A brief overview on the retrofitting possibilities of masonry infill walls

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Abstract

This work presents a brief review on the seismic behavior on non-loadbearing masonry walls used as masonry infills. O Some examples of inefficient performance are shown based on information available of recent earthquakes. Additionally, a literature overview on the techniques for retrofitting existing masonry infills is provided. Finally, alternative braided reinforced composite materials are briefly described and pointed out as an alternative solution for retrofitting masonry infill walls.

1 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 prone seismic regions. It is known that seismic vulnerability is not exclusive of ancient masonry structures but affects also the built heritage from XX century, composed in a majority of reinforced concrete (RC) buildings, both in structural and non-structural elements. In this constructive typology, brick masonry walls represent the most traditional enclosure system 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 serviceability by purposing newly solutions [1-2]. According to [1] masonry infills represent approximately 15% of the total construction volume.
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 in the

building response is correctly taken into account [3-6]. Conversely, they need to be checked against in-plane severe damage and possible out-of-plane collapse. Indeed, as demonstrated by recent earthquakes, the inefficient behavior of masonry infills 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. The latter aspect is the focus of this paper. Indeed, it is of paramount importance to act promptly in the retrofitting of masonry infill walls, taken into account that great part of RC buildings was designed before the advent of seismic regulations. With this respect, some guidelines are provided in some international codes but in a majority of countries there are no standardized guidelines for the retrofitting of masonry infills.

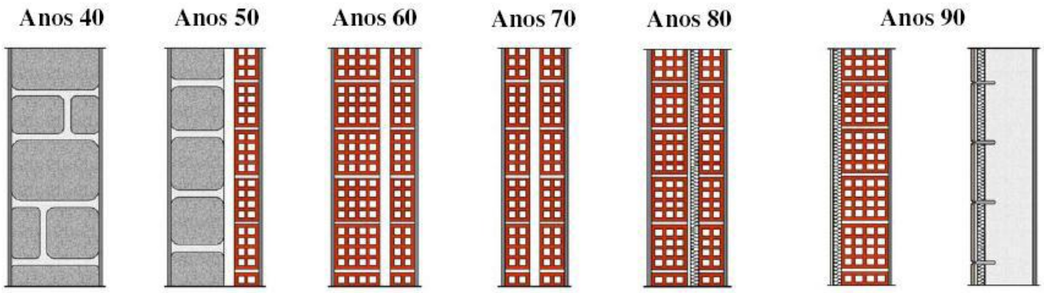
This paper intends to provide; (1) information on the seismic behavior of masonry infill walls under seismic action, by focusing on post mortem survey in recent earthquakes; (2) a brief overview of the retrofitting techniques of masonry infill walls; (3) information of alternative braided fibrous reinforcing materials regarding the traditional retrofitting carbon or glass reinforcing polymer solutions.

2 Tipology of non loabearing walls

The brick masonry walls as non-loadbearing elements have been used since the generalized adoption of the reinforced concrete as a main structural system in Portugal, which dates back to 1960. In Figure 1 one can see the evolution of masonry walls in Portugal during the xx centuy:

a) decade of 40: single leaf walls in stone masonry;
b) decade of 50: stone masonry walls with a internal leaf in brick masonry;
c) decade of 60: Cavity Wall with brick masonry with thick external leaf;
d) decade of 70: Cavity Wall with brick masonry with médium thickness;
e) decade of 80: Cavity Wall with brick masonry with médium thickness with termal insolation in between the leaves;
f) decade of 90: Single leaf walls with external termal insulation

The single walls become to be used again with the solution of vertically perforated brick masonry units, being associated to innovative solution of external thermal insulations solution [8].



(a) (b) (c) (d) (e) (f)

Figure 1- Evolution of non-loadbearing brick masonry walls in Portugal [8]

3 Behavior of nonloadbearing walls under seismic loading

Masonry infills are not considered as structural elements, as they do not have to bear vertical loads, and, thus, no specific design guidelines are provided in design codes, including Eurocode 6 [9]. However, in case of occurrence of earthquakes they can have an active role on the global resisting mechanism of the RC masonry infilled frames. The problem of the interaction between infill and RC frames, on how the infills influence the structural response, has been object of many experimental and numerical research [10-12].

According to past research [10, 13-14] it is known that masonry infills can have a beneficial effect under controlled damage, when it develops before the maximum shear forces occur, being able to dissipate energy and control inter-storey lateral drifts of RC frames. However, it very often happens that damage and collapse of RC buildings is due to improper consideration of, or neglecting, the infill walls influence on the surrounding RC elements. Indeed, the negative effect of the masonry infills is related to the soft storey and torsional effects, due to irregular distribution of masonry walls in height and in plan respectively. Masonry infills can be unfavourable when leave a short portion of the column clear, leading to the shear collapse of the columns [5]. It should stressed that the unfavourable effect of infills can also result from its own inefficiency in developing in-plane resisting mechanisms under large deformations imposed by enclosing frames leading to its severe damage or even partial collapse [15].

The inadequate in-plane behavior of infills can also prevent the developing of out-of-plane resisting mechanism by arching effect [16]. In addition, the detachment from the surrounding frame elements at early stages of the seismic event and the absence of efficient connections to RC frames results in their out-of-plane collapse. This type of deficiency has been shown to be worrying from the last recent earthquakes.

3.1 The example of recent earthquakes

According to [17], 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, and apart from the collapse of rural masonry residential buildings, it was observed that widespread extensive damage in masonry infill walls and internal partition walls developed, being responsible for the highest losses in RC buildings [18]. 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 elements in case of cavity walls, resulting often in the complete and independent collapse of the leaves, see Figure 2.

Figure 2 – Failure patterns of masonry infill walls found in the recent earthquake of LÁquila

4 The use of alternative reinforcing materials in civil engineering construction

In order to solve deterioration of steel as a reinforcing material in concrete structures, there was a need to introduce newly material able to resist to the corrosion. In this scope, the fiber composite materials have been assuming an important role in new construction and also for retrofitting of existing structures. The composite materials used are commonly reinforced by fibrous braided and axially reinforced impregnated by epoxy resin or of polyester [19]. This combination provides materials with interesting mechanical properties and low volume mass. Figure 3 shows the typical stress-strain diagrams under tensile loading for distinct reinforcing materials. The properties of the fibrous materials can be designed according to the structure or selected fibers.

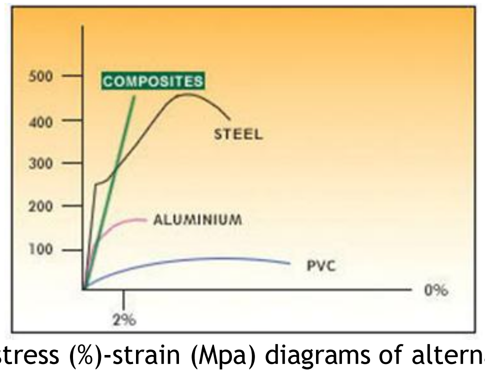


Figure 3 – Typical tensile stress (%)-strain (Mpa) diagrams of alternative reinforcing materials [19]

The composite materials recently produced allow additional features like the monitoring of construction structures, enabling the continuous assessment of stress state of the structures and promoting a premature, fast and adequate intervention in case of need. This composite materials present also a more extended durability [19].

4.1 Types of fibers

The fibers used in civil construction can be of natural and natural sources, depending on the specific use.

The natural fibers present higher variability and lower performance in terms of mechanical properties regarding non-natural fibers but can be used with advantages in the reinforced composite materials. Natural fibers are biodegradable, have interesting mechanical properties and low volume mass. Among the natural fibers, the most used are the flax fibers, sisal and jute fibers, see Table 1.

Table 1 – Properties of natural fibers [20]

Fiber	Tenacity (N/Tex)	Volume mass (g/cm^3)	Ultimate strain (%)
Flax	0,54	1,54	3
Jute	0,31	1,50	1,8
Sisal	0,42	1,5	2-2,5

However, the most used fibers in civil construction of non-natural nature with focus on glass and carbon fibers. This type of inorganic fibers presents the advantages of geometries and dimensions according the required properties. These fibers are usually used as reinforcement in composite materials due to the high mechanical resistance and low volume mass.

The carbon fibers are composed of carbon atoms which are linked to form microscopic crystal along the molecular chain. The fibers are extremely thin with a diameter ranging from 0.005-0.010 mm. These fibers present an excellent ultimate tensile strength, being variable according to the manufacture conditions.

The glass fibers are produced from silica. They have a high fusion temperature of about 2000ºC. These fibers are used in reinforcement but also as insulation and filtration.

The basalt fibers come from volcanic minerals. This fiber can be used as reinforcement in civil construction [20]. Table 2 shows some properties on synthetic fibers.

Table 2 – Properties of high performace fibers [20]

Fiber	Tenacity (N/Tex)	Volume mass (g/cm^3)	Ultimate strain (%)
Carbon	1,2	1,83	0,7-1,7
Glass	0,78	2,58	4
Basalt	0,67-0,93	2,65	3,1

4.2 Architecture of reinforcements based on fibrous materials

The fibrous architectures most used in civil construction derive from four basic structures, namely (1) nonwoven, (2) weave; (3) knit; (4) braided. The architectures are usually selected based on requirements for the specific application, namely in terms of orientation of the fibrous materials [8].

The fibrous architectures are classified in: (1) Conventional planar structure (2D); (2) three-dimensional structure (3D); (3) directional oriented structures (DOS); (4) hybrid structures. Some planar structures are shown in Figure 5, where the orientation of the fibers in the plane is visible.

The weave present fibers oriented continuously at 0° e 90°. The knitted fabrics are formad by loops, exhibiting high elasticity. The structures nonwoven are distributed in scatter manner the plane without continuity [21].

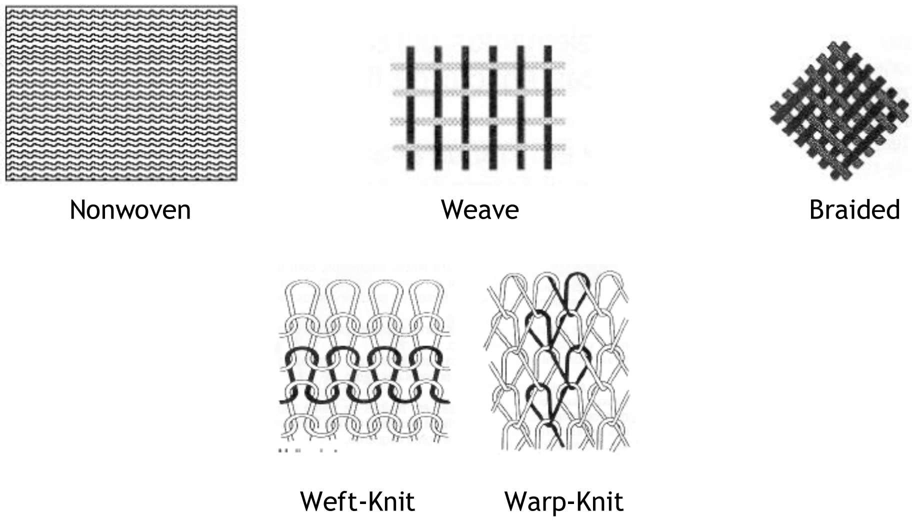


Figure 5 – Examples of planar structures [22]

The technique for the production of braided fabrics is usually used for the manufacture of fibrous reinforcements for application in construction [22]. This technique has been used for two centuries and is being increasingly used in technical applications. The technique consists in the braiding in the transversal and longitudinal direction forming a tubular structure. The wires are in two groups of spindles and rotate in opposite orientations, in the clock and counter clock [10]. With the aim of improving the physical and for adding new functionalities axial fibers can be added. This structure can be composed of different materials for achieving the reinforcing aim. The braiding angle is the most relevant parameter in the characterization of a textile braiding, influencing directly its behavior. The braiding angle is the angle between the longitudinal axis and the direction of insertion of the braiding wires, see Figure 5. The diameter of the braiding is the straight line connecting the two extremities passing through the braiding center, see Figure 6. This measure can vary according to the wire diameter of the braiding, of the diameter of the axial structures and of circulation velocity [10].

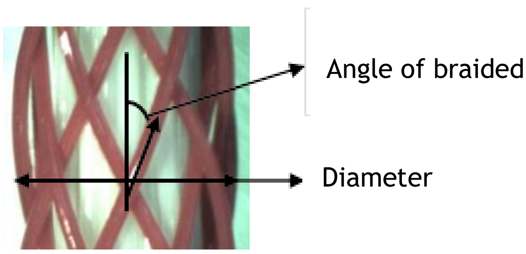


Figure 6 – Schematic representation of the diameter and angle of the braiding

A three dimensional structure include multiaxial oriented fibers. Usually, these structures are manufactures with wire insertion in the third direction based on the conventional structures [22].

The fibrous architectures oriented directionally (DOS) allows the achievement of improved mechanical properties in certain direction. In this case, the fibers can be inserted in preferential directions resulting in mono-, bi-, three-, and multiaxial structures, according to the number of directions in which the fibers are inserted, see Table 3 [22].

Table 3 - Fibrous architectures oriented directionally [22]

Monoaxial structure	**Biaxial structure**	**Triaxial structure**	**Multiaxial structure**
			
Warp reinforced	Warp and Weft reinforced	Warp and diagonal directions reinforced	Warp, weft and diagonal directions reinforced
			
Weft reinforced	Diagonal directions reinforced	Weft and diagonal directions reinforced	Warp, weft and diagonal directions reinforced

The hybrid structures are formed by the combination of two or more structures aiming at achieving the synergetic effect of ensured properties from the orientation of fibers in the structure. The hybrid structures can also be developed aiming at combining several types of fibers in the same fibrous architecture [22].

5 Retrofitting non-loabearing walls: a brief overview

In spite of EC8 [7] implicitly mention the need of preventing premature failure and disintegration of masonry infills and out-of-plane collapse, by considering light wire meshes adequately anchored on the walls and concrete frames or ties across the walls, in case of new construction [2], no explicit guidelines are provided as concern the design and particularly in relation to strengthening of existing masonry infills.

However, the high seismic vulnerability of infill walls led to recent investigation on development of strengthening techniques for the masonry infills aiming at improving both the in-plane and out-of-plane performance, namely prestressing and jacketing or more innovative materials, such as fiber reinforced polymers (sheets and bars).

The carbon fiber reinforced polymer retrofitting systems are usually composed of surface bonded CFRP sheets applied directly on the masonry walls through the application on an epoxy resin. Besides, the CFRP sheets are usually adequately anchored to the surrounding reinforced concrete frames. These anchors secure the sheets to the frames preventing the delamination and promotes frame-infill interaction during seismic response. The orientation of the CFRP schemes influences the performance of the retrofitted structures under lateral loading. Distinct configurations of CFRP systems on infill walls were applied on non-loadbearing walls by Yuksel et al. 2010 [23], see Figure 7, resulting in an important increase on the lateral strength of the reinforced concrete masonry infill frames and delay of diagonal cracking leading to the improving of the overall behaviour of the structures under lateral cyclic loading. With this respect, some authors [24-26], pointed out that the use of retrofitted reinforced concrete masonry infill was by cross braced CFRP sheets results on the drift control and deformation demands under cyclic loading, improving thus the behavior under seismic actions. Other authors have demonstrated that the use of glass fiber reinforced polymer laminates along the bed joints of infill masonry walls can also improve the shear strength of masonry, leading to the control of damage [15].

Figure 7 – Distinct retrofitting schemes on masonry infills by using carbon fibers reinforced materials [23]

Several other studies have carried out to evaluate the improvement on the in-plane and out-of-plane behavior of existing structural unreinforced masonry walls retrofitted with composite materials [27-28], showing that the FRP retrofitting technique is effective in significantly increasing the in-plane strength, stiffness, and deformability of URM walls, contributing also for the increase of the out-of-plane flexure resistance.

As mentioned above, the retrofitting systems of infill masonry walls focus mainly on the use of composite material based on CFRP laminates or bonded sheets directly to the masonry walls, which perform reasonably well as concern the overall improvement of the seismic behavior of reinforced concrete masonry infill frames. However, one of the main problems related to the performance of these retrofitting materials is the delamination between the composite materials and the masonry as pointed out by Valluzzi et al. (2002) [29]. Thus, an alternative solution for the seismic retrofitting infill masonry walls consists of using braided reinforced composite materials according to what has been already applied in concrete structures [30]. The idea is to manufacture braided textile meshes with a core composed of fibrous materials which can be synthetic fibers such as carbon, glass or basalt or even natural fibers such us sisal, which are embedded in the walls plaster. It is foreseen that the technic of production of braided textile materials can be used as an advantage in the production of fibrous structures due to its simplicity and ability of orientation of fibers. Besides, these fibrous materials have the advantage of protection of the axial reinforcement material assuring an improvement in the durability and improvement of adhesion to the masonry.

6 Concluding remarks

This paper intended to provide a brief overview on the seismic behavior of non-loadbearing masonry walls, which is viewed as a non-structural material but under seismic actions, should perform in adequate manner to avoid brittle failures resulting in huge economic losses and losses of human lives. Indeed, considerable damage has concentrated in their non-structural elements as demonstrated by recent earthquakes.

The inefficient performance of in masonry infilled reinforced concrete frames under seismic events has promoted research on the retrofitting of these composite structures. In this paper, a brief overview is also given on the most used studied retrofitting schemes, which has focused on the application of carbon or glass fiber reinforced polymer composite materials in the masonry walls adequately anchored to the reinforced concrete enclosure elements. Additionally a brief review on alternative braided reinforced composite materials is given and pointed out as an alternative for retrofitting masonry infill walls.

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