Flexural strengthening of timber beams by traditional and innovative techniques

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Abstract

This work presents experimental analyses for validating various strengthening techniques applied to historic timber floors using traditional and/or innovative materials (FRP, fibre reinforced polymer). The traditional method proposed here consists of placing reinforcing planks above the existing floor beams and fixing them with 'dry' connections by means of wooden dowels. As an innovative technique, strengthening with wet lay-up carbon FRP laminates (CFRP) applied at the underside of the beams is examined, both as unique strengthening for floor beams and in combination with the above-mentioned traditional method on the composite structure. Results on the characterisation of the connections between materials ('dry' wooden dowels and FRP bond behaviour) and flexural tests on simple and mechanically jointed beams with or without CFRP strengthening are discussed. The main execution phases of the strengthening technique, and their limits and advantages, are also described.

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INTRODUCTION

The main problems affecting the structural behaviour of historic timber floors are due to the lack of bending and in-plane stiffness and to the inadequate mechanical properties of the existing material. Several strengthening techniques have been developed in order to increase the bending stiffness and load-bearing capacity of existing timber floors, particularly in the case of simple frame floors made of rectangular load-bearing timbers (Tampone, 1996).

Among these, some are based on introducing strengthening elements like fibre reinforced polymer (FRP) strips or bars at the floor underside; others aim at creating a T-beam section, where the original timber behaves like a web, and a new element, placed at the floor upper side and connected to the existing beam, works as a flange. This element may be made of various types and materials, like the shear connection between the existing beam and the strengthening element (Parisi and Piazza, 2003). In particular, when the existing boarding is to be maintained, special shear and flexural fasteners must be used in order to reduce the possible loss of stiffness at the connection. For this purpose, steel beams coupled to the original beams (Tampone, 1996) or reinforced concrete slabs collaborating with the existing beams are usually used (Piazza *et al.*, 2005).

In the last decade, an intervention technique, based on the use of wooden elements for both flange and dowels connecting the original beam, has been developed in order to preserve and strengthen existing wooden floors (Modena *et al.*, 1997, 1998, 2004). Several experiments have validated this reinforcing system as highly compatible with the original floors, and led to the identification of the proper parameters to control for *in situ* applications (Modena *et al.*, 2004), according to the basic principles of cautious repairs (Modena, 1997). In particular, the choice of type of dowels (steel or wood), their diameter, and possible connection at the interface between flange and web (with glue or resins at the interface, or in 'dry' conditions, ie, simply forcing them into pre-bored holes) is important (Modena *et al.*, 2004). The technique is applied from the floor upper side (to which access is required) and only causes small increases in floor thickness and dead load. Traditional materials, the time-dependent behaviour of which is well known, and 'dry' assembly methods promote the durability, compatibility, reversibility, and/or recoverability of the intervention.

The contribution of FRP strips (Gentile *et al.*, 2002; Borri *et al.*, 2004) applied at the floor underside can increase beam structural performance, with or without specific strengthening at the upper side. Mechanical behaviour strongly depends on the local bond at the interface between wood and fibres subjected to various types of action (debonding, peeling), and may be particularly sensitive to the environmental conditions of the wood, mainly the relative humidity of the substrate. Italian standards recommend a limit of 10 per cent relative humidity to ensure proper adhesion of fibres to porous materials like masonry (CNR-DT200, 2004), and the use of polymer resins able to ensure durability, in cases of mechanical and dimensional variations in timber materials (CNR-DT201, 2005). In wood, relative humidity of the substrate of 12 per cent seems to be adequate to allow proper bond behaviour of glued elements (Piazza *et al.*, 2005).

The behaviour of 'dry' wooden connections compared with steel dowels and glued wooden dowels (ascertained by push-out tests), the bonding behaviour between carbon FRP laminates (CFRP) and wood (pull-off and double-lap shear tests), and the bending behaviour of simple and T-beams, with or without CFRP strengthening, have been experimentally investigated. The results of experimental tests on compound beams have been analysed according to the theory provided by Eurocode 5 (2003).

STRENGTHENING TECHNIQUES

Timber flange connected by dowels to main beams

The reinforcing technique consists of placing a new plank connected by means of dowels above each beam of the existing frame (Modena *et al.*, 1997, 1998). To facilitate execution and to ensure compatibility with existing structures and materials, in the original conception of the intervention the dowels were made of hardwood and driven into the preferably ‘dry’-planks, that is, without any material to improve adhesion inside the hole (Figure 1a). Moreover, with proper connection of main beams to load-bearing walls, and possible additional planks in the upper surface, the system can efficiently work even in seismic zones (Figure 1b) (Modena *et al.*, 2004). A T-beam compound section, whose web (original beam) and flange (new plank) are made of wood, with deformable connections between the flange and web, is thus obtained. Web and flange are separated by the existing boarding, having a thickness of 2–2.5 cm. Figure 1c shows the typical unequal spacing of the dowels along a beam in the prevalent shear zone, and Figure 1d

Figure 1: Stiffening intervention with dry hardwood pins to connect planks and/or boardings to original timber floors (a, b) and detail of connection to walls (b); distribution of dowels along a main beam (c); and different working of connections depending on contribution of boarding (d): combined flexural and shear (left), bending (centre), pure shear (right)

shows the different mechanical behaviour of compound sections with deformable connections. The operation is executed from the underside of the floor, thus preserving possible valuable floor surfaces and enables the instalment of systems (electrical, water, etc) without impairing the walls at their base (Figure 2).

The stiffening planks must be sawn before being placed on the boarding and their undersides levelled to allow perfect adhesion with the existing surface. The planks can be fixed to the existing boarding by means of screws to facilitate subsequent intervention phases and, when the floor beams are not propped, to provide adhesion between the straight planks and the permanently deflected floor beams. The screws can be placed every four to six dowels, in pre-drilled countersunk holes. The planks must be placed with the pith upward, in order to maintain the screws in tension even after wood shrinkage. Subsequently, the position where the dowels were inserted can be drawn into the plank by means of a template.

Dowel positions are staggered by about half a diameter from the longitudinal beam axis, in order to increase the resistance of the system to longitudinal splitting. The pre-bored holes are about 1 mm smaller than the dowel diameter. They are cleaned with

Figure 2: Execution phases: pre-boring (a), fixing of dowels on strengthening planks (b), and detail of technical installations placed between two planks (c)

compressed air before forcing the dowels by hammering. Figure 2 shows some work phases in an historical building (Modena *et al.*, 2004).

Application of FRP at underside of main beams

The innovative strengthening technique concerns gluing FRP strips to the floor underside and has already been proposed for simple rectangular beams (Gentile *et al.*, 2002; Borri *et al.*, 2004). The bond at the interface and the strengthening configuration are the main aspects that influence the mechanical behaviour of the reinforced beam.

A wet lay-up system is applied on the experimental beams, according to the manufacturer's recommendations. It consists of applying thin layers of adhesive (primer, epoxy resin) to guarantee proper homogeneity of the support to the fibres (Figure 3) as done for concrete substrates, although recent research (Cruz *et al.*, 2004) demonstrates good gluing without application of primer. As regards possible applications to historical structures, it is worth noting that an FRP application is not compatible with preservation principles, for instance, in the case of decorated intrados.

Combined technique

The combination of the two above-mentioned techniques, that is, the dry connection with a timber flange at the upper side and a sheet of CFRP at the underside, may be considered for strengthening and/or repair of an earlier intervention applying one of them. This may be due to specific damage (failure of dowels, peeling of fibres) or, as an example, the influence of

Figure 3: Application phases of primer (a) for preliminary preparation of surface and subsequent positioning of a layer of CFRP between adhesive resin (b)

Figure 4: Compound section resulting from application of two techniques (FRP layer at bottom) (a) and equivalent timber I-section after homogenisation (b)

Figure 5: Experimental execution phases of combination of two techniques: preliminary drilling of extrados of main beam (a), positioning of hardwood dowels (b), complete strengthening on the upper side (c), and final application of CFRP at the underside (d)

humidity, which can reduce bond efficiency and lead to brittle collapse. The combined system also allowed checking the appearance of new modes of failure and their possible interference. From a structural point of view, the new element behaves like an I-section, where the flanges are the new plank and the homogenised FRP strip (Figure 4). Figure 5 shows an example of preparation of an experimental sample to be tested in the laboratory.

EXPERIMENTAL PROGRAMME AND TEST SET-UP

A comprehensive experimental campaign, aimed at characterising the mechanical behaviour and studying the parameters needed for proper design of upgrading existing wooden floors with the proposed techniques, was carried out at the Laboratory for Structural Materials Testing of the University of Padova. Several experimental phases were carried out, first on characterising the extrados technique (1997–2004), and then of FRP strengthening and combined interventions (2005).

As regards strengthening with timber flanges and dowels, various types of connections (wood or steel dowels, screws or rivets, or a combination of them), of various lengths (from 110 to 180 mm) or diameters (from 20 to 29 mm for wooden connections, and from 12 to 20 for steel ones), with or without the use of different types of glue (vinyl, phenol, melamine, resorcinol, or epoxy resins) were tested (Modena *et al.*, 1997, 2004). Characterisation was performed by push-out tests on the various connection types, under loading control and according to the UNI-EN 26891 (1991) standard (Figure 6a), which allows evaluation of the main parameters characterising the connection (Figure 6b). The simplified design method for mechanically jointed beams with deformable fasteners was developed by Möhler (1956) and is assumed by Eurocode 5 (2003). The compound section is characterised by effective bending stiffness $(EJ)_{eff}$, as in the equations of Figure 6c,

where subscripts 1 and 2 refer to the stiffening plank and the existing beam, respectively, d is the distance between the barycentres of plank and beam, γ ($0 \leq \gamma \leq 1$, where 0 and 1 refer to infinitely deformable and rigid connections, respectively) is the coefficient of efficiency of the connection, l is the beam length, s_i is the dowel spacing, and K_i is the value of the instantaneous slip modulus. This last parameter is conventionally estimated for the serviceability limit state (K_{ser}) and ultimate limit state (K_u) from the experimental load–displacement ($F-v$) curve obtained by push-out tests (UNI-EN 26891, 1991) (Figure 6a and b). In particular, according to Eurocode 5 (2003), the slip modulus of a connection for ultimate limit state K_u should be taken as $K_u = 2/3 K_{ser}$, where K_{ser} corresponds to the parameter K_s defined in UNI-EN 26891 (1991).

Connections that showed the best behaviour were also tested in beams under flexure, according to the UNI-EN 380 (1994) standard. The beams were all made of spruce timber, with beech dowels and screws spaced at five diameters, according to the requirements of Eurocode 5 (2003) (Figure 7). The moisture content of the specimens was

Figure 6: Push-out tests on compound sections: samples (a), typical experimental curve (b), parameters for definition of slip moduli K_i and (c) characterising stiffness of connection

Figure 7: Geometry and bending test set-up for T-beams, showing position of transducers

measured according to UNI 9091 (1987) after their construction and before carrying out tests. The reference value in compound beams before test was around 12 per cent; however, it was observed that small differences in moisture content did not cause any space at the dowel–hole interface.

The subsequent phase of the experiment was aimed at evaluating the structural behaviour of the FRP strengthening technique applied to wooden beams. Characterisation of the bond behaviour of CFRP laminates and the flexural behaviour of FRP-strengthened simple and compound beams was performed. Bonding was studied by pull-off tests, according to ASTM C1583 (2004) (Figure 8), and double-lap shear

Figure 8: Pull-off test set-up according to ASTM C1583 (2004)

Figure 9: Double-lap shear test set-up (dimensions in mm)

testing of CFRP strips (Figure 9) (see also Aiello and Sciolti, 2005; Piazza *et al.*, 2005). All specimens were made of spruce timber, and bending tests were carried out according to UNI-EN 380 (1994) and UNI-EN 480 (1997) (see Figure 7). Moisture content was measured according to UNI 9091 (1987) after beam construction (12 per cent) and before carrying out tests (up to 22 per cent). This difference in moisture content, probably accidentally due to transportation, was expected to influence the mechanical properties of the beams, as indicated in the relevant literature (Giordano, 1999; Piazza *et al.*, 2005). The same four-point test illustrated in Figure 7 was adopted for beams strengthened with FRP sheets.

TEST RESULTS OF LOCAL BEHAVIOUR

Timber connection with dowels

In the first experimental phase (1997–2001), push-out tests showed that the best behaviour of the compound section was obtained by any intermediate boarding between original beam and reinforcing plank (Modena *et al.*, 1997). When an empty space was left instead of the boarding, failure turned into combined shear–flexural collapse, with lower values of slip modulus and coefficient of efficiency (Table 1, Figure 10).

Table 1: Results of push-out tests: Average values (three tests for each condition) obtained during various experimental campaigns

Sample: name, fastener material, and type of connection			$\varnothing$ (mm)	Length (mm)	$F_{\max}$ (N)	F_{est} (N)	$v_{i,\text{mod}}$ (mm)	v_{fail} (mm)	K_s (N/mm)
<i>First experimental phase (1997–2001)</i>									
Sc20	Wood	Vinyl resin	20	130	8,612	8,326	0.62	11.91	5,721
Srm20	Wood	Phenol resin	20	130	8,561	8,243	0.77	7.21	4,400
Sn20	Wood	Resorcin resin	20	130	9,245	9,667	1.16	15.00	3,336
Scv20V	Wood	Vinyl+screws	20	130	10,894	10,895	0.65	10.04	6,757
S20	Wood	Dry	20	130	6,189	6,070	2.40	14.63	1,033
S20V	Wood	Dry+screws	20	130	9,042	8,542	0.84	15.00	4,068
St20*	Wood	Dry	20	110	7,325	7,438	0.87	10.96	3,436
Sct20V*	Wood	Vinyl+screws	20	110	15,783	15,292	0.65	10.04	8,011
Scv20**	Wood	Vinyl resin	20	130	4,192	4,236	0.97	10.59	1,866
Sv20**	Wood	Dry	20	130	4,725	3,772	1.01	11.01	1,495
Sc22	Wood	Vinyl resin	22	130	9,129	9,571	0.99	10.13	3,973
S22	Wood	Dry	22	130	6,067	6,625	3.06	15.00	867
ScM22	Wood	Vinyl resin	22	185	6,800	6,875	1.07	8.50	2,608
Sc26	Wood	Vinyl resin	25.4	130	9,472	9,535	0.85	14.15	4,933
S26	Wood	Dry	25.4	130	8,633	8,358	3.99	15.00	837
Bc26	Wood	Vinyl resin	25.4	110	8,263	7,925	0.74	15.00	4,313
B26	Wood	Dry	25.4	110	7,635	7,528	1.73	15.00	1,788
B26V	Wood	Dry+screws	25.4	110	8,415	8,688	2.16	15.00	1,614
Bc26V	Wood	Vinyl+screws	25.4	110	8,843	8,731	0.79	15.00	4,404
Sa20	Steel	Dry	20	130	8,331	7,868	2.46	15.00	1,332
Pre14	Steel	Epoxy resin	14	180	12,374	13,859	0.72	15.00	7,785
<i>Second experimental phase (2001–2004)</i>									
L20	Wood	Dry	20	130	5,606	5,994	1.92	10.07	1,270
L23	Wood	Dry	23	130	8,381	7,972	2.62	13.82	1,220
L26	Wood	Dry	26	130	9,979	9,278	1.59	14.86	2,337
L29	Wood	Dry	29	130	10,207	9,833	2.46	14.61	1,600
A12	Steel	Dry	12	130	6,213	5,971	3.15	15.00	759
A16	Steel	Dry	16	130	7,456	7,519	2.88	15.00	1,065
A20	Steel	Dry	20	130	9,310	9,358	3.86	15.00	999

Notes: * tested without boarding in pure shear (adhesion); ** tested without boarding, leaving empty space; $F_{\max}$: maximum load at failure; F_{est} : maximum estimated load; $v_{i,\text{mod}}$: modified initial slip, equal to 4/3 of difference between slip at 40% ($v_{0,4}$) and 10% ($v_{0,1}$) of maximum estimated load (F_{est}); v_{fail} : slip at failure according to UNI-EN 26891 (1991); slip modulus: $K_s = 0.4F_{\text{est}}/v_{i,\text{mod}}$; parameters required by current version of Eurocode 5 (2003)

Glued dowels, particularly when vinyl resins were used, showed better results than dry dowels (Figure 10). Screws improved the behaviour at small displacements (higher initial slip modulus), but their contribution was lost at displacements exceeding 10 mm. The best results in terms of connection efficiency were obtained with glued steel dowels (Table 1, Figure 10), although they had a stronger tendency to dowel bearing (splitting).

The second experimental phase (2001–2004) focused on optimisation of the diameter of dry beech wood dowels. Despite the lower K_s values obtained in the preliminary phase, for preservation purposes, due to their easier positioning and removability, dry connections combine advantages in execution and sufficient mechanical effectiveness compared with other fastening systems. The proper optimised diameter was sought among 20, 23, 26, and 29 mm on beech wood dowels (L) 130 mm long. Comparisons were carried out with low-diameter (12, 16, 20 mm) smooth stainless-steel dowels (A).

The failure mode of the various beech wood connections is shown in Figure 11. It was characterised by combined shear–flexural behaviour, where small-diameter dowels failed in bending, whereas larger-diameter ones behaved mainly in shear. The best results were obtained for specimen L26 (dowels of 26 mm diameter) as seen in Table 1

Figure 10: Comparison of various types of dowel connection. In dry connections, best results were obtained with beech dowel L26, since dowel St20 was tested without boarding in pure shear

Figure 11: Combined shear–flexural failure of beech wood fasteners: L20 (a), L23 (b), L26 (c), and L29 (d)

Figure 12: Prevalent splitting failure of hole for stainless-steel fasteners: A12 (a), A16 (b), and A20 (c)

Table 2: CFRP properties

Ultimate tensile stress	(MPa)	3550
Elastic modulus	(MPa)	230,000
Ultimate tensile strain	(%)	1.5
Nominal thickness	(mm)	0.165
Coefficient of expansion	(K ⁻¹)	10 ⁻⁷

Table 3: Results of pull-off tests

Specimen label	P_u	Tensile stress orthogonal to grain	Relative humidity	Failure mode S = substrate FM = fiber-matrix
	(N)	(MPa)	(%)	
PO/C1	2,630	2.05	12	FM
PO/C2	1,920	1.50	13	S
PO/C3	1,840	1.44	13	FM
PO/C4	2,420	1.89	12	S
PO/C5	2,310	1.80	12	S
PO/C6	2,160	1.68	12	S
Average value	2,213	1.73	12.33	
Standard deviation	301.3	0.23	0.52	

and Figure 10. Its maximum load at failure, F_{max} , was lower than in specimens L29, but the slip moduli had the highest values, leading to a stiffer and more efficient connection. On average, connections made with dry beech wood dowels showed better behaviour than those made with steel dowels. The difference was due to the different failure modes (see Figures 11 and 12): wooden dowels failed in a combined shear–flexural state, with slight splitting of the hole for the larger diameters, whereas connections made with steel dowels failed, due to the bearing of the hole, before any deformation of the dowels could occur.

CFRP–timber bond behaviour

Before the application of CFRP to the simple and compound beams, the bond behaviour of the fibre laminate on spruce timber was evaluated, by pull-off and double-lap shear tests (Figures 8 and 9). The mechanical properties of CFRP materials are listed in Table 2.

The pull-off tests were performed by gluing steel cylinders (40 mm in diameter) to the specimens with epoxy resin. After curing, six specimens were tested monotonically until failure. Spruce timber had relative humidity of 12 per cent. The average ultimate load (P_u) was 2210 N, and the average tensile stress orthogonal to the grain was 1.73 MPa (Table 3). This value is in good agreement with the relevant literature (eg, Giordano, 1999), which suggests 1.68 MPa as the ultimate value for tensile stress measured

Figure 13: Pull-off test, failure surface inside fibre-matrix

Figure 14: Pull-off test, failure surface inside wooden substrate

Figure 15: Double-lap shear test

Table 4: Results of double-lap shear tests

Specimen label	P_u (N) ultimate load on 2 CFRP sheets	σ_u (MPa) average tensile stress on 1 CFRP sheet	τ_{average} (MPa) average bond stress over anchoring length of 150 mm
ST-C1	18,788	1,139	1.25
ST-C2	19,177	1,162	1.28
ST-C3	24,404	1,479	1.63
ST-C4	22,532	1,366	1.50
ST-C5	20,289	1,230	1.35
ST-C6	25,516	1,546	1.70
Average value	21,783	1,320	1.45
Standard deviation	2,805	170	0.19

Figure 16: Bonding failure inside wooden substrate: specimens ST/C1 (a) and ST/C3 (b)

orthogonally to grain for spruce timber. Failure surfaces were mainly located inside the substrate (Figures 13 and 14), revealing good bond behaviour between CFRP and spruce timber.

For double-lap shear tests, the instrumentation illustrated in Figure 9 was set up (Figure 15); six tests were executed in displacement control. Strain gauges were applied along the CFRP anchoring zone (150 mm) to calculate the effective anchoring length due to the development of bonding shear stresses. As in the previous case, spruce timber had a relative humidity of 12 per cent. CFRP ultimate loads and tensile stresses were experimentally determined (Table 4). A first evaluation of average bond stress over the anchoring length gave a value of 1.45 MPa (Table 4). Failure surfaces involved the wooden substrate, again confirming the good bond behaviour between CFRP and spruce timber (Figure 16).

It is worth noting that local bond shear stress may be several times higher than average stress over the anchoring length. This is due to the nonlinear distribution of local shear stresses, as shown in Figure 17, in which the highest value (7 MPa) is comparable with the ultimate shear stress parallel to grain (9 MPa), as noted in the relevant literature (eg, Giordano, 1999) for spruce timber.

Figure 17: Local shear bond stresses, specimen ST/C4

TEST RESULTS ON BEAMS

Strengthening with optimised hardwood dowels with a mean diameter of 26 mm and a length of about 130 mm was adopted, for traditional reinforcement of existing floor beams with additional planks. The optimised diameter allows combined shear–flexural behaviour, avoiding both pin rupture and damage to plank and beam.

The geometrical dimensions of the basic rectangular beams were $b = 115$ mm $h = 145$ mm, to which a flange of $b = 250$ mm $h = 50$ mm was added to build the compound beams; the extrados was strengthened by boardings 3 cm thick.

The physical and mechanical characteristics of the wood used in the experimental samples are given in Table 5. The spruce timber employed for the rectangular sections of the compound beams and reinforcing planks had a basic bending elastic modulus of 10,000 MPa (according to UNI-EN 480, 1997) and a shear modulus of 721 MPa. The rectangular beams used later for FRP strengthening had high relative humidity (16–22 per cent), and reduced mechanical properties by up to 7,000 MPa for the bending elastic modulus. It is worth noting that conventional values for the elastic modulus of spruce timber are around 11,000 MPa, as reported by Giordano (1999). In particular, rectangular beams tested in original and FRP reinforced conditions revealed 16 per cent of relative humidity content, whereas for T-beams strengthened with FRP this parameter rose to 22 per cent.

Three rectangular-section beams were tested under flexure in original and strengthened conditions, by gluing CFRP sheets covering the base at the intrados for 100 mm (for CFRP properties, see Table 2). The same strengthening was applied to three compound sections preliminarily strengthened as described above.

Figure 18 shows the ultimate behaviour of plain beams, both rectangular and compound sections, and Figure 19 compares the reinforced samples. Average behaviour is also compared in Figure 20.

For rectangular beams, an average ultimate load of 12.54 kN and an ultimate deflection of 58.75 mm were detected. Bending behaviour was slightly nonlinear (Figure 20); in

particular, the beams collapsed at midspan, with a crack following the direction of the fibres (Figure 18a).

Plain compound beams preliminarily strengthened on the upper side were loaded to about 37 kN, and two of the three samples were loaded until failure to measure maximum strength. Fairly elastic behaviour was observed during the first loading cycle (UNI-EN 380, 1994). In the second cycle, failure occurred within the field of large displacements, at an average load of 43.90 kN and an average displacement of 117 mm. In particular, the beam collapsed at midspan and a crack, following the direction of the fibres, involved its whole width (Figure 18b). The chosen fasteners, of diameter 26 mm, showed good behaviour. Only at the maximum load did they reveal small vertical displacements and slight splitting of the holes. The overall flexural behaviour of the tested specimens is shown in Figure 20.

Table 5: Properties of wood used in samples

Wood	Use	Volume mass (kg/m ³)	Compressive strength (MPa)	Flexural strength (MPa)	Shear strength (MPa)
Spruce	Rectangular beams, planks, and boarding	455	44–45	66	—
Beech	Dowels	729	58–63	121	19

Figure 18: Bending failure in original samples: (a) simple rectangular-section timber beam; (b) compound timber beam

Figure 19: Bending failure in beams strengthened with CFRP sheet: (a) simple timber beam, cracking of timber and an FRP; (b) compound timber beam, detachment of fibres

Figure 20: Comparison among flexural behaviour of tested beams (curves represent average data of three tests in each condition; acquisition of displacement was interrupted before collapse to preserve transducer integrity)

Tests on rectangular-section beams strengthened with FRP sheets confirmed the improved bending behaviour described by other researchers (eg, Gentile *et al.*, 2002; Borri *et al.*, 2004). The average ultimate load was 25.11 kN, with a deflection of 129 mm. These increases were, respectively, 100 and 122 per cent of those of plain beams. Failure was characterised by abrupt rupture of the CFRP and fibres in the tensile zone (Figure 19a).

Compound timber beams strengthened by CFRP sheets on the underside showed an ultimate load of 32.91 MPa and a corresponding deflection of 110 mm. These values were higher than those of simple beams strengthened by CFRP sheets, but smaller than those of compound timber beams in plain conditions (see Figure 20). Failure was characterised by sudden peeling of the CFRP sheets.

These results indicate not only that the combined technique applied at the upper surface increases strengthening level, but also that the humidity content in the wood before applying an FRP should be carefully checked, as it may influence the overall efficiency of the technique.

Confirmation of this was provided by direct comparison of bending stiffness (EJ) in the various test conditions and the theoretical values were computed according to Eurocode 5 (2003) (Figure 21). As expected, for rectangular beams this parameter decreased, due to the progressive plasticisation of the wood in the compression part of the section.

For compound sections strengthened only at the upper side, comparison of experimental results and theoretical bending stiffness, and assuming $K_{ser} = K_{ser, \emptyset 26}$, revealed good agreement at a load corresponding to the serviceability state (applied load lower than or equal to 15 kN).

In simple rectangular-section beams strengthened with an FRP, bending stiffness, computed by homogenisation of the cross-section (Figure 4), showed a trend almost constantly close to the corresponding theoretical value up to a load of 15 kN, after which it decreased, due to progressive plasticisation of the wood in the compressed zone. This behaviour was mainly responsible for the reduced deflection in simple beams strengthened by an FRP.

Figure 21: Comparison between experimental and theoretical average bending stiffness values

Lastly, the poorer performance of compound beams strengthened additionally at the underside with CFRP may be attributed to their high relative humidity, which does not allow even the initial stiffness of unreinforced compound beams to be reached. The theoretical value of bending stiffness, computed according to Eurocode 5 (2003) using homogenised main beam as in Figure 4, was higher than the experimentally determined value.

CONCLUSIONS

Flexural strengthening of timber floors may be efficiently improved by the use of compatible techniques, applied by overlapping planks at the upper surface, and connecting them to the main rectangular beams with hardwood fasteners. This technique has been sufficiently validated by experimental campaigns carried out at the University of Padova in the last decade, and it has also been proposed and applied in some case studies.

The application of FRP sheets at the underside of the floor is a promising method of strengthening main beams in order to carry tensile stresses due to bending. Proper preparation of the substrate at the interface and control of the humidity content in wood are, however, particularly important in influencing final mechanical behaviour.

Comparison of results in plain rectangular sections and compound beams strengthened at the upper surface with the 'dry' technique revealed that their ultimate capacity was 3.5 times higher in the strengthened configuration. This advantage fell to about 2.0 times when simple beams were reinforced at the underside with CFRP but was still positive, regardless of the high relative humidity (around 16 per cent). The concurrent presence of upper and lower techniques did not yield the same advantages as with the single application of a mechanically jointed flange, probably due to the high humidity (22 per cent) in the beams, even when reinforced at the underside with an FRP, in comparison with the first experimental work (12 per cent). An increase of about 30 per cent was, however, measured in fully strengthened beams in comparison with rectangular

beams reinforced at the underside with an FRP, thus evidencing the superiority of the 'dry' connection technique on final beam behaviour (relative humidity changes from 16 to 22 per cent from rectangular to T-sections, both in intrados-strengthened conditions).

Control of humidity is confirmed to be very important: it influences the bending elastic modulus of the wood (average of 30 per cent reduction), ultimate strength in bending conditions (36 per cent on compound beams), and bending stiffness (32 per cent reduction in serviceability state).

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