The use of FRP in the strengthening of timber-reinforced masonry load-bearing walls

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ABSTRACT: Fibre reinforced polymers (FRP) combined with structural adhesives have been used in the reinforcement of both new and existing timber members – to increase their strength or stiffness –, and in the strengthening of old timber structures, mainly to deal with local damage due to biological attack or to excessive loading.

This paper presents the results of the experimental study carried out at LNEC, within the European research project COLORETIM in which these various topics were addressed. The specific programme of work hereby described intended to assess the possibility and the efficiency of using FRP rods and glass fibre fabric, together with epoxy adhesives, in the strengthening of damaged timber-reinforced masonry load-bearing walls from Portuguese traditional buildings.

1 INTRODUCTION

Fibre reinforced polymer materials (FRP) combining glass or carbon fibres and a matrix resin (epoxy, polyester, vinylester) have a wide variety of industrial applications, due to their high strength/weight ratio, ease of handling and versatility.

In the construction industry they have been largely used for many years, specially for local strengthening of concrete structures. More recently the techniques were also extended to timber.

Pultruded profiles (rods, plates) of FRPs, as well as glass or carbon fibre fabrics (GFF, CFF) have an expanding and particularly effective application for the local reinforcement of structural timber joints, namely to cope with tension perpendicular to grain. These materials are also commonly used in structural repair operations, either being inserted in critical cross-sections, or used for load transmission when damaged beam ends are cut off and replaced with new timber or epoxy mortar.

Epoxy adhesives include a wide variety of products with quite different properties in terms of adherence to timber, viscosity, reaction and setting time, creep, strength and elasticity, therefore suitable formulations should be identified for each job. Despite some less good qualities, epoxy adhesives are in general terms the most suitable family of glues for *in-situ* repair operations, since they do not require high pressure during their application and curing and they can be reasonably tolerant to glue line thickness variation.

Fibre reinforced polymers (FRP) and epoxy adhesives have been used to repair or to strengthen structural members for many years, generally based on empirical knowledge. This approach is nevertheless difficult to extend to less common wood species, less favourable environmental conditions, new adhesive formulations or other variables.

Besides, the lack of established design rules available to engineers and other decision makers has strongly restrained the use of FRP strengthening techniques in many situations where these could be a preferable option to most traditional techniques or to the total replacement of timber members (unfortunately still the option in many cases).

A research project named COLORETIM – COmposite LOcal REinforcement for TIMber structures – was conducted in 1999-2000 under the CE/FAIR programme involving several research laboratories, materials producers and repair/strengthening building contractors from France, the United Kingdom and Portugal, with the following general objectives (Cruz et al, 2000a and 2000b).

- To gain skills and knowledge about the reinforcement/strengthening of structural members and joints and the strengthening of timber structures by using composite materials, namely glass or carbon fibre fabrics (FF) and glass fibre reinforced polymers (FRP), having in mind both new construction and old buildings rehabilitation;
- To develop and disseminate information that is relevant to the concept, the design and the execution of structures repair or strengthening.

2 CONSERVATION PROBLEMS AND STRENGTHENING NEEDS OF TIMBER--REINFORCED MASONRY LOAD-BEARING WALLS

Following the big earthquake that destroyed large areas of Lisbon in 1755, and the empirical knowledge collected from the buildings which survived this earthquake, a structural solution, generally referred to as c*onstrução pombalina*, was imposed, in order to speed up reconstruction and to guarantee the required seismic resistance of the buildings.

The basis of this building system was the three-dimensional timber structure, called "gaiola" (birds cage), that was totally built up to the roof prior to in-filling the wall frames with the "masonry" (small stones, brick and mortar), that would subsequently wrap up the timber elements. In some cases, exterior masonry walls (as thick as 90cm at the basis) would enclose timber elements to which the floors and the orthogonal load-bearing walls from *gaiola* were connected (timber-to-timber); in other cases the exterior masonry walls would lay against the *gaiola* and be connected to it through short timber pieces (*mãos*) or steel elements (*esquadros*) bearing in the masonry.

The *gaiola*, composed of timber floors and timber-reinforced masonry load bearing walls, was meant to support vertical loads (and to give lateral restrain to the exterior masonry walls), leading to a solid interaction between different structural materials and producing a strong, light and energy dissipative structure.

After the mid XIX century, such building techniques became progressively altered, till concrete was introduced in the early XX Century and soon became the most used material in new buildings.

A significant amount of the standing buildings in Lisbon were built before the "concrete age", either dating from before the 1755 earthquake or contemporary to the intensive reconstruction that followed it. Although most of the old buildings have already suffered some kind of repair or strengthening action, the large majority of these buildings still rely on their original timber frame structures, and some very fine examples of the original solutions can still be found and should be preserved.

Frequent conservation problems found in these buildings result from the inadequate use that was given to them at a certain stage of their life, that may have introduced excessive loading and even cause mechanical failure of some structural elements.

Besides, whenever high moisture content of timber occurred for a long period, either due to intentional modification to the building or to natural ageing of building components, severe decay may have developed in timber elements.

A suitable strategy to recover or improve the structural behaviour of these buildings includes in most cases the following steps:

- replacement of decayed timber elements, namely the ends of timber floor and roof beams;
- improvement of connections between walls and between these and the floors.
- strengthening of timber-reinforced masonry load-bearing walls, namely when timber members have suffered biological degradation or mechanical failure.

Although this situation is frequently dealt with integral replacement of timber beams or with beams strengthening by using steel plates, it is believed that Fibre Reinforced Polymers (FRP) or Glass fibre fabric glued with epoxy adhesives may be a preferable alternative technique for many situations.

3 OBJECTIVES OF THE STUDY

The Portuguese participation in the COLORETIM project (carried out by LNEC and STAP) was oriented to the repair of old structures only, and included three experimental studies:

a) assessment of gluing ability of several epoxy adhesives with four wood species (pine, spruce, chestnut, oak) with different moisture contents; study of these parameters' influence (Cruz and Machado, 2000c);
b) assessment of practical difficulties and advantages of five alternative methods for strengthening timber beams previously bent to failure (Cruz and Moura, 2000);
c) evaluation of the efficiency of FRP repair of timber-reinforced masonry load-bearing walls.

In the case of these timber frame walls, most frequent damage is related to timber decay or to its destruction by subterranean termites resulting from high moisture content attained in the timber for sufficiently long periods. These biological degradation frequently spreads from the timber pieces that are encased or adjacent to exterior walls, or located near windows or balconies, directly under the influence of defective roofs, or even in the area of *ad-posteriori* fitted-in facilities (kitchens, washing, toilets).

As a consequence of this, suitable repair of major timber elements is often needed. Their *in-situ* strengthening may be then the preferable solution, specially where the affected member also supports timber floor or roof beams.

The work programme described in this paper (part c) intended to exploit the possibility of using pultruded glass fibre reinforced bars, either on their own or in conjunction with glass fibre fabric, to repair damaged timber frame wall panels like the ones used in the *construção pombalina.*

In spite of the limitations associated with the use of scale models tested in diagonal compression, such preliminary tests are much less time consuming and easy to perform than panel shear tests on real size walls, besides giving already useful indications about the structural behaviour of strengthened wall panels as compared to the performance of undamaged walls.

One indication sought from this study was therefore the possibility of repairing partially damaged or distorted walls in old buildings in such a way that they are not only kept in place but one can still rely on their contribution to the global structural performance.

4 EXPERIMENTAL WORK

4.1 General

Six scale models of an individual unit of a typical timber frame wall panel were produced and tested in diagonal compression close to complete failure. After testing, the distorted test panels were brought back to their initial configuration, strengthen and subjected to diagonal compression again.

4.2 Construction of scale models of a wall panel

Several basic configurations of timber-reinforced masonry load-bearing walls have been identified in the old Lisbon buildings. Timber species used in these buildings and their cross-section dimensions also presented some variation, that was attributed to some extent of recycling of materials recovered from demolition.

In this study, six similar dimension-scale models (scale 1:3, figure 1) of a typical timber frame load-bearing structure were produced with European redwood timber (respecting the basic configuration and connection details found in buildings survey) and a low strength mortar.

The low strength mortar used in the in-filling has mechanical characteristics similar to the masonry found in old buildings. The composition of such a low strength mortar had been optimised through a series of compression tests both on masonry specimens collected from various buildings and different trial mortars. The advantages of using this low strength mortar rather than masonry are that the in-filling has a similar strength in all six panels and that it is possible to reproduce in future tests.

The in-filling mortar was poured into the timber frame, and also allowed to cover it by 5mm thickness (according to observations carried out in building surveys) and left to cure for 28 days. Then a render layer was applied to the panel faces: a cement-based render mortar, which was applied in a very thin layer. Further to this operation a further curing period of about two months was allowed.

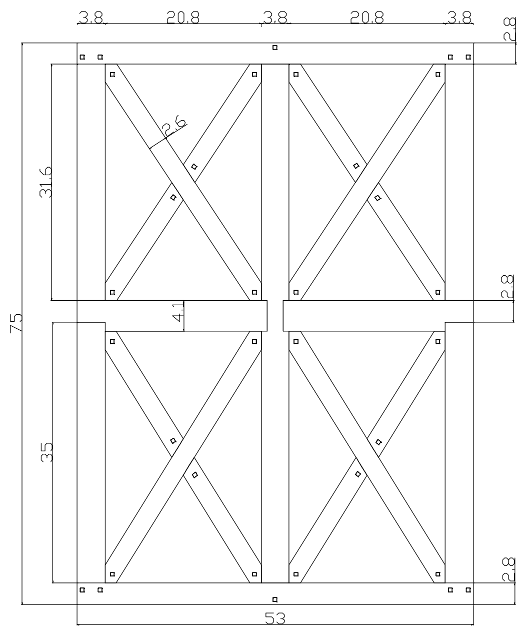

Figure 1 : Dimensions of wall panel timber frame elements (cm)

4.3 Testing

The test panels (wall panels) were subjected to diagonal compression.

The test panel was simply supported on a V-shape steel plate; thin hardwood wedges were inserted between test panel and metal supports to provide suitable bearing for the rectangular wall panel and vertical alignment of its two loaded corners. A similar V-shape plate and wedges group was intercalated between the top corner and the loading head of the machine. No lateral restrain was necessary during the test as no instability developed (figure 2).

Figure 2 : Diagonal compression of the wall panels

Loading was applied until serious failure developed in each test panel. In the first round of tests, that serious failure would correspond to a load-head displacement of about 25mm, when significant damage was already observed in the panel structure.

Load-displacement diagrams are presented in figure 10, including both the diagrams obtained for each wall panel prior to and after strengthening.

It should be noted that load and load-head movements were continuously recorded only up to the beginning of failure of the panels that occurred at an earlier stage in the less ductile original panels. The maximum imposed displacement and the corresponding load obtained in the initial tests are reported in table 1.

For every one of the six test panels (wall panels), from an early stage of the test deformation, the render fissured on the contact line between timber frame elements and the in-filling mortar and eventually detached from the panel. Soon after this, the tensioned joints started to open, although no lateral instability developed. Test was finished when the outer timber member of the frame (on the shortest sides of the panel) failed in bending (typical panel failure and detail are shown in figures 3 and 4).

Figure 3 : Original wall panel after diagonal compression test (typical failure)

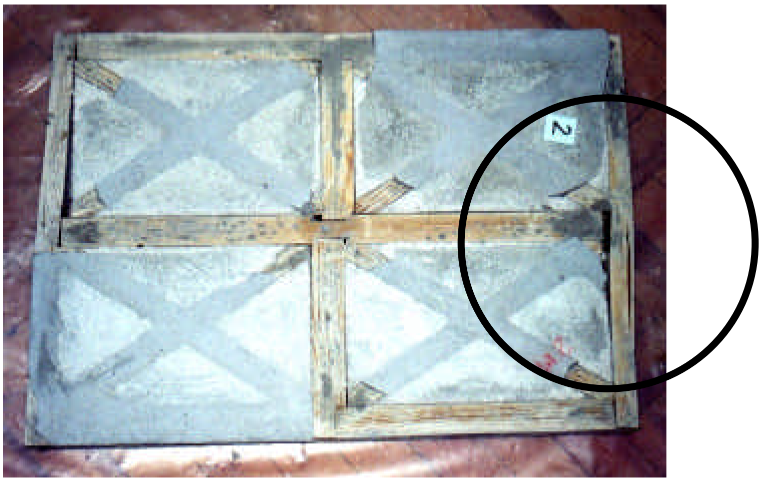

Figure 4 : Detail of the timber member failure in bending

4.4 Strengthening of panels

After testing, any loose render and fractured in-filling mortar was taken out and nails were removed, in order to allow the straightening of the tested panel (bringing it back into a rectangle). This was done by creating a rig with steel U-profiles and long bolts, and applying pressure to two parallel sides of the test panel each time (figure 5).

Figure 5: Rig where tested panels were straightened

Having reshaped the tested wall panels, while the above described clamping was maintained, new nails were introduced as close as possible to their original positions and clamping was then removed.

Every test panel was strengthened by repairing both outer timber members of the frame on the shortest sides of the panel. This was done by opening one slot in the broken timber member and placing in it one 10mm diameter glass fibre reinforced polymer (GFRP) bar glued with SlowSet 10T tyxotropic epoxy adhesive from ROTAFIX. Each GFRP bar was positioned the nearest possible to the centre of the corresponding member cross section, in order to avoid non-symmetrical strengthening effect. Two bars were therefore used for each panel (figure 6).

Figure 6 : Strengthening by inserting FRP bars (done in all panels)

In panels 1,2 and 3, further to the reinforcing bars, glass fibre fabric (GFF) stripes were glued to the joints where tension conducted to the separation of timber elements during previous testing. This was done on both faces, after the above-mentioned slot had been filled with epoxy adhesive and this left to cure.

The GFF stripes were as wide as the timber member they were glued to and 25cm long; in the case of extreme joints, glass fibre (GF) fabric stripes were therefore folded around the edge of the panel. (figure 7).

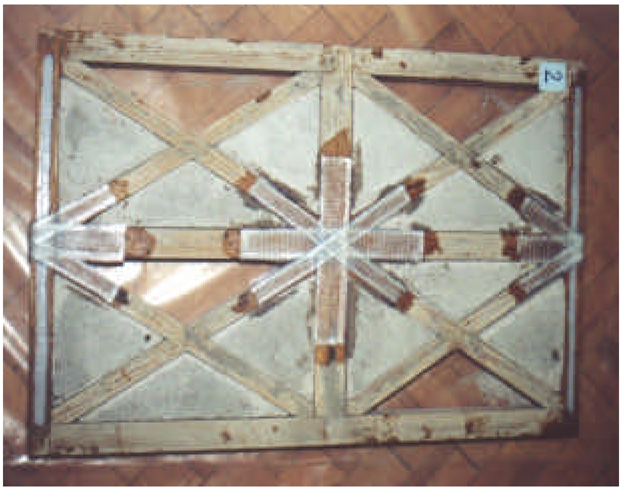

Figure 7 : Further strengthening of panels 1, 2 and 3 by gluing GFF stripes

The glass fibre fabric selected was alkali-resistant, as it would be covered with a cement-based mortar. Regarding fibre orientation, 90% of the fibres were in the main direction (parallel to wood fibres) with the remaining in a 90º angle. The fabric density was 2.6 g/cm^2.

SlowSet 10T adhesive was used for this purpose (one layer prior to and another one after GFF application). During this process, some adhesive was allowed to penetrate the existing residual gap between timber members under the GF fabric.

Epoxy adhesive was left to cure for two weeks. After that, new in-filling mortar was put in every wall panel as required, and as before, a covering layer of 0.5 cm would wrap the wall panel. After the initial curing took place, a cement-based render was applied. The whole wall panel was allowed a further curing period of about two months, prior to be subjected to new testing. Both the in-filling mortar and render mortar used in this stage were identical to the ones applied initially.

5 CONCLUSIONS FROM EXPERIMENTAL WORK

5.1 Test results

Strengthened test panels were tested again following the same method as before and making sure that the compressed diagonal in the first round of tests was also compressed this time.

The apparent behaviour of test panels under loading was similar to the one that had been obtained before strengthening, as regarding fissuring of the render and opening of tensioned joints. Failure of test panels occurred when timber members of the shortest sides of the panels failed in bending – like it happened before strengthening. It was observed however, that FRP bars and its bonding to the surrounding timber were not affected in the process, as failure in these timber elements developed in the nearby fibres (figure 8).

In panels 1, 2 and 3, which joints were also strengthened with GFF stripes glued to timber, the ends of GF fabric peeled of the timber by delamination of glue line near the end of testing (figure 9).

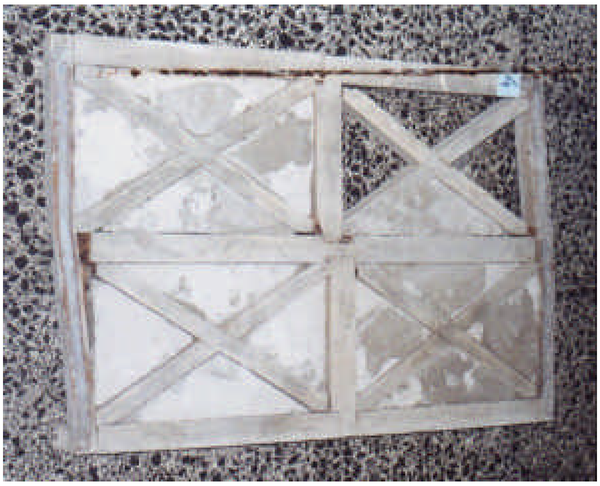

Figure 8 : Strengthened wall panel after diagonal compression test (typical failure)

Figure 9 : GFF delamination in strengthened panels 1, 2 and 3 after test (typical failure)

It should also be mentioned that for all the strengthened panels, the render remained attached to the in-filling mortar for longer (thus withstanding larger deformations), than in the case of unstrengthened panels. Although these render mortars may have had a slightly different composition and consequently different elastic properties, they are believed to have given a weak contribution to the overall results due to their small thickness and low strength.

Load and loading-head movement were continuously recorded up to the first serious failure of each test panel. Load-displacement diagrams of strengthened panels are presented in figure 10, together with the corresponding diagrams obtained in the first round of testing, for comparison between individual results.

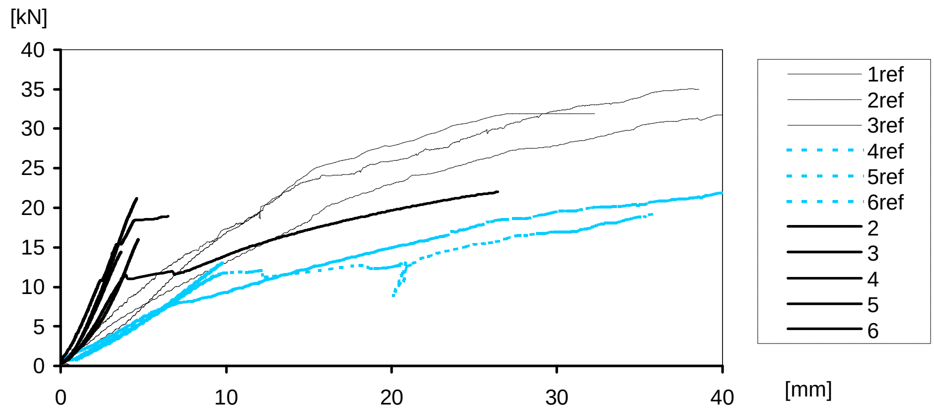

Figure 10 : Load-displacement diagrams obtained in diagonal compression of the wall panels, prior to and after strengthening (for deformation up to 40mm only)

2, 3, 4, 5, 6 – initial state panels
1ref, 2ref, 3ref – strengthened with FRP rods and GF fabric
4ref, 5ref, 6ref – strengthened with FRP rods only

5.2. *Evaluation of strengthening efficiency*

Table 1 summarises test results, in terms of maximum load and displacement (corresponding approximately to length reduction of the compressed diagonal). The strengthened wall panels present a very reasonable recovery of strength (between 73% and 127% of the strength of the initial panel) and a very good improvement in their ductility (between 158% and 316% of the maximum diagonal deformation withstood in the first test).

Table 1 : Summary of test results (load and deformation)

Wall panel	Before strengthening		After strengthening		Relative efficiency (strengthened/initial)	
	Max. imposed displacement (mm)	Corresponding load (kN)	Ultimate displacement (mm)	Ultimate Load (kN)	Displacement (mm)	Load (kN)
1	-	-	31.9	32.0	-	-
2	24.3	29.0	38.6	35.0	1.59	1.21
3	25.0	33,5	41.8	32.2	1.67	0.96
4	25.0	27.1	79.1	30.7	3.16	1.13
5	22.0	26.5	36.0	19.3	1.63	0.73
6	20.5	17.9	32.4	22.7	1.58	1.27

Table 2 presents the initial stiffness estimated from the linear part of the diagrams, taken between F_1=3kN and F_2=8kN.

In terms of strength and ductility efficiency, there is not a significant difference between the two strengthening systems tested (GFRP rods *versus* GFRP rods plus GF fabric stripes).

Table 2. Estimated initial stiffness of test panels

Wall panel	ki = $(F_2-F_1)/(d_1-d_2)$ Before strengthening		kf = $(F_2-F_1)/(d_1-d_2)$ After strengthening		Relative efficiency (strengthened/initial)
1	-		1.66		
2	4.71	(mean = 4.51)	1.97	(mean = 1.68)	0.37 (mean)
3	4.30		1.40		
4	3.22		0.97		
5	3.44	(mean = 3.76)	1.25	(mean = 1.20)	0.32 (mean)
6	4.63		1.39		

However, there are obvious differences in terms of the initial stiffness, when the two groups of panels are compared.

Even though all strengthened panels show lower stiffness than they had initially (prior to any test), it can be clearly seen, both from table 2 and figure 10, that the further application of Glass Fibre Fabric (in panels 1, 2 and 3) leads to a significant improvement, as compared to the application of GFRP rods only.

The results obtained in the above-referred experimental programme are quite promising. The strengthening techniques based on the use of glass fibre reinforced pultruded profiles and glass fibre fabric, in association with epoxy adhesives, are considered to have good potential for *in-situ* strengthening of timber reinforced masonry walls.

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