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Bond behaviour of Steel Reinforced Grout for the extrados strengthening of masonry vaults

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HIGHLIGHTS

- Lab and field bond tests are carried out on SRG applied to convex masonry substrates.
- SRG-to-substrate bond behaviour is improved by compressive normal stresses induced by curvature.
- Bond strength increases with the increase of substrate curvature and bond length.
- Cord-to-matrix interlocking is crucial for the effectiveness of the reinforcement.
- Bond behaviour is independent from the mechanical properties of the vault substrate.

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ABSTRACT

Steel Reinforced Grout (SRG), consisting of ultra high tensile strength steel cords embedded in a mortar matrix, is an effective solution for the upgrade of existing structures. Among its various applications, it can be applied to the extrados and the intrados of masonry vaults to improve their load-carrying and seismic capacity. Nevertheless, its bond strength on curved substrates, which is crucial for the design of the reinforcement of masonry arched members, has not been properly explored yet. This paper presents an experimental investigation on the bond behaviour of SRG applied to convex masonry substrates. Double-lap shear bond tests were carried in the laboratory on small-scale brickwork specimens to investigate the effect of curvature radius, bond length and textile architecture on bond strength and failure mode. Full-scale field tests were performed to study the bond behaviour and the resisting mechanisms of SRG applied to the extrados of an existing masonry vault, taking into account the actual substrate preparation and mortar curing conditions at a construction site.

1. Introduction

The use of brick masonry vaults in existing buildings is widespread in several countries worldwide. They typically span some metres and their thickness ranges between 250 mm (two-brick heads) and 120 mm (one-brick head) or even 40–50 mm (timbrel or Catalan vaults) [1]. The load-bearing capacity of masonry vaults strongly depends on shape and slenderness, as well as on material properties (no tensile strength), making them particularly vulnerable against unsymmetrical service loads, support displacements and seismic actions. Nowadays, the vaults of numerous existing structures need retrofitting to ensure an adequate safety level according to current standard codes (see, amongst others, [2–4]). For this purpose, externally bonded reinforcements with composite materials are particularly advantageous, since they provide high mechanical performances with minimum thickness and mass increase, they can be applied to curved substrates and can adapt to various shapes, and are relatively cost-efficient [5,6]. In the last decades, research activities and field applications have mainly used composites with polymeric matrix (Fibre Reinforced Polymers, FRPs). Nevertheless, reinforcements with inorganic matrix have been recently proposed as they offer important advantages over FRPs in terms of cost, ease of installation (also on uneven or wet surfaces) and resistance at high temperatures [7,8]. When the matrix is a lime-based mortar, these systems also ensure vapour permeability, physical-chemical compatibility with the substrate, and reversibility (i.e., possibility of being removed without damage in the original substrate), which makes them compliant with the principles of preservation of architectural heritage and thus suitable for applications to historic masonry structures [6]. On the other hand, the bond strength of mortar-based reinforcements is generally lower than that of FRPs and their bond resisting

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mechanisms are more complicated, since failure may occur not only by cohesive debonding within the substrate (as usually happens in FRPs), but also by detachment at the reinforcement-to-substrate or textile-to-matrix interface, or by textile sliding [9,10].

Different names have been proposed for mortar-based reinforcements, including Textile Reinforced Mortars (TRM) or Fabric Reinforced Cementitious Matrix (FRCM) when comprising carbon, glass, basalt, or PBO fabrics, arranged in the form of open meshes, or Steel Reinforced Grout (SRG) when using steel textiles. Steel textiles are unidirectional (no bidirectional meshes are available yet) and comprise cords or ropes of Ultra High Tensile Strength Steel (UHTSS). With respect to the fabrics with other fibre materials, steel textiles are stiffer and stronger than glass and basalt and thicker than carbon, aramid and PBO, are isotropic (which provides better toughness) and more durable in alkaline environment. On the other hand, they need to be either coated with brass or zinc, or made of stainless steel, to protect against rusting [11], and, since their use for civil engineering applications is more recent than carbon and glass, they have not been yet included in design codes for epoxy [12–15] or mortar [16] based reinforcements.

The SRG-to brick/masonry bond behaviour, which is crucial for a broad range of applications, has been investigated by a number of studies [17–23], which provided fundamental information on bond strength and failure modes, and analysed the role played by the mechanical properties of the matrix, the layout of the textile, and the surface roughness of the substrate. Nevertheless, the bond behaviour on curved substrates has not been investigated yet, except from one study only dealing with concave surfaces [24]. The design of the extrados strengthening of masonry vaults would instead require that a deeper knowledge is gained on the SRG-to-convex substrate bond behaviour.

This paper presents an experimental investigation on the bond behaviour of SRG reinforcements comprising UHTSS textiles applied to convex brickwork substrates with lime-based mortar. Double-lap shear bond tests were carried out in the laboratory to investigate the influence on failure mode and load transfer capacity of (i) curvature radius (R): infinite (plane surface), 5000 mm, 2650 mm and 1800 mm; (ii) bond length (L_b): 320 mm, 450 mm and 580 mm; and (iii) cord spacing: 2.12 mm and 6.35 mm.

Since SRG has already been applied to several existing vaults, especially within reconstruction and retrofitting works after severe earthquakes [6], it is crucial to assess its effectiveness through in-situ tests, in which it is possible to test very long bonded areas, and to take into account the conditions at a construction site related to the actual surface properties and to the setting and curing of the mortar matrix. To this aim, field tests were carried out on the bond performance of SRG applied to the extrados of an existing vault. The experimental setup was designed to simulate the loading conditions that the development of a crack at the extrados of the vault, due to the activation of a mechanism, would induce in the reinforcement, so as to investigate the reaction that this latter is able to provide.

The research aims at gaining an improved understanding of the bond behaviour of SRG for the extrados reinforcement of masonry vaults and providing experimental results that could contribute to the calibration of numerical models, to the development of design relationships, and to the optimization of strengthening layouts for the protection of existing masonry arched members.

2. Extrados strengthening of masonry vaults with SRG

A number of research studies carried out in the recent past have shown the effectiveness of composite materials to increase the structural capacity of masonry vaults [2–4,25–31]. The scientific outcomes have hence promoted the development of technical and design solutions to integrate the reinforcement of vaults with composites in the rehabilitation of historic structures [5,6]. To retrofit masonry arched members, externally bonded reinforcements can be applied either at the intrados or at the extrados. The former solution is faster and cheaper since the intrados surface is easily accessible from below. However, the curvature of the surface may reduce the adhesion of the composite, requiring the installation of mechanical pins to prevent premature detachment. In addition, covering the surface of a vault is unfeasible when the masonry is painted or when its fair face has to be preserved. The extrados reinforcement requires that the flooring and the fill (which are placed on top of interstorey vaults, but not of those at the last floor below the roof) are removed, which entails longer and more expensive work. On the other hand, this allows substituting the existing filling material with a lighter one, adding a binder (e.g., a grout), building side buttresses or backing in solid brickwork to constrain the deflection of the vault, inserting tie-bars to prevent the relative movement of the side walls supporting the vault, and, finally, preserve any paintings at the intrados.

The installation of SRG at the extrados of the vault includes the following phases:

(i) the vault is shored up with props from below;
(ii) fill material is removed and damage is repaired by repointing the mortar joints and restoring dislocated bricks. In this phase, badly cracked units can be replaced and small portions of the vault that have collapsed can be rebuilt;
(iii) holes are drilled in the side walls for the installation of the end connectors (if in the design);
(iv) the surface of the vault is cleaned and residues of mortar and filling are removed, and (if in the design) the roughness of the vault surface is improved artificially (e.g., by bush hammering) (Fig. 1a);
(v) the strips of steel textile are cut to size (Fig. 1b);
(vi) the surface of the vault is wet with water (Fig. 1c);
(vii) the first mortar layer (having thickness of about 5 mm) is laid down;
(viii) the steel textile is installed (Fig. 1d) taking care of the full protrusion of the mortar between the cords (Fig. 1e);
(ix) the end connectors are prepared, installed and injected in drilled holes at the abutments (Fig. 1f);
(x) the top layer of mortar (5 mm thickness) is laid (Fig. 1g);
(xi) a second transversal set of strips is installed (Fig. 1h), if foreseen by the design (usually in vaults with double curvature);
(xii) tie-bars are installed and side buttresses or backings are built in solid brickwork; new fill material is placed (Fig. 1i). This latter may include a grout that contributes to constraining the deflection of the vault and/or lightened aggregates (e.g., expanded clay) to reduce the vertical load.

3. Laboratory investigation

3.1. Materials and experimental setup

The SRG systems used in this study comprise unidirectional textiles of UHTSS cords (Fig. 2a). Cords are made of five wires with 0.11 mm^2 cross section area, three rectilinear and two twisted around them at a short lay length to enhance the interlocking with the mortar. Wires are galvanized (coated with zinc) to provide protection against rusting, and are fixed to a supporting glass mesh to ease handling and installation. Two textiles differing only for their density (i.e., 4 cord/inch, corresponding to 0.158 cord/mm and 12 cord/inch corresponding to 0.474 cord/mm) were used. In the former (S4, Fig. 2b), the cords are spaced 6.35 mm, the design thickness is 0.084 mm, and the surface mass density is 670 g/m^2.