Antonio Borri*, Marco Corradi**, Giulio Castori***

Reinforcement of softwood beams using unglued composite laminates

Wzmocnienie belek z miękkiego drewna materiałami kompozytowymi bez użycia kleju

Słowa kluczowe: taśmy węglowe, pręty bazaltowe, miękkie drewno, belki drewniane, próba zginania

Key words: Carbon plates, basalt bars, softwood, timber beams, bending tests

1. INTRODUCTION

Softwood as a traditional construction material has been extensively used in civil engineering. Timber construction is 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. Natural defects (knots, shakes, cross grain) and defects caused during treatment of felled timber may highly reduce timber mechanical properties and particularly tensile strength and cause high decreases of timber beam capacity. This reduction of the tensile strength may be as high as 95%.

Existing timber beams have been usually subjected either to replacement or reinforcement with traditional methods involving the use of common building materials such as metals (aluminum, steel, etc.) or modern techniques with composite materials. The need for a reinforcement 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].

The use of composite materials for reinforcement of existing timber members in not new [2–14]. 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 advantageous properties, e.g. high tensile strength, high corrosion resistance, may be exploited simultaneously. In these situations, the total costs (material, application and maintenance) of using composite materials are commensurate with metallic competitor materials such as stainless steel and aluminum or with replacement.

There are three "traditional" procedures for reinforcing timber beams with FRP composites: 1) Bonding of consolidated (pultruded) laminates [2–4]; and 2) Resin infusion of fabric reinforcement into grooves cut in the wood [5–8] and 3) Wet lay up of FRP sheet reinforcement using epoxy adhesives [9–14]. According to the above procedures in the last two decades, FRP composites have been increasingly used in highway bridge decks, trusses, timber floors, etc. [15–16].

However the wide range of composite products and the scattered mechanical properties of FRP elements currently available can lead to serious difficulties for the designer who approaches this problem. For this

* Professor, Department of Engineering, University of Perugia, Italy
** Senior Lecturer, Department of Mechanical & Construction Engineering, Northumbria University Department of Engineering, University of Perugia, Italy
*** Lecturer, Department of Engineering, University of Perugia, Italy

Cytowanie / Citation: Borri A., Corradi M., Castori G. Reinforcement of softwood beams using unglued composite laminates. Wiadomosci Konserwatorskie – Journal of Heritage Conservation 2016;47:30-39

Otrzymano / Received: 10.12.2015 • Zaakceptowano / Accepted: 20.12.2015 **doi:10.17425/WK47REINFORCEMENT**

Praca dopuszczona do druku po recenzjach *Article accepted for publishing after reviews*

reason, selection of the reinforcement layout and material should be guided by an accurate analysis of the characteristics of the timber element to be reinforced in order to avoid ineffective interventions [13]. The long-term durability of some FRP products needs to be studied and demonstrated [17–18].

Significant architectural and structural issues remain to be resolved. For example the application of FRP composites to timber structures without epoxy adhesives is less well established. Only in the last few years has the use of natural fibres, non-organic matrixes or mechanical connections been the subject of research [19–20], and it aims at developing a valid alternative to the use of organic oil-based fibres or matrixes, especially those based on epoxy resins, which present problems of reversibility, compatibility with timber, durability and poor performance at temperatures higher than 60–80°C. Many historic buildings are restricted by protection and heritage conservation authorities, which in many cases do not authorize an extensive use of epoxy adhesives.

This paper describes an experimental study on the use of two different reinforcing techniques: the first one addresses the problem of the use of CFRP plates, applied on the tension zone of timber without the use of a polymeric adhesive. Plates have been fixed to the beam's intrados surface using metal screws. This allows the removal of the reinforcement without causing significant damage to the timber beam. The second technique was used to restore the continuity of cracked beams by the insertion of transversal BFRP spikes.

2. MATERIAL CHARACTERIZATION

2.1. Timber

The test program was divided into two series: bending tests on beams reinforced with unglued composite pultruded laminates and bending tests on beams repaired with basalt (BFRP) spikes. All beams were made of softwood (fir-wood) Tests were carried out on sharp-edged timber beams (Fig. 1) in fir wood (*Abies Alba*).

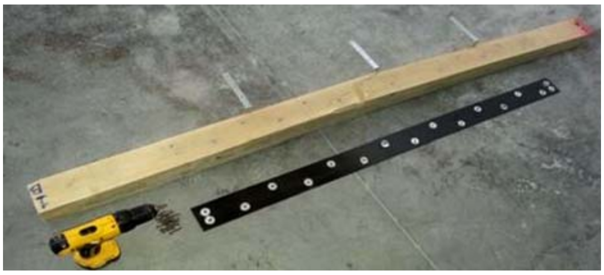

Fig. 1. Softwood beam and CFRP plate

All the timber beams had the same width (95 mm), height (95 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 [21].

2.2. CFRP plate

The CFRP plates consisted in high-volume fraction high-strength unidirectional carbon fiber in an epoxy resin. Plates are produced by *Draco italiana SpA* under the commercial name of *Armoshield CFK* (Fig. 2). According to ASTM D 3039 standard [22] the modulus of elasticity was 205381 N/mm^2 with an ultimate tensile strength of 3252 N/mm^2. Manufacture of the CFRP plate was by pultrusion process. Plates were made of unidirectional carbon fibres and epoxy resin (Tab. 1).

Tab. 1. Properties of the CFRP plate

Thickness (mm)	1.2
Tensile Strength (N/mm^2)	3252
Young's Modulus (N/mm^2)	205381
Strain at failure (%)	1.36

CFRP plates were reduced to a length of 1400 mm and symmetrically applied on the tension side of the timber beams. In order to avoid the use of polymeric adhesives to fix the CFRP to timber surface, steel screws and washers were used (Fig. 3). Plates were pre-drilled and a small quantity of epoxy resin was only inserted between the contact surface of the CFRP plate and steel washer in order to facilitate the stress transfer (Fig. 4).

Fig. 2. CFRP plate

Fig. 3. Detail of application of the CFRP plate

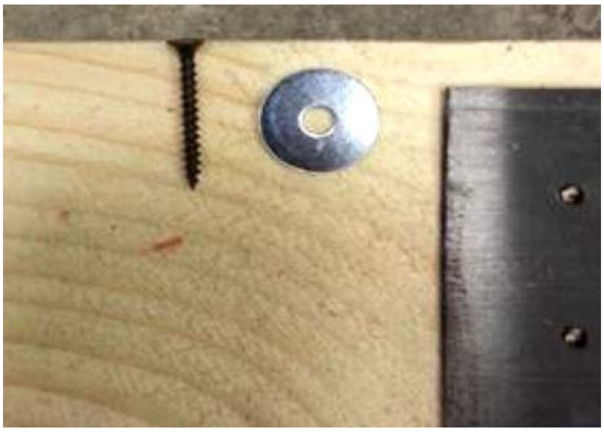

Fig. 4. Metal screw and washer

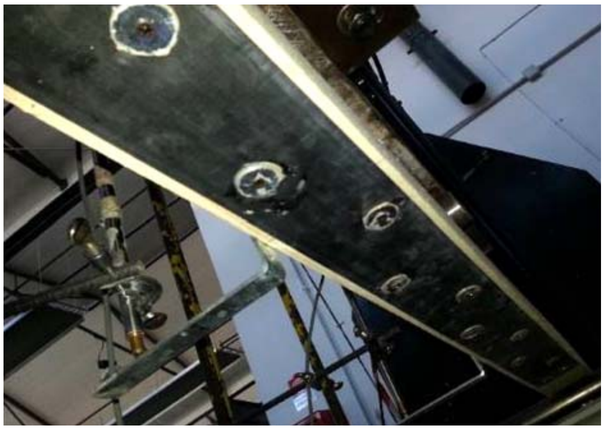

Fig. 5. CFRP plate applied on the timber tension side

For the geometrical arrangement of the screws, four configurations have been used. According to the first configuration, (screw layout No. 1 (Figs. 5 and 6a), screws were placed at a centre-to-centre distance of 200 mm. All screws were positioned 25 mm from plate's edges. Two screws were applied on both CFRP plate ends. For second configuration (screw layout No. 2 (Fig. 6b), screws were placed at a centre-to-centre distance of 100 mm.

In order to reduce the shear stress between CFRP plates and timber, for the third configuration (screw layout No. 3 (Fig. 6c), screws were placed at a centre-to-centre distance of 50 mm. Finally for the fourth configuration (screw layout No. 4 (Fig. 6d), screws were placed at a centre-to-centre distance of 25 mm.

For configurations No. 1 and No. 2 screw length was 40 mm. For configurations No. 3 and No. 4 screw length was reduced to 30 mm in order to reduce the damage of timber beams and facilitate stress distribution. Table 3 summarizes the characteristics of the reinforced timber beams.

2.3. BFRP spikes

Due to its anisotropic behavior, 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. Basalt Fiber Reinforced Polymers (BFRP) spikes (Fig. 7) were used here to restore the continuity

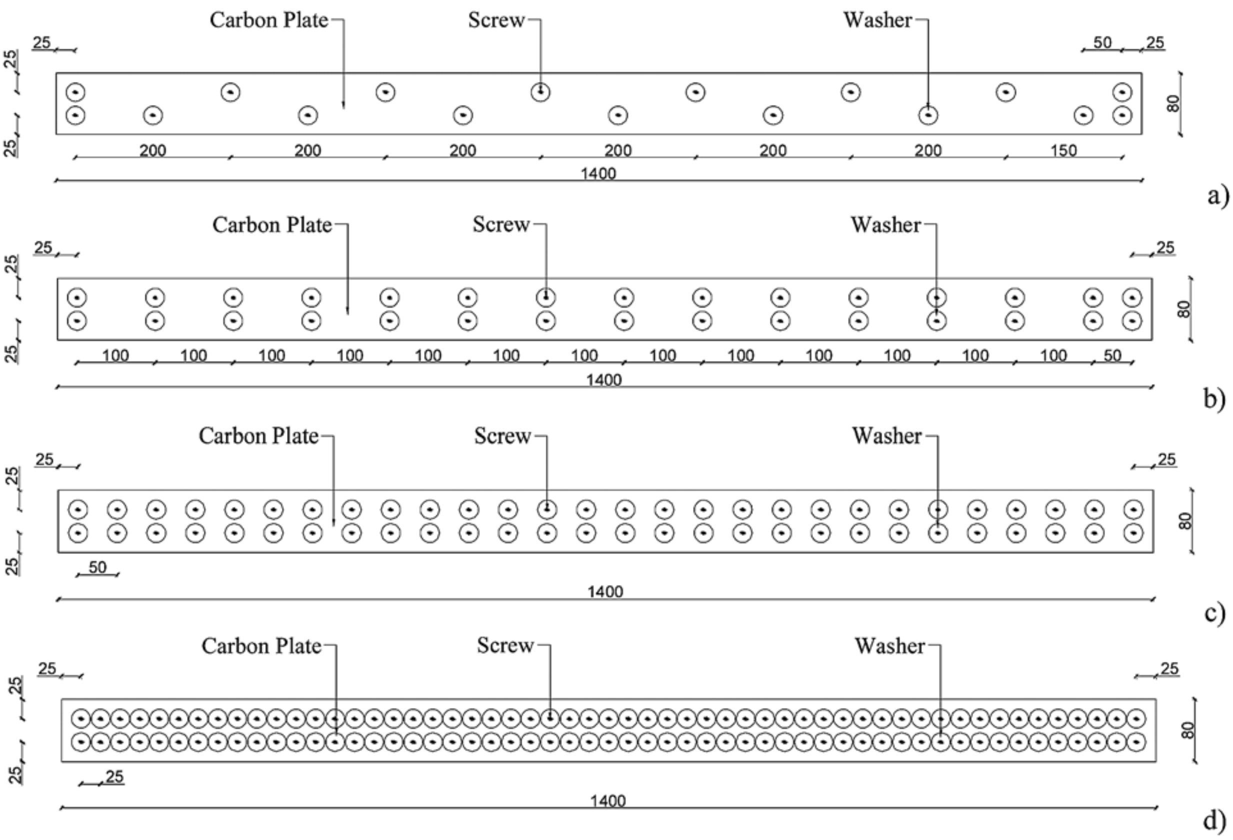

Fig. 6. Different screw layouts [dimensions in mm]

Fig. 7. BFRP spikes

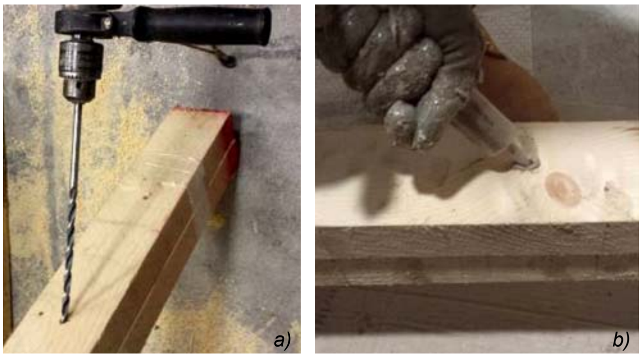

Fig. 8. Application of BFRP spikes

of damaged or cracked timber beams. For this purpose timber beams, from the same batch, were artificially damaged. Six beams were cut in half and three beams were partially cut on both sides. Two notches (35 mm long) were made along the entire longitudinal direction.

The reinforcement technique consists in the application of eight 95 mm long BFRP bars (Fig. 8a). Bars were inserted into diagonal holes (45°) perforated in the timber beams (Figs. 8a and 9) at centre-to-centre distance of 200 mm. No bars were applied on the central part of the timber beams where bending moment is maximum and shearing force equal to zero. Thermosetting bi-component epoxy resin was injected inside the holes before inserting the BFRP bars to facilitate the connection between the timber and reinforcement (Fig. 8b). Six bars were tested in tension and their strains recorded with a 50 mm gauge length mechanical extensometer. The average of the six coupon test values in given in Table 2.

Tab. 2. Properties of the BFRP spikes

Nominal diameter (mm)	6
Weigth density (kg/m)	0.452
Failure load (kN)	21.5
Tensile strength (N/mm^2)	761
Young's Modulus (N/mm^2)	36557
Strain at failure (%)	2.08

3. TEST SET UP AND TEST RESULTS

Six series of bending tests was performed on unreinforced and reinforced timber beams (Tab. 3). 29 beams were subjected to the four-point-bending, according to UNI EN 408 standard [23]. 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 reduce the local crushing of the wood, the load was applied through two 42 mm diameter steel cylinders. Displacement controlled loading ensued with a crosshead speed of 2 mm/min.

Tab. 3. Test matrix

Index	Number of beams	Timber Beam	Reinforcement
UNS_series	10	–	–
US_series	2	Cut in half	–
UN_series	2	Notched	–
CP_series	10	–	CFRP plate
RS_series	4	Cut in half	BFRP bar
RN_series	1	Notched	BFRP bar

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

$$f_m = a\frac{F_u}{2W} \qquad (1)$$

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 can be calculated with the following formulation:

$$E_{m,g} = \frac{l^3\left(F_2 - F_1\right)}{bh^3\left(w_2 - w_1\right)}\left[\left(\frac{3a}{4l}\right) - \left(\frac{a}{l}\right)^3\right] \qquad (2)$$

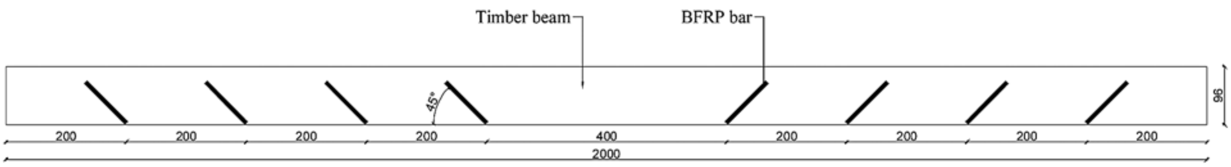

Fig. 9. Reinforcement layout using BFRP spikes

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. The test setup is shown in detail in Fig. 10.

Fig. 10. Four-point-bending test

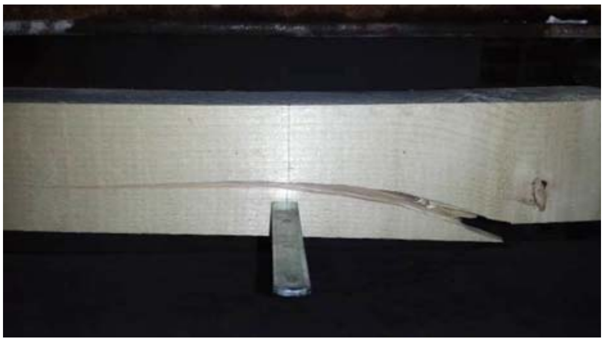

Fig. 11. Typical tensile failure mode of unreinforced beams near a knot or due to grain deviation

3.1. Un-reinforced beams

Fourteen un-reinforced beams were subjected to flexure in four-point-bending. These results have been reported solely for the purpose of quantitatively evaluating the effectiveness of the interventions through a comparison with the results of identical tests performed on the beams strengthened with CFRP plates. Various modes of fracture were detected in the timber unreinforced beams, but all on the tension side:

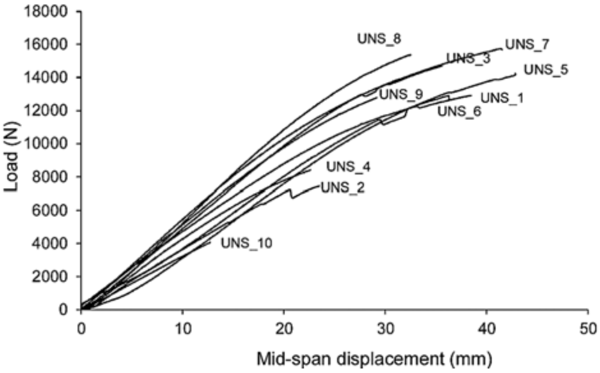

Fig. 12. Load-Displacement curves of un-reinforced un-damaged beams

simple tension, cross grain tension, knot influenced (Fig. 11). Knots and grain deviation highly influenced the propagation of the cracks for all un-reinforced specimens. Deflection characteristics of the tested un-reinforced beams are shown in Table 4, the average bending strength was 24.48 N/mm^2 (dev. 8.31 N/mm^2) and the global modulus of elasticity 5932 N/mm^2 (dev. 907 N/mm^2).

Load-Displacement curves (Fig. 12) 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 (Fig. 11). The scatter in the capacity values of un-reinforced beams, where the presence of grain deviation and knots influence the failure mode, is very high.

The un-reinforced notched specimens (UN_1 and UN_2) exhibited an average bending strength of 16.67 N/mm^2 and a global modulus of elasticity of 5897 N/mm^2. Furthermore the failure of these specimens occurred in the area where bending moment is maximum.

Four beams were subjected to four-point-bending after been artificially damaged. The un-reinforced specimens cut in half (US_1 and US_2) exhibited an average bending strength of 12.34 N/mm^2 and a global modulus of elasticity of 1126.5 N/mm^2. Failure emerged in proximity of the application point of the load at the tension side.

Tab. 4. Test results (unreinforced beams)

	Index	Maximum load (kN)	Bending strength (N/mm^2)	Global modulus of elasticity (N/mm^2)	Deflection at max laod (mm)
Undamaged Beams	UNS_1	13.02	26.24	6077	37.01
	UNS_2	7.55	15.22	5148	23.49
	UNS_3	14.83	29.89	6825	36.52
	UNS_4	8.56	17.25	6029	21.37
	UNS_5	15.66	31.56	5668	60.35
	UNS_6	12.66	25.52	4684	36.24
	UNS_7	16.77	33.80	7059	45.53
	UNS_8	15.46	31.16	7059	32.51
	UNS_9	12.88	25.96	6158	29.16
	UNS_10	4.06	8.18	4611	12.64
	Average	12.14	24.48	5932	33.48
	(St. deviation)	(4.12)	(8.31)	(907)	(13.32)
Notched beams	UN_1	6.76	13.47	6137	16.31
	UN_2	9.85	19.87	5657	28.56
Beams cut in half	US_1	6.55	12.79	1112	81.04
	US_2	6.15	11.89	1141	72.69

3.2. CFRP reinforced beams

The test procedure was the same for all unreinforced and reinforced beams. For each of the 10 beam tests, graphs of mid-span deflection versus vertical load have been drawn. These are presented in Figure 13. Numerical results are reported in Table 5. It can be seen that the measured ultimate (maximum) load did not increase significantly after the application of the CFRP reinforcement. The most part of reinforced timber beams failed because of timber cracking on the tension side; it was also observed that CFRP plates did not fail (Fig. 13). For this reason a residual bending strength has been detected following timber cracking (Fig. 14).

The beams reinforced according to screw layout No. 1 evidenced an average bending strength of 24.61 N/mm^2 and a global modulus of elasticity of 6935 N/mm^2. A negligible increase (4.8%) of the bending strength has been recorded for beams reinforced according to screw layout No. 2 (bending strength 25.42 N/mm^2 and global modulus of elasticity of 8708 N/mm^2). Beams reinforced according to screw layout No. 3 exhibited an average bending strength of 26.35 N/mm^2 and a global modulus of elasticity of 8969 N/mm^2.

Finally the application of a large number of metal screws according to layout No. 4 produced a significant increase of the bending strength (26%) compared to the values recorded for beams reinforced according to layout No. 1 (average bending strength 30.85 N/mm^2 and global modulus of elasticity of 10007 N/mm^2). The number of screws has been increased in order to reduce stress concentration and to facilitate the load transfer between timber and CFRP plate. The application of CFRP plates according to the screw layout No. 4 also caused an increase of the global modulus of elasticity of 68.7%. Beams reinforced according to screw layout No. 4 exhibited a linear elastic behaviour until a bending load of approx. 11 kN. Yielding of timber material in compression and the low bearing resistance at the joint screw-timber produced a plastic behaviour for higher values of bending load.

Tab. 5. Test results (CFRP-reinforced beams)

Index	Screw layout	Maximum load (kN)	Bending strength (N/mm^2)	Global modulus of elasticity (N/mm^2)	Deflection at maximum load (mm)
CP_1	1	17.75	35.77	8408	52.71
CP_2	1	6.67	13.44	5463	22.81
CP_3	2	8.62	17.37	8040	20.43
CP_4	2	13.51	27.23	8181	41.57
CP_5	2	15.71	31.66	9903	32.93
CP_6	3	12.89	25.98	8675	42.47
CP_7	3	12.79	25.78	9209	22.62
CP_8	3	13.54	27.29	9025	30.86
CP_9	4	14.77	29.77	9438	81.08
CP_10	4	15.84	31.92	10577	44.22
Average		13.21	26.62	8692	39.17
(St.deviation)		(3.34)	(6.74)	(1380)	(18.20)

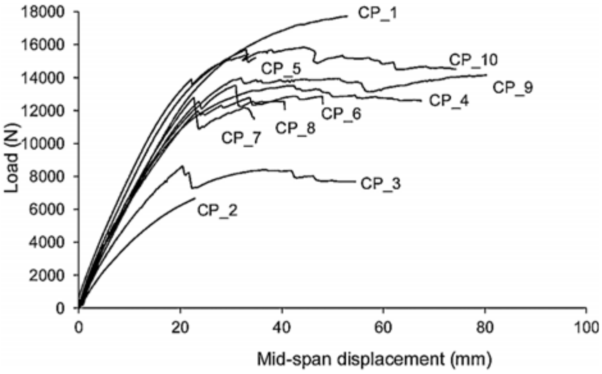

Fig. 13. Load-Displacement curves of un-reinforced and reinforced beams (screw layout No.4)

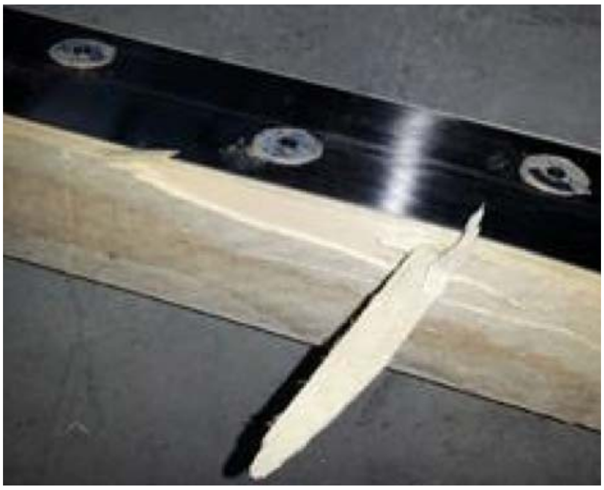

Fig. 14. Detail of the typical failure mode of reinforced beams

Fig. 15. Timber beams cut in half

3.3. BFRP reinforced beams

For each of the 19 beam tests, graphs of vertical load versus mid-span deflection have been drawn for both the un-reinforced and BFRP-reinforced beams. BFRP spikes have been applied to timber beams cut in half (Fig. 15) and to notched beams (Fig. 16). The reinforced beams cut in half (RS_1, RS_2, RS_3 and RS_4) exhibited an average bending strength of 14.66 N/mm^2 and a global modulus of elasticity of 5154.5 N/mm^2. Failure occurred in the timber material on the tension zone where the bending moment is maximum. After timber failure, the BFRP bars do not exhibit any damage, but partially separated from the epoxy resin in the holes (Fig. 17).

Fig. 16. Notched beams

Fig. 17. Pull out of the BFRP spike

Tab. 6. Test results (BFRP-reinforced beams)

Index	Maximum load (kN)	Bending strength (N/mm^2)	Global modulus of elasticity (N/mm^2)	Deflection at maximum load (mm)
RS_1	9.91	19.42	5855	75.61
RS_2	5.11	9.97	6250	29.22
RS_3	5.29	10.55	3136	48.44
RS_4	9.68	18.71	5377	71.05
RN_1	12.42	29.85	7524	29.76

Fig. 18 shows the behaviour of unreinforced and reinforced beams cut in half. The vertical load graphs generally show that there is a large amount of vertical mid-span deflection even at low loads due to the slippage of the BFRP spikes. Un-reinforced specimens without BFRP spikes (US_1 and US_2) exhibited a linear elastic response. After an initial elastic phase, reinforced beams (RS_series) exhibited a plastic behaviour. Increases of bending strength compared to unreinforced beams were limited due to low quality of timber material (fir wood) and separation of BFRP bars 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 (+18.8%) while more significant improvements in the stiffens were obtained (+56.6%).Another interesting feature of the vertical load--deflection curves is that reinforced specimens after an initial decrease of the load due to a beam cracking, were able to withstand a further increase in load. As stated earlier for CFRP-reinforced beams, 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 reinforced beams has been recorded.

Only one reinforced notched beam was tested (RN_1) and test result is reported in Table 6. The application of the reinforcement produced an increase of the average bending strength of 79% and of the global modulus of elasticity of 27.6% compared to unreinforced notched beams. Both for un-reinforced and reinforced beams an elastic behavior has been recorded and beams exhibited tensile timber failures initiated by defects. However since the number of beams tested was very limited, results should be confirmed by a larger experimental programme.

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 unreinforced beams. However this non-linear behaviour was mainly caused by slippage phenomena of the BFRP spikes demonstrating a limited effectiveness of these epoxy-bonded connections. In fact shear failures between softwood and epoxy resin caused a progressive pull-out of the BFRP spikes.

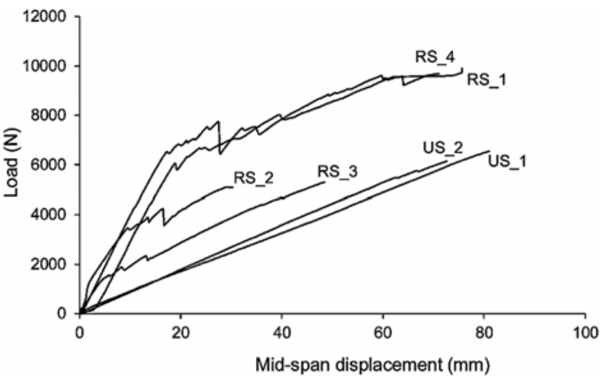

Fig. 18. Load-displacement curves of un-reinforced (US-series) and reinforced (RS-series) beam cut in half

a)

b)

Fig. 19. Timber tensile-flexural failures (cut in half beams): a) only in the lower half, b) both in the lower and upper halves

4. CONCLUSIONS

This article has presented an experimental campaign to study the effect of the application of unbonded pultruded CFRP plates on softwood (fir-wood) beams using ordinary metal screws and the use of BFRP spikes to restore continuity of cracked timber beams.

The pultrusion process is ideally suited to the economic production of prismatic composite profiles and their applications without polymeric adhesives may be of interest to avoid irreversible interventions and to guarantee a more durable mechanical connection between substrate and reinforcement. However the low compression strength parallel-to-grain of the used softwood material partially compromised the effectiveness of the reinforcement. In order to reduce the stress-concentration around the screws, the number of screws was increased: in this way it was possible to achieve an increase of bending strength of 26% and of the global modulus of elasticity of 68.7%. The typical failure mode of CFRP-reinforced beams was timber cracking on the tension side without any significant damage to the CFRP plate. Four different reinforcement configurations were tested. The increase of the bending capacity was very limited for the first three configurations. It could be concluded that the effectiveness of the reinforcement was significant only when the number of screws applied to connect the CFRP plate to the timber surface was high (screw layout No.4) (Tab. 7).

The results of the second part of this test program indicate that the application of the proposed BFRP spikes partially recaptures both bending stiffness and capacity of the 'undamaged' beams. Enhanced repair performance is directly related to the number and position of the BFRP bars. The diagonal insertion of BFRP bars into beams cut in half produced an increase of the bending strength of 18.8% and of the global modulus of elasticity of 57.6% compared to the unreinforced beams (Tab. 7). However the original capacity of undamaged unreinforced beams has not been achieved.

Tab. 7. Results of un-reinforced and reinforced beams

		Damage	Maximum load (kN)	Bending strength (N/mm^2)	Deflection at maximum load (mm)
UNS_series	Un-reinforced	–	12.14	24.48	31.44
US_series	Un-reinforced	Notched	8.31	16.67	22.43
UN_series	Un-reinforced	Sectioned	6.35	12.34	76.86
CP_series	Reinforced[1]	–	12.21	24.61	37.76
CP_series	Reinforced[2]	–	12.61	25.42	32.93
CP_series	Reinforced[3]	–	13.07	26.35	30.86
CP_series	Reinforced[4]	–	15.31	30.85	62.65
RN_series	Reinforced	Notched	12.42	29.85	29.76
RS_series	Reinforced	Sectioned	7.50	14.66	56.08

[1] screw layout No. 1; [2] screw layout No. 2; [3] screw layout No. 3; [4] screw layout No. 4

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, bar slippage is highly facilitated. However this problem could not be completely solved; a limited slippage was noted during the bending tests. The bonded-in fiberglass shear spikes showed substantially better modulus retention than did the steel nailed beams. The reinforcement was more effective for notched beams. The insertion of BFRP bars into notched beams produced an increase of 49.4% of bending strength and of 27.6% of the global modulus of elasticity compared to unreinforced ones.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Structural Engineering Laboratory at Perugia University for the use of test and measurement equipment critical to the collection and evaluation of the data presented. The experimental program was carried out with the help of Alessandro Maraca and Federico Ricci, undergraduate students, and Mr Alessio Molinari, Graduate Research assistant. Authors are also grateful for contribution to the research to Mr Antonio Del Mastro. BFRP bars were supplied by Aldebran srl (www.materialicompositi.com).

REFERENCES

[1] US Department of Transportation, FHWA. Seventh annual report to the congress on highway bridge replacement and rehabilitation program, 1986.

[2] Davanos J.F., Zipfel M.G., Quiao P. Feasibility study of prototype GFRP-reinforced wood railroad crosstie. Journal of Composites for Construction 1999;3(2):92-99.

[3] Radford D.W., Van Goethem D., Gutkowski R.M., Peterson, M. L. Composite repair of timber structures. Construction and Building Materials 2002; 16(7):417-425.

[4] Corradi M., Borri A. Fir and chestnut timber beams reinforced with GFRP pultruded elements. Composites Part B: Engineering 2007;38(2):172-181.

[5] Gentile C., Svecova D., Rizkalla S.R. Timber Beams Strengthened with GFRP Bars: Development and Applications. Journal of Composites for Construction 2002;6(1):11-20.

[6] Borri A., Corradi M., Grazini A. A method for flexural reinforcement of old wood beam with CFRP materials. Composites Part B: Engineering 2005;36(2):143-153.

[7] Micelli F., Scialpi V., La Tegola A. Flexural reinforcement of glulam timber beams and joints with carbon fiber-reinforced polymer rods. Journal of Composites for Construction 2005;9(4):337-347.

[8] Raftery G.M., Whelan C. Low-grade glued laminated timber beams reinforced using improved arrangements of bonded-in GFRP rods. Construction and Building Materials 2014;52:209-220.

[9] Plevris N., Triantafillou T.C. FRP-Reinforced Wood as structural material. Journal of Materials in Civil Engineering 1992;4(3):300-317.

[10] Lopez-Anido R., Hu H. Structural characterization of hybrid FRP-Glulam panels for bridge decks. Journal of Composites for Construction 2002;6(3):194-203.

[11] Borri A., Corradi M., Speranzini E. Reinforcement of wood with natural fibres. Composites Part B: Engineering 2013;53:1-8.

[12] Nowak T.P., Jasieńko J., Czepiżak D. Experimental tests and numerical analysis of historic bent timber elements reinforced with CFRP strips. Construction and Building Materials 2013;40:197-206.

[13] Jasieńko J., Nowak T.P., Bednarz Ł. Baroque structural ceiling over the Leopoldinum Auditorium in Wrocław University: tests, conservation, and a strengthening concept. International Journal of Architectural Heritage 2014;8(2):269-289.

[14] Jankowski L.J., Jasieńko J., Nowak T.P. Experimental assessment of CFRP reinforced wooden beams by 4-point bending tests and photoelastic coating technique. Materials and Structures 2010; 43(1-2):141-150.

[15] Chajes M.J., Kaliakin V.N., Meyer A.J. Behaviour of engineered wood-CFRP beams. In: H. Saadatmanesh & M.R. Ehsani (eds) Proc. of the 5th Int. Conf. on Camp. in Infrastr., Univ. of Arizona, Tuscon, Arizona, 1996, 870-877.

[16] Hay S., Thiessen K., Svecova D., Bakht B. Effectiveness of GFRP sheets for shear strengthening of timber. Journal of Composites for Construction 2006;10(6):483-491.

[17] Tascioglu C., Goodell B., Lopez-Anido R., Peterson M., Halteman W., Jellison J. Monitoring fungal degradation of E-glass/phenolic fiber reinforced polymer (FRP) composites used in wood reinforcement. International Biodeterioration & Biodegradation 2003;51(3):157-165.

[18] Borri A., Castori G., Corradi M., Speranzini E. Durability analysis for FRP and SRG composites in civil applications. Key Engineering Materials 2015;624:421-428.

[19] Borri A., Corradi M., Speranzini E. Reinforcement of wood with natural fibers. Composites Part B: Engineering 2013;53:1-8.

[20] Papanicolaou C.G., Triantafillou T.C., Papathanasiou M., Karlos K. Textile reinforced mortar

(TRM) versus FRP as strengthening material of URM walls: out-of-plane cyclic loading. Materials and Structures 2007;40(10):1081-1097.
[21] EN 13183–1:2002. Moisture content of a piece of sawn timber. Determination by oven dry method.
[22] ASTM D3039:2009. Standard test method for tensile properties of fiber-resin composites.
[23] EN 408:2010. Timber structures. Structural timber and glued laminated timber: determination of some physical and mechanical properties.

Abstract

This article describes aspects within an experimental programme aimed at improving the structural performance of solid fir-wood beams reinforced with unglued composite laminates applied on the beam tension zone. Softwood is from gymnosperm plants and it is the basis of approx. 85% of the world's production of wood elements. Fir wood is characterised by low weight 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 addition of modest ratios of FRP composite reinforcement can suppress tension failure in beams. However the application of epoxy adhesives presents problems of reversibility, compatibility with timber, durability and poor performance at temperatures higher than 60–80°C. The study of failure modes, particularly in tension-reinforced beams, is the main focus of this paper. The experimental campaign is dealing with the evaluation of bending strength and deformation properties of a significant number of unreinforced and reinforced beams strengthened with unbonded carbon (CFRP) plates or basalt (BFRP) spikes. Increases of beam capacity, bending strength and of modulus of elasticity and analysis of failure modes were measured and discussed.

Streszczenie

Artykuł opisuje aspekty programu badań eksperymentalnych, mającego na celu poprawę pracy konstrukcyjnej belek z litego drewna jodłowego, wzmocnionych materiałami kompozytowymi bez użycia kleju, zastosowanymi w strefie belki poddawanej rozciąganiu. Miękkie drewno pochodzi z roślin nagonasiennych i stanowi podstawę dla około 85% światowej produkcji elementów drewnianych. Drewno jodły charakteryzuje niska gęstość wagowa, niska wytrzymałość na ściskanie i wysoki poziom defektów i wad. Drewno takie ma tendencję do wypaczania się po wyschnięciu oraz ulega zniszczeniu przy rozciąganiu z uwagi na obecność pęknięć, sęków lub nieregularności włókna. Zastosowanie niewielkich ilości wzmocnienia kompozytowego FRP może zapobiec zniszczeniu belek na skutek rozciągania. Jednak zastosowanie klejów epoksydowych jest problematyczne ze względu na brak możliwości odwracalności interwencji, kompatybilność z drewnem, trwałość oraz niekorzystne zachowanie w temperaturach powyżej 60–80°C. Badania nad mechanizmami zniszczenia, zwłaszcza belek wzmocnionych na rozciąganie, są tematem niniejszego artykułu. Program badawczy ma na celu ocenę wytrzymałości na zginanie oraz właściwości deformacyjnych znacznej liczby niewzmocnionych i wzmocnionych belek, do których wzmocnienia wykorzystano taśmy węglowe (CFRP) lub sztyfty bazaltowe (BFRP) bez użycia kleju. Dokonano pomiarów wzrostu nośności belek, ich wytrzymałości na zginanie i modułu elastyczności, przeprowadzono analizę mechanizmów zniszczenia. Artykuł prezentuje otrzymane wyniki.