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Experimental behaviour of non-structural masonry vaults reinforced through fibre-reinforced mortar coating and subjected to cyclic horizontal loads

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ABSTRACT

The paper collects the results of an innovative experimental campaign carried out on full-scale, non-structural masonry barrel vaults, so to assess, by means of quasi-static cyclic tests, the lateral performances of a strengthening technique based on the application, at the extrados or the intrados, of a 30 mm thick mortar layer with Glass Fiber-Reinforced Polymer meshes embedded. The samples were made of solid bricks, with a radius of 2060 mm and are 770 mm wide and 120 mm thick; three vaults have a span of 3980 mm and other three of 3575 mm. It emerged that the presence of the composite mesh contrasted the collapse mechanism, leading to resistance increases ranging from 2 to 4 times that of plain masonry and increasing considerably the ultimate horizontal displacements at crown section. A simplified analytical approach is also presented in the paper, to quantify the samples lateral resistance for assigned geometry and mechanical characteristics of materials.

1. Introduction

Historic masonry structures constitute a significant part of the architectural heritage in the worldwide, for their cultural and artistic relevance. Many of these buildings and infrastructures are currently still in service, thus a crucial issue is to ensure their safety and preservation by adopting effective and compatible intervention strategies. The paper deals with the rehabilitation of masonry arches and vaults, which are particularly common in historic masonry structures, but are extremely vulnerable to seismic actions, due to the intrinsic weak tensile behavior of masonry, despite of its substantial compressive performances.

The systematic study of the stability of unreinforced masonry arches [1–3], accompanied with the critical observation of damage after seismic events, evidenced that their crack pattern is generally characterized by the formation of structural hinges induced by the masonry flexural failure for tensile cracking, due to the horizontal inertia forces experienced by the arch and/or to differential motions of the abutments. The occurrence of four hinges activates the collapse mechanism, consisting in a sequence of arch portions connected through pins, whose failure is governed by equilibrium (Fig. 1). Neglecting the end effects of head walls at the ends of the vault, the behaviour of masonry barrel vaults can be analysed as a series of adjacent arches.

The mechanism activation can be prevented by introducing tensile resistant elements, which transmit tension between the two sides of a crack, improving the masonry bending resistance and delaying the formation of the last hinge, so retarding the mechanism activation. If the opening of tensile cracks in masonry are prevented, the collapse of a reinforced arch can generally occur for the masonry compressive or shear failure, for the reinforcement debonding from the substrate or for its tensile failure.

Traditional strengthening techniques, based mostly on the application of steel reinforced concrete jacketing (or, sometimes, on the insertion of steel bars in slots cut into the masonry and bonded with cement-based grouts) evidenced some critical aspects concerning corrosion of the reinforcement, detrimental chemical reactions with historic masonry, reduction of vapour permeability and not negligible mass and stiffness increases. Thus, since late Nineties, the use of non-corrosive, composites materials based on Fiber-Reinforced Polymers (FRPs), characterised by high tensile resistance, for the reinforcement of masonry arches and vaults has gradually begun [4–8]. At first, FRP elements, in the forms of rods, laminates or strips, were bonded to the curved surface (at the extrados, at the intrados or to both, adopting a discrete or diffuse layout) through epoxy resins and resulted generally able to improve the masonry vaults performances in both strength and ductility, contrasting the opening of cracks in masonry with negligible mass alterations. However, the reinforcement collapse often occurs prematurely, for delamination [9–11]; moreover, epoxy resins, besides high-costs and the need of skilled installation staff, suffer of

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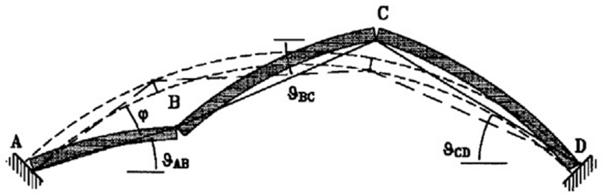

Fig. 1. Typical collapse mechanism of an arch subjected to lateral forces [2].

characteristics degradation in case of exposition to high or low temperatures, fire, ultraviolet, water and alkaline ambient [12–14]. Furthermore, the difficulty in removal the intervention make the application unsuitable for listed historical buildings.

Thus, epoxy resins were gradually replaced by inorganic matrices, overcoming most of the FRP's drawbacks [15–18]. In these technique, known as FRM (Fiber-Reinforced Mortar), dry, coated or pre-impregnated fabrics or meshes (mostly based on carbon, glass, basalt or PBO) are embedded in a 10 to 30 mm thick mortar coating, which can be based on cement (FRCM – Fiber-Reinforced Cemetitious Matrix) or also on natural binders. The acronyms TRM (Textile Reinforced Mortar) and CRM (Composite Reinforced Mortar) distinguish FRM reinforcement based on dry fabrics or coated meshes, respectively.

Besides the use of fibers, other effective techniques for the strengthening of masonry vaults have to be mentioned, concerning the application of steel reinforced mortars layers (SRG, Steel-Reinforced Grout technique) [19–21], the installation of steel cables [22], the masonry structural repointing [23] and the use of extrados reinforced ribs [24,25] or lightweight plywood restraining structures [26].

The effectiveness of the diverse strengthening techniques has been investigated in the literature; however, the complexity to recreate in the laboratory field the stress state of a masonry arch or vault subjected to seismic lateral forces has led researchers to identify simplified load patterns. In fact, the experimental results available are based mostly on the application of monotonic, pseudo-static vertical loads concentrated at a determinate section (typically, 1/4 or 1/3 of the span), so to qualitatively reproduce the actual element deformation [5–9,16,17,19,23,24,27–29]. Only in a restricted number of cases, the effects of loading–unloading steps [18,20,21], reverse cyclic loading [26,30,31], horizontal actions [15,22,26,30,32] or dynamic excitation [25,33,34] were investigated. Thus, as already evidenced by the authors through a preliminary numeric study [35] and observed also in [25], testing methods currently adopted are not generally able to simulate the actual seismic behavior of an arch or a vault, as the concentrated forces tended to localise damage, leading to an erroneous quantification of the reinforcement benefits.

Analytically, the evaluation of the resistance of reinforced masonry arches, according to the approach adopted for unreinforced ones, is generally based on the simplified assumption of no-tension masonry model and is performed through the Limit Analysis theory, by applying the lower or upper bound theorems [5,16,17,36–40]. However, some authors [41] observed that in slender masonry vaults the use of classical approaches (e.g. Heyman's theory [1]) to evaluate their lateral capacity would produce inaccurate results and adapted the standard limit analysis approach to tensile resistance structures.

Typically, the resistance capacity of reinforced masonry sections, subjected to combined axial and bending loads, is evaluated by applying the relationships commonly used in the design of reinforced concrete beams; typically, a linear elastic behavior is assumed for the reinforcement and rectangular stress-block law for the masonry in compression. Possible premature failures due to shear or to reinforcement debonding has also to be checked.

In the paper, the results of an experimental campaign performed to assess the performances of a strengthening technique for masonry vaults based on the application, at the extrados or at the intrados, of a FRM reinforcement are presented and discussed. An innovative bench set up was properly designed so to reproduce the effects of the samples lateral inertia forces, by means of quasi-static cyclic tests. Full-scale, non-structural masonry barrel vaults were tested, considering two different geometries: the performances of reinforced specimens are compared with the unreinforced ones in terms of failure mechanism, lateral resistance and displacement capacity, proving the effectiveness of the strengthening system. Moreover, an analytical procedure is proposed for the prediction of the lateral resistance capacity of reinforced vaults starting from the vaults geometry and mechanical characteristics of the materials.

2. Specimens and materials characteristics

Six full-scale masonry barrel vaults were tested experimentally. The samples reproduced the typical geometrical features and configuration of historical masonry vaults carrying their own self-weight (shelters, without any backfill) and were made of solid brick units arranged in a running bond normal to the vault's surface (thickness 120 mm), with a radius of 2060 mm and a width of 770 mm; the average thickness of the mortar joints was 10 mm. Two different rise/radius ratio were considered: 0.75 (rise 1540 mm – Fig. 2a) and 0.50 (rise 1030 mm, Fig. 2b). For both geometries, the tests concerned one unreinforced specimen, one specimen with the reinforcement applied at the extrados and one at the intrados. The samples identifier is split in three parts: the former (from V01 to V06) distinguishes sequentially the samples, the second differentiates the vaults geometry (75 or 50, for rise/radius ratios of 0.75 and 0.50, respectively), the latter indicates plain masonry (NR), or masonry reinforced at the extrados (RE) or at the intrados (RI).

The Glass Fiber-Reinforced Mortar (GFRM) reinforcement (or, alternatively, CRM – Composite Reinforced Mortar), illustrated in Fig. 3a, consisted in a layer of plaster, about 30 mm thick, in which a mesh based on Glass Fiber-Reinforced Polymer (GFRP) was embedded. The mesh had a grid pitch of 66 × 66 mm^2. L-shaped GFRP connectors (6 per square meter, 7 × 10 mm^2 cross section – Fig. 4) were applied by insertion into holes in masonry (12 mm diameter) and injection of vinylester epoxy resin. 165 × 165 mm^2 GFRP mesh devices (33 × 33 mm^2 grid pitch) were introduced to improve the anchorage of the connectors in the mortar layer. The reinforcement was applied on

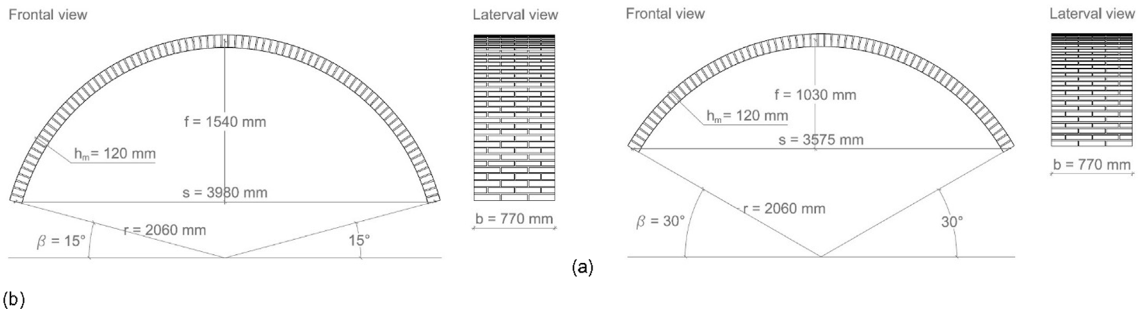

Fig. 2. Geometrical characteristics of masonry vaults: (a) rise/radius ratio 0.75 and (b) 0.50.