Reinforcement of maritime pine cross-laminated timber panels by means of natural flax fibers

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Abstract

The present paper shows the first results of an ongoing research aimed at studying the potentiality of the combination of laminated timber and natural fibers to obtain high-performance structural elements. The experimentation conducted has involved a set of Cross Laminated Timber (CLT) panels made of maritime pine grown in Sardinia (Italy) and externally reinforced with natural flax fibers fabrics. A bending test program has been carried out on two CLT layouts, three-layers and five-layers panels, for a total of 34 specimens. Three-layers panels have been tested with single and double strip of flax fibers aiming to evaluate any difference in the rupture mechanism, capacity and stiffness. The proposed technique allows a straightforward application on the intrados of the panel, aimed at increasing its capacity and stiffness. Results show that in case of three-layers panels a significant increment of load-carrying capacity and stiffness has been achieved, whilst for five-layers panels the effectiveness of the reinforcement is negligible. Variations in the failure mechanisms of reinforced panels have been discussed.

Keywords: Cross Laminated Timber panels, Reinforcement with natural fibers, Strength increment, Stiffness increment.

Introduction

Production of Cross Laminated Timber (CLT) is recently increasing due to its remarkable advantages [1]. CLT technology is economical and particularly effective for modular buildings, since CLT panels can be effectively utilized for both horizontal and vertical elements [2]; moreover, CLT technology, due to its ease of assembly, can be employed for assembling prefabricated panels in case of large spans and guaranties a rapid construction [3]. If properly designed, CLT technology has good performance when exposed to fire [4], and the construction system is safe in case of earthquakes [5, 6].

CLT technology has been developed in Europe in the 1990*s* and consists of solid wood panels, made at least of three cross-bonded layers of solid timber boards [7-9]. The wood species typically utilized for this technology are spruce and fir.

In recent years, different wood species have been investigated aiming to consider their application for Glue Laminated Timber (glulam or GLT) or CLT structural elements. Frese and Blaß derived the characteristics in bending of beech glulam [10]; Castro and Paganini investigated the properties of small sized joint-free composed laminated beams of poplar and eucalyptus in different combinations [11]; the feasibility of manufacturing three-layer Cross Laminated Timber using fast-grown small diameter eucalyptus wood was evaluated by Yuchao Liao et al. [12]and by Pangh et al. [13]; Minjuan He et al. [14] studied the bending and compressive properties of CLT panels made from Canadian hemlock; maritime pine from Sardinia (Italy) and radiata pine from New Zealand to be used in CLT have been studied by Concu et al. [15], Giaccu et al. [16] and Fortune et al. [17] respectively.

With increasing efforts to promote the use of sustainable materials such as timber in the construction industry, considerable potentiality is associated with the use of low-grade timber in CLT panels because the lamination and the system effect in CLT production reduce the influence of the irregularities of timber due to its organic nature, such as geometrical defects (e.g. wane, warp), strength reducing defects (knots, slope of grain, density, rate of growth, fissures), biological damage (fungal and insect) and other characteristics (e.g. reaction wood) [18-20]. As an example, Cherry et al. discussed in [21] new challenges and developments for incorporating of out-of-grade sawn pine in CLT building systems, while Colin et al. discussed in [22] the novel concept of reusing secondary timber as feedstock for CLT.

This attention to sustainability, reuse and restoring of construction materials, on one hand is encouraging new studies on restoring and reinforcing of existing timber structures, on the other hand is exploiting the possibility of manufacturing new composite structural timber elements.

In this field various studies regarding the strengthening of timber elements by using Fiber Reinforced Polymers (FRP) based on epoxy resins and artificial fibers have been published, several of which were focused on resins-timber bonding properties [23-25]. In Italy guidelines have been issued by the National Research Council [26], providing preliminary provisions on the design of FRP reinforcements for timber elements. Results of investigations [23, 27] show that there are improvements in the performances of timber elements and advantages in terms of strength and to a lesser extent of stiffness properties. Different tests have been carried out concerning various types of artificial carbon and glass fibers reinforcements, with and without pre-stressing, highlighting beneficial effects on solid beams [27-31] and glulam beams [32-35]. Moreover, recent studies on shear reinforcements have been performed [23, 29, 36], dealing with the improvement of the load-carrying capacity of existing timber beams by means of external reinforcements, such as FRP plates or fabrics [37], or internal reinforcements, such as FRP rods and pins [30]. Recently, flexural strengthening consisting in steel fibers cords glued in the wooden beams have also been tested [38].

However, the increase in awareness of the need of environmentally sustainable products is leading to the use of natural materials, readily available and more environment-friendly than products based on artificial/chemical fibers. Composite materials based on natural fibers have several advantages due to their straightforward application, low production costs, renewability and biodegradability [39]. In addition, natural fibers ensure several advantages in terms of mechanical properties such as tensile strength and lightness. Borri et al. [40, 41] carried out an experimental campaign on timber elements reinforced in the tension zone through the application of strips of natural flax, hemp, bamboo and basalt fibers; Speranzini and Tralascia [42] performed experimental tests on elements made of LVL wood and elements in solid wood reinforced with FRP in natural fibers of basalt, flax and hemp; Moezzipour et al. [43] investigated the reinforcing effect of date palm and kenaf fibers on practical properties of plywood manufactured from horn beam wood (Carpinus Betulus); Raftery and Kelly [44] carried out an experimental test program in which the low-grade GLT has been reinforced using bonded-in basalt FRP (BFRP) rods, while Pengyi et al. [45] tested the reinforcing effect of BFRP sheets on glulam beams; Carvalho et al. [46] presented an experimental study of Eucalyptus Grandis and Pinus Elliiottii timber beams reinforced with sisal fibers laminated composite materials and Mascia et al. [47] performed bending test on Glulam beams of Pinus species reinforced by Sisal fibers.

To the authors knowledge, literature doesn’t show evidences of FRP reinforcements applied on CLT panels, least of all natural fiber reinforcements, since CLT construction technology is rather new; moreover, the authors consider of some interest the possibility of providing such reinforcement on existing CLT slabs and walls in case of design errors, or local stress concentrations due to openings (e.g. for staircases) and other geometrical irregularities, for which the proposed reinforcement approach would allow an effective solution.

In the present work, CLT specimens made of maritime pine (Pinus Pinaster) timber grown in Sardinia have been reinforced with external flexural reinforcement by means of one and two layers of flax fabrics fibers. The specimens have been therefore tested aiming to investigate their performances in terms of load-carrying capacity, deflection and rupture mechanism. Both three and five-layers panels were tested, in order to detect any difference in their mechanical behavior and in the effectiveness of the flexural reinforcement.

Materials

Experimental tests have been extended to a total number of 34 CLT panels made of maritime pine boards previously graded according to the visual strength rules developed at the Department of Civil, Environmental Engineering and Architecture (DICAAR) of University of Cagliari in cooperation with the CNR IVALSA of Florence, [15, 16, 18, 48] according to UNI 11035-1 [49] and UNI 11035-2 [50]. Two series of panels have been examined: three-layers panels (60-PF), both non-reinforced and externally reinforced with a single or double layer of flax fibers fabrics, and five-layers panels (100-PF), both non-reinforced and reinforced with a single layer of reinforcement.

A direct comparison between reinforced and non-reinforced panels has been carried out in the present work. Moreover, the two typologies of reinforced CLT panels (three and five layers lay-out) were investigated and compared aiming at pointing out any difference in the effects provided by the reinforcement.

Timber

CLT specimens are composed by layers of finger-jointed maritime pine boards, crosswise arranged and glued together. Boards have been previously graded and sorted into strength classes according to EN 338 [51] as C16 (outer and central layers for 100-PF,outer layers for 60-PF) and C14 (inner layers). Mutual adhesion of layers was secured by applying a pressure of 0.1 MPa by means of a vacuum press. The panels manufacturing took place at the Area Legno Factory in Pescara (Italy). Panels layout is shown in Fig.1.

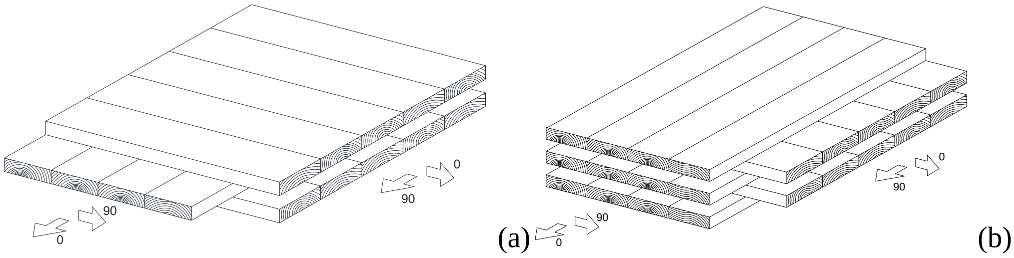


Fig. 1. Scheme of (a) three-layers 60-PF CLT panel (b) five-layers 100-PF CLT panel.

Cross-section features and main properties of the CLT tested specimen are shown in Table 1 and Fig.2 respectively.

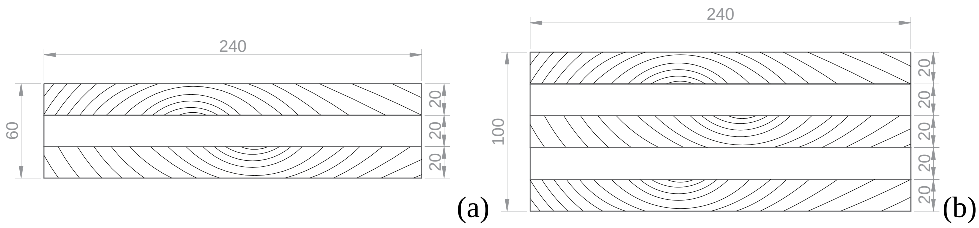


Fig. 2. Cross section features of the considered CLT specimens: (a) 60-PF and (b) 100-PF

Table 1 Specimen properties.

Series	Layers	Boards thickness	Specimen length	Specimen width	Specimen thickness	Boards strength class
60-PF	3	20 mm	1280 mm	240 mm	60 mm	C16 outer layers
						C14 inner layers
100-PF	5	20 mm	2000 mm	240 mm	100 mm	C16 outer layers
						C16 central layer
						C14 inner layers

Fibers

Materials for fibers reinforcements were provided by Innovation s.r.l. (Fidia - Technical Global Services). Reinforcements are made by a high-strength balanced mesh fabric, highly stable due to the particular weave and side seams. The bidirectional flax fibers fabric FIDFLAX GRID 300

HS20® was used supplied in roll of 1 m in width and 15m in length. Physical and mechanical properties of fabric have been recovered from the manufacturer technical sheets and are resumed in Table 2 and Table 3, while Fig. 3 shows some of the steps of the reinforcement application on CLT specimen.

(a) (b) (c)

Fig. 3. Application steps of the reinforcement on a CLT specimen (a) flax fiber, (b) fiber positioning, (c) resin application.

Table 2 Properties of dried fabric (from manufacturer).

Flax fiber (yarn)	
Tensile strength	512 MPa
MOE	21.4GPa
Density	1.5 g/cm^3
Ultimate Strain	3.27%

The flax fabric has been applied at the intrados of the CLT specimen strip by using FIDSATURANT HM-T, a solvent-free product based on a bi-component thixotropic epoxy resin. Component A is of a milky color with a viscosity of 350 GPa and density of 0.97 g/cm^3, component

B is black with a viscosity of 300 GPa and density 1.2 g/cm^3. The mixture of the two components provides a dark gray resin with a density of 1.1 g/cm^3.

Table 3 Properties of impregnated fabric (from manufacturer).

Impregnated fabric	
Number of wires/cm	4.3/cm
Mass	300g/m^2
Equivalent thickness of FRP	0.1mm
Characteristic tensile strength of FRP	459MPa
MOE	20GPa
Ultimate strainat rupture of FRP	1.74%

The primer FIDPRIMER has been applied on the CLT specimen surface first. It is a solvent–free bi-component thixotropic epoxy resin, whose use is suggested by the manufacturer in order to ensure a good bonding of the reinforcement to the support according to the hypothesis of perfect adhesion between the two materials.

The resins have high mechanical performances for tensile and compression stresses and their main properties are reported in Tables 4 and 5 respectively.

Table 4 Properties of mixed resin (from supplier).

Name	FIDSATURANT HM-T
Workability time	15 [min]
Frost time	50 [min]
Exothermic peak	160 [C°]
Cross-linking time	15 [h]

Table 5 Properties of primer (from supplier).

Name	FIDPRIMER
Workability time	30 [min]
Frost time	60 [min]
Exothermic peak	190 [C°]
Cross-linking time	5 [h]

Bending test on CLT specimens

A total number of 34 CLT specimens have been bending-tested according to EN 408 [52]. Characteristics of the samples are shown in Table 6. The experimental set-up has been arranged in the laboratory of DICAAR.

Table 6 Tested specimens.

Series	Sample size	Non-reinforced sample size	Specimens with one-layer reinforcement	Specimens with two-layer reinforcement
60-PF	20	7	9	4
100-PF	14	7	7	0

Specimens have been tested, as shown in Fig.4, under four-point loading apparatus; loading has been increased monotonically until rupture by means of a hydraulic jack; vertical displacements have been measured by means of a Linear Displacement Transducer (LDT) placed in the mid span, at the center of the specimen tension edge. The technical features of the used LDT are: nominal displacement 50 mm, nominal sensitivity 2 mV/V, sensitivity tolerance ± 0.1 %, measure resolution 1 μm. Both loads and displacements were recorded while strength and stiffness of the specimens were calculated afterwards.

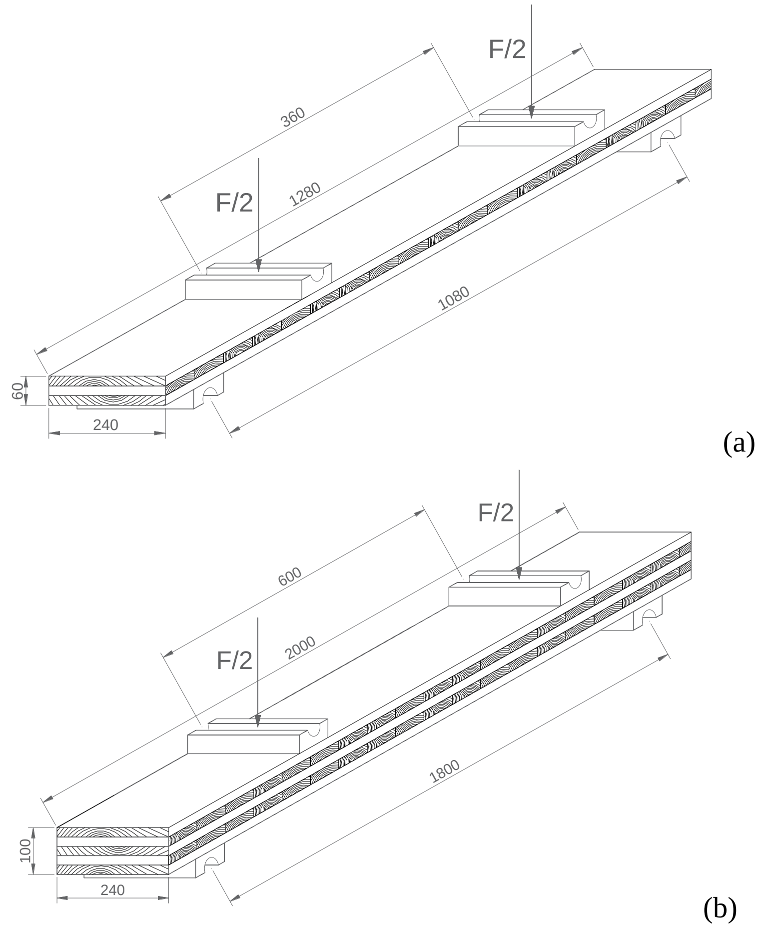


Fig. 4. Schematic view of loading configuration for bending tests of CLT specimens. (a) 60-PF specimens, (b) 100-PF specimens.

The specimens were first loaded at a low loading level (around 40% of the estimated ultimate load F_u), in order to evaluate displacements and bending stiffness in the linear behavior range, then the LDT was removed to avoid damages in case of sudden collapse and load was increased until failure. Specimen mid-span displacements after the LDT removal were extracted automatically from the test machine jack vertical displacements.

A global flexural stiffness $K=\Delta F/\Delta w$(N/mm) was derived from bending tests for both reinforced and non-reinforced elements as a linear regression between $0.1F_u$ and $0.4F_u$, were F is the load and w is the vertical displacement.

A testing machine having capacity of 300 kN and a maximum displacement of 300 mm was used. Testing load was applied at the third points of the span by means of a steel beam positioned on two rollers acting on the specimen extrados. Two steel plates (220mm × 70mm) have been interposed between rollers and specimen surface, in order to allow deflection of the specimen to develop without significant friction (Figs. 4, 5). The supports of the rollers at the two ends of the specimen allowed the element to move horizontally; local indentations and lateral torsional buckling effects were properly prevented. According to EN 408 the loading-rate has been set to 4 mm/min.

Two different experimental setups were arranged for the simply supported configuration depending on the specimen length to height ratio, in order to evaluate mechanical properties of the two specimen series. Tests set-up is resumed in Table 7.

Table 7 Test set-up.

Series	Length	Height	Loading Span	Distance between the loading points
	mm	mm	mm	mm
60-PF	1280	60	1080	360
100-PF	2000	100	1800	600

Bending strength f_b has been calculated through the following formula:

$$f_b = \frac{a}{2}\frac{F_u}{W_{eff}}. \quad (1)$$

where F_u(N) is the ultimate load of the panel, a (mm) is the distance between the two loading points and W_{eff} (mm^3) is the effective elastic section modulus of the specimens, calculated from its effective modulus of inertia J_{eff} (mm^4) as follows:

$$W_{eff} = \frac{2 \cdot J_{eff}}{t} \quad (2)$$

$$J_{eff} = \sum_n J_i + A_i \cdot z_i^2 \quad (3)$$

where t (mm) is the total depth of the panel, J_i (mm^4) the *i-th* layer moment of inertia, A_i (mm^2) is the *i-th* layer cross sectional area and z_i is the distance between the *i-th* layer centroid and the specimen cross section centroid.

Only longitudinal layers have been considered to be participating to determine J_{eff}. It must be noted that the presence of the reinforcement has not been taken into account in the transformed elastic section modulus *Wi*, therefore, a “conventional” wood strength of the reinforced specimen has been calculated through Eq. (1) neglecting the contribution of the reinforcement.

A deflection index D_i of the *i-th* CLT specimen is defined as:

$$D_i = \frac{w_{u,i} - w_{u,0}}{w_{u,0}} \quad (4)$$

where $w_{u,i}$ and $w_{u,0}$ are the displacements measured through the hydraulic jack of the testing machine at maximum load for the reinforced and non-reinforced specimen respectively.

Bending test on 60-PF CLT specimens

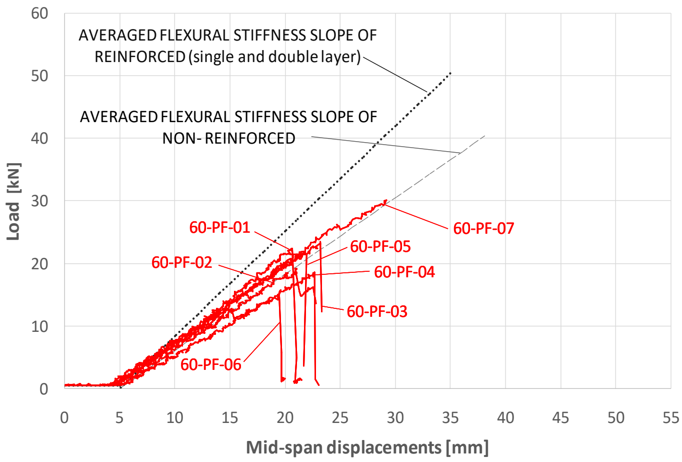
Bending tests have been carried out on a total number of 20 specimens of the 60-PF series (Fig.

5).

Fig. 5. Loading set-up for bending test of 60-PF CLT specimens.

In order to investigate the effectiveness of the applied reinforcement and to possibly perform a better comparison between reinforced and non-reinforced specimens, different groups of 60-PF specimens were considered: a first group, with increasing numbering from 60-PF-01 to 60-PF-07, has been tested without any reinforcement; a second group, with increasing numbering from 60-PF-08 to 60-PF-11 and from 60-PF-16 to 60-PF-21, has been tested with single layer reinforcements; a third group, with increasing numbering from 60-PF-12 to 60-PF-15, has been tested with double layer reinforcements.

Figure 6 shows results of the tests on the 60-PF specimens. A direct comparison between Fig. 6a and Fig. 6b highlights that the reinforcement has a beneficial effect in terms of global stiffness of the specimen which visibly increases its global rigidity, as pointed out by the slope increment of the average flexural stiffness in Fig. 6; moreover, a significant increment of the load-bearing capacity can be observed.



(a)

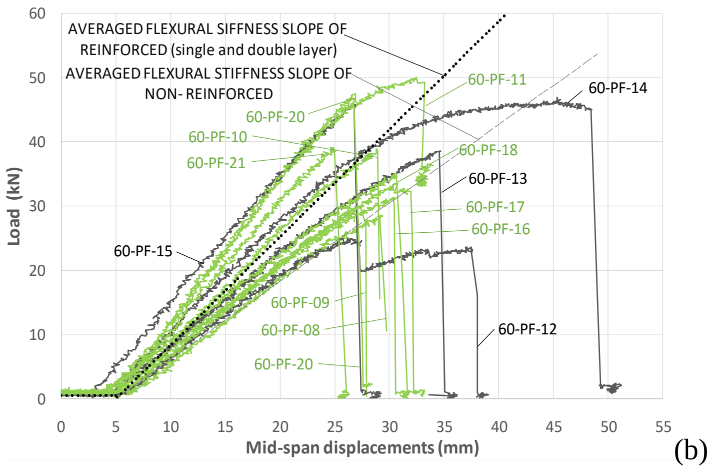


Fig. 6. Load-displacement curves for the 60-PF CLT specimens. (a) Non-reinforced. (b) Single (light color curves) and double layer reinforcement (dark color curves).

Table 8 reports a summary of the results and highlights that, on average, reinforced specimens show a remarkable increasing of the rupture load, of 63% and 73% for single and double layer reinforcement respectively, with a related deflection index of 31% and 65%. Moreover, a significant increment of the global flexural stiffness, of 37% and 28% for the single and double layer reinforcement respectively, can be noticed. On the other hand, it is worth noting that the double-layer reinforcement, if compared with the single one, marks a negligible improvement on rupture load and global stiffness of the specimens, but provides a marked increment of the deflection index. These outcomes are supported by the results of the Student's t test applied to the mean values of the parameters analysed.

Table 8 Test results of 60-PF specimens (mean values).

Series	Sample number	Rupture Load (kN)	Equivalent Flexural Stiffness (kN/m)	Deflection index D_i (%)
60-PF NR (not reinforced)	7	22.51±4.66	1221±71	-
60-PF R1 (1 layer)	9	36.65±7.37	1679±392	31.01
60-PF R2 (2 layer)	4	39.05±10.1	1570±344	65.12
Mean comparison (Student's t test)		Rupture Load	Equivalent Flexural Stiffness	
60-PF NR and 60-PF R1 $t^*(p=0.05) = 2.14$		$t = 4.4168$	$t = 3.0284$	
60-PF NR and 60-PF R2 $*(p=0.05) = 2.26$		$t = 3.7880$	$t = 2.6867$	
60-PF R1 and 60-PF R2 $*(p=0.05) = 2.20$		$t = 0.4870$	$t = 0.5676$	$t = 0.5807$

t= Student's test value; t^*= minimum t value for rejecting the null hypothesis with a 95% significance

It should be noted also that some reinforced specimens exhibit a significant variation of the rupture mechanism. For instance, 60-PF-14 exhibits a ductile failure mode, while specimen 60-PF-

11 shows a rolling shear failure (Fig.6b and Fig.8). As illustrated in Fig.7, remaining specimens went through a brittle failure characterized by a bending rupture mechanism (flexural cracks in the tensile area); the collapse is generally characterized by transversal cracks propagating through the depth of the cross section and occurring when the stress level reaches the value of bending strength. As shown in Fig.8, a rolling shear failure mechanism developed exclusively in the case of the specimen 60PF-11; the mechanism is confirmed by the respective load-displacement curve illustrated in Fig. 6b which reports a residual flexural strength of the specimen due to the presence of the middle span reinforcement after the rolling shear failure has occurred. It is noteworthy that no bonding failure of the reinforcing strips occurred in any of the considered specimens while the composite fracture was triggered by the propagation of the timber cracks through the depth of the specimen.

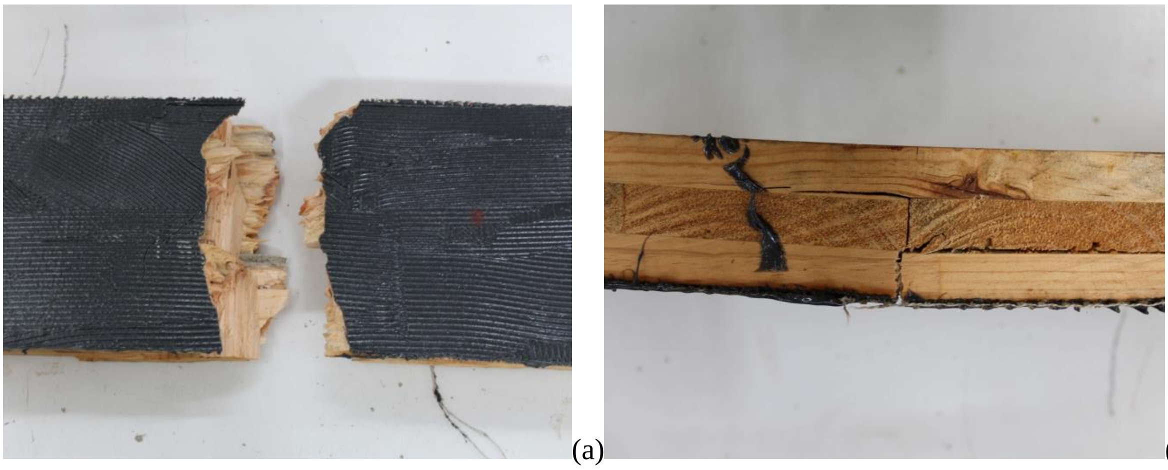

(a) (b)

Fig. 7. Flexural cracks of representative rupture mechanism of the single layer strengthened CLT specimen. (a) 60-PF-13, (b) 60-PF-10.

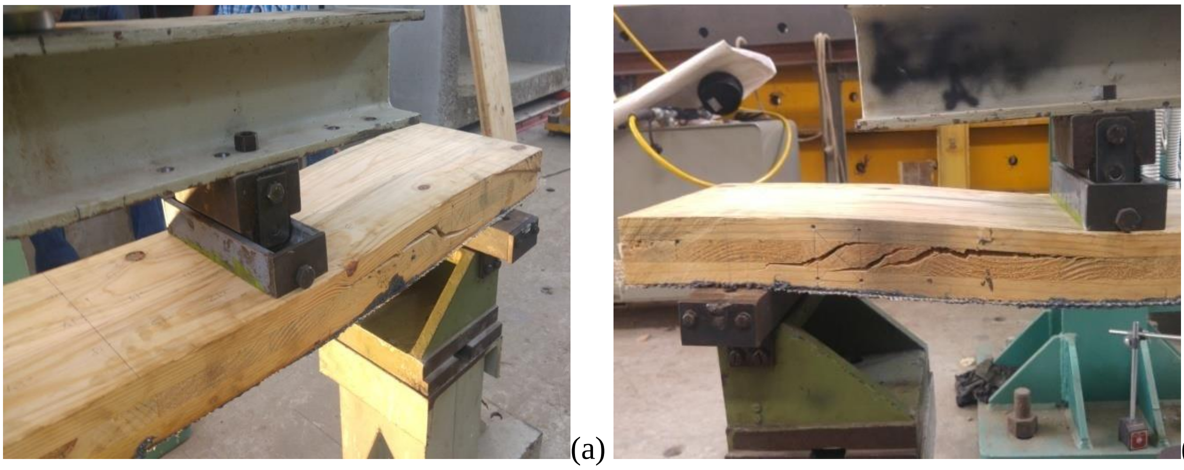

(a) (b)

Fig. 8. Rolling shear rupture mechanism of the single layer strengthened 60-PF-11 CLT specimen. (a) Failure mechanism, (b) Rolling shear cracks.

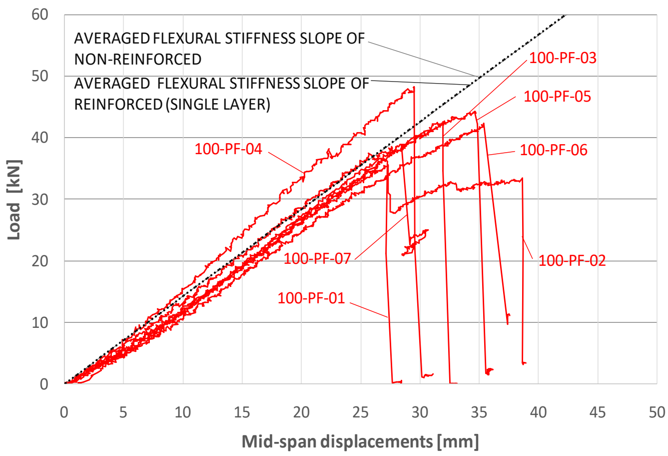
Bending test on 100-PF CLT specimens

Bending test have been carried out on 14 specimens of the 100-PF CLT series (Fig.9).

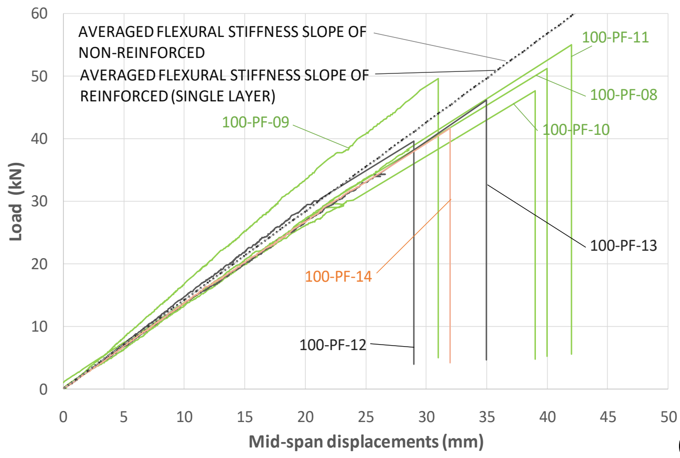
Fig. 9. Laboratory set-up of loading configuration for bending test of 100-PF CLT specimens.

100-PF specimens have been sorted into two groups: a first group, with increasing numbering from 100-PF-01 to 100-PF-07, has been tested without any reinforcement; the second group, with increasing numbering from 100-PF-08 to 100-PF-14, has been tested with a single-layer reinforcement.

Figure 10 shows the results of the bending tests conducted on non-reinforced and reinforced 100-PF specimens. A direct comparison with the results of the 60-PF typology shows that for both bending strength and global stiffness the beneficial effects are negligible.



(a)



(b)

Fig. 10. Load-displacement curves for the 100-PF CLT specimens: (a) non-reinforced, (b) single layer reinforcement.

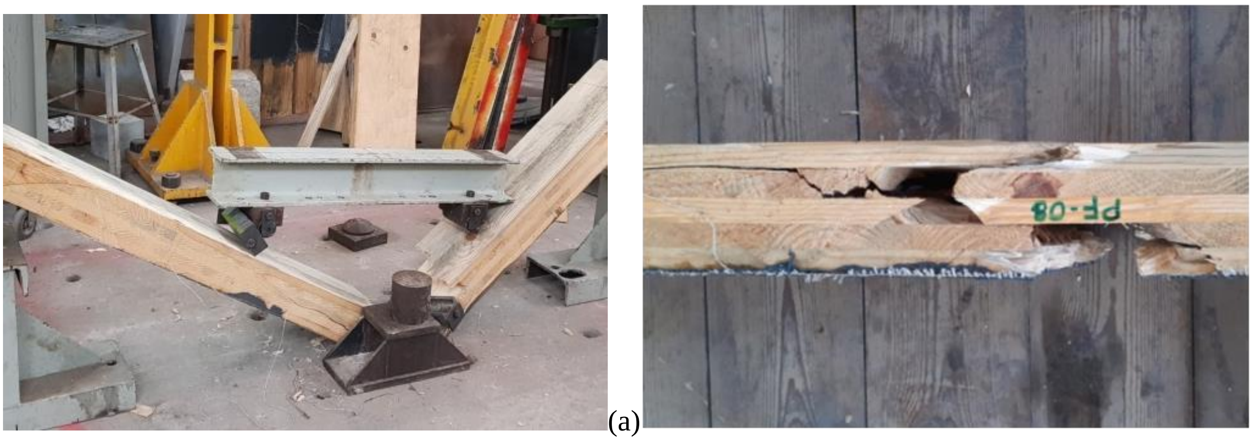
Results of the 100-PF specimens are summarized in Tab.9; according to the results of the Student's t test applied to the mean values, rupture load and equivalent flexural stiffness are not appreciably affected by the reinforcement, as pointed out in Fig. 10 by the same slope of the averaged flexural stiffness; the deflection index of the reinforced specimen is about 6%.

Table 9 Test results of 100-PF specimens (mean values)

Series	Sample size	Rupture Load (kN)	Equivalent Flexural Stiffness (kN/m)	Deflection index D_i(%)
100-PF (not reinforced)	7	42.56±4.48	1416±142	-
100-PF (1 layer)	7	47.25±4.35	1420±154	6.41
Mean comparison (Student's t test) $t^*(p{=}0.05) = 2.18$		$t = 1.7802$	$t = 0.0464$	

t= Student's test value; t^*= minimum t value for rejecting the null hypothesis with a 95% significance

Figure 11 shows the failure mechanism of the 100-PF-08 specimen (brittle bending failure) in the tension side, that is the type of rupture exhibited by both the reinforced and non-reinforced 100-PF specimens. No rolling shear collapse modes were witnessed for this typology. Even in this case bonding failure or detachment of the reinforcement layers were not observed.



(a) (b)

Fig. 11. Rupture mechanism of the single layer strengthened 100-PF-08CLT specimen. (a) Global brittle bending failure, (b) Local flexural cracks.

Results comparison and discussion

Results of performed loading tests suggest that fiber composite external strengthening provided a beneficial effect on the global behavior of the CLT specimens almost exclusively in the case of 60-PF specimens, in which a remarkable increment of mechanical characteristics has been detected, such as ultimate bending load, equivalent flexural stiffness and deflection index. Namely, an average increment of load carrying capacity of 63% and 73% respectively for single and double layer reinforcements and a related deflection index of 31% and 65% has been achieved. On the other hand, for the case of 100-PF layout specimens reinforced with one fabric layer, no remarkable beneficial effects have been noticed in the rupture load and almost no improvement in the stiffness. In this case the deflection index is about 6 %.

A comparative analysis of the bending strength for the reinforced typologies (60-PF and 100-PF) is reported in Table 10; the comparison points out that the maximum bending strength achieved in the most stressed fiber for both reinforced specimens' typologies is approximately the same; these results are supported by the Student's *t* test, applied to the mean values for $p<0.05$, performed for the couples of groups 60-PF R1, 100-PF R1 and 60-PF R2, 100-PF R1. These outcomes deserve further theoretical-experimental investigations, starting from the hypothesis that the reinforcement is able of granting a maximum value of bending strength of the reinforced CLT specimens thanks to its ability, acknowledged by various studies [29, 33, 36, 38, 40, 42], to overcome stress concentrations due to wood defects, especially those located in the tensile zone responsible of cracks onset and propagation leading to failure, thus mitigating and redistributing the stress field around knots, grain deviations and other wood irregularities.

This capability of the reinforcement would explain the greater improvement of load-bearing capacity of the 60-PF respect to the 100-PF, since given a certain value of bending strength granted by the reinforcement, a different increment of carrying capacity is expected due to the different size of the specimens.

Table.10 Bending strength comparative analysis.

	60-PF R1 Reinforced 1 layer	60-PF R2 Reinforced 2 layer	100-PF NR Non-reinforced	100-PF R1 Reinforced 1 layer
Bending Strength (MPa)	44.87±8.91	48.27±12.29	37.19±3.72	44.75±5.07

Mean comparison (Student's t test)	60-PF R1 and 100-P NR $t^*(p=0.05) = 2.14$	60-PF R2 and 100-P NR $t^*(p=0.05) = 2.26$	60-PF R1 and 100-P R1 $t^*(p=0.05) = 2.14$	60-PF R2 and 100-P R1 $t^*(p=0.05) = 2.26$
	$t = 2.1298$	$t = 2.2894$	$t = 0.0330$	$t = 0.6832$

t= Student's test value; *t**= minimum *t* value for rejecting the null hypothesis with a 95% significance

The experimental tests showed in most cases fragile bending failures, due to tensile fractures, so that none or minor plasticity is supposed to occur in the compression side of the specimens; this fact, according to the literature [26, 34, 53], is desirable in order to effectively exploit the reinforcements benefit in the case of solid and glued laminated timber.

Table 10 also reports a comparative analysis between bending strengths of reinforced three-layers specimens (60-PF) and non-reinforced five-layers specimens (100-PF); it is interesting to note that the application of one or two reinforcing fabric layers allows the three-layer specimens (60-PF) to achieve values of bending strength comparable with those of the non-reinforced five-layer specimens (100-PF), as supported by the results of the Student's t test, applied to the mean values for $p<0.05$. This outcome encourages further investigations on the use of natural fibers composites as reinforcing technique in CLT timber specimens and their application to improve specimens bending strength, especially in case of thin panels with reduced number of layers (such as 60-PF). E.g., this option can be attractive in case of existing CLT slabs or walls damaged or with incorrect design, or in case of bending moment concentrations, that can occur due to concentrated loads, planimetric irregularities or openings (e.g. for staircases). In addition, possible improvement of mechanical properties of the panels with consequent reduction of their thickness could be a solution that fits well with both highly-demanding structures where the depth of the elements is important [54] and the current sustainability trend of the building sector. In fact, despite wood is the eco-compatible building material par excellence, being natural, biodegradable, renewable, less energy-consuming in the manufacturing and construction phases compared to traditional competitors such as concrete and steel, capable of storing CO_2 from the environment; despite the unquestionable performance of construction systems such as GLT and CLT; the manufacturing of laminated timber presents some problems of environmental impact, linked on the one hand to the possible intensive exploitation of the forests [55] and above all to the production process of the laminated timber itself. The manufacturing of the laminated panels requires considerable amount of energy embedded in the process: sawing, drying, trimming, grading and finally bonding. It has to be noted that drying is the most environment-impactful phase of the entire process [56, 57], due to the high energy required to remove moisture from the wood and the possible emission of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) [58]. Bergman and Bowe [59] report that the drying process consumes approximately 70-80% of the total energy needed to produce hardwood lumber, and that the sawing process consumes the highest share of electricity. The possible reduction of the number of boards of the CLT panels could therefore allow a saving in terms of energy consumed and of waste produced during the process. Of course this possibility must take into account the sustainability of the natural fiber production process and the reinforcement bonding process. About production, Sanjay et al. [60] propose a comprehensive review of techniques for manufacturing natural fibers as reinforcements in composites and list a number of advantages offered by natural fibers over synthetic ones, including small energy consumption for production, low CO_2 emission, simply and environmental-friendly processing methods. Dittenber and Ganga Rao [61] present a very comprehensive review on the use of natural fibers in infrastructure and highlight that compared to most synthetic fibers, natural fibers are low-cost and easier to handle and require around 20–40% of the production energy. Natural fibers may also present some problems related to their hydrophilic characteristics that should be taken into account [60, 61]. Regarding the bonding of the reinforcement, the high economic and environmental cost of the commonly used epoxy resins must be considered, especially in relation to human toxicity and cost of production of raw materials. In this regard, Brunetti et al. [54] highlight how the substitution of the epoxy resins used for the application of a CFRP reinforcement with the polyurethane glue commonly used in the manufacturing of laminated timber would determine the optimization of the production process of reinforced laminated timber without compromising the performance of the elements. In addition, it is worth noting that current research trend is exploring the possibility of using glues based on natural substances both for the application of the reinforcement and for the gluing of the boards of the laminated wood elements in order to mitigate the high environmental impact of synthetic resins [62, 63].

The preceding considerations encourage the study of a possible reduction of the layers in laminated timber elements to the advantage of the use of natural fibers reinforcement, but there is certainly a need for quantitative life-cycle analysis to clearly demonstrate that this is indeed the case.

Conclusions

The paper shows the results of an ongoing research activity carried out on CLT specimens strengthened by natural fiber reinforcements; reinforcement has been applied in the tension zone of the specimens through the application of an external flax fibers layer. Two different typologies of CLT specimens were tested, 60-PF and 100-PF specimens, with three-layers and five-layers layout respectively. For both typologies, non-reinforced and reinforced specimens' behaviors were compared addressing the evaluation of any beneficial effect in terms of load-carrying capacity, deflection and failure mode. The following main results have been pointed out.

A remarkable increment of mechanical characteristics, such as ultimate bending load, equivalent flexural stiffness and deflection index due to the presence of the reinforcement has been noticed for the 60-PF typology, whilst negligible improvements have been detected in the 100-PF typology.

Most of the reinforced specimens exhibit a brittle failure, so that none or minor plasticity is supposed to occur in the compression side of the specimens; the failure is characterized by flexural cracks in the tensile side, the rupture being generally characterized by transversal cracks propagating through the cross section and occurring when stress level reaches the bending strength. Rolling shear failure has been noticed in only one specimen belonging to the 60-PF reinforced group; this failure mode can potentially occur in all the cases of excessive bending reinforcements and should be carefully checked for a safe design of the specimen. In all examined cases no bonding failure of the reinforcements has been detected.

A comparison between bending strengths of reinforced three-layers specimens (60-PF) and non-reinforced five-layers specimens (100-PF) shows that the application of one or two reinforcing fabric layers allows the three-layer specimens (60-PF) to achieve values of bending strength comparable with those of the non-reinforced five-layer specimens (100-PF).

Results previously listed suggest that natural fibers reinforcements could be utilized as recovering technology for existing CLT slabs and walls with damage or with incorrect design or in case of bending moment concentrations. In addition, results encourage to deepen, through proper studies and a quantitative life-cycle analysis, the convenience of reducing the number of layers in laminated timber elements to the advantage of using natural fibers reinforcement.

Future studies will aim to extend the reinforcement to diverse specimen layout, different depth to height ratio and different timber layers class.

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