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Full-scale tests on masonry vaults strengthened with Steel Reinforced Grout

Stefano De Santis*, Francesca Roscini, Gianmarco de Felice

Roma Tre University, Department of Engineering, Via Vito Volterra 62, 00146 Rome, Italy

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ABSTRACT

Masonry vaults can be particularly vulnerable against unsymmetrical service loads, support displacements and seismic actions. Retrofitting is often needed to ensure an adequate safety level according to current standard codes. Externally bonded composites are emerging as a possible retrofitting technique, but no experimental evidence is still available on the response of reinforced vaults taking into account the contribution of buttresses and backfill. This paper describes an experimental investigation on four full-scale vault specimens. One of them was tested unreinforced, whereas the other ones were strengthened with Steel Reinforced Grout (SRG), comprising ultra high tensile strength steel cords, bonded with lime-based mortar either to the extrados or to the intrados. The vaults were subjected to cyclic loading at 1/3 span. The backfill was visible through a panel of Plexiglas, allowing for the use of Digital Image Correlation to measure the displacement field and derive information on damage pattern and arch-fill interaction. Tests showed that SRG prevented the development of the four-hinge mechanism and avoided damage concentrations, increasing the deflection capacity and the strength of the arch by 2–3 times. Finally, it is shown that a simplified analytical approach based on limit analysis provides a reliable estimate of experimental load carrying capacity.

1. Introduction

In many existing buildings all over the world, there are brick masonry vaults that either carry a floor or are simply a ceiling below the roof. They typically span some meters and their thickness ranges between 25 cm (two brick heads) and 12 cm (one brick head) or even 4–8 cm. This latter typology of vaults, in which bricks are laid lengthwise in one single leaf, or multiple leaves, are named timbrel vaults, Catalan vaults (they are widely used in Catalonia, but also in other Spanish regions, in Italy, etc.), or Guastavino vaults (from the name of the Spanish architect Guastavino who patented this arch style in the United States in 1885) [1]. Since their load carrying capacity mainly relies on the shape, the more slender vaults are particularly vulnerable against concentrated forces, unsymmetrical loads, support displacements and seismic actions. Therefore, retrofitting works are sometimes needed to ensure an adequate safety level according to current standard codes. For this purpose, externally bonded reinforcements with composite materials are particularly advantageous, since they provide high mechanical performances with minimum thickness and mass increase [2].

In masonry arched members, due to the lack of tensile strength, a failure mechanism activates by the formation of four hinges, alternated at the intrados and at the extrados. Composite reinforcements prevent the opening of cracks and, therefore, the onset of such collapse mechanism, avoid local falls of bricks, constrain the deflections of the vault and reduce the lateral thrust at the abutments [3]. In principle, the application of the strengthening system to one side only (either to the intrados or to the extrados) is sufficient to prevent the development of the hinges on this side and, therefore, the onset of the mechanism, whereas bonding the composite material to both surfaces is generally unnecessary. The intrados reinforcement is faster and cheaper than the extrados one, since the intrados surface is easily accessible from below. Its concave curvature may however reduce the adhesion of the composite, such that mechanical pins could be added. Many times, however, covering the lower surface of the vault is unfeasible since the paintings, the plaster or the fair face of the masonry have to be preserved. In this case, the strengthening system needs to be applied to the extrados. This requires that the flooring and the backfill are removed, which entails longer and more expensive work, but it can be easily combined with building side buttress walls or backings in solid brickwork over the abutments to constrain the deflection of the vault and with inserting tie-bars to prevent the relative movement of the side walls.

In the last decades, research activities and field applications have mainly used composites with polymeric matrix (Fibre Reinforced Polymers, FRPs) [4–8]. More recently composites with inorganic matrix, named Textile Reinforced Mortar (TRM), have also been applied [2,6]. TRMs consist of high strength fabrics (unidirectional textiles or

* Corresponding author.
E-mail addresses: stefano.desantis@uniroma3.it (S. De Santis), francesca.roscini@uniroma3.it (F. Roscini), gianmarco.defelice@uniroma3.it (G. de Felice).

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bidirectional meshes) applied to the external surface of the structural members by means of cement or lime mortars. The use of inorganic matrices in place of organic ones provides better resistance at high temperatures, higher cost-efficiency, and the possibility of application to wet or irregular surfaces. TRMs with lime-based matrices also fulfil the preservation criteria required for applications to cultural heritage, as, with respect to cement mortars, they ensure a better physical/chemical compatibility with masonry substrates, vapour permeability, and reversibility/removability (possibility of being removed with minimum damage to the substrate). On the other hand, the TRM-to-substrate bond strength may be lower than that of FRPs. The bond resisting mechanism of TRM systems is itself more complex, as failure may occur not only by cohesive debonding within the substrate (as with FRPs) but also by detachment within the thickness of the system or by textile sliding within the matrix [9].

TRMs have already been proposed to retrofit masonry arches making use of basalt [8,10,11], polyparaphenylene benzobisoxazole (PBO) [12,13], carbon [14], glass [15], and steel [6,8,16,17]. They have been applied either to the intrados of the arch [6,13,17], to its extrados [6,8,10,12–15,17], or to both surfaces [6,10]. In some cases, mechanical connectors have been used at the abutments to prevent end debonding [6], whereas in other studies the application of TRM systems has been combined with the construction of additional vault rings to increase the arch thickness (the *tabicada* technique) [15]. With respect to the unreinforced specimens, the ultimate load of strengthened arches increased by 3–20 times, and even more in case of application to both surfaces. The presence of the reinforcement modified the failure mode, since the activation of the four-hinge mechanism was replaced by a combination of reinforcement debonding, shear sliding and crushing of masonry, or tensile rupture of the textile. The deflection capacity also increased, in terms of both peak displacement and ductility, which resulted up to 10–15 times larger than those of unreinforced specimens, especially when steel or PBO textiles were used. Relatively lower enhancements were generally found on vaults reinforced with weaker textiles (e.g., glass or basalt) due to the brittle failure occurring by fibre rupture.

Despite the variability of the results, which is due to the different specimen geometry, material properties, experimental setups and TRM systems under investigation, these studies demonstrated the effectiveness of mortar-based composites for retrofitting masonry arches. The strength improvement achieved with TRMs also resulted comparable, or even higher, when compared to that obtained with FRPs [6,8,16]. Nevertheless, the specimens tested so far were generally free-standing arches, i.e., backfill was not included. Only few works [11,16] took into account the influence of the buttresses. In Ref. [16], however, the buttresses were not built in contrast with a reaction structure, whereas in Ref. [11] only the vaults reinforced with TRM were provided with buttresses (that is, the retrofitting work included both the installation of the TRM and the construction of the buttresses). Finally, none of the specimens that have been tested so far were timbrel vaults, the most vulnerable vaulted structures. No experimental results are available on the gain in load carrying and deflection capacity that can be achieved with mortar-based composites applied to timbrel vaults that are filled to carry a floor on top and provided with buttresses, even if this situation is often faced in retrofitting works.

This paper describes an experimental investigation performed in the laboratory on four vault specimens with 2.9 m span, 650 mm rise and 55 mm thickness, provided with buttresses and backfill. One specimen was unreinforced and three were reinforced with Steel Reinforced Grout (SRG), comprising steel cords applied with lime-based mortar [18], with the aim of enhancing the load carrying capacity. With respect to the other fabrics used in TRM reinforcements, steel fabrics are unidirectional, are stiffer and stronger than glass and basalt, and thicker than carbon, aramid and PBO, are more durable in alkaline environment, and their shape provides a better interlocking within the mortar matrix [19]. To ensure durability, steel wires are coated with zinc to provide protection against salt attack and prevent rusting [20]. In this study, SRG was applied either to the extrados or to the intrados of the vault to investigate the different strengthening layouts can could be designed for structural applications in the field. Digital Image Correlation was used to measure displacements, which was possible thanks to the use of a Plexiglas spandrel panel that made the lateral surface of the specimen (arch barrel, buttresses, backfill) visible. A vertical load was applied over the backfill at 1/3 span and increased cyclically up to failure to investigate the increase in load carrying and deflection capacity provided by SRG and the modification of the associated damage pattern, failure mode, and arch-fill interaction. Finally, the load carrying capacity of the strengthened arches is estimated by limit analysis, using both a static and a kinematic approach.

2. Experimental setup

2.1. Construction of the vault specimens

Four full-scale vault specimens were built in the laboratory, using clay bricks (with 250 mm × 120 mm × 55 mm size, 15.8 kN/m^3 unit weight, 14.8 N/mm^2 compressive strength, 2.5 N/mm^2 tensile strength and 5.76 kN/mm^2 Young's modulus [21]) and 10 mm joints of lime mortar (5.2 N/mm^2 compressive strength, 0.8 N/mm^2 tensile strength and 1.5 kN/mm^2 Young's modulus). The vaults had 2790 mm span, 500 mm width, 650 mm rise. The bricks were laid lengthwise, i.e., on the shortest side, which resulted in a thickness of 55 mm (Fig. 1).

The experimental setup was designed to apply the most severe static loading condition that a vault can experience, that is, a concentrated load at 1/3 span [22], and the abutments were fixed. In the field, the relative support movements can be prevented by means of tie-bars [23].

First, 205 mm high abutments (Fig. 2a) were built in contrast with a reaction wall on one side and a stiff steel frame on the other side. Then, the arch barrel, made of 25 voussoirs, two entire bricks alternated with one brick and two half bricks, was built on wood forms (Fig. 2b). Two buttresses, having 120 mm thickness (one brick head), and 445 mm height (seven layers), were built at each side (Fig. 2c). The wood form was removed five days after the construction of the arch (Fig. 2d). Two 20 mm thick lateral panels, one of wood and one of Plexiglas, were placed on wood supports, and connected by 12 ∅8 mm threaded bars to minimize out-of-plane deflections (Fig. 2e). The backfill, consisting of 4 ÷ 8 mm grain size gravel with 12.5 kN/m^3 weight and $\varphi = 39°$ angle of internal friction, was set down manually (it was not densified mechanically), with a depth of 100 mm in crown. Finally, a 20 mm rubber mat was placed on top (Fig. 2f).

2.2. Strengthening system and installation

2.2.1. Materials

The SRG systems used in this study comprise unidirectional textiles of Ultra High Tensile Strength Steel (UHTSS) cords (Fig. 3a). Cords are made of five wires with 0.11 mm^2 cross section area each, three rectilinear and two twisted around them, galvanized (coated with zinc) to provide protection against rusting. Two textiles were used, having either 8 cord/inch or 4 cord/inch density. The former has 3.18 mm cord spacing, 0.168 mm design thickness and 1200 g/m^2 surface mass density (Fig. 3b), whereas the latter has 6.35 mm cord spacing, 0.084 mm design thickness and 670 g/m^2 surface mass density (Fig. 3c). The steel textiles have 3186 N/mm^2 tensile strength (f_t), 184 kN/mm^2 Young's modulus (E_f) and 2.26% ultimate strain (from direct tensile tests [24]). To bond the steel textiles to the vault surface, a lime-based mortar was used, having grain size range of 0 ÷ 1.4 mm, 20.6 N/mm^2 compressive strength (from compression tests on cubic specimens), 11.4 kN/mm^2 Young's modulus (from tests on cylinders), and 5.4 N/mm^2 tensile strength (from three point bending tests).

For the 4 cord/inch textile, the SRG-to-brickwork bond strength (axial stress in the textile at debonding) is $f_b = 2630$ N/mm^2 on plane