| RN_series | 3 | Notched | BFRP spike |

Load was applied monotonically until failure by means of a hydraulic cylinder connected by a circuit to a hand pump. The vertical displacement of the beams was recorded using three inductive transducers (LVDT). The bending strength $f_m$ was calculated according to:

$$f_m = a\frac{F_u}{2W} \tag{11}$$

where $F_u$ is the maximum load; $a$ is the distance between the point of application of the load and the nearest support; $W$ is the modulus of resistance of the section. From these measured values and taking into account the cross-sectional dimensions of the timber beams, a global modulus of elasticity $E_{m,g}$ can be calculated with the following formulation:

$$E_{m,g} = \frac{l^3(F_2 - F_1)}{bh^3(w_2 - w_1)}\left[\left(\frac{3a}{4l}\right) - \left(\frac{a}{l}\right)^3\right] \tag{12}$$

where $l$ is the distance between the rollers; $F_2$-$F_1$ is an increment of load on the straight-line portion of the load deformation curve; $w_2$-$w_1$ is the increment of deformation corresponding to $F_2$-$F_1$; $b$ is width of cross section. . In order to have a overall information of the stiffness properties of the timber beams it was decided to measure and calculate only the global modulus of elasticity evaluated according to [12].The test setup is shown in detail in Figure 5a.

### *4.1. Control beams*

Fourteen control beams were subjected to flexure in four-point-bending. These results have been reported only for the purpose of quantitatively calculating the effectiveness of the repair intervention through a comparison with the results of identical tests performed on the strengthened beams. Various modes of fracture were detected in the timber beams, but all on the tension side: simple tension, cross grain tension, knot influenced (Figure 5b). Knots and grain deviation highly influenced the propagation of the cracks for all control specimens. Deflection characteristics of the tested control beams are shown in Table 4, the average bending strength was 24.48 MPa (dev. 8.31 MPa) and the global modulus of elasticity 5932 MPa (dev. 907 MPa).

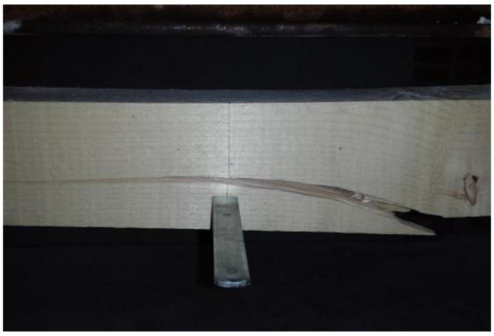
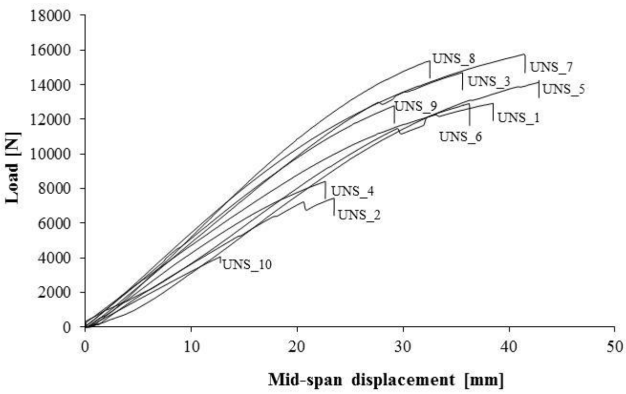

(**a**)

(**b**)

**Figure 5.** (**a**) Four-point-bending test setup; (**b**) Typical tensile failure mode of control beams near a knot or due to grain deviation.

Load-displacement curves (Figure 6a) are initially linear. As the load increases, timber begin to yield in the compression zone and failure occurs in the tension zone when the tensile strength is reached. Three beams (UNS_2; UNS_4 and UNS_10) exhibited an early failure influenced by the presence of a large defect (knot) in the tension side (Figure 5b). The scatter in the capacity values of control beams, where the presence of grain deviation and knots influence the failure mode, is very high.



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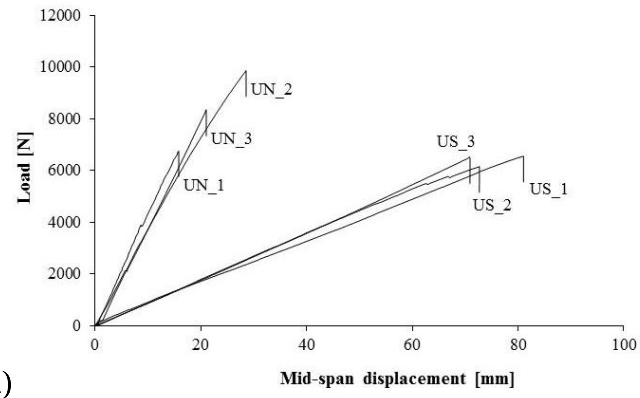


(**b**)

**Figure 6.** Load-Displacement curves: (**a**) control un-damaged beams; (**b**) cut in half and notched beams.

Six beams were subjected to four-point-bending after being artificially damaged: three timber beams were divided in-half and three were cut with two 35 mm horizontal notches (Figure 7). The control notched specimens (UN_1, UN_2 and UN_3) exhibited an average bending strength of 16.66 MPa and a global modulus of elasticity of 5622 MPa. Furthermore the failure of these specimens occurred in the area where bending moment is maximum. Fracture was influenced by the presence of the two notches: beams UN_1 and UN_3 failed due to separation of upper part half from lower half and subsequent tensile failure in tension side. This caused a significant reduction in beam capacity shifting from 12.14 (undamaged beams) to 8.32 kN (notched beams):

**Table 4.** Test results (control beams).

| | **Index** | **Maximum load (kN)** | **Bending strength (MPa)** | **Global modulus of elasticity (MPa)** | **Deflection at max laod (mm)** |
|---|---|---|---|---|---|
| Undamaged Beams | UNS_1 | 13.0 | 26.2 | 6077 | 37.0 |
| | UNS_2 | 7.5 | 15.2 | 5148 | 23.5 |
| | UNS_3 | 14.8 | 29.9 | 6825 | 36.5 |
| | UNS_4 | 8.6 | 17.2 | 6029 | 21.4 |
| | UNS_5 | 15.7 | 31.6 | 5668 | 60.3 |
| | UNS_6 | 12.7 | 25.5 | 4684 | 36.2 |
| | UNS_7 | 16.8 | 33.8 | 7059 | 45.5 |
| | UNS_8 | 15.5 | 31.2 | 7059 | 32.5 |
| | UNS_9 | 12.9 | 26.0 | 6158 | 29.2 |
| | UNS_10 | 4.1 | 8.18 | 4611 | 12.6 |
| | Average | 12.1 | 24.48 | 5932 | 33.5 |
| | (St. deviation) | (4.1) | (8.31) | (907) | (13.3) |
| Notched beams | UN_1 | 6.8 | 13.5 | 6137 | 16.3 |
| | UN_2 | 9.8 | 19.9 | 5657 | 28.6 |
| | UN_3 | 8.3 | 16.6 | 5073 | 21.0 |
| | Average | 8.3 | 16.7 | 5622 | 22.0 |
| | (St. Deviation) | (1.3) | (2.6) | (435) | (5.0) |
| Beams cut in half | US_1 | 6.5 | 12.8 | 1112 | 81.0 |
| | US_2 | 6.1 | 11.9 | 1141 | 72.7 |
| | US_3 | 6.5 | 13.0 | 1203 | 71.0 |
| | Average | 6.4 | 12.5 | 1152 | 74.9 |
| | (St. Deviation) | (0.18) | (0.47) | (38.0) | (4.39) |

(**a**)


(**b**)

**Figure 7.** (**a**) Timber beams cut in half; (**b**) Notched beams.

The control specimens cut in half (US_1, US_2 and US_3) exhibited an average bending strength of 12.55 MPa and a global modulus of elasticity of 1152 MPa, with a reduction compared to undamaged beams of approximately 49 and 87 %, respectively. Failure emerged in proximity of the application point of the load at the tension side. A significant slippage of the two parts of the beams was obviously recorded during the tests. All the artificially damaged (cut in half and notched timber beams) usually showed an elastic-linear response up to the failure (Figure 6b).

### *4.2. Repaired beams*

BFRP spikes have been applied to cut-in-half (Figure 7a) and to notched beams (Figure 7b) with the aim to restore the continuity of damaged timber beams.

Three repaired notched beams were tested (RN_1, RN_2 and RN_3) and test results are reported in Table 5. The application of the BFRP spikes produced an increase of the average bending strength of 56.1 % and of the global modulus of elasticity of 19 % compared to the control notched beams (Table 6). Both for control and repaired beams an elastic response has been recorded. The main result is that timber beams did not fail due to separation of the upper from the beam's lower part near the notches, but beams exhibited tensile timber failures initiated by defects (mainly grain deviation and knots). The deviation in the strength value of beams, also considering the limited number of tests performed, is also relatively low. Furthermore, it can broadly be said that the repaired notched beams allow the achievement of the bending capacity and stiffness of the control and undamaged beams.

The repaired cut-in-half beams (RS_1, RS_2, RS_3, RS_4 and RS_5) exhibited an average bending strength of 15.03 MPa and a global modulus of elasticity of 4904 MPa. Failure, again knot influenced, occurred in the timber material on the tension side where the bending moment is maximum. After timber failure, the BFRP spikes did not exhibit any damage, but partially separated from the epoxy resin in the holes. Slippage was also generated by timber shear failure near the holes caused by the low shear strength of fir wood (Figure 8). Figure 9 shows the load-deflection response of control and repaired beams cut in half. The load-displacement graphs generally show that there is a large amount of vertical mid-span deflection even for low loads due to the slippage of the BFRP spikes.

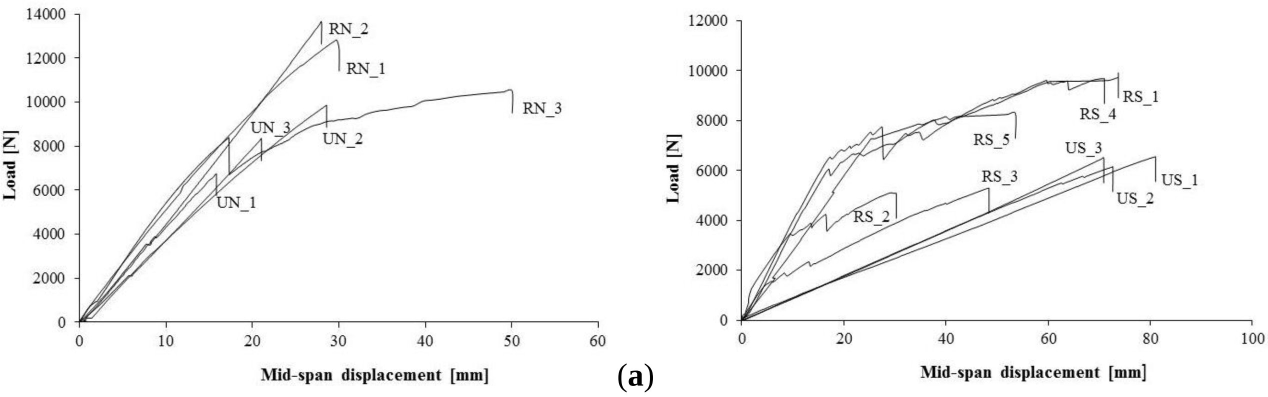
**Table 5.** Test results (repaired beams).

| Index | Maximum load (kN) | Bending strength (MPa) | Global modulus of elasticity (MPa) | Deflection at maximum load (mm) |
|---|---|---|---|---|
| RS_1 | 9.91 | 19.4 | 5855 | 73.8 |
| RS_2 | 5.11 | 9.97 | 6250 | 29.2 |
| RS_3 | 5.29 | 10.5 | 3136 | 48.4 |
| RS_4 | 9.68 | 18.7 | 5377 | 71.0 |
| RS_5 | 8.28 | 16.5 | 3900 | 54.2 |
| Average | 7.65 | 15.0 | 4904 | 55.3 |
| (St. Deviation) | 2.08 | 4.02 | 1189 | 16.2 |
| RN_1 | 12.4 | 29.8 | 7524 | 29.8 |
| RN_2 | 13.6 | 27.2 | 6233 | 28.8 |
| RN_3 | 10.5 | 21.0 | 6327 | 51.0 |
| Average | 12.2 | 26.0 | 6695 | 36.5 |
| (St. Deviation) | 1.29 | 3.73 | 588 | 10.3 |

After an initial elastic phase, repaired beams (RS_series) exhibited a plastic behaviour. Increases of bending strength compared to control beams were limited due to low quality of timber material (fir wood) and separation of BFRP spikes from the epoxy resin. Beams RS_2 and RS_3 collapsed for a low bending load due the presence of a large knot defect in timber tension zone. The insertion of the BFRP spikes resulted in moderate enhancements in the beam ultimate capacity (+19.8 %) while more significant improvements in the stiffness were obtained (+325.7 %) and it is essentially due to the low values of stiffness of cut-in-half beams. However the insertion of the BFRP spikes did not cause the achievement of the values of the control timber beams in terms of bending capacity and stiffness.

**Figure 8.** Pull out of the BFRP spike.

Another interesting feature of the load-deflection curves is that repaired specimens after an initial decrease of the load due to a beam cracking, were able to withstand a further increase in load. The BFRP repaired beams demonstrated an initial linear elastic behaviour and exhibited brittle timber tensile-flexural failures on the lower half timber beam when subject to flexural loading. After this, a pseudo-ductile behaviour of the repaired beams has been recorded.




(**a**) (**b**)

**Figure 9.** Load-Displacement curves: (**a**) control (US-series) and repaired (RS-series) beams cut in half, notched beams; (**b**) control (UN-series) and repaired (RN-series) beams cut in half.

**Table 6.** Results of control and repaired beams.

| Index | Repaired | Damage | Maximum load (kN) | Bending strength (MPa) | Deflection at maximum load (mm) |
|---|---|---|---|---|---|
| UNS_series | No | - | 12.1 | 24.5 | 33.5 |

| | | | | | |
|---|---|---|---|---|---|
| US_series | No | Notched | 6.40 | 12.5 | 71.0 |
| UN_series | No | Cut-in-half | 8.32 | 16.7 | 22.0 |
| RN_series | Yes | Notched | 12.2 | 26.0 | 36.5 |
| RS_series | Yes | Cut-in-half | 7.65 | 15.0 | 55.3 |

For both notched and cut-in-half beams, experimental testing in flexure has demonstrated that the insertion of BFRP spikes incorporating basalt fibre reinforcement epoxy-bonded onto softwood (low-grade) beams can increase beam capacity and stiffens and introduce pseudo-ductile behaviour into the hybrid beams in comparison to the linear elastic brittle tensile failure experienced by the control beams (Figure 10). However this non-linear behaviour was mainly caused by slippage phenomena of the BFRP spikes demonstrating a limited effectiveness of these epoxy-bonded connections.


(**a**)

(**b**)

**Figure 10.** Timber tensile-flexural failures (cut in half beams): (**a**) in the lower half; (**b**) both in the lower and upper half.

## 5. Conclusions

This article illustrates an experimental study on the effect of BFRP spikes to restore continuity of softwood (fir-wood) cracked beams. The following conclusion can be drawn:

1. Various modes of fracture were detected for the control timber beams, but all on the tension side: simple tension, cross grain tension, knot influenced. Knots and grain deviation highly influenced the propagation of the cracks for all control specimens and were the main cause of beam's failure.
2. For both notched and cut-in-half beams, experimental testing in flexure has demonstrated that the insertion of BFRP spikes incorporating basalt fibre reinforcement epoxy-bonded onto softwood (low-grade) beams can increase beam capacity and stiffens and introduce pseudo-ductile behaviour into the hybrid beams in comparison to the linear elastic brittle tensile failure experienced by the control beams.
3. Bending test results indicate that the application of the proposed BFRP spikes partially recaptures both bending stiffness and load capacity of the 'undamaged' beams. Enhanced repair performance is directly related to the mechanical properties of the substrate (timber material).
4. Slippage phenomena of the BFRP spikes demonstrated a limited effectiveness of epoxy-bonded connections as slippage was generated by both resin and timber shear failures near the holes, the latter caused by the low typical mechanical properties of fir wood.

5. It is evident that the addition of the epoxy adhesive in the grooves has a strong effect on the success of the proposed repair method. Without the epoxy adhesive, spike slippage is highly facilitated. However this problem could not be completely solved as a slippage was noted during the bending tests.

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## Author Contributions

Dr Corradi and Prof. Borri conceived and designed the experiments; Mr. Righetti performed the experiments; Dr. Corradi and Mr. Righetti analysed the data; Mr. Righetti wrote the paper.

## Conflicts of Interest

The authors declare no conflict of interest.

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