THE USE OF A CFRP REINFORCED RENDER IN THE SEISMIC STRENGTHENING OF OLD BUILDINGS

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Abstract. Testing Pombalina Walls reinforcement with new carbon composite grids.

1 INTRODUCTION

Old buildings are commonly composed by loadbearing masonry walls and wooden floors and roofs. Those type of construction has undeniable low seismic reliability that is aroused from a group of inefficient behaviours, extensively studied in a recent past [1-6]. Those studies showed that to improve the old building seismic performance the retrofitting strategy must be guided for the reduction of the effects of specific behaviour malfunctions. The most recognized are the out-of-plane bending and the connection ineffectiveness between structural elements, while in-plane bending and the shear mechanisms are also often a concern.

Structural retrofitting of an old building has nowadays the awareness that an efficient seismic response can only be established when the old building structural identity is respected. It can be stated that it is unworthy to develop reinforcing interventions that counteract the natural behaviour of an old building, removing from the scope of possible strengthening techniques the most widely used for steel and concrete structures. Likewise, the development of efficient strengthening techniques can only be achieved when the structural particularities of vertical structural elements composed by masonry and horizontal structural elements composed by wood are a given knowledge.

The development of the strengthening technique presented in this paper had the same guideline. The main concern for its development was the respect for the potential intervened structure, rather than the mechanical enhancements that its features could achieve. The basic idea for this technique was the addition of a structural layer to the masonry wall that could enable significant out-of-plane displacements without significant mechanical differences regarding the non-intervened masonry wall. Therefore the added material needed to be compatible with the masonry element, mechanically, physically and chemically.

One of the main problems within the reinforcement development was that the needed compatibility was roughly against the masonry basic mechanical needs for out-of-plane bending. Such mechanism, for the masonry walls, has the basic need to add to the masonry material tensile skills that such material does not initially has. For such purpose it was designed a composite render, with a Carbon Fibre Reinforced Polymer (CFRP) mesh responsible for the tensile strength of the reinforcement material involved by a non-cementitious mortar that could transmit the tensile strength to the masonry while keeping the reinforcement and the masonry working together. As a composite material the compatibility of the render matrix would be dependent of the render itself as the tensile strength enhancement would depend on the CFRP mesh.

2 OTHER STRENGTHENING TECHNIQUES WITH TE SAME PURPOSES

Due to the interest in the seismic strengthening of old buildings, some seismic strengthening techniques have arisen to improve the seismic performance of non-reinforced masonry buildings. Fibre reinforced polymers (FRP) have naturally aroused the interest of the academic environment and practicing engineers for the application to the seismic retrofitting of non-reinforced masonry buildings. Its appeal came from its recognized advantages as its high strength to weight ratio, thinner cross-sections, non-corrosive nature of the constituent materials and their application easiness [7-11].

One typical FRP-based seismic retrofit solution is the full overlay of epoxy impregnated FRP sheets (usually glass based, GFRP) applied directly to the surface of the masonry walls. However several challenges or disadvantages are usually associated with the use of organic epoxies in such FRP application [12]. Among these disadvantages are their irreversible nature, stiffness incompatibility with the non-reinforced masonry, the absence of vapour permeability, and poor performance both at elevated temperatures (typically higher than the 60° C to 80° C range, that is the glass transition temperature for the epoxy resins) and in alkaline environments [13].

One alternative to overcome these challenges is the use of reinforced concrete jacketing. The aim of the technique is to connect the several wall leafs in deficient conditions, creating a new section, constituted by the masonry one, surrounded with two reinforced concrete parts. Its design creates a thicker section, to increase the resistance to compression, tensile and shear efforts. The masonry panel thus achieves high strength but also sees its stiffness considerable incremented, which is not always beneficial, especially when considering the overall behaviour of the building. In addition, discontinuities due to the presence of floors produce local decreases in stiffness and strength, as well as irregular reinforcement provisions. Therefore, reinforced concrete jacketing counteracts the natural behaviour of the masonry walls and as initially referred should not be considered as an efficient strengthening technique for old buildings. Such features in such a way that the wall presence can be assumed as negligible, once the reinforced concrete will become the main responsible for the behaviour of the strengthened wall, removing to the building its structural identity. Furthermore, the absence of vapour permeability provoked by the concrete jacketing becomes again a disadvantage, as the bi-carbonation of the masonry mortar becomes a potential anomaly.

The described techniques, despite its specific disadvantages have undeniable adhesion to the masonry substrate. The CFRP reinforced render, although without the presented disadvantages, could eventually be dysfunctional if the needed adhesion levels were not achieved. Therefore, the greater obstacle to cope for the success of the developed technique became the grant of the desired adhesion between the CFRP reinforced render and the masonry substrate.

3 DESCRIPTION OF THE STRENGTHENING TECHNIQUE

As referred, the developed technique consists on the application of a reinforcement layer to the masonry walls substrate (Figure 1.a), providing to the masonry tensile resistance skills. Such layer is endowed of high tensile strength and bonding capacity to the original masonry substrate, as its material (the CFRP reinforced render) is the main responsible for the referred abilities.



The reinforced render material can be described as a bi-component material, composed by a hydraulic but non cementitious coating mortar and a carbon fibre reinforced polymer (CFRP) mesh (S&P ARMO-mesh 200/200

Table 1: Reinforcement	grid	mechanical	characteristics
	ω		

	Elastic modulus	Elastic modulus for design	Tensile strength	Ultimate tensile
	KN/mm ²	KN /mm ²	N/mm ²	force KN/m
ARMO-mesh 200/200	240	160	4300	185

The coating mortar function is to bond the reinforcement layer to the masonry wall, as it keeps chemical, physical and mechanical compatibility with the masonry. On the other hand, the CFRP mesh will provide to the reinforcement layer the needed tensile strength.

There went some doubts regarding the coating ability to keep its bond to the masonry when the CFRP mesh is fully requested, in the case of a traditional mortar coating application. It was then developed an innovative application technology to assure the needed bonding, mainly driven from the shotcrete technology. As the coating mortar is applied by high-speed spraying to the masonry substrate, it is granted the adhesion levels needed to bond the reinforcing render material to the masonry substrate.

While masonry walls acquire tensile resistance to bend, they also can be, from it, highly compressed. One issue that tends to aggravate masonry walls behaviour is its multi-leaf morphology, especially when the connection between leafs is poor or non-existent [15]. To avoid the masonry leafs detachment provoked by highly compressed stress states, the strengthening technique allows, when needed, to connect both sides of the masonry walls, by applying steel confinement devices that will ensure such effect. Those steel confinement devices are also responsible to enhance the layer bonding (to the masonry) at the zones where the CFRP mesh is stretched till fracture, making possible its tensile failure with total bonding effectiveness between the reinforcement layer and the masonry wall.

The reinforcement layer anchorage at singularity zones assumes the same matter as its overall capacities. The layer will only be effective if well anchored at its endings, as well at specific transitional zones that need the layer interruption (for instance while crossing the building wooden floors). In the developed technique such purpose is granted mainly from the organic adhesion (by epoxy resins) of the CFRP mesh of the reinforcement layer to specific devices (Figure 1.b) that will assure mechanically the anchorage needs.

4 THE SHOTCRETE OPERATION

Shotcrete is widely used as rock support in mines and in civil engineering projects. It is applied through a process by which concrete or mortar is sprayed onto a surface to produce a compacted self-supporting and loadbearing layer. In many cases the adhesion between the shotcrete and the substrate is one of the most important properties that the designer needs to consider.

The adhesion is traditionally defined as the strength of an interface between two materials, for instance between the masonry and the shotcrete material. However, in many cases the location of the failure surface will differ depending on the strength of the contact zone, the tensile strength of the substrate and the tensile strength of the shotcrete layer [16].

For the developed technique the adhesion strength mainly depends on treatment (cleaning), roughness of the surface, mineral composition of the masonry substrate and the shotcreting technique (dry or wet). The shotcrete technique includes the skill of the operator which is of great importance. After mechanical scaling, the masonry surface has to be cleaned in order to achieve adhesion strength between the masonry and the shotcrete material. To ensure such feature water jet-scaling may be used in order to assess the potentials of the operation and to ensure an improved adhesion.

Rebound is an important factor causing poor shotcrete quality and is a good indicator of the quality of the shotcreting technique [17]. The amount of rebound depends mainly on the nozzle angle to substrate and the nozzle distance to the masonry. The most significant influence is from the angle of the nozzle to the masonry. The nozzle should always be held at a right angle (90°) to optimise compaction. The distance between the nozzle and the masonry should be between one and two meter while for longer distances, longer than three meter, the rebound will increase and the compaction and strength of the shotcrete material will decrease.

The mortar shrinkage is sensitive to its water content and the final value of shrinkage can be reduced by decreased content of water in the mortar mixture. For a given water-binder ratio, shrinkage increases with higher binder content [18]. Wet-mix shotcrete, with its higher water/binder ratio generally shows higher shrinkage. Therefore, dry-mix shotcreting is always preferable for the use of this strengthening technique.

Specific lime based mortars are beginning to be widely used in conservation operations involving ancient masonry, due to its compatibility with the interposed part, given the similarity of their nature. These mortars are made exclusively from natural hydraulic or air lime, having particular thixotropic properties, as well as adhesion, chemical resistance and durability better adapted to the intended function. Satisfying such demand, it have recently appeared commercial mortars guided for repairing ancient buildings. Their coherent mechanical strength and stiffness, high vapour permeability and low content of soluble salts (recurrently emphasized at their technical sheets), constitute excellent characteristics for the bonding solution to the masonry substrate.

Preliminary tests to the mortar shotcreting operation were conducted, using a commercial solution for the mortar applied to a rock substrate by dry-mix shotcreting. The obtained

operational results were widely satisfactory as depicted in Figure 2, given the reduced shrinkage of the shotcrete layer.



Figure 2: Shotcreting testing

5 EXPERIMENTAL PROCEDURES

The experimental programme was designed to provide the basis for a subsequent calculation model (and design rules) for the application of the technique presently under development. In general, the experimental programme devised to develop this technique was divided into four distinct (but dependent) intervention fields, thus:

- Material characterization tests;
- Cyclic adhesion/anchorage tests on CFRP reinforced render strips;
- Cyclic tests for in-plane horizontal loads;
- Cyclic tests for out-of-plane horizontal loads.

The characterization tests envisaged sought to determine the main mechanical characteristics of the materials constituting the reinforcing solution (the CRFP reinforced render). Seven CFRP reinforced render strips underwent direct tensile strength tests (Figure 3), each with different objectives, namely the assessment of the tensile strength of different strengthening materials, and the study of the effect of different anchoring details.



Once the reinforced render material had been characterised, the rest of the experimental work focused on the study and characterisation of the bond behaviour (and anchorage),



followed by the in-plane and out-of-plane behaviour of masonry walls strengthened accordingly.



To test the full-scale specimens there were conceived specific test schemes to characterize the behaviour of the strengthened masonry walls: quasi-static testing of reversed cycles of horizontal displacements. The geometry of the specimens had to be representative of the walls of old masonry buildings. Therefore, they were constituted by an inferior spandrel, a pier and a superior spandrel (Figure 5). All the walls were 40 cm thick, as one of the wall sides (the one where went the reinforcement layer application) had small slits to simulate the mortar joints revival operation that the reinforcement technique may require (for instance by water jet-scaling).



The reversed cyclic pseudo-static lateral loading of the tests to walls specimens was applied using a screw jack coupled with a load cell, which were together positioned, enforcing a steel helmet embedded to the specimen superior spandrel (Figure 6). As it was not characterized the non-reinforced behaviour of the idealized walls, there were needed six reference tests with different axial loading and following four different test schemes schemes A, B, C for the in-plane tests and one more for the out-of-plane tests - scheme D.

Test scheme A (Figure 6.a) did not restrain the inferior spandrel and from such release there went a rigid-body movement that significantly influenced the test results. The subsequent tests (with the test schemes B, C and D) had the inferior spandrel displacements restrained by a steel structure, in order to prevent any rigid-body failure mechanisms. Test scheme B (Figure 6.b) kept the horizontal load applied at the top of the wall, in order to make prevail the in-plane flexural mechanisms in the walls tested with it. Two reference tests were conducted, varying the applied axial load, as the test scheme B still led to the realization of eight tests to strengthened specimens.

By reducing the height of the applied horizontal load, such should induce the in-plane shear failure mechanisms. This principle led to the idealization of the test scheme C (Figure 6.c), similar to the test scheme B but with a smaller loading height. Only one reference test was made with this test scheme, and with the same axial load were performed four tests to strengthened specimens.

For the out-of-plane testing, two initial reference tests were performed to characterize the non-reinforced behaviour of the masonry walls specimens, with different axial loading and following the test scheme D (Figure 6.d). The same test scheme led to the realization of eight tests to strengthened specimens.



Figure 6: In-plane and out-of-plane test schemes

The test parameters considered were based on the main variables that should affect the masonry walls behaviour when requested horizontally, by varying the axial load applied and the presence of the confinement devices. A total of 26 tests to full-scale masonry specimens were conducted, achieving significant improvements to the in-plane and out-of-plane bending behaviours, which are presented in the following section.

6 OVERALL EXPERIMENTAL REMARKS

The direct tensile tests gave an indication of the tensile strength of the CFRP reinforced render, also giving some valuable insight on the most adequate clamping solution. The best clamping detail for the reinforced render was achieved with an organic adhesive, applied between the carbon fibre mesh and the steel device anchoring the composite material. The importance of this observation was considered in the remaining experimental work (adhesion/anchorage tests and in-plane and out-of-plane bending tests on wall specimens).

With the completion of the adhesion/anchorage tests, one of the development stages for the strengthening technique consisting in the application of external layers of CFRP reinforced render, the basis for the definition of the technique bonding behaviour and the anchorage solutions were established. The tests showed that the adopted anchorage and bonding solutions were suitable for the intended purposes as the CFRP mesh fracture characterized the tests collapse (Figure 7).



a. Reinforced render mortar detachment b. Fracture of the CFRP mesh Figure 7: Damage features of the adhesion/anchorage tests [19]

However, those results do not explain to what extent the increased strength provided by this strengthening technique is proportionate to the desired seismic behaviour of old buildings. The awareness of the structural solution abilities (the mechanical ones) depends largely on the differences of strength, stiffness and deformation capacity between nonreinforced masonry walls and similar strengthened walls. Its assurance could only be established with experimental tests that could represent real masonry walls.



a. Test Scheme B (lower axial load) b. Test Scheme B (higher axial load) c. Test-scheme C Figure 8: Load-displacement curves envelops for the in-plane tests to full-scale wall specimens, adapted from [20]

For the full-scale specimens and for the situations of axial and transverse loading studied, the walls capacity to resist to horizontal in-plane actions was significantly enhanced (Figure 8). For both levels of axial loads the in-plane bending strength was always increased, but started to be dependent on the compressive strength of the wall (either from excessive axial loading or excessive shear loading).



Figure 9: Load-displacement curves envelopes for the out-of-plane tests to full-scale wall specimens, adapted from [14]

For the out-of-plane testing, there were also achieved greater strengths when the specimens were strengthened (Figure 9) and when the reinforcement was tensile stressed. Following the strength increment, the tests also revealed, with significant meaning, a considerable increase in the deformation capacity of the strengthened specimens, again only when the reinforcement was tensile stressed.

However, by increasing the axial load applied on the specimen, their capacity to resist horizontal out-of-plane actions was not significantly enhanced. This suggests some limitations due to excessive compression in the masonry material, which was not sufficient to lead the specimens to its collapse, since the fracture of the CFRP mesh was the main failure observed in the out-of-plane tests. It should also be noticed that the situation corresponding to the compression of the reinforcement layer provides, by obvious meanings, lower-resistant capacities.

7 CONCLUSIONS

The performed scientific study assertively shows that the developed strengthening technique has potential to improve the behavioural parameters of the masonry walls of ancient buildings. If the original purpose to overcome the functional and structural incompatibilities that other strengthening techniques (guided towards the same goal) show, was at the beginning granted by its own definition, the level of improvement that the strengthening achieves (both in terms of strength and deformation capacity) turned out as a pleasant surprise, given that, in the initial phase of its development, it was not expected to achieve such good results. Those achievements were only possible by specializing the principles for the implementation of the structural strengthening, noticing that to take proper advantage of the strengthening solution a set of implementing rules must be respected (scrupulously followed throughout the experimental campaign), which need to be summarized in a specific procedure for the application of the strengthening technique.

The conduction of experimental tests have an essential matter for a knowledge evolution process of this kind, but it is only the first step to design a solid foundation for the assessment of this strengthening technique - the definition of a comprehensive calculation model summarized in a technical guideline. An extensive numerical work is also completed, that allowed to achieve this aim. The main conclusions of this works will be reported in future publications of the same authors.

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