Masonry vaults reinforcement with FRCM-PBO: conservative and structural issues

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Keywords: Built heritage, Masonry vaults, Composites materials, Seismic retrofitting, Preservation

Abstract. Historic masonry buildings are complex structures whose behavior is strongly affected by the quality of materials, by traditional constructive techniques and by alterations occurred over centuries. Therefore, it is important to deepen the knowledge of existing buildings in order to identify potential vulnerabilities and to define suitable reinforcing interventions. In order to properly deal with cultural heritage criteria these interventions must satisfy not only the structural requirements but also the conservative issues. In this regard, each retrofitting intervention should be planned according to the specific case, acknowledging all the peculiar features that should lead to the definition of a proper reinforcing solution. Consequently, it is not possible to uncritically apply a generic reinforcing system given by manuals in compliance with standard typologies of traditional architectural elements. In this paper several case studies located in Parma (Italy) will be presented in order to highlight the need of a critical approach based on a deep knowledge of existing buildings. In particular, the given examples are focused on strengthening interventions carried out on vaulted structures. Sometimes composites proved to be one of the most effective reinforcing solutions for these masonry elements, allowing to improve the structural strength without increasing its stiffness. The strengthening intervention, designed according to both structural and conservative issues, definitely proved that a critical awareness is fundamental for a positive contribution of non-traditional techniques – such as composites – applied to traditional masonry structures.

Introduction

The preservation of historic masonry buildings is a complex issue because of the many aspects we need to examine dealing with an unsafe historical structure. In such buildings, the reinforcement intervention must be actually planned in consideration of both the structural requirements and the conservative issues: proper levels of safety must be obtained with strengthening actions that pursue the restoration principles of compatibility, durability, removability and minimization of invasiveness.

To this aim, the real behavior of the exiting building must be identified considering the quality of materials, the traditional constructive rules, the techniques and all the modifying alterations to the geometrical and structural organization overlapped over centuries. All these features deeply influence the structural response to static loads and, above all, to seismic actions.

It is therefore essential to deepen the knowledge of the actual existing building [1,2]. Archival research, geometrical survey and in situ inspections and diagnostics tests are the main steps for the acknowledgment of the real masonry behavior, in order to identify the most critical points and elements to strengthen and reinforce. However, the cognitive process requires great resources in terms of time, costs and, above all, scientific knowledge and expertise in order to critically analyse and correctly interpret the data collected and thus define effective reinforcing solutions, consciously planned for the specific case. Manuals and technical codes usually offer generic lists of reinforcing systems for standard typologies of architectural elements, ruling their application. However, these technical and legislative prescriptions cannot be employed uncritically, as shown by past experiences. Damages induced by earthquakes (Umbria and Marche, 1997; Molise, 2002; etc.) highlighted that some of the previous reinforcements, carried out according to generic technical indications, did not achieve a real safety increase [3]. This misalignment between the expected behavior and the real one is more evident when new materials, such as reinforced concrete elements cast in the 70s-80s, were employed [4]. The replacement of traditional timber roofs with reinforced concrete structures, the insertion of excessively rigid ribs at the top of the masonry walls (Fig.1), the use of stitching (in italian "*cuciture armate*") instead of traditional metal tie rods have often resulted in a greater damage for the building if compared to the probable disorders expected with the previous structure.

Fig.1 San Felice sul Panaro fortresses:
effect of seismic action on merlons reinforced with excessively rigid ribs.

Therefore, as reinforced concrete in the previous century, nowadays composite materials could be considered innovative materials, since their strengthening application to historic structures started a few decades ago. The use of new materials for intervention on cultural heritage always caught the interest of architects and engineering giving rise to the 19th century debate: while Ruskin (1819-1900) encouraged the use of new material to reinforce damaged building affirming that "it is better to have a crutch than remain without a leg" [5], Viollet-le-Duc (1814-1879) avoided any changes of the original structural behavior promoting the use of traditional materials. After the release of the Athens Chart (1931), that approved the "judicious" use of modern technologies to reinforce historic structures, the following documents and regulations allowed invasive application of hidden modern strengthening systems, causing the previously cited seismic damages. The past experience thus taught that innovative materials could be a useful tool only if applied with awareness of their potentialities and their limits, in order to properly plan their use preserving the historic construction in its material an immaterial feature.

Differently from traditional masonry buildings, the long-term behavior of innovative techniques and materials cannot be related to past experience. Therefore, their application should be carefully conceived and their effectiveness should be verified by means of modern numerical methods. In this regard, models must be representative of the reality [6]: a detailed study of the building, aimed at recognizing all the peculiar features that influence its structural response, is thus fundamental.

The following sections focus on the reinforcement intervention with composites materials in order to highlight the need of a critical approach based on a detailed knowledge of the existing building in its structural aspects and cultural significance. In particular, the examples will focus on strengthening of vaulted structures whose behavior, besides the standard formal typologies, is deeply influenced by differences in thickness, textures, shapes, constructive techniques and relationship with the other parts of the building [7,8].

Strengthening historic vaults with composites

Masonry vaults were used since ancient times to cover large spaces. According to the technical requirements and symbolic needs, vaulted structures were realized with different shapes, brick patterns and thickness.

Over centuries, the building masteries gave rise to a plurality of vaults typologies, frequently richly decorated. However, vaults also represent one of the most vulnerable constructive systems in historical buildings, especially in seismic areas, since they are characterized by a brittle collapse [9].

The Guidelines for the assessment and reduction of seismic vulnerability for cultural heritage [10] refers to the option of strengthening masonry vaults with composites strips. These cost-effective techniques have proved to be efficient tools in order to repair and strengthen existing structures, especially comparing their low specific weight to their very good mechanical properties. This feature allows to minimize the intervention in term of invasiveness, deciding to hide or not its applications, according to the requirements of authenticity [11].

However, durability of interventions is still uncertain, lacking today a suitable experimental test on the effectiveness of the strengthening over time (i.e. durability) [12]. Moreover, compatibility problems could arise because of the differences in physical properties. In particular, epoxy matrix does not allow a proper transpiration of the masonry substrate: for this reason, textiles should not cover the whole surface extensively, they should be used instead in discrete strips, especially in case of decorated or frescoed surfaces.

There are also problems about incomplete reversibility: the removal of fibers without altering the original material requires particular attention in case of need.

To overcome these drawbacks, several researches and studies [13,14,15,16] have focused increasingly on the experimentation of new advanced materials and techniques, offering more options with different levels of effectiveness, invasiveness, reversibility, durability, etc.

Among these possible solutions, the intervention must be specifically determined, also in consideration of residual structural resources. In particular, the original behavior should not be altered not only because it represents an historical mark but also because any changing in stiffness could affect the traditional structural seismic response, exposing thus the structural components to unknown mechanical performance [17,18]. In this regard, composites allow to improve the seismic response without neither increasing the load of the original structure nor significantly affecting its stiffness properties [12]: if properly designed then, brittle failure of components could be avoided.

In the following, some examples of seismic improvement with composites of historic masonry building, located in Parma (Italy), are presented to highlight the importance of a critical approach to structural and conservative issues. In this regard, a global improvement retrofitting method has been applied for a performance-based design: the strengthening interventions, aimed at avoiding local collapse mechanisms, are conceived to also improve the building global behavior by reducing the added stiffness, increasing ductility and favoring energy dissipation.

Masonry vaults strengthened with FRCM-PBO: the case of Palazzo APE Parma Museo

The palace (Fig. 2a), located near the main square of the city center, was built in the medieval period. Since then, several modifications – occurred over centuries – transformed this masonry construction into a richly decorated renaissance building. Ex-seat of Banca d’Italia from the beginning of 20th century, in 2015 the palace undergone restoration works to become a contemporary cultural center and Fondazione Monte Parma seat. The masonry building did not show a severe crack pattern, since it was limited at the interaction points between the original masonry walls and the reinforced concrete addition. However, the interventions carried out in 1955 altered the original structural configuration: the demolition of some walls at the raised floor generated discontinuities in the vertical masonry elements, weakening the structure in case of occurring earthquakes. Seismic improvements (Fig. 2b) were therefore required to avoid local damages and improve the overall masonry behavior. The strengthening techniques were chosen in order to improve the capacity of the masonry system without excessively increasing stiffness or seismic loads.

First of all, the vulnerabilities caused by previous interventions were solved by means of steel jacketing to strengthen masonry columns at the raised floor (portions of masonry walls demolished in 1955) and by means of a steel bracing damping system (Meldamp®) to increase resistance allowing energy dissipation without significantly increase structural stiffness (Fig. 2c).

Moreover, to reinforce historic masonry vaults, metal tie-rods (Fig.3a) were inserted at the intrados and/or composites systems were applied at the extrados (Fig.3b). Note that, since the vaults intrados is frescoed (Fig.3c), the composites strips were applied straight along the tensile load path, reducing at the minimum the covered area.

To properly choose the most effective composite system, specific tests, in collaboration with the university of Parma and the university of Modena and Reggio Emilia, were performed. In the specific, mechanical properties of Carbon Fabric Reinforced Cementitious Matrix (CFRCM) [19] and Fiber Reinforced Cementitious Mortar with Polyphenylene Benzobisoxazole (FRCM-PBO) [20,21] were analyzed. The latter proved to be more effective for the specific case of masonry vaults, since the failure occurs due to sliding of the fibers in the matrix and a thinner layer of detached material is involved in the possible failure mode. Moreover, particular attention was paid for the connection between composites and masonry walls (Fig.4) to ensure the effectiveness of the system [6].

Fig.2 Seismic improvement: (a) Palazzo APE Museo in Parma; (b) cross section of the structure with strengthening interventions; (c,d) brick columns jacketing and Meldamp ® damping system.

Fig.3 Masonry vaults reinforcement: (a) insertion of tie-rods; (b) FRCM-PBO system applied at the extrados; (c) Frescos at the intrados of cross-vault.

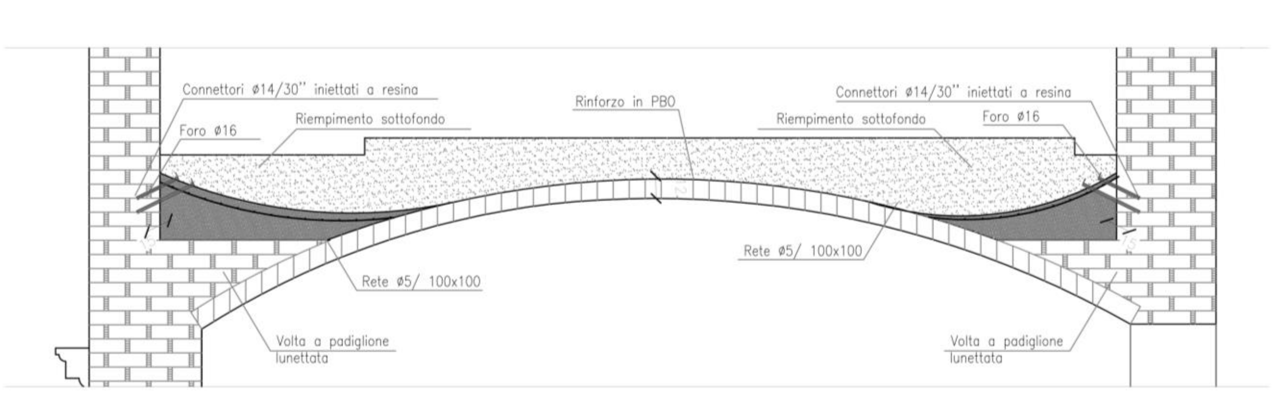

Fig.4 FRCM-PBO executive design: detail of anchorages.