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MODERN STRENGTHENING TECHNIQUES FOR MASONRY STRUCTURES

BY

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Abstract. Masonry structures are the world's earliest construction systems. Nowadays, it is roughly estimated that the masonry constructions occupy more than 70% of the world dwelling stock. Moreover, a significant part of these structures consist of heritage buildings exhibiting various types of damages. Research programs including numerical and experimental works have been conducted in order to develop new strengthening methods that can improve the structural response and the overall seismic performances of masonry structures with minimum use of resources. Thus, the modern retrofitting techniques use light weight and durable materials that can be easily applied in various strengthening systems. Many of the current retrofitting techniques that are applied to the masonry works are based on fibre reinforced polymer (FRP) composite products due to the indisputable advantages of these materials. This paper presents and describes the most recent developments related to the strengthening solutions and technologies of masonry structures.

Keywords: masonry structures; structural rehabilitation; strengthening techniques; fibre reinforced polymer (FRP) composites.

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1. Introduction

Even though most of the advanced strengthening and rehabilitation methods use new and efficient materials like fibre reinforced polymer (FRP) composite products, in some particular cases, only traditional methods of rehabilitation may be applied.

Over time, masonry has been successfully used in different engineering applications for both structural and non-structural elements, including: foundations, plinths, basements, floorings, walls, retaining walls, columns, straps, lintels, abutments, arches, vaults, domes, architectural monuments, bedding layers, fences, drains, and drainage systems. A masonry system is obtained by combining different masonry units (stone, fired clay bricks, concrete/ cinder blocks) in a defined sequence, with or without using binding materials (lime or cement-based mortar) (Ngapeya *et al.*, 2018).

Usually, the main parameters that are quantified in the selection stage of the masonry rehabilitation method are referring to the physical and mechanical properties of the system components and to the environmental exposure conditions. Various studies (Tumialan & Nanni, 2002; Ehsani *et al.*, 1999) showed that the FRP composite materials may be used for the efficient strengthening of the masonry structures subjected to adverse environmental conditions, with limited use of time and material resources. Also, the rehabilitation methods based on FRP composite products offers other significant advantages such as longer service life and minimum additional weight. According to Chmielewski and Kruszka (2015), the FRP strengthened masonry structures are expected to outperform the service life periods (norm CR 0-2012 for Romania) (Table 1) due to their superior potential long-term performances. The later consists in resistance to both physical degradation (abrasion from wind action, salt crystallization and freeze-thaw action) and chemical deterioration (usually caused by the reactions of mortars with soluble salts).

2. FRP Systems for Masonry Strengthening – Constituents Materials

The FRP systems for masonry repair and rehabilitation works consists of high strength composite products (textile, strip, lamella) that are usually applied to the outer or inner surface of the masonry members by using a mortar matrix or an adhesive product. The FRP composite products consist of either continuous or disperse fibres arranged in the form of open meshes, or banded in a specific pattern by an epoxy, vinyl-ester, or polyester resin matrix (Groll & Țăranu, 2003).

In case of pultruded FRP composite products, the most commonly used reinforcing fibres are glass, carbon, aramid and basalt, while the resin is usually an epoxy, vinylester, phenol formaldehyde or polyester thermosetting resin. Moreover, extensive research was conducted in order to introduce new types of yarns in the FRP composite products, aiming to obtain both stand-alone self-bearing members and materials for strengthening systems with high mechanical properties. For example, one of the latest types of yarns used as main reinforcing fibres for composite products is spider silk. The spider silk reinforced polymer (SSRP) composite elements (Hsia *et al*., 2011) were experimentally tested by loading in tension. Based on the experimental results, the authors concluded that the SSRP composite products have superior mechanical properties (extremely high tensile strength, high toughness), compared to the ones of common FRP composite products (glass fibre reinforced polymers – GFRP, carbon fibre reinforced polymer – CFRP).

The development of new FRP composite systems should be treated according to the operational and the structural requirements of the final product, in agreement with the recommendations of the national and the European legislations. Although the FRP manufacturing and supplier community is highly diversified, it is often the case that the production of new materials is based on patented technologies that do not allow flexibility within the manufacture process. A common basis for the mass production of more complex FRP structural components and materials is therefore required. According to Sims (2007), a new structural FRP composite product can be released for distribution to the end users, regardless of the type of the manufacture method, only if the specific requirements for mechanical resistance, stability and resistance to fire are fulfilled. Based on literature survey, the authors recommend a minimum set of tests that should be performed in order to provide a liaison between both ISO and national standards of the European Member States (EMS), (Fig. 1).

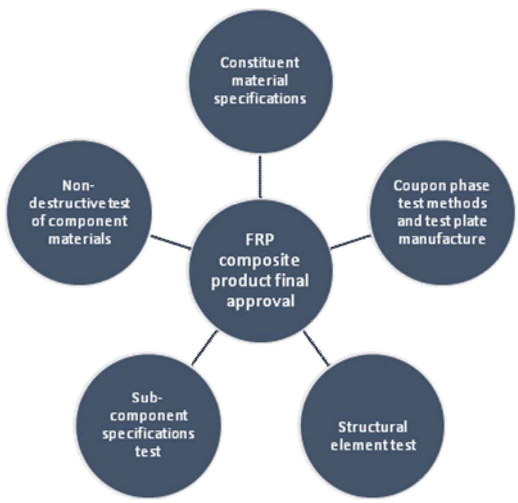


Fig. 1 – Minimum tests that should be performed for liaison between ISO and national standards (Sims, 2007).

3. Masonry Structures in Romania

According to the National Institute of Statistics, the Romanian national dwelling stock exhibits a continuous ascending trend of approximately 0.5 % per year (8.882.100 residential units – 2015, 8.929.200 residential units in 2016). Furthermore, a significant part of the existing structures has exceeded their service life periods (Table 1), and are developing various types of degradations which negatively impact their long term performances.

Table 1
CR 0-2012

Category of life service	Service life	Examples
5	≥100	Structures for monumental buildings/ edifices and important engineering constructions
4	50-100	Structures for buildings and curent constructions
3	15-30	Structures for agriculture use or similar
2	10-25	Parts of structure that can be replaced
1	10	Temporary structures

Taking into consideration the share of the masonry structures related to the total number of the dwelling stock, it is observed that more than three quarters of the existing structures consist in various types of masonry systems. This is due to the advantageous properties of masonry structures, such as: high strength, resistance against fire and noise barrier characteristics. However, despite these advantages, it is observed that the masonry members develop several structural deficiencies, including large deformation due to earthquake loading and degradation due to slow ongoing settlements. In addition, the masonry elements are exhibiting more deterioration under extreme environmental conditions when compared to the reinforced concrete elements and to the steel members. Table 2 presents the main masonry systems that are used in Romania, and their distributions related to the total number of the dwelling stock from 2010 to 2016 as provided by the National Institute of Statistics (2017).

Table 2
Romanian Dwelling Stock in 2016 (National Institute of Statistics, 2017)

2010			
Type of structure/masonry	**Total(%)**	**Urban(%)**	**Rural(%)**
Reinforced concrete/URM	35	59	2,4
Reinforced concrete/RM	26,3	28,9	23,8
Wood/ masonry	12,8	5	25,2
Wood- other materials	26	7,2	48,7
2011			
Type of structure/masonry	**Total(%)**	**Urban(%)**	**Rural(%)**
Reinforced concrete/URM	34,9	58,8	2,4
Reinforced concrete/RM	26,6	29,1	24,1
Wood/ masonry	12,7	5	25,1
Wood- other materials	25,8	7,1	48,4
2012			
Type of structure/masonry	**Total(%)**	**Urban(%)**	**Rural(%)**
Reinforced concrete/URM	34,8	58,6	2,5
Reinforced concrete/RM	26,8	29,3	24,4
Wood/ masonry	12,7	5	24,9
Wood- other materials	25,7	7,1	48,1
2013			
Type of structure/masonry	**Total(%)**	**Urban(%)**	**Rural(%)**
Reinforced concrete/URM	34,6	58,4	2,5
Reinforced concrete/RM	27,1	29,5	24,7
Wood/ masonry	12,6	5	24,9
Wood- other materials	25,6	7,1	47,9
2014			
Type of structure/masonry	**Total(%)**	**Urban(%)**	**Rural(%)**
Reinforced concrete/URM	34,5	58,2	2,6
Reinforced concrete/RM	27,4	29,8	25
Wood/ masonry	12,6	5	24,7
Wood- other materials	25,5	7,1	47,6

Table 2
Continuation

2015			
Type of structure/masonry	**Total(%)**	**Urban(%)**	**Rural(%)**
Reinforced concrete/URM	34,4	57,9	2,7
Reinforced concrete/RM	27,7	30,1	25,3
Wood/ masonry	12,6	4,9	24,6
Wood- other materials	25,4	7,1	47,4
2016			
Type of structure/masonry	**Total(%)**	**Urban(%)**	**Rural(%)**
Reinforced concrete/URM	34,3	57,7	2,8
Reinforced concrete/RM	28	30,4	25,6
Wood/ masonry	12,5	4,9	24,5
Wood- other materials	25,2	7	47,1

Moreover, the existing national statistics reveal that an important number of masonry structures are historical buildings. According to the Institute of Cultural Heritage, there are 28.273 historical monuments nationwide. Fig. 2 presents the distribution of masonry historical monuments in each county of Romania (Institutul Național al Patrimoniului,2015).

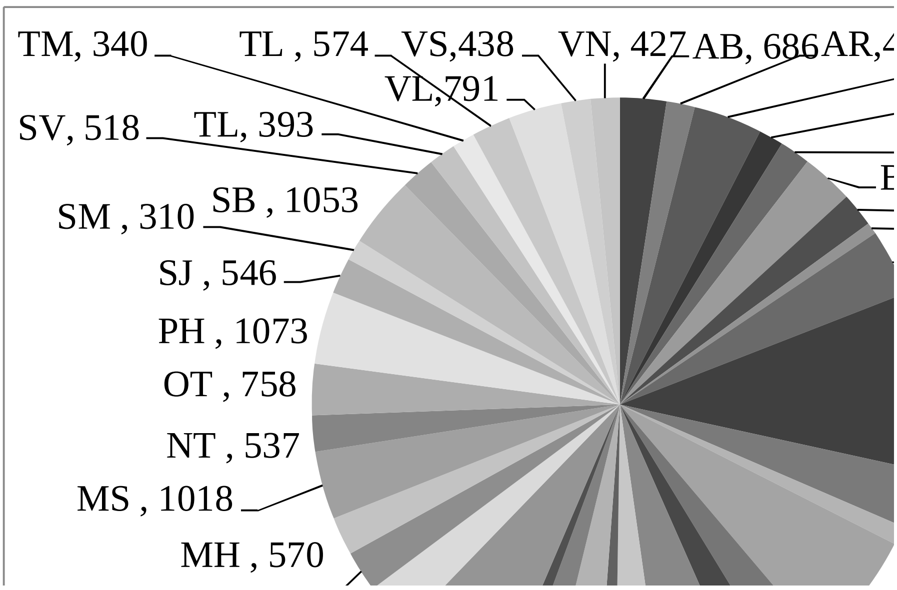


Fig. 2 – Total Number of Monuments – The National Heritage Institute 24.12.2015.

By analysing the statistical data, it can be concluded that masonry represents the main structural system used in Romania both for historical monuments and currently erected buildings. The need to strengthen or repair the masonry elements may have various causes, including destructive natural disaster, environmental influence and increase in the load of the construction or ageing processes. Therefore, researchers are currently showing an increased interest in developing masonry strengthening and retrofitting methods with high degree of applicability, in agreement with the seismic design and the serviceability requirements.

4. Strengthening Systems

The main aim of a strengthening or retrofitting work is to increase both the ability of the structure to behave better in case of inelastic deformation and the structure load carrying capacity and its integrity (Babatunde, 2016). One of the most commonly used methods to upgrade the masonry structures consists in the application of externally bonded FRP composite materials. The use of the latter has become popular due to their light weight and advantageous mechanical properties. However, the potential of FRP strengthening techniques is still far from being fully exploited when applied to masonry structures because of compatibility issues. Some of the most utilised FRP based strengthening methods that are applicable to masonry structural systems are presented in the following sections.

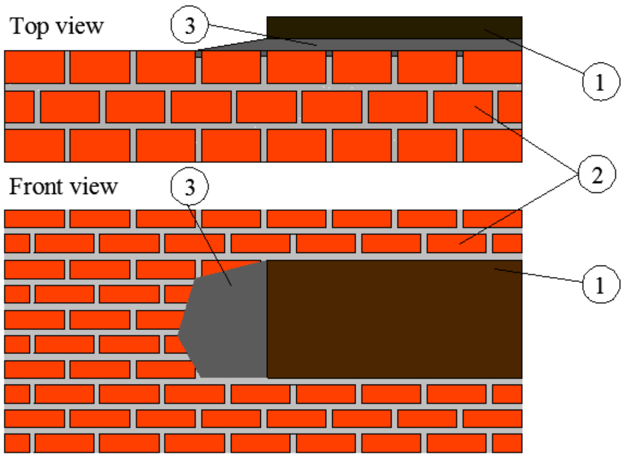
4.1. Externally Bonded Reinforcement – EBR

This technique uses either FRP sheets applied by using wet lay-ups or pre-cured FRP laminates bonded onto the masonry surface with an adhesive. The orientation of the laminates can be horizontal, vertical, diagonal, or in a grid pattern; they can be applied on one side or on both sides of the wall (Kerstin & Schumacher, 2014).

The wet lay-up FRPs are widely used in strengthening techniques for masonry structures and consists in the impregnation of dry unidirectional or multidirectional fibre sheets with adhesives 9(Fig. 3). Generally, the adhesive products are two part thermosetting systems composed of a resin (Part A) and a hardening agent (Part B) (Yarigarravesh *et al.*, 2018).

On the other hand, the precured FRP based strengthening systems consist of a large variety of composite products in the form of plates, grids, strips or shells that are typically applied to the masonry structures by using adhesives, primers or putties. Prior to installation, the FRP composite laminates are cut to their nominal dimensions and the masonry surface is cleaned.

The cleaning of the masonry surfaces is performed for both wet lay-up and precured strengthening systems in order to remove the pollutants. Additionally, the bonding surfaces are milled in accordance with the provisions of ACI 546R norm. Prior to the cleaning process, the uneven regions are levelled with putty (norm 440.7R-10).



1 - FRP composite product (plates, grids, strips or shells);
2 - masonry; 3- adhesive.

Fig. 3 – Externally Bonded Reinforcement (EBR) for a masonry wall.

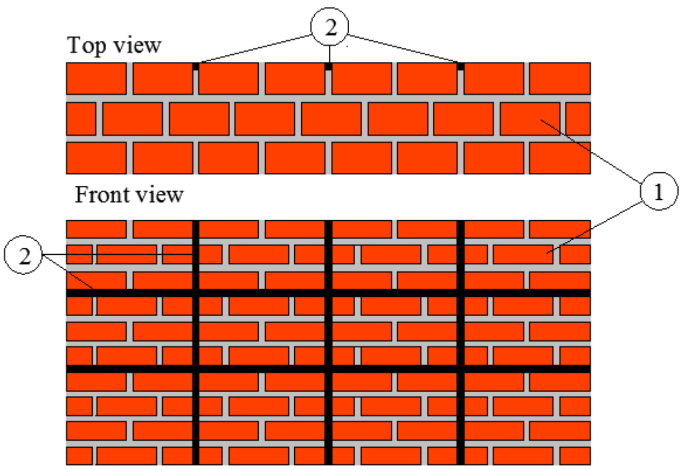
The first experimental program related to *externally bonded FRP* products was performed at the Swiss Federal Laboratory for Material Testing and Research, (Babatunde, 2016). Several FRP composite materials, including strips and fabrics, were bonded to the masonry shear wall using epoxy adhesives. Based on the experimental results, it has been concluded that the in-plane deformation capacity of the masonry walls can be increased by 300%.

Over the last decade several research works focused on the effectiveness of EBR strengthening systems for masonry structures. The experimental and the numerical studies were performed on various masonry substrates (*i.e.* stone, fired clay bricks, concrete/ cinder blocks) strengthened with several FRP composite materials. Valluzzi et al. (2002) performed single-lap and double lap shear tests on masonry bricks strengthened with glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP) composite laminates. The experimental outcomes show that in most of the cases, failure was caused by the debonding of a relative thin layer of the brick. Based on the characteristics of the dominant failure mode and the experimentally determined stress-strain variation, the authors proposed several bond-slips laws applicable to numerical investigations.

More recent studies (Maljaee *et al.*, 2016; Maljaee *et al.*, 2016) were focused on the bond degradation issues and on the FRP delamination that may occur in EBR systems due to thermal incompatibility (adhesive curing conditions) and moisture attack. Based on the experimental data, the authors proposed a degradation model to predict the long-term performance of EBR systems for masonry walls.

4.2. Near Surface Mounted Systems - NSM

The near surface mounted (NSM) strengthening technique uses FRP bars or strips that are bonded with adhesives into cuttings or chamfers in depth of masonry surface (Lang & Schumacher, 2014) (Fig. 4). The NSM strengthening systems for masonry can be designed and performed in order to meet various objectives. Usually, the FRP products are inserted into the masonry structures to improve the in-plane behavior of walls and increase the load-carrying and deformation capacity of the masonry elements. Also, the NSM systems improve the out-of-plane behavior of masonry walls by enhancing the links between the orthogonal walls, thus increasing the bending moment capacity.



1 - masonry; 2 FRP strips embeded in adhesive layer.

Fig. 4 – Near surface mounted systems – (NSM) for a masonry wall.

The NSM strengthening method has six different stages: surface cleaning works, preparing for externally bonded FRP, resin mixing, constituent materials threading, FRP bars or strips installing, protective coatings. The cleaning stage is usually performed by air blasting the masonry surface. Then, the grooves or slots are cut by keeping a diameter of one and a half times the bar diameter in bed joints. The FRP bars are inserted in the groove and fully encapsulated with mortar made of epoxy resin liquid compound, cement and cementitious materials. To avoid tilting or twisting of the strengthened wall, FRP reinforcement should be placed symmetrically on both faces of the wall (Maljaee *et al*., 2018).

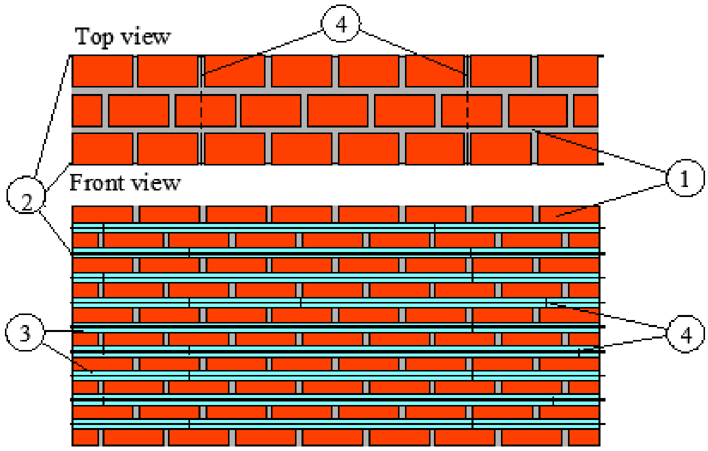
According to Rizkalla *et al*. (2003), the NSM strengthening systems applied to masonry structures are almost three times more efficient than externally bonded FRP systems since the ageing effects are highly diminished and, therefore, the long term performances of the system are highly increased. Also, the authors reported two types of debonding failure that can occur with NSM FRP bars: the debonding due to splitting of the epoxy cover and the debonding due to cracking of the concrete surrounding the epoxy adhesive. These debonding mechanisms may be diminished by increasing the thickness of the epoxy cover, or by using adhesives of high tensile strength.

The effects of the geometry parameters (the dimensions and the shape of the reinforcement, the dimensions of the groove, the bond length) have been deeply investigated in NSM strengthened masonry structures (De Lorenzis, 2000; Fam, 2010; Milani, 2010). However, the majority of the available studies focused on large bonded length and the short bonded length still remains unexplored.

4.3. Repointing Technique

Repointing (Fig. 5), one of the more recent strengthening techniques applicable to masonry structures, was proposed by Borri *et al*., (2010), “Reticolatus” technique. This method consists in small diameter, high strength stainless steel cords embedded in the repointing mortar and connected to the masonry panels by stainless steel connectors passing through the wall. The intercepting nodes of these cords are then rigidly connected to the opposite face of the masonry wall by means of transverse stainless-steel bars (typically in a number of 5 elements per m^2), able to provide a full interaction between the cords and the specimen (Gattesco *et al*., 2015).

The main advantage of this technique is that it can also be applied to masonry walls with uneven surfaces and made of irregular components, like the historic masonry walls obtained by assembling together rubble stone elements.

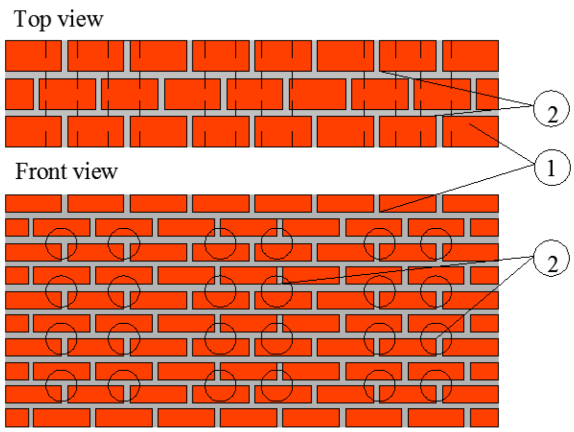


1 - masonry; 2- cords; 3- mortar; 4- connectors.

Fig. 5 – Repointing technique for a masonry wall.

4.4. Centre Core Technique

This masonry strengthened technique involves drilling continuous straight vertical grooves through the head joints and the brick units and horizontally at the bed joints (Fig. 6).



1 - masonry; 2 -grooves.

Fig. 6 – Centre core technique for a masonry wall.

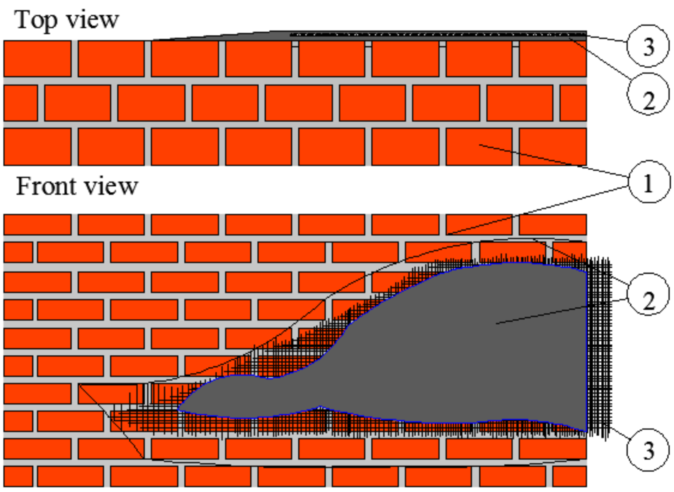
The grooves are about 1 inch deep and as wide as the mortar thickness. After drilling the groove, the debris is removed by a vacuum.

After the cleaning process, an epoxy primer is applied and the grooves are partially filled with an epoxy adhesive. The reinforcement consists of FRP rods installed in the grooves and encapsulated by an epoxy adhesive product. In some particular cases, lateral ties are used to connect the FRP rods to the roof.

According to El Gawady *et al.*, (2004), the reinforced homogeneous vertical beam increases the masonry wall capacity to resist in-plane and out-of-plane loading. Furthermore, the research conducted by Korany and Drysdale, (2004) showed that this technique produces significant increase in capacity, deformability and energy dissipation over unreinforced masonry structures. However, according to ElGawady et al. (2004), the main drawback of the technique is that it creates zones of varying stiffness and strength properties.

4.5. Cement Based Matrix Grid System

This technique (Fig. 7) uses a layer of engineered cementitious composite (ECC) that is bonded, partially or fully, onto the face of masonry walls (Pourfalah, 2017). The Fabric Reinforced Cementitious Matrix (FRCM) materials are composed of a dry fibre grid embedded in an inorganic matrix, which may contain short fibres. These materials are particularly well-suited for the reinforcement of masonry structures due to their high compatibility with the substrate, vapour permeability and durability against environmental agents (Carozzi, 2017).



1 - masonry; 2 matrix ; 3- fiber grid

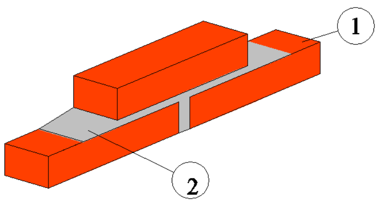
Fig. 7 – Cement based matrix grid system.

Studies by Aldea *et al*., (2005), have shown that the use of masonry strengthening systems based on FRCM materials can improve the structural performance by increasing strength and ductility. Moreover, this strengthening system offers good compatibility and bond with the substrate, provides a breathable system which allows air and moisture transfer through the matrix and allows for ease of installation through the use of trowel.

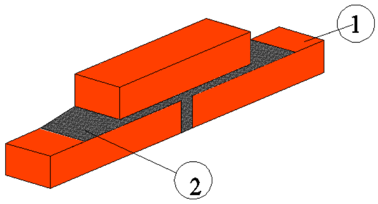
Menna *et al*., (2015), introduced an innovative composite grid using bi-directional hemp fibre, embedded in two different mortars. The experimental results have shown that, in diagonal compression behaviour, mechanical properties of the panels increased by 2 to 3 times in the case of Neapolitan yellow tuff bricks and 5 times in case of clay panels.

4.6. Micro and Macro Reinforcement of Joints

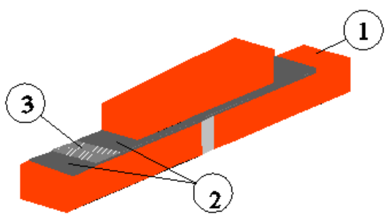
This strengthening technique uses a cement lime rich mortar reinforced with polypropylene fibres and non-metallic meshes that is applied to the masonry joints (Fig. 8). Used as mortar joints, the mixture can reduce cracks induced in ordinary mortar and can improve flexibility and toughness. Furthermore, tests conducted by Bosiljkov (2006) have shown that the compression strength of the micro-reinforced masonry is increased by almost 15%.



1 - masonry; 2 - mortar.
(1)



1 - masonry; 2- micro reinforced mortar.
(2)



1 - masonry; 2 - mortar; 3- mesh (macro-reinforcement).
(3)

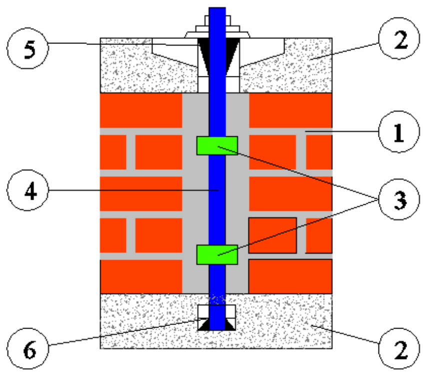
Fig. 8 – (1), (2), (3) – Micro and macro reinforcement of joints.

4.7. Post-Tensioning Strengthening System

The post-tensioning (P-T) strengthening technique is based on the introduction of external forces to the masonry structural members that would offset part or all of the effects of the external loads (Fig. 9). Strengthening with P-T is particularly more effective and economical for large masonry walls and masonry dome structures, and it has been employed with significant results to increase the bending and shear resistance and correct excessive deflections.

Incorporating post-tensioning into masonry offers a simple and potentially cost-effective structural system. The post-tensioning techniques can be applied to different types of masonry members as either bonded or unbonded reinforcement (Garcia *et al*., 2017; Hassanli *et al*., 2017). Post-tensioned (PT) walls can be ungrouted, partially grouted, or fully-grouted. In unbonded PT masonry walls, where grout is used in the cells containing the post-tensioning (PT) bars, the PT bar is enclosed in a PVC tube and hence is not embedded in or bonded to the grout. An unbonded PT bar is designed to provide a restoring force to return the wall to its original vertical alignment, therefore reducing residual drifts after a seismic event (Popehn *et al*., 2007; Wight, 2006).

The P-T strengthening method may be applied externally or internally by drilling vertical cores through the middle of a masonry wall and then inserting FRP tendons located inside a duct along the cores. The FRP tendons are light weight and have high strength, being very suitable for posttensioning applications. The most commonly utilized composite materials in P-T strengthening systems for masonry structures are the CFRP and aramid FRP. The CFRP tendons whose fibres are aligned in the longitudinal of the tendon have strength in the range of 290,075 psi–362,594 psi (2000–2500 MPa), while aramid FRP tendons have a variety of strengths depending on the manufacturer.



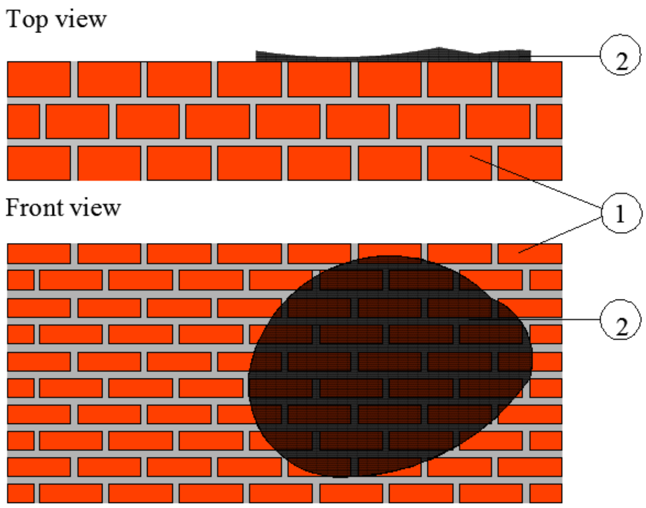
1 - masonry; 2- reinforced concrete element; 3- threaded sleeve; 4 - FRP tendon; 5- stressing anchorage; 6- end of anchorage.

Fig. 9. – Post-tensioning strengthening system.

4.8. Sprayed-FRP Composites

A more recent method of strengthening of masonry structures involves spraying high performance fibres with a durable hybrid polymeric resin onto the surface of the masonry walls at high speeds (100 km/h), so that a well compacted and well-bonded composite with high strength and stiffness is formed (Fig. 10). With the resulting random distribution of the fibres in 2-D, the FRP layer inherits non-linear stress-strain behaviour and has isotropic in-plane strength performance (Banthia & Boyd, 2000).

However, limited research has been carried out on sprayed-FRP strengthened masonry structures, most of the researchers' interest being rather dedicated to the investigation of the effectiveness of the method as strengthening system for concrete structures (Lee & Hausmann, 2004; Furuta *et al.*, 2001; Kanakubo *et al.*, 2005; Banthia *et al.*, 2002; Harries & Young, 2003; Lee, 2004; Boyd *et al.*, 2008; Lee *et al.*, 2007; Lee *et al.*, 2008; Parghi, 2017).



1 - masonry; 2 fibres embedded polymeric resin .

Fig. 10 – Sprayed-FRP composites.

5. Conclusions

Due to a continuous search to improve the image of the construction industry by striving to promote modern materials and techniques, various studies on FRP strengthening techniques have been conducted. These studies justify the necessity for repairing and strengthening of vulnerable infrastructures and structures worldwide.

After 25 years of analyses, retrofitting techniques using FRP composite solutions are increasingly utilized due to their convenient physical and mechanical properties. The use of FRP strengthening systems, the design of specific solutions and waste management are issues that require a more in depth approach.

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TEHNICI MODERNE DE CONSOLIDARE A STRUCTURILOR DIN ZIDĂRIE

(Rezumat)

Structurile din zidărie reprezintă cele mai vechi sisteme de construcție din lume. În prezent, se estimează că aproximativ 70% din patrimoniul mondial construit este reprezentat de clădirile din zidărie. De asemenea, o parte semnificativă a acestor structuri se regaseşte în monumentele istorice care prezintă diferite tipuri de degradări. Au fost realizate diverse programe de cercetare, inclusiv testări numerice şi experimentale, pentru a dezvolta noi metode de consolidare care pot îmbunătăți răspunsul structural şi performanțele seismice generale ale structurilor de zidărie cu utilizarea minimă a resurselor. Astfel, tehnicile moderne de consolidare utilizează materiale durabile cu greutate redusă, care pot fi uşor aplicate în diferite sisteme de întărire. O bună parte a tehnicilor de consolidare care se aplică lucrărilor de zidărie se bazează pe produse din compozite polimerice armate cu fibre (FRP) datorită avantajelor evidente ale acestor materiale. Lucrarea prezintă cele mai recente evoluții legate de solutiile si tehnologiile de consolidare compozite ale structurilor din zidărie.