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Conference Paper

Experimental Behavior of Natural Fiber-Based Composites Used for Strengthening Masonry Structures

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This paper deals with the experimental characterization of the tensile behavior of fiber-based composites and flexural strength of natural fiber-reinforced polymer (NFRP) sheets externally glued on masonry bricks, in terms of load capacity and stress distribution along the bonded length. The bricks adopted for this experimentation are solid clay bricks, typically used in ancient masonry structures. Nonimpregnated and impregnated flax, hemp, jute, and sisal fibers were examined. Two types of matrices have been used, polymer matrices and mortar-based matrices. Composite materials defined as NFRP (Natural Fiber Reinforced Polymer) and NFRG (Natural Fiber Reinforced Grout) were obtained.

1. Introduction

In the last few years, the scientific community has shown a particular interest in the use of natural composite materials, focusing on themes related to recyclable, renewable, and environmentally sustainable materials as substitutes of some of the most common man-made fibers. In the civil construction area, several attempts have been done in this field [1]. Recently, the attention has been paid to the possibility of using natural fibers to strengthen masonry structures [2].

Historic masonry buildings show specific challenges when compared to ordinary buildings regarding conservation issues, because of their cultural heritage value and low-strength substrate. Consequently, choosing appropriate strengthening techniques is extremely important and complex. Attention has to be focused on limiting interventions to a minimum, avoiding unnecessary strengthening. This goal is clearly in agreement with the principles of sustainable development.

2. Experimental Plan

The experimental program was organized into two main phases, mechanical characterization of natural materials and study of adhesion between composite systems and masonry. Bidirectional fabrics of flax, hemp, sisal, and jute fibers were used. Tensile tests on fabrics were carried out on impregnated and nonimpregnated fabrics. Two types of matrices were used, polymer matrices and mortar-based matrices. The polymer thermosetting matrices used were epoxy resin and polyester resin in order to produce Natural Fiber Reinforced Polymer (NFRP), while, mortar-based matrices were used in order to produce Natural Fiber Reinforced Grout (NFRG) [3]. In the second part of the experimental plan, three point bending tests and pull-off tests were carried out in order to study the behavior between NFRP composites and the masonry system [4–6]. In this case, flax-based composites and hemp-based composites were used with a thermosetting matrix in epoxy resin, following the results achieved from the tensile tests.

Table 1: Average mechanical properties of matrices (CoV is provided inside parentheses).

	Epoxy resin	Polyester resin	Mortar
Tensile strength [MPa]	53.8 (9.7%)	29.0 (17%)	—
Flexural strength [MPa]	—	—	0.19 (5%)
Compressive strength [MPa]	—	—	11.3 (5%)

Table 2: Stress and Young's Modulus of the NF, NFRP, and NFRG (CoV is provided inside parentheses).

Matrix/fiber	Nonimpregnated		NFRP-Epoxy		NFRP-Polyester		NFRG	
	f_t [MPa]	E [MPa]	f_t [MPa]	E [MPa]	f_t [MPa]	E [MPa]	f_t [MPa]	E [MPa]
Jute	32.9 (14%)	691.5 (11%)	87.3 (31%)	1382.2 (17%)	80.3 (10%)	4135.3 (20%)	25.9 (7%)	531.3 (10%)
Sisal	55.2 (17%)	863.3 (15%)	73.5 (15%)	748.1 (20%)	64.3 (21%)	1431.5 (18%)	35.6 (8%)	345.5 (13%)
Hemp	46.7 (8%)	618.7 (7%)	63.1 (12%)	1674.7 (9%)	58.2 (13%)	1535.0 (9%)	33.1 (8%)	268.2 (5%)
Flax	68.8 (7%)	1746.9 (10%)	117.4 (17%)	1866.6 (20%)	109.8 (17%)	4393.3 (9%)	57.2 (3%)	774.2 (7%)

Table 3: Average of results obtained from three point bending tests (CoV is provided inside parentheses).

Material	F_{max} [kN]	ε [μm/m]	$f_{flexural}$ [kPa]
Brick	4.81 (14%)	—	800 (14%)
Flax	6.49 (2%)	1284 (17%)	1050 (3%)
Hemp	6.18 (4%)	1142 (44%)	980 (3%)

Table 4: Average of results obtained from pull-off tests.

Fiber type	F_{max} [kN]	Tensile strength [kPa]
Flax	2.28 (9%)	1208 (9%)
Hemp	2.38 (4%)	1265 (4%)

2.1. Tensile Tests. Tensile tests on non-impregnated and impregnated fabrics were performed using natural materials, in particular bidirectional fabrics based on flax (w = 388 g/m^2, CoV = 1%), hemp (w = 455 g/m^2, CoV = 2%), jute (w = 254 g/m^2, CoV = 2%), and sisal (w = 1099 g/m^2, CoV = 4%). These four types of natural materials were examined because they have relatively good mechanical proprieties. All the specimens were cut in the warp direction (90°) and in weft direction (0°) with size equal to 300 × 50 mm^2. The test length is equal to 200 mm. Specimens were tested with and without the consideration of the matrix. Each specimen has been equipped with special steel plates on the edges, in order to ensure a uniform distribution of the load and to avoid the specimen from slipping during the test [7]. Specimens with polymer matrix were tested after 15 days from the preparation in order to ensure the proper curing of the matrix, while in the case of the mortar, the experimental tests were carried out after 28 days. Moreover, in the first part of the experimental program, mechanical characterization tests were performed on the matrices used for the production of NFRP and NFRG. Table 1 summarizes the mechanical properties obtained.

2.2. Three Point Bending Tests. To carry out three point bending tests, Portuguese traditional solid clay bricks were used as substrate. These bricks have a compressive strength of 14.3 MPa (CoV = 4%). In particular flax fiber-based composites and hemp-based composites were prepared using a matrix-based thermosetting epoxy resin, which is commonly used in the field of civil applications.

The testing machine is composed of the fixing of three points (Figure 1(a)), two lower supports and striking edge and the load at midspan, with a radius of 125 mm. The sizes of the specimens are schematically indicated in Figure 1(b). Natural fiber-based composites under study have a thickness of t_{fiber} = 3 mm for flax (six specimens, CoV = 16%) and t_{fiber} = 2.5 mm for hemp (six specimens, CoV = 11%). One layer of fabric, previously cut in the warp direction (90° direction) with dimensions equal to 140 × 50 mm^2, for each specimen that was applied to the brick, after the cleaning of the substrate and the primer application. To measure the displacements, two LVDTs were applied to the specimen, one in the midpoint of the brick and another, of control, corresponding to the load cell. However, to know the value of the strain, one strain gage was bonded at the centerline of the composite [8].

2.3. Pull-off Tests. Also for pull-off tests, the same solid clay bricks were used. This type of test was carried out in order to assess the direct tensile strength (mode I) of the composite system. In particular, failure will occur along

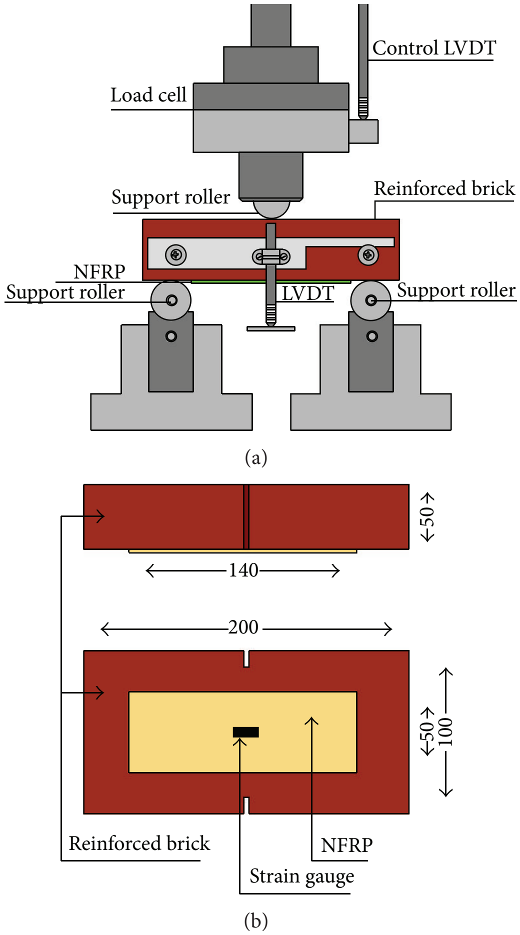


Figure 1: Three points bending test: (a) schematic representation for TPBT and (b) specimen's size, plan view and elevation view.

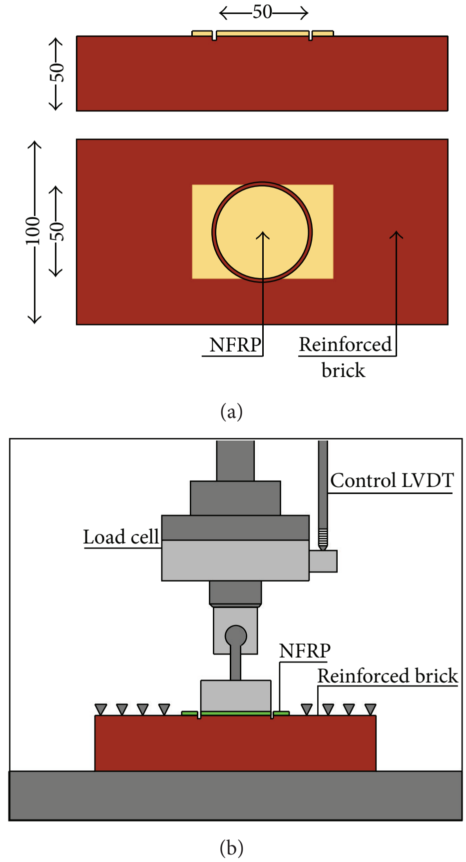


Figure 2: Pull-off tests: (a) specimen's size (plan view and elevation view) and (b) schematic representation.

the weakest plane within the system composed of the test fixture, adhesive, coating system, and substrate, and will be exposed by the fracture surface. The tests were carried out only on bricks strengthened with flax and hemp fibers. For each type of fabrics, 5 specimens were tested. Following the cleaning of the bricks, the composite system was applied. After primer application, a fiber strip of 70 mm width was glued on the brick (Figure 2(a), plan view). Afterwards, a partial-depth core with 49 mm diameter and 10 mm depth was drilled, see Figure 2(a) (elevation view), which leads to the creation of circular strengthened areas where rigid steel plates were glued. The testing machine is schematically indicated in Figure 2(b). In this case, only the LVDT control was considered, in correspondence to the load cell.

3. Results

3.1. Tensile Tests Results. Experimental tensile tests were carried out according to EN ISO 13934-1/2 [9]. All tensile tests were conducted in a normal atmosphere on specimens previously acclimatized, by means of a high-precision universal testing machine and conducted under displacement control. Before each test, a preload of 10 N (NFRP) and 1.5 N (NFRG)

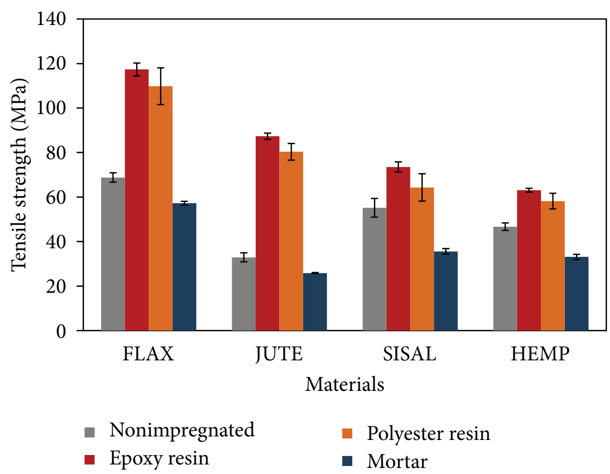


Figure 3: Tensile strength-Materials diagram.

was applied and a velocity equal to 100 mm/min (NFRP) and 25 mm/min (NFRG) was used. The results obtained from the tensile tests are listed in Table 2. It is possible to note that the flax is the material with higher mechanical properties, followed by jute and sisal. Fabrics impregnated with epoxy resin (NFRP) present greater tensile strength than polyester resin, so consequently it can be stated that the epoxy resin is the most suitable from the mechanical point of view as a matrix of the natural fiber composite materials

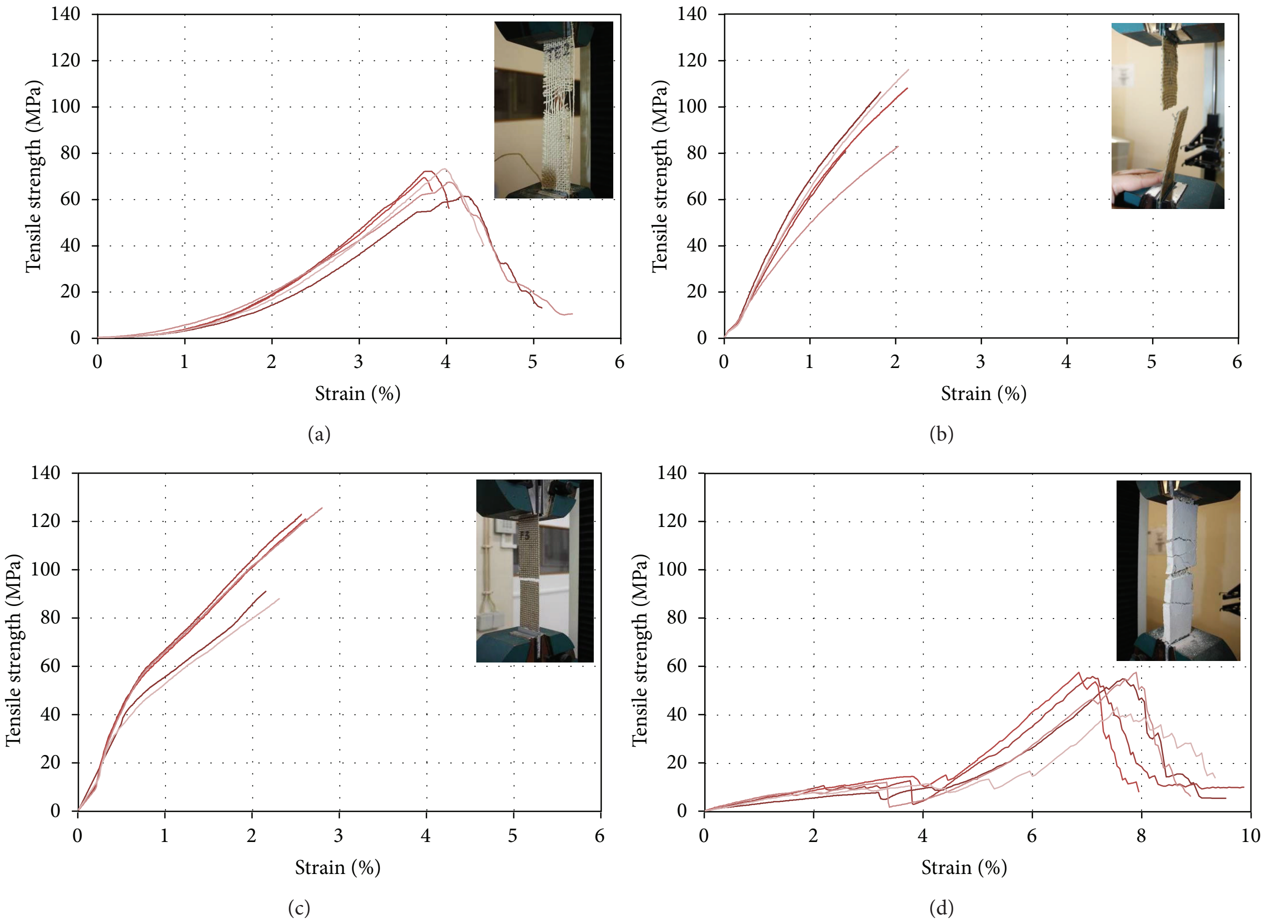


Figure 4: Failure modes for the flax-based composites, (a) nonimpregnated fabrics, (b) NFRP-epoxy, (c) NFRP-polyester, and (d) NFRG.

was tested. Concerning the fabrics with the cement-based matrix, further studies are still needed, especially regarding the thickness of the mortar which is to be applied to the specimen and the relation between water and the fibers. The results can also be observed in Figure 3. In previous tests done by the authors [10], it was observed that the fabrics have a higher strength at 90° (warp), rather than at 0° (weft), for this reason Table 2 shows the relative values obtained in the warp direction only. Figure 3 shows the different levels of strength of the natural fiber composite examined with the different matrices used.

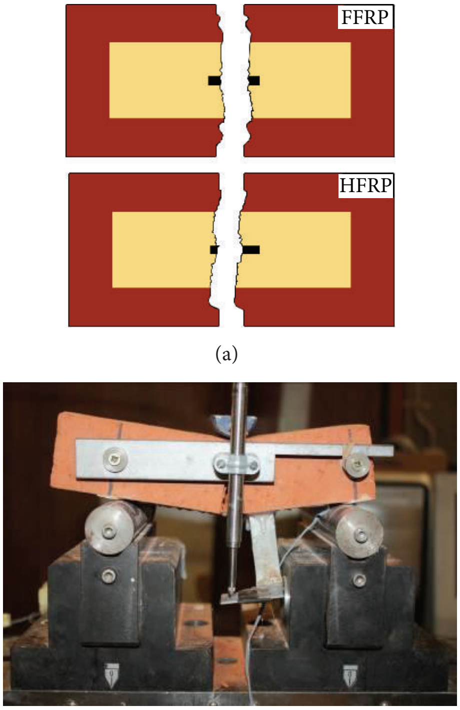
For the different strengthening systems used, it is ofprimary importance to discuss the failure modes of the specimens. In the case of non-impregnated specimens, there is a reduction of the area of the individual yarns that makes up the fabric (Figure 4(a)) with a softening final part, while in the impregnated specimens with the polymer matrix, epoxy (Figure 4(b)), and polyester (Figure 4(c)), it is possible to notice an instantaneous and uniform break of the specimen with a particular hardening final part. Finally, in the case of the cement-based composite, the failure mode occurs slowly marked by the rupture of the mortar at the beginning and follows the break/stretching of single yarns that make up the fabric (Figure 4(d)). Figure 4 is relative to flax-based composites, but a similar behavior was found for the other three types of fibers tested.

3.2. Three Point Bending Tests Results. Experimental tests were carried out according to BS EN 1015-11:1999 [10]. However, the tests carried out in this present work differ from the tests described in the standard procedure; in the current test, the specimens are bigger ($200 \times 100 \times 50\,\text{mm}^3$) and they are masonry bricks externally strengthened with natural fiber-reinforced sheets.

These tests were carried out in order to analyze the load capacity between unreinforced and reinforced masonry bricks. The results obtained demonstrate that the reinforced bricks are more resistant when compared to unreinforced bricks, as expected. Indeed, it is possible to note that the reinforced bricks are characterized by an increment of flexural resistance of almost 38% with flax and 32% with hemp (see also Table 3).

The failure mode of the specimens is characterized by the breakage of the specimen in the section at the mid-span. This mode is the same for both flax-based reinforced and hemp-based reinforced bricks (Figures 5(a) and 5(b)).

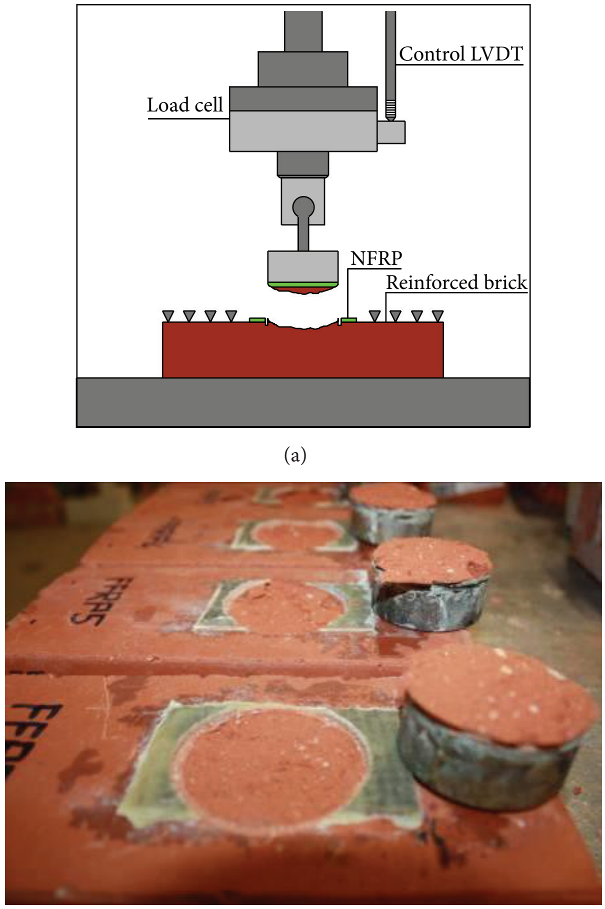
3.3. Pull-off Tests Results. Experimental pull-off tests were performed under displacement control. These tests were performed following the guideline ASTM D4541-02 [11]. Table 4 illustrates the average pull-off test results for the two types of fibers used (flax and hemp). The results indicate that the pull-off strength is practically independent of the



(a)

(b)

Figure 5: (a) Schematic failure modes for TPBT and (b) testing machine.



(a)

(b)

Figure 6: (a) Schematic failure modes for PT and (b) specimens tested.

fiber, in fact the same value of tensile bond strength can be observed. This feature can be explained based on the failure behavior registered. For all specimens tested, failure was characterized by the ripping of a thin layer of brick (peeling), as illustrated in Figure 6. Indeed, the results show that the tensile strength of the interfaces depends on the tensile strength of the substrate, and therefore of the bricks, which is the weakest element of the NFRP-resin-substrate composite system under direct tensile loading.

4. Main Conclusions

Natural fiber-based composite materials have a wide variety of mechanical properties. This is a consequence of the fact that the properties of natural materials are influenced by several variables, as the type of fiber, the diameter of the fibers, the environmental conditions, and possible methods of fiber treatment [5, 7, 8]. This is also confirmed by the variety of the results obtained and shown in this paper, especially in the case of tensile tests. It is possible to note that flax is the material with higher mechanical properties, followed by jute and hemp; low performances were obtained with sisal fibers. However, these first data obtained, confirm the significant development that the natural materials are acquiring in the function of their biodegradability, low cost, low relative density, adequate specific resistance, and renewable nature.

Experimental tensile, three point bending, and pull-off results provided an effective base to deal with a more detailed study of the adhesion between the NFRP composites and the masonry substrates. The primary problem always present is the interfacial adhesion between the natural fiber and the matrix. It determines the final properties of a composite. The results obtained from the tests carried out show that the composites produced with epoxy or polyester resin matrixes increase considerably the mechanical properties of the composite systems based on natural fibers, even more than composites produced with inorganic-based matrices (mortar).

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