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REINFORCEMENT OF WOOD WITH NATURAL FIBERS

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ABSTRACT

This paper describes an experimental programme which examines the reinforcement in flexure of timber beams with composite materials based on natural fibers in the form of fabrics made from hemp, flax, basalt and bamboo fibers. The industrial use of natural fibers has been continuously increasing since 1990s due to their advantages in terms of production costs, pollution emissions and energy consumption for production and disposal. The technique allows the reinforcement of the intrados of beams, avoiding the dismantling of the overlying part of the structure with significant savings in terms of costs and work time. The test program consists of three phases incorporating 45 beams. The bending tests on the wooden elements made it possible to measure the increase in capacity and stiffness resulting from the composite reinforcement. This was applied to beams, creating different arrangements and using different quantities (number of layers). Despite the diversity of the various tests carried out, the results obtained in some cases showed significant increases in terms of load-carrying capacity and in deflection ductility

Keywords: A. Fibres, A. Wood, B. Adhesion, B. strength, D. Mechanical testing.

1. INTRODUCTION

In the field of consolidation techniques for wooden elements through reinforcement with new materials, numerous experimental investigations and analyses have been published in recent years regarding the use of FRP (*Fiber Reinforced Polymers*) materials based on epoxy resins and artificial fibers (glass, carbon, aramid fibers etc.).

These investigations have shown that in some cases the application of composite materials can be of structural interest, as they give greater strength and ductility to wooden elements, compared to the performance that wood is able to provide on its own. Some tests on the reinforcement of wooden beams with composite materials have been carried out, limited to the case of Carbon Fiber fabrics (CFRP) by Plevris and Triantafillou [1], by Schober et al. [2,3] and by Jasieńko et al. [4]. A preliminary research in the quasi-static loading of glulam beams with carbon fibre reinforcement were performed by Meier [5], Johnsson et al. [6] Piazza and Parisi [7] and Johns and Lacroix [8]. Triantafillou [9] subsequently studied the shear behavior of glulam beams reinforced at the ends with carbon fiber strips. Other studies on the shear reinforcement of wooden elements with composite materials have been conducted in recent years (Fiorelli et al. [10]). In this area Borri et al. [11] have increased the load-carrying capacity of existing wooden beams through the application of bars and strips of CFRP, GFRP and AFRP. Recently the same authors [12] investigated the effectiveness of flexural reinforcement consisting of steel fibers glued in the tension zone of wooden beams. Gentile et al. [13] have done a series of bending tests on beams reinforced laterally with GFRP bars.

However, the increasing cost of producing the composite materials most commonly used is substantially widening of the field of research, especially toward natural materials, readily available and considerably more economical. Fiber-reinforced composite materials based on natural fibers have advantages, since they lend themselves to applications that are simple to construct and extremely versatile, both for recovering existing structures and designing new structures. In addition to the elevated mechanical properties in terms of tensile strength and lightness, natural fibers have advantages in terms of production costs, pollution emissions and energy consumption for their production and disposal. This can be seen from the well-known LCA (*Life Cycle Analysis*) [14] parameter, which by now always accompanies the study of any new industrial product. The main properties of a natural fiber regard its energy and mechanical aspects [15-17]: flax, bamboo, basalt fibers etc. are non-artificial products that can be easily found or grown in nature, the production of which may have a negative balance in terms of the carbon dioxide emitted into the atmosphere. In addition, the costs for the production and disposal at the end of their life is generally significantly cheaper than for an artificial composite material. The development of a system made entirely from natural products is still only partially possible, as natural fibers are available, but not natural resins with mechanical properties similar to artificial epoxy resins.

If totally eco-friendly natural resins are available, it will be possible to create fiber-reinforced wooden elements with natural materials, thus creating structural elements in keeping with the philosophy of the current low environmental-impact development projects.

This experimental study is divided into three parts: in the first stage the results are given for a series of tests done on 20 fir wood rafters reinforced in the tension zone with basalt, flax and hemp fibers [18]. In the second and third stages of the experiment 25 beams 200x200x4000 mm in size were reinforced, and the increase incapacity, stiffness and ductility following reinforcement with natural basalt, hemp, basalt and bamboo fibers was investigated.

2. MATERIAL CHARACTERIZATION

2.1. Wood

The experimentation regarded 20 rafters and 25 beams in fir wood (*Abies Alba*). The rafters had a weight density of 430 kg/m^3. The beams were divided into two groups, coming from two different lots: of medium and good quality, characterized respectively by a weight density of 436 kg/m^3 (dev. 31.36 kg/m^3) and 462 kg/m^3 (dev. 35.66 kg/m^3). The humidity of the medium and good quality beams was 9.51% and 5.37% respectively.

2.2. Resin

The application of natural fibers to the tension zone of the wooden beams was done using an epoxy resin that could transfer the stresses with perfect adhesion between the materials. The epoxy system is composed of a two-part thixotropic adhesive based on an epoxy resin without solvents, available under the brand name Kimitech EP-IN. The resin has elevated mechanical properties both in traction and in compression and it offers good adhesion to various supports and does not shrink while hardening. The properties of this epoxy system as declared by the producer appear in Table 1.

2.3. Natural fibers

Unidirectional natural basalt, flax and bamboo fibers and bidirectional hemp fibers were used to reinforce the wooden elements (Fig. 1). Basalt, flax (*Linum usitatissimum*) and hemp fibers (*Cannabis sativa*) were provided by Tec Inn srl. As regards the bamboo fibers (manufacturer: Ecodekò-Italia), a very large number of species of bamboo exist in nature, with different rheological and mechanical properties. Considering how widespread it is and the size it reaches (up to a height of 20 m and diameter of 18 cm), the species that is usually used for making natural fibers for structural applications is *Phyllostachys pubescens*, which was used also for this experiment.

Table 2 gives the physical and mechanical characteristics of the natural fibers used to reinforce the wooden beams, taken from the manufacturer’s data sheets. Mechanical properties were evaluated using an equivalent thickness of fabric materials to the base material of FRP. The knowledge of these mechanical properties is a precondition for the sustainable application of natural fibre. However mechanical testing of natural fibre are not yet defined by standards.

The natural fiber materials used for the flexural reinforcement of the wooden beams were subjected to mechanical characterization through tensile tests. Young's modulus (MOE) was determined by linear regression between 1000 and 3000 microstrain. The natural fiber having the greatest tensile strength among those used was basalt fiber (1880 MPa), while considerably lower values were found for the other natural fibers. The elastic modulus (Young) varies from 91 GPa for basalt fibers to 18.1 GPa for hemp fibers. Table 3 gives the results of the mechanical characterization tests by means of tensile tests on the natural fibers.

Given that the production processes, the type of natural fiber and the mechanical properties are very different from each other, it was not possible to proceed with an equivalent reinforcement of the wooden beams in terms of the ultimate tensile load of the fibers applied in the tension zone on the intrados of the wooden beams. The increases obtained in the load-carrying capacity must therefore be analyzed in light of the different quantities of reinforcement applied for each type of fiber.

3. BENDING TESTS ON REINFORCED ELEMENTS

The experiment was carried out on a total of 20 rafters and 25 fir wood beams subjected to 4-point bending tests, according to UNI EN 408 [19] standard. The beams had nominal dimensions of 200x200x4000 mm and sharp edges. Two lots of beams were purchased on the market, the first of which had inferior mechanical properties compared to the second lot. Both were reinforced with natural fibers in the tension zone in order to investigate the effectiveness of the reinforcements applied. In addition a lot of 20 rafters with nominal dimensions of 40x50x1000 mm were reinforced with the same natural fibers used for reinforcing the wooden beams.

In the preparation of the test apparatus, special care was given to the supports of each test specimen, which was laid on two steel half cylinders with a diameter of 600 mm. In order to reduce the local crushing of the wood, the load was applied through beaming timber blocks across the full beam width which are of sufficient thickness to eliminate high-stress concentrations at places of contact between beam and bearing blocks (Fig. 2). The load was applied monotonically until failure by means of a hydraulic jack connected by a hydraulic circuit to the pump. The vertical displacements of the beams were recorded using inductive transducers (LVDT). The reinforcement of some beams were also instrumented with strain gauges applied at midpoint.

The results recorded were then processed according to the indications of the reference standards. The bending strength f_m was calculated according to the equation:

$$f_m = \frac{a \cdot F_u}{2 \cdot W} \tag{1}$$

where: F_u is the ultimate load (in N); a is the distance between the point of application of the load and the nearest support (mm); W is the modulus of resistance of the section (mm^3) established with reference to its actual dimensions.

For the modulus of elasticity (MOE), the following equation indicated by the standard was used:

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

where: l is the distance between the supports (mm); F_2-F_1 is the increment of load (in N) on the straight section of the load-displacement curve; w_2-w_1 is the increment of displacement (in mm) corresponding to F_2-F_1, measured at the midpoint of the beam.

The deflection index, D, of the FRP-strengthened timber beams is defined as Eq. 3.

$$D = \frac{w_u}{w_{u0}} \tag{3}$$

where w_u and w_{u0} are the deflections at the maximum load of the reinforced and unreinforced beams, respectively. By definition, D is unity for the control specimen. This deflection index was modified from the concept suggested by Buell and Saadatmanesh [20] that included a method to quantify ductility of reinforced timber beams.

3.1. Reinforcement of fir wood rafters

Twenty 4-point bending tests were carried out on wood rafters reinforced using natural basalt, flax and hemp fibers. The rafters had a cross section of 40x50 mm (base x height) and length of 1000 mm and were reinforced with the application of a 40 mm wide strip glued with a two-part epoxy resin. The distance between the end-supports was 900 mm and the shear span was 300 mm.

5 beams were subjected to bending tests without any reinforcement in order to determine the strength and stiffness values to be compared to those of the reinforced beams. In the analysis of the results it was observed that the failure mode depends essentially on the ratio between the ultimate tensile and compression wood strengths and on the non-linearity of the behavior at the ultimate limit state of the wood in compression. The behavior of the rafters was initially linear; with the increasing of the load the beam begins to show plasticity in the compressed zone, and failure occurs when the tensile stress limit is reached.

With the addition of the natural fibers, the greatest increase in strength (+35.3%) was measured for rafters reinforced with flax, while smaller increases were observed for rafters reinforced with hemp (+23.9%) and basalt fiber (+23.2%) (Tab. 4). Both the unreinforced and the reinforced rafters showed an elastic-plastic behavior with a prolonged and evident plastic branch. This is mainly because the rafters, being smaller in size, are better selected when they are cut. Deteriorated or defective rafters are eliminated by the producer and those put on the market are usually free of major defects, such as large knots or significant deviations in the grain. The absence of large defects allows a plastic behavior due to the plasticization of the wood in compression, as premature failures in the tension zone are excluded precisely by the absence of defects.

The collapse of all test rafters was brittle. The cracks rapidly propagated along the span or across the rafter section as soon as the stress level reached the modulus of rupture. No bond failure was observed for the reinforced rafters although a secondary debonding failure of the FRP occurred in some cases because of the push-off of the split timber near midspan. Deflection characteristics of the test beams are also shown in Tab. 4. An increase of 71.8% in the deflection index D was observed for rafters reinforced with basalt fiber, when compared to that of unreinforced rafters, whereas increases of 43.4% and 52.4% were observed for rafters reinforced with hemp and flax fiber.

3.2. Reinforcement of fir wood beams of low-quality

The second stage of the experiment involved 8 fir wood beams, from the same lot, with a size of 200x200x4000 mm. The static bending tests were conducted with a the depth/span ratio of 18 (distance between the end-supports 3600 mm, shear span 1200 mm)

The beams were of low-quality, with the common defects of wood: cross grain, shrinkage cracks and knots. Two beams (S2-1 and S2-2) were tested without reinforcement in order to determine the flexural strength of the wood. The average capacity was 40.9 kN.

Three beams reinforced with basalt and three beams with flax were tested along with two beams without reinforcement, in order to be able to compare directly the behavior in terms of flexural strength and stiffness. In consideration of the different equivalent thicknesses of dry fabric of the different fibers (Tab. 1), the FRP resistant area (A_{FRP}) for each type of fiber and the relationship between the fiber area and that of the cross section of the wooden beam (A_{FRP}/A_{wood}) take on different values. It was attempted to remedy this by preparing a greater number of layers for low strength fibers than for high strength fibers (for basalt fiber a 10 cm wide strip + a 5 cm wide strip was applied (A_{FRP}/A_{wood}=0.0525%), for flax two 10 cm wide 2 strips (A_{FRP}/A_{wood}=0.1335%).

All the beams were subjected to 4-point bending tests using the same test apparatus used for the rafters. The beams showed the behavior in Fig. 3. Both types of reinforcement provide an increase in the load capacity compared to the unreinforced beams (Tab. 5). In particular the three beams reinforced in the tension zone with 2 basalt fiber strips (S2-4, S2-5 and S2-6) showed a load-carrying capacity increase of approximately 38.4%, while the beams reinforced with flax fiber (S2-3, S2-7 and S2-8) had an average increase of 67.8%. Even being cautious due to the fact that the statistical sample is limited in terms of number of beams, it can be clearly inferred that the natural fibers brought about a significant increase in the load-carrying capacity of the wooden beams. On the contrary the slope of the load-displacement curves of the reinforced beams is similar to that of the unreinforced beams, a result foreseen from the start, considering the arrangement of the reinforcement, its thinness and its low modulus of elasticity.

In all types of reinforcement there was a shear failure of the reinforcement caused by the preceding failure of the wood in the tension zone; no type of FRP reached the tensile failure stress limit. Thus it is the wood in the tension zone that reaches failure: this always happens starting from a defect in the wood, in most cases a knot or another defect such as a high degree of grain deviation.

The application of reinforcement to the beam tension zone has the further characteristic of mitigating the influence of defects in the wood, blocking the propagation of the cracks. This has a further positive effect which can be observed from the considerable increase of the vertical displacement at midpoint and by the greater plastic behavior of the reinforced beams compared to the unreinforced beams. The unreinforced beams showed a displacement of 45 mm at midpoint at the moment of the critical stage, whereas for the beams reinforced with basalt and flax fiber values of 63.1 and 71.2 mm were obtained respectively.

An increase of 40.2% in the deflection index D was observed for beams reinforced with basalt fiber, when compared to that of unreinforced beams, whereas an increase of 58.2% was observed for beams reinforced with flax fiber, as shown in Fig. 3.

3.3. Reinforcement of fir wood beams of good quality

A second lot of 17 fir wood beams, with better mechanical properties than those used in the preceding experimental investigation, was subjected to bending tests after being reinforced with basalt, flax and bamboo fibers in the tension zone. The test methods (test set-up, load speed, size and shape of supports and loading fulcrums) and the size of the wooden beams (200x200x4000 mm) were both the same as those applied in the second stage of the experiment. The basalt and flax fibers were also supplied by the same producer and are the same as those used previously.

Tab. 6 gives the results of the bending tests. It can be observed that beams n°. S3-12, S3-14, S3-15 and S3-17 subjected to testing without any type of reinforcement applied showed a higher bending strength than that of the second stage of the experiment. The average load capacity value of these beams was 91.7 kN.

In this stage of the experiment the beams were reinforced with natural flax, basalt and bamboo fibers. The reinforcement was done using 10 cm wide strips, 2 or 3 of which were applied in the case of the basalt and flax fibers lino (Basalt: A_{FRP}/A_{wood}=0.070% and 0.105%; Flax: A_{FRP}/A_{wood}=0.133% and 0.200%)[1], and 5 or 7 in the case of bamboo fibers (A_{FRP}/A_{wood}=0.75% and 1.05%).

In general, but not in all cases, the measurements showed a roughly linear distribution, implying that plane sections remained plane and there was no slip of the reinforcement. The reinforcement was less

[1] evaluated using equivalent thickness as defined by manufacturer data sheet.

effective compared to the preceding experiment stages. More specifically, the good quality of the wood beams diminished the reinforcement action in the tension zone, and the lesser presence of defects in the wood made the action of confinement of the defects less important.

For this lot of beams as well, reinforcement with flax fibers gave the highest load-carrying capacity increase, with mean increases of 29.2% and 9.4% respectively for beams reinforced with 2 and 3 overlapping layers of flax. Reinforcement with unidirectional basalt fibers provided an increase in the load-carrying capacity of 25.9% and 11.2% for beams reinforced with 2 and 3 strips.

Failure of all reinforced beams was initiated by flexural cracks of the wood in the un-reinforced part of tension side (Fig. 4). Examination of the failure surface after the load had been removed showed tensile failure in the wood substrate, with the adhesive and the laminate remaining intact with the only exception of the zone where wood cracked. Shortly after flexural failure of the wood, a shear failure also appeared at the level of the composite reinforcement (Fig. 5). No sign of evident wood crushing was observed.

The results of the tests on beams reinforced with bamboo fiber showed the limited effectiveness of these fibers in terms of load-carrying capacity. The beams reinforced with 5 overlapping strips of bamboo fiber showed a load-carrying capacity similar to that of unreinforced beams: the average value of the capacity decreased by 9.2%, but this result must be analyzed in the normal dispersion of the results for tests on unreinforced wood beams. A slightly greater increase in capacity (15%) was found for reinforcements with 7 layers of bamboo fiber (Fig. 6). In this case the value, although positive, did not meet the expectations for the effectiveness of reinforcement with this natural fiber.

Decreases of 7 and 7.7% in the deflection index D were observed for beams reinforced with 3 layers of basalt fiber and 5 layers of bamboo fibers, when compared to that of unreinforced beams, whereas increases in the range of 8-14% were observed for beams reinforced with other reinforcement configurations. These inconsistent observations for the reinforced beams are attributed to the natural variation of the timber material and to the limited effectiveness of bamboo reinforcement.

4. CONCLUSIONS

This paper gives the first results of an experiment on timber elements reinforced in the tension zone through the application of strips of natural flax, hemp, bamboo and basalt fibers.

The use of these types of composite materials has made it possible to obtain wood beams with strength and stiffness characteristics superior to unreinforced wood, confirming one of the fundamental aspects on which the idea of reinforcement is based, i.e. the obtaining of a final product that is stronger as a result of the considerable reduction of the influence of physiological defects in the wood on structural behavior.

The increased strength was less than that obtained in preceding similar tests done by the same authors on beams reinforced with glass, carbon and aramid fibers [10]. The use of natural fibers, however, has advantages connected not only with the increase in the load-carrying capacity, but also in terms of energy in consideration of the limited production costs, energy consumption and disposal at the end of their life.

The wooden rafters showed high capacity and an interesting ductile behavior due to the plasticization of the section in the compressed zone. A high benefit was obtained with flax and basalt fiber reinforcement, with which increases in capacity were achieved that were only slightly lower than those obtained with carbon fibers.

As regards the 25 200x200x4000 mm beams, natural fiber reinforcement was applied to two lots of wooden beams, the first of which had poorer mechanical properties than the second. The reinforcement of the beams with poorer mechanical properties brought considerable increases in the ultimate load, comparable to that of the beams reinforced with traditional FRP (Carbon, Glass etc.), while there were no appreciable increases in the stiffness.

The wooden beams with greater mechanical properties (good quality) did not show high increases in the load-carrying capacity when reinforced with natural fibers. Unsatisfactory results were found in particular for reinforcement with bamboo fibers.

For low-quality beams, reinforcement with basalt fibers gave high strength, providing the beam with good ductile behavior. For these beams, reinforcement with flax fibers provided very high increases in capacity, better than those obtained with basalt.

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Type	epoxy
Compression strength* (MPa)	50
Tensile strength** (MPa)	30
MOE** (MPa)	1760
Weight density (g/cm^3)	1.08

*according to ASTM D695 [21], **according to ASTM D638 [22]

Table 1. Properties of adhesive (from manufacturer).

	Basalt fiber	Hemp fiber	Flax fiber	Bamboo fiber
Type	Unidirectional	Unidirectional	Bidirectional	Unidirectional
Tensile strength (MPa)	2000	496	532	-
MOE (MPa)	95000	22000	43000	-
Density (g/m^2)	400	234	430	-
Cords per cm (n°/cm)	3.3	7.0	9.0	-
Equivalent thickness (mm)	0.14	0.155	0.267	-
Elongation (%)	2.3	3.1	2.34	-

Table 2. Properties of FRP (from manufacturer).

	Basalt fiber	Hemp fiber	Flax fiber	Bamboo fiber
Sample size	10	10	10	10
Density (g/m^2)	442	281	479	408
Tensile strength (MPa) (CoV) (MPa)	1880 (101)	535 (46.1)	240 (27.6)	58.3 (1.58)
MOE (MPa) (CoV) (MPa)	90968 (10286)	36529 (2357)	18052 (1498)	5304 (545)
Thickness (mm)	0.14*	0.155*	0.267*	0.600

* Evaluated using equivalent thickness as defined by manufacturer data sheet.

Table 3. Results of testing on the FRP coupons.

FRP type and configuration	Sample size	Max load F (kN)	F_{reinf}/F_{unrinf} (%)	Midspan deflection at max. load w (mm)	MOE (GPa)	Deflection index D (%)
None	5	8.07	-	20.23	14.23	-
hemp, 1 layer	5	10.00	23.9	29.01	16.59	43.4
flax, 1 layer	5	10.92	35.3	30.83	17.67	52.4
basalt, 1 layer	5	9.94	23.2	34.75	15.11	71.8

Table 4. Bending stiffness and strength results of reinforced and unreinforced rafters.

FRP type and configuration	Sample size	Max load F (kN)	F_{reinf}/F_{unrinf} (%)	Midspan deflection at max. load w (mm)	Deflection index D (%)
none	2	40.90	-	45.0	-
flax, 2 layers	3	56.60	38.4	71.2	58.2
basalt, 2 layers	3	67.80	65.8	63.1	40.2

Table 5. Bending stiffness and strength results of reinforced and unreinforced low-quality beams.

FRP type and configuration	Sample size	Max load F (kN)	F_{reinf}/F_{unrinf} (%)	Midspan deflection at max. load w (mm)	Deflection index D (%)
none	4	91.7	-	61.3	-
flax, 2 layers	2	118.5	29.2	66.9	9.1
flax, 3 layers	2	100.3	9.4	57.0	-7.0
basalt, 2 layers	2	115.4	25.9	70.2	14.5
basalt, 3 layers	3	102.7	11.2	53.0	13.5
bamboo, 5 layers	2	82.7	-9.2	56.6	-7.7
bamboo, 7 layers	2	105.5	15.0	66.6	8.6

Table 6. Bending stiffness and strength results of reinforced and unreinforced high-quality beams..

(a) (b) (c) (d)

Figure 1. (a) flax fiber, (b) bamboo fiber, (c) basalt fiber, (d) hemp fiber.

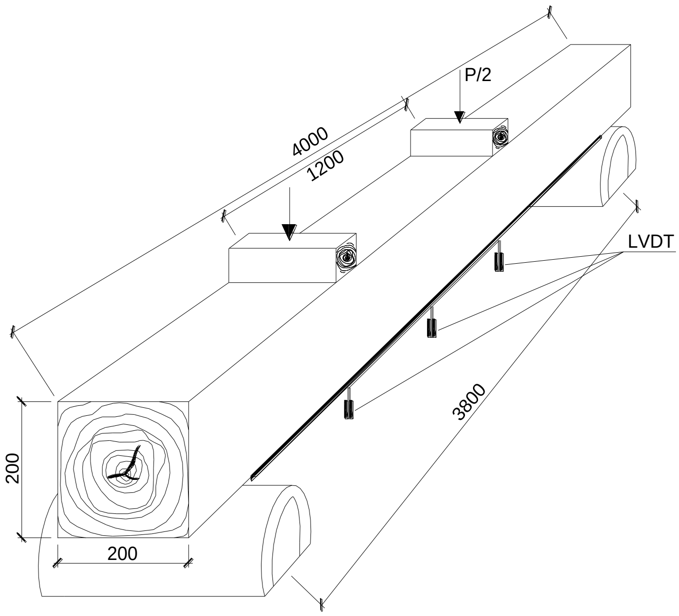

Figure 2: Loading configuration for bending tests of timber beams.

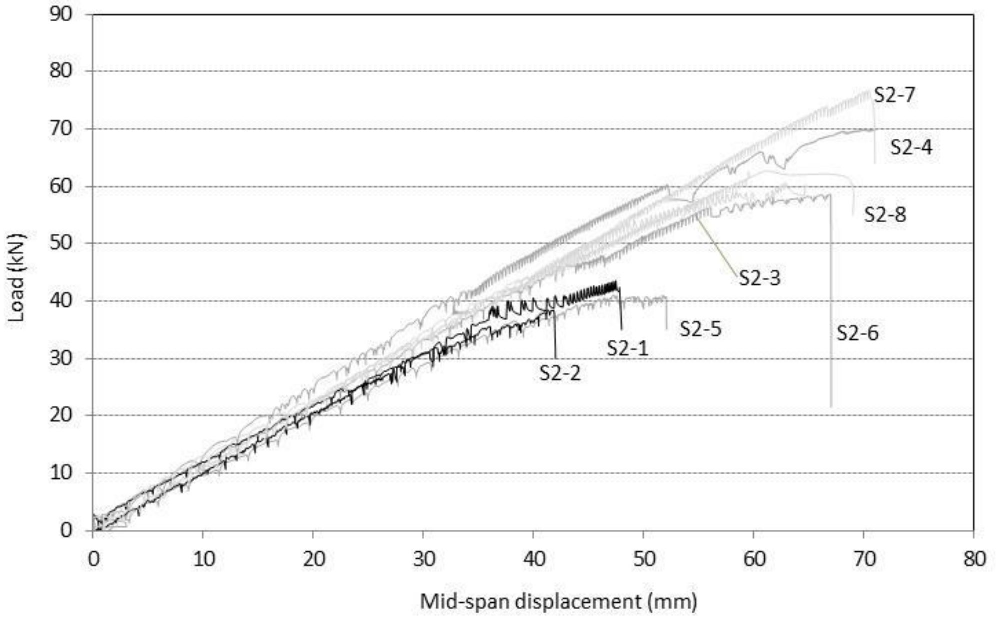

Figure 3. Load–displacement curves for low-quality beams (black curves: unreinforced beams, ligh grey curves: basalt fiber reinforcement, dark grey: flax fiber reinforcement).

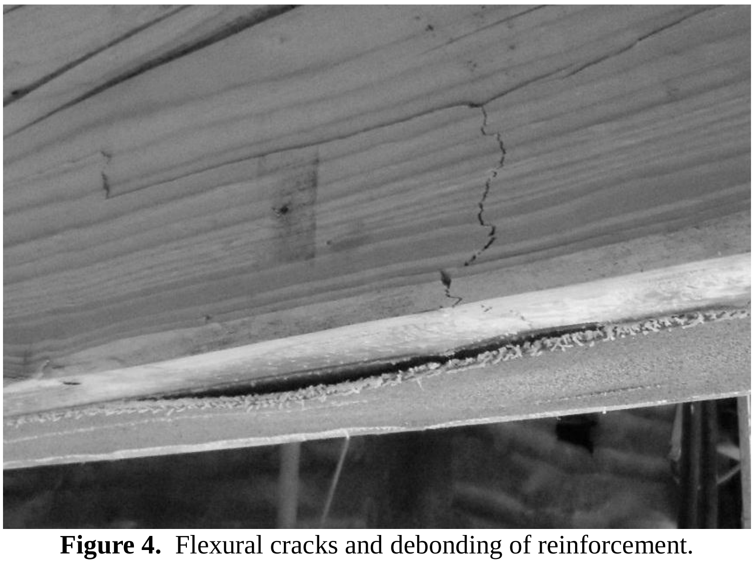

Figure 4. Flexural cracks and debonding of reinforcement.

Figure 5. Flexural cracks and shear failure of reinforcement (bamboo reinforcement).

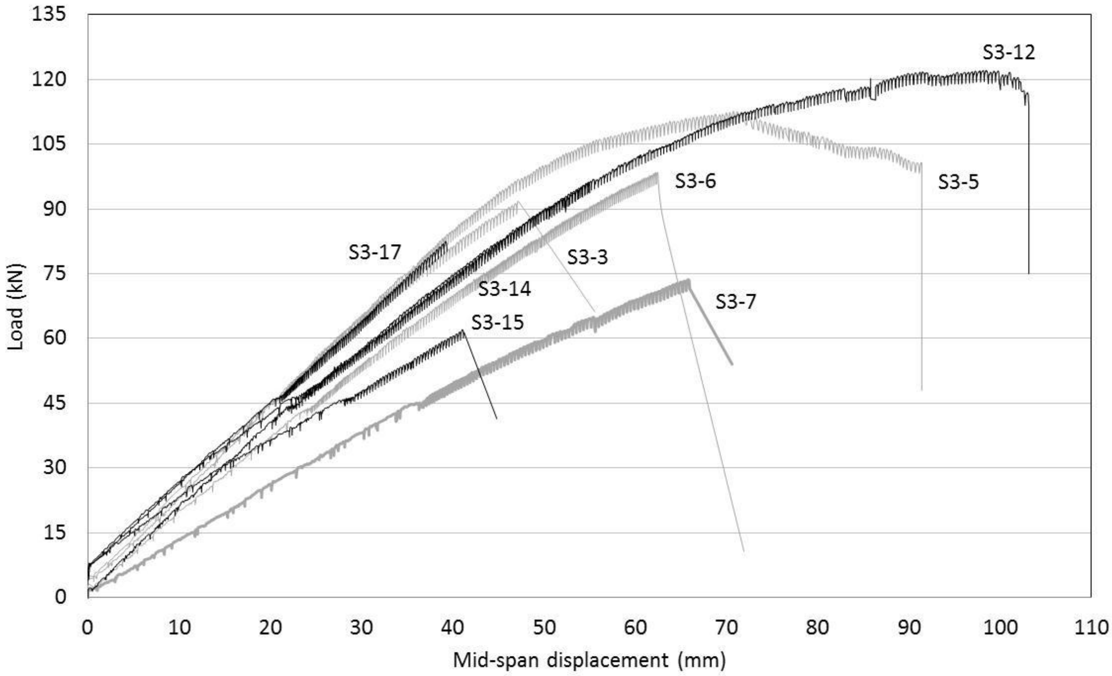

Figure 6. Load–displacement curves for high-quality beams (black curves: unreinforced beams, grey curves: bamboo fiber reinforcement).