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DEVELOPMENT OF NEW BRAIDED FIBROUS MATERIALS FOR RETROFITTING OF MASONRY WALLS

Fernando Cunha[1(*)], Sérgio Patinha [1] Sohel Rana[1], Raul Fangueiro[1, 2], Graça Vasconcelos[2]

[1]Fibrous Materials Research Group (FMRG), School of Engineering, University of Minho, Guimares, Portugal.
[2] Department of Civil Engineering, University of Minho, Guimaraes, Portugal
[(*)]*Email:* fernandocunha@det.uminho.pt

ABSTRACT

The most recent earthquakes in Turkey (Kocaeli 1999, Duzce 1999, Bingol 2003), Italy (L'Aquila, 2009) and Spain (Lorca, 2011) demonstrated the vulnerability of non-loadbearing unreinforced masonry walls acting as infill of reinforced concrete frames. To address this issue, the main focus of this work was to develop a fibrous structure that will provide very good adhesion with the cement mortar and will present excellent ductility in order to sustain the structure of masonry walls after a seismic event, avoiding complete splitting and collapse. Different fibrous structures were produced with different surface characteristics (height of surface undulations and spacing between them). The adhesion between these braided structures and cement mortar was characterized using pull-out tests and according to the experimental results, the braided structures with polyester braids as braiding yarn and, produced using optimized process parameters showed excellent adhesion with cement mortar, leading to complete breakage of these structures before being pulled out from the cement mortar.

Keywords: masonry wall**,** braided structure, cement mortar, adhesion, pull-out test.

INTRODUCTION

The quality of the built heritage play a central role on the quality of daily human lives as they interact continuously with the built spaces, either in the work, social events and at home. In particular, the safety of the built spaces is indeed a demand of modern societies and remains a huge concern in seismic prone regions. In reinforced concrete (RC) buildings, brick masonry walls represent the most traditional enclosure systems and have demonstrated reasonable performance with respect to healthy indoor environment, temperature, noise, moisture, fire and durability, even if there has been some trend for improvement of serviceability by proposing newly solutions (Lourenço *et all*, 2010). Despite masonry infill walls have been considered for long time as non-structural elements, they can play a positive role in the seismic behavior of RC buildings, if their influence on the building response is correctly taken into account (Bertero & Brokken, 1983) (Charr *et all*, 2002). Indeed, as demonstrated by recent earthquakes, the inefficient behavior of masonry infill's can result in extensive economic losses, resulting in low levels of reparability, and in the loss of human lives. This situation raises the need of improvement of the construction technology and design of non-structural elements for new buildings and of retrofitting in case of existing buildings. Strengthening of masonry infill walls using fibrous materials and composites (FRPs) is becoming a common practice to prevent complete collapse of masonry walls under seismic events. However, one of the major drawbacks of these strengthening materials is their delamination from the cement mortar when subjected to loads (Lourenço, 2000) and this fact reduces their performance. To overcome this problem, the present paper reports a new fibre based strengthening system of masonry walls.

SEISMIC BEHAVIOUR OF MASONRY INFILL WALLS

According to (Karakostas *et all*, 2003), after the Lefkada earthquake in Greece in 2003, it was seen that the major damage was concentrated at the non-structural elements, particularly in clay masonry infills, including out-of-plane collapses, shear cracking and detachment of the walls from enclosing frames. From the recent earthquake of L´Áquila in 2009, in Italy, apart from the collapse of rural masonry residential buildings, it was observed that the widespread extensive damages in masonry infill walls and internal partition walls, were responsible for the highest losses in RC buildings (EEFIT. 2009). This type of non-structural damage requires in general high investment as it requires extensive repair, or in case of low reparability, results in the demolition and reconstruction, resulting in a major waste of time and money. The major concern about the out-of-plane vulnerability of masonry infills is the lack of detailing at the level of materials, connections to the surrounding RC frames and absence of fastener in case of cavity walls, resulting often in the complete and independent collapse of the walls, as seen in Figure 1.

Figure 1 – Failure patterns of masonry infill walls found in the recent earthquake of LÁquila

BRIEF OVERVIEW ON THE RETROFITTING TECHNIQUES FOR MASONRY INFILL WALLS

The principal techniques are: surface bonded fiber reinforced polymer systems (Carbon fiber reinforced polymers CFRP, Glass fiber reinforced polymers GFRP, Basalt fiber reinforced polymers BFRP), fiber reinforced shotcrete (FRS), near surface mounted twisted steel bars and textile reinforced mortar (TRM).

Fiber-Reinforced Polymer composites (FRP) are being widely used during the last few years, in order to increase the in-plane shear resistance or to provide out-of-plane load bearing capacity of masonry walls. In fact, composite materials can be advantageously applied at the intrados or extrados surfaces of both flat and vaulted masonry structures, to prevent or delay the most important collapse mechanisms, and consequently to increase the overall load carrying capacity, even in case of seismic action.

USE OF REINFORCED TEXTILE MORTAR AS A RETROFITTING TECHNIQUE

The development of textile materials starts with the development of high-performance fibres such as fiberglass (in the 30s) and carbon fibres (early 60s), developed for high technology industry such as the aeronautics. Its application in the building industry as part of reinforcement of cement-based materials starts in the beginning of the 80s, and they were through a slow process of investigation until the late 90s (Papanicolaou *et all*, 2007). Textile reinforcing materials, viewed as a material highly resistant to tensile stresses, can be embedded in a mortar matrix that acts as the bonding agent with the main structure to be reinforced. These materials consist on long woven, knitted or even unwoven fiber rovings in at least two directions. The first investigated solutions were related to its tensile properties and its application to reinforcement of reinforced concrete structures, which made it suitable for the reinforcement of beams (both for bending and shear) or the jacketing and confining concrete columns. The application as a method of jacketing for retrofitting masonry walls is a relatively new concept still under investigation. Nonetheless, it is already one of the recommended reparation techniques in some guidelines. Among the parameters that affect the performance of the textile mortar reinforcement, there are some remarkable ones: (1) density of the mesh, depending on quantity of fibres in each thread (defined by mass) and the separation among them; (2) properties of the mortar, affecting the bond between the element and the reinforcement; (3) properties of both mortar and textile surfaces, affecting the bond among them to make the composite adequately.

Textile reinforced mortar (TRM) is being developed mainly as an alternative retrofitting technique to glass or carbon fiber reinforced polymers (GFRP, CFRP), that have been a great development and widespread use in the field of structural strengthening. Nevertheless, some disadvantages, mainly linked to the use of resins as bonding agents, are leading to the investigation of other materials of similar behavior. Some of the most important disadvantages are: (1) high costs due to both the materials and the requirement of highly skilled workmanship; (2) need of good protection against fire action, given its very low performance in this situations; (3) impermeability both to water and to vapour, that can lead to bond problems; (4) hazards of using resins: dissolvent, toxic vapours, etc.; (5) difficult reversibility of the strengthening, which is specially problematic for historical structures or in cases where problems such as cracking must be checked afterwards.

The use of an inorganic matrix would solve most of these problems, given that the properties of cementitious binders are more alike to the properties of concrete, and also masonry. Nonetheless, its behavior is not still fully investigated and there are many parameters that must be studied to get to a better understanding of the behavior of this material, as well as its advantages when compared to other reinforcement techniques. Studies by Papanicolau and Triantafillou have compared the performance of FRP and TRM for many applications, namely for strengthening masonry for both in-plane and out-of-plane actions (Triantafillou *et all*, 2006 and Papanicolaou *et all*, 2007). For in-plane loading, they found that, compared with a FRP reinforcement of the same fibre density, TRM had an effectiveness of 60-70%. In general, but specially for out-of plane actions (which are usually the ones to cause major damage and potential victims during earthquakes), TRM is a very promising technique, thanks to its capacity of rising highly deformability of the infill walls before the collapse, as well as its strength.

Experimental Methods

The surface tailored FRP rods were produced using a low-cost, flexible and single-step braiding technique (patented by authors) in which impregnation of core fibres with resin, braiding and consolidation of the braided structures were performed simultaneously (Papanicolaou *et all*, 2007) Produced braided structures were subsequently cured to produce composite rods. Four types of rods were produced. In the basic type, 16 polyester yarns (linear density of 11 Tex) were braided around the carbon fibres at a take up velocity of 0.54 m/min to produce composite rods with relatively soother surface. The other three types of rods were surface tailored and produced by replacing one or two polyester yarns with polyester braids and varying the take up velocity, as listed in Table 1.

Table 1. Details of produced composite rods

Sample code	Core structure	Braided structure	Speed (m/min)	Braiding angle (°)
SIMPLE	2 carbon yarns	16 polyester yarns	0.54	35
1EVmin	2 carbon yarns	15 polyester yarns and 1 braided structure made of 8 polyester yarns	0.54	33
2EVmax	2 Carbon yarns	14 polyester yarns and 2 braided structures made of 8 polyester yarns	1.07	15
2EVmin	2 Carbon yarns	14 polyester yarns and 2 braided structures made of 8 polyester yarns	0.54	49

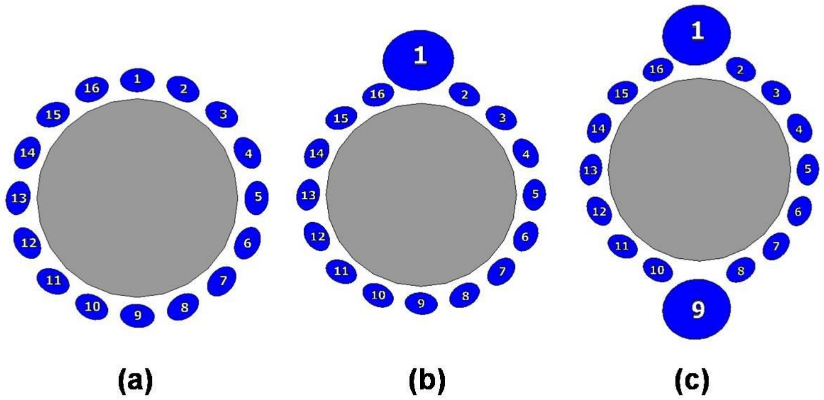


Fig. 2. Schematic representation of structure of various composite rods: (a) SIMPLE, (b) 1EVmin, (c) 2EVmax or 2EVmin

The schematic representation of the structure of the produced rods is provided in Fig. 2. The change in the braided structure and take up speed resulted in significant difference in the surface geometry of the rods as illustrated in Fig. 3. It was noticed that the height of the ribs (h) was approximately same (~0.5 mm) for all the surface tailored rods. However, the distance between the ribs (D) varied significantly from one rod to another.

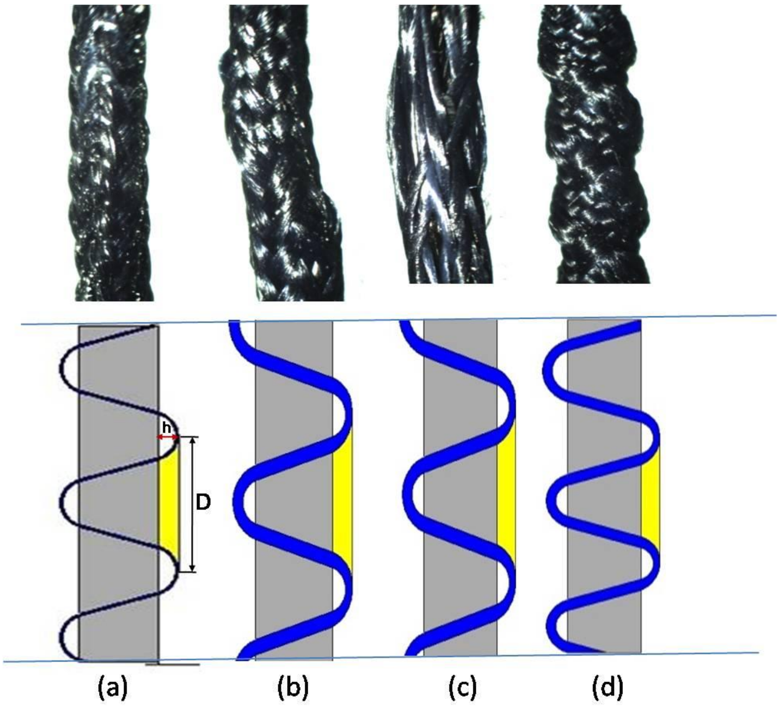


Fig. 3. Surface geometry of produced composite rods: (a) SIMPLE, (b) 1EVmin, (c) 2EVmax and (d) 2EVmin

EXPERIMENTAL CHARACTERIZATION OF ADHESION OF BRAIDED RODS WITH MORTAR

As above mentioned, the adherence between the braided rods and the mortar take a central role on the performance of the retrofitting technique as it is intended that the retrofitted infill masonry exhibit an improvement in terms of initial cracking load, maximum flexural and shear resistance and ductility. In fact, it is important to avoid brittle failures and promote cracking distribution, contrarily to happen in case of unreinforced masonry that presents normally crack localization.

SPECIMENS AND TESTING PROCEDURE

The experimental assessment of the influence of the surface tailoring of braided structures on the adhesion with mortar was carried by carrying out simple tensile bond tests (pull-out test) in mortar cylinders, where single braided rods were embedded, see Figure 4.

Figure 4: Samples for pull-out test

It was decided to use mortar cylinder specimens with 5 cm diameter and 10 cm height. The mortar used in the specimens is a pre-mixed mortar, appropriated to make the rendering of the masonry infill walls. The preparation of the mortar specimens was carried out through NP EN 196-1 (2006). The braided rods were introduced in the full height of the mortar specimens. Four specimens for each type of braided rod with distinct rugosity were considered.
A system for fixing the mortar specimens to avoid any displacement of it was designed. It is composed of bottom and top steel plates connected together by means of steel rods. The tensile bond tests were carried out in an electrical machine by using a speed of 0.5 mm/min. The distance between the clamps was of 130 mm and it was considered a preload of 10 N. The displacement was measured using an extensometer, as seen in Figure 5. The tests were carried out after 28 of curing of the mortar.

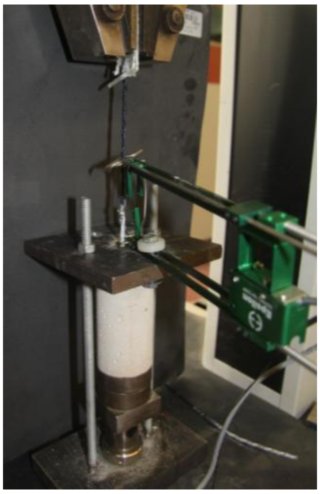


Figure 5**:** Setup for tensile bond tests

ANALYSIS OF RESULTS

The tensile force vs. displacement diagrams obtained in the tensile bond tests corresponding to the braided rods with distinct rugosity are indicated in Figure 6. As can be observed, the higher value for the tensile bond strength is obtained for the braided rod 2EVmin, being the minimum value obtained in the braided rod 2EVmax.

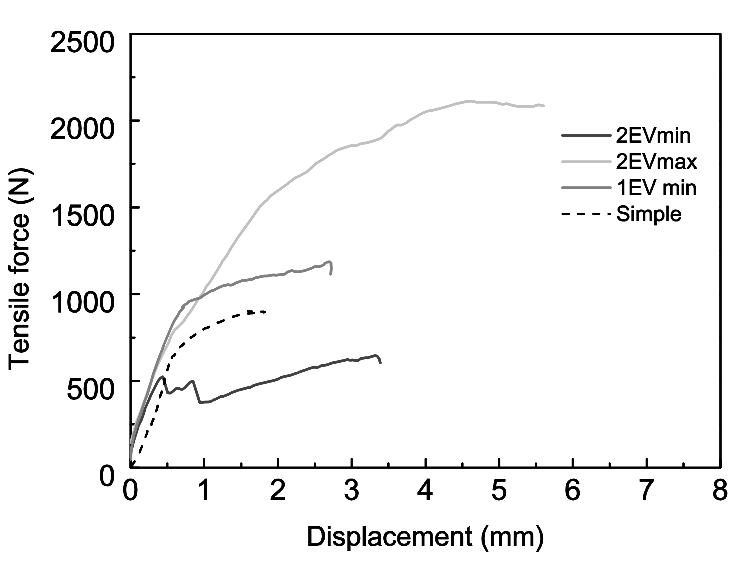
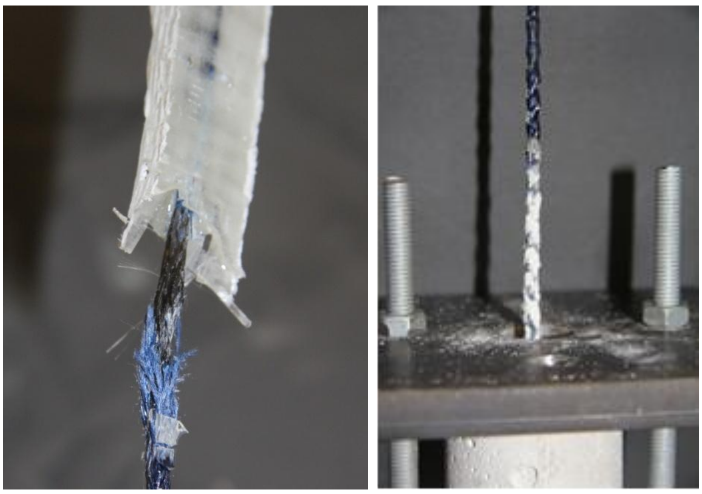


Figure 6**:** Load-displacement diagrams obtained in the pull-out tests

This structure represented an excellent adhesion with cement mortar and resulted in complete breakage of the braided structure before pull-out. In fact, from Figure 7a it can be seen that the maximum value of the tensile bond strength is controlled by the tensile load of the braided rod. In the other cases, the maximum load is controlled by the bond strength, as the braided rods slip clearly from the mortar specimens, see Figure 7b. This new type of braided structure (2EVmax) can support a pull-out load of 2113 N, which is 135% higher, when compared to the control sample (SIMPLE). On the other hand, it is seen that in spite of the braided rod 2EVmin appears to have a considerable rugosity and thus could improve the bond strength, it resulted in the minimum bond strength. This behavior should be related to the premature local breakage of the mortar in between the salient rugosity. This means that use of additional braided structure combined with higher values of the angle should be avoided.
In any case, it can be concluded that if the braided rods are adequately tailored, it is possible to improve the tensile bond strength and thus lead to a better performance when combined in a mesh to retrofit masonry infill walls.



(a) (b)

Figure 7**:** Details of the failure patterns obtained in the tensile bond strength: (a) specimen with braided rod 2EVMax; (b) specimen with control braided rod (SIMPLE)

CONCLUSIONS

The tensile bond strength of the distinct braided rods embedded in mortar was obtained based on direct tensile bond tests. From the experimental results, it was observed that the surface tailored braided structures produced with a take up speed of 1.07 m/min and braided surface containing 14 multifilament polyester yarns (11 tex) and 2 braided structures each made with 8 multifilament polyester yarns (11 tex) were found to provide excellent adhesion with cement mortar, being this controlled by the tensile strength of the braided rods. This means that if stronger braided rods are produced the tensile bond strength can be improved and completely characterized. Therefore, these novel fibrous structures have potential to act as an alternative material to existing other retrofitting solutions. With this respect, it should be mentioned that additional tensile bond tests should be performed by varying the strength of the braided rods by introducing higher amount of reinforcing fibers. Additionally tensile bond strength tests on the mesh composed of the braided rods disposed in two perpendicular directions must be also carried out.

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