

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.

Keywords

Double-lap shear bond tests; Fabric Reinforced Cementitious Matrix (FRCM); Field tests; Laboratory tests; Masonry; Retrofitting; Textile Reinforced Mortar (TRM).

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 250mm (two-brick heads) and 120mm (one-brick head) or even 40-50mm (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 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), 5000mm, 2650mm and 1800mm; (ii) bond length (L_b): 320mm, 450mm and 580mm; and (iii) cord spacing: 2.12mm and 6.35mm.

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);

- 98 (iv) the surface of the vault is cleaned and residues of mortar and filling are removed, and (if in the design)
99 the roughness of the vault surface is improved artificially (e.g., by bush hammering) (Figure 1a);
- 100 (v) the strips of steel textile are cut to size (Figure 1b);
- 101 (vi) the surface of the vault is wet with water (Figure 1c);
- 102 (vii) the first mortar layer (having thickness of about 5mm) is laid down;
- 103 (viii) the steel textile is installed (Figure 1d) taking care of the full protrusion of the mortar between the
104 cords (Figure 1e);
- 105 (ix) the end connectors are prepared, installed and injected in drilled holes at the abutments (Figure 1f);
- 106 (x) the top layer of mortar (5mm thickness) is laid (Figure 1g);
- 107 (xi) a second transversal set of strips is installed (Figure 1h), if foreseen by the design (usually in vaults
108 with double curvature);
- 109 (xii) tie-bars are installed and side buttresses or backings are built in solid brickwork; new fill material is
110 placed (Figure 1i). This latter may include a grout that contributes to the constraining the deflection of
111 the vault and/or lightened aggregates (e.g., expanded clay) to reduce the vertical load.



Figure 1. Phases of the installation of SRG to the extrados of a brickwork vault.

3. LABORATORY INVESTIGATION

3.1. Materials and experimental setup

The SRG systems used in this study comprise unidirectional textiles of UHTSS cords (Figure 2a). Cords are made of five wires with 0.11mm^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, Figure 2b), the cords are spaced 6.35mm, the design thickness is 0.084mm, and the surface mass density is 670g/m^2 . In the latter (S12, Figure 2c), cords are spaced 2.12mm, the design thickness is 0.254mm and the surface mass density is 2000g/m^2 .

124 The steel textiles were applied with a lime-based mortar with grain size range of 0-1.4mm, 20.6N/mm²
 125 compressive strength (from compression tests on cubic specimens), 11.4kN/mm² Young's modulus (from
 126 tests on cylinders), and 5.4N/mm² tensile strength (from three point bending tests). The SRG composites
 127 have a tensile strength (f_t) of 3254N/mm² with S4 textile) or 2852N/mm² with S12, corresponding to a
 128 maximum load per unit width of 272.4kN/m and 730.3kN/m, respectively. The lower strength detected in
 129 direct tensile tests on coupons with S12 is due to the fact that the higher cord density entails a lower
 130 interaction between cords and matrix and makes it more difficult to apply a uniform load distribution among
 131 the cords. For both systems, the tensile modulus of elasticity after cracking is about 180kN/mm² [32].
 132 In order to investigate the bond behaviour of SRG applied to convex masonry substrate, shear tests were
 133 carried out in the laboratory with a double-lap double-prism setup (Figure 3). Each specimen consisted of
 134 two brickwork prisms (an upper prism and a lower prism) connected to each other by two SRG strips (one on
 135 the left side and one on the right side). The two prisms were moved apart to apply a tensile load to the SRG
 136 strips, simulating the loading condition that would be caused by the development of a crack in the vault
 137 substrate [10].
 138 Prisms comprised 250mm×120mm×55mm clay bricks and 10mm thick joints of natural hydraulic lime
 139 mortar. In order to obtain a masonry with relatively weak mechanical properties (similar to those of historic
 140 structures) the bricks had 12.3N/mm² compressive strength, 3.9N/mm² Young's modulus and 5.8N/mm²
 141 tensile strength [33], while the mortar had 5.9N/mm² compressive strength, 7.2kN/mm² Young's modulus
 142 and 0.5N/mm² tensile strength.
 143 The bricks were holed in the middle and 420mm long Ø14mm steel bars were placed in the holes through
 144 each prism (one bar in the lower prism and one bar in the and the upper prism). The bars were welded to
 145 250mm×120mm×10mm steel plates (Figure 3a). To run the test, on the other side, they were gripped in the
 146 wedges of the testing machine and pulled. By doing so, the steel plates pushed the two prisms apart.
 147 Before manufacturing the prisms, the bricks were shaped by realizing inclined cuts at their sides, to obtain
 148 curved substrates with uniform radius (Figure 3b). The SRG strips were bonded to the curved surfaces of the
 149 prisms for the whole length (Figure 3c). Each specimen comprised four reinforcements nominally identical
 150 (left upper, left lower, right upper, and right lower).

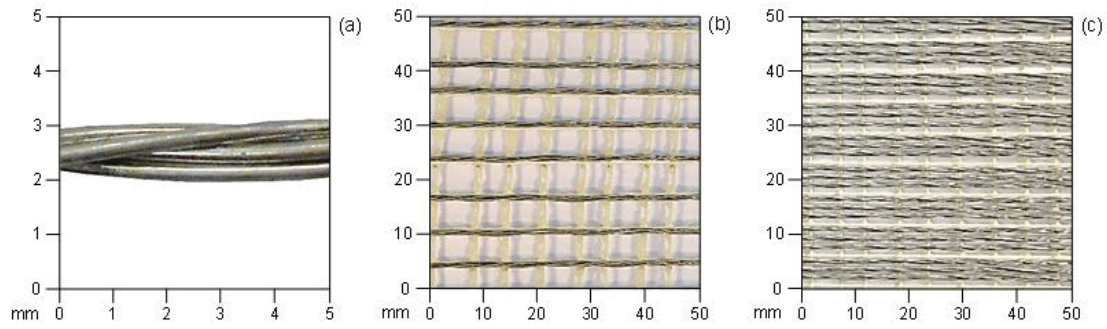


Figure 2. Ultra High Tensile Strength Steel (UHTSS) textiles: detail of the steel cord (a), textiles with 4 cord/inch (S4, b) and 12 cord/inch (S12, c).

Nine tests were carried out with the S4 textile on prism substrates comprising 5 bricks and four mortar joints, resulting in a bonded length of $L_b=320\text{mm}$. Three values of the curvature radius were tested, including $R=5000\text{mm}$, $R=2650\text{mm}$, and $R=1800\text{mm}$. Three specimens with plane surface (R infinite) were tested and taken as a reference for comparisons. Six additional specimens with $R=1800\text{mm}$ were tested, three with 7 and three with 9 brick layers, corresponding to $L_b=450\text{mm}$ and $L_b=580\text{mm}$, respectively. Finally, S12 textile was applied to two specimens with 7 layers and two specimens with 9 layers, all having $R=1800\text{mm}$ (Figure 4). SRG reinforcements were 50mm wide. The strips of S4 textile comprised 8 cords and had a cross section area of 4.26mm^2 , while those of S12 had 24 cords and 12.80mm^2 area. The cross section area can be evaluated as the number of cords multiplied by their individual area (0.534mm^2), or as the design thickness (0.084mm for S4 and 0.254mm for S12) multiplied by the width of the textile (50.8mm), the latter being the product of the number of cords (8 or 24) and of their spacing (6.35mm or 2.12mm).

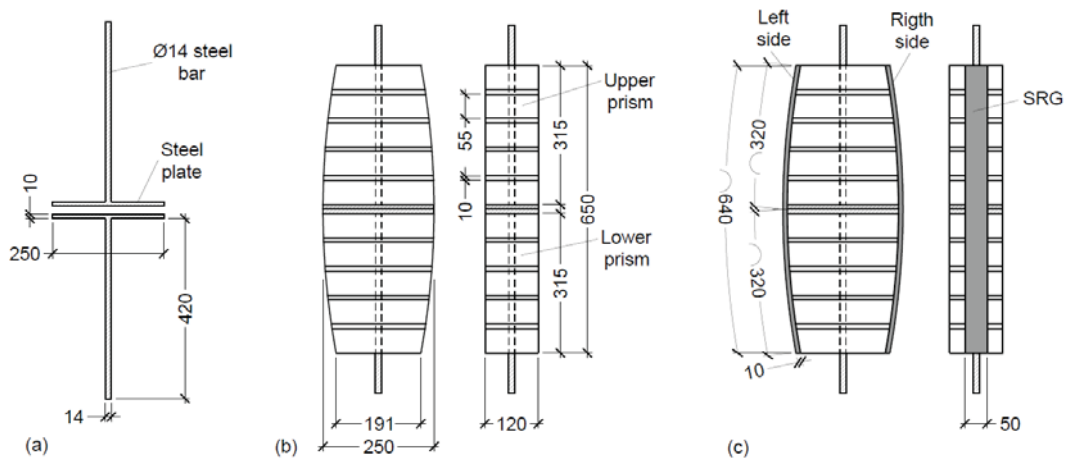


Figure 3. Specimen geometry: steel bars and plates (a) and brickwork prisms before (b) and after (c) SRG installation (specimen with $R=1800\text{mm}$ and $L_b=320\text{mm}$ shown as sake of example).

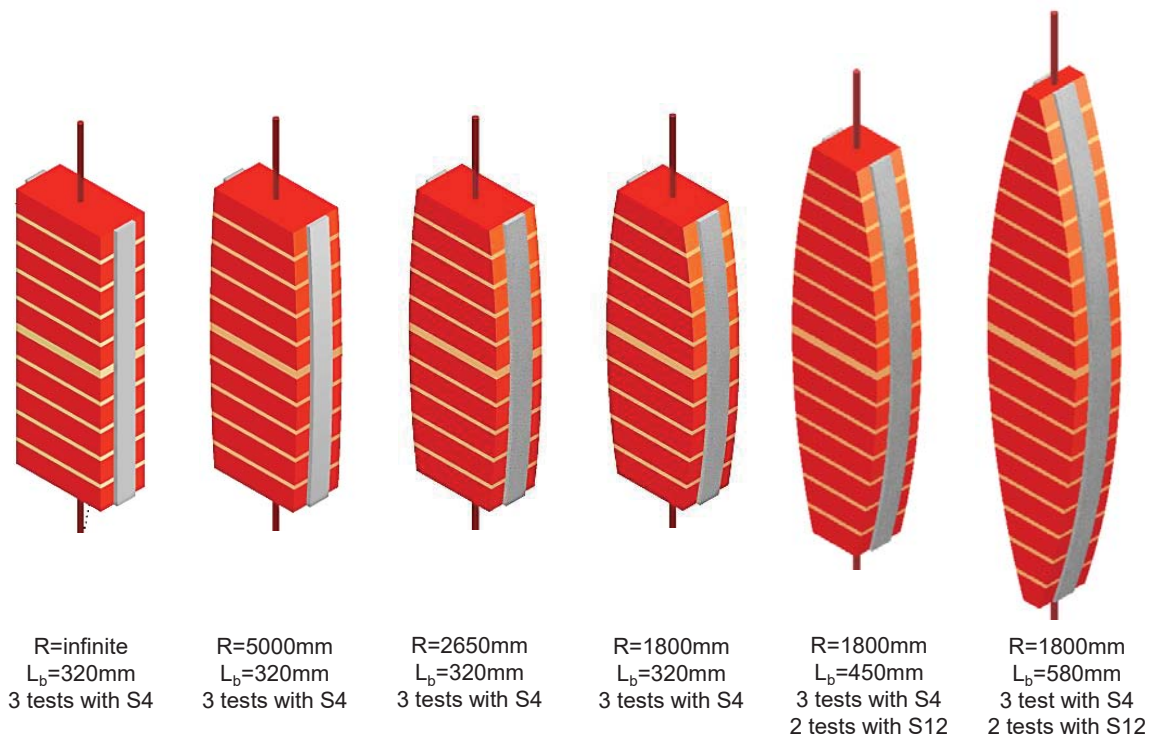


Figure 4. Specimen types.

Prior to bonding the SRG reinforcements, the surfaces of the brickwork prisms were brushed, cleaned with compressed air and wet with water. No specific treatment was applied to improve artificially their roughness. Since the local properties of the substrate faced in field applications may vary largely and can hardly be predicted, no attempt was made in the laboratory to reproduce the in-service conditions of the surface of an existing vault. Two resistive strain gauges (one per side) were applied to the textiles before SRG installation. Given the small diameter of the steel cords and their roughness, which may compromise the proper adhesion of the strain gauges and, therefore, the reliability of their measurements, thin plates of epoxy resin were realized on the central cord to create a smooth surface on which the strain gauges were glued [17]. The strain was measured in the middle of the specimen to derive the maximum load applied to the steel textile. Furthermore, since, in this region, the SRG was subjected to tensile load due to symmetry, the resin plates did not significantly compromise its bond performance.

A first 5mm thick layer of mortar was laid down within polyethylene frameworks placed in the middle of the substrate (Figures 5a,b). The steel textiles were manually placed on the first mortar layer and pressed enough to make the fresh mortar protrude through the voids between steel cords (Figure 5c). Finally, a 5mm thick

184 layer of mortar was laid on top (Figure 5d). In order to reproduce the condition that an SRG reinforcement
185 would experience in field applications, specimens were not provided with an initial interfacial notch
186 (distance between the loaded end of the bonded area and the edge of the substrate block). Specimens were
187 kept wet (R.H.>95%) for 15 days and then stored, for at least other 25 days, in the laboratory before testing.
188 In order not to compromise the possible repeatability of these tests, and given the large variability of
189 temperature and humidity at a construction site, no attempt was made to reproduce the curing conditions that
190 a reinforcement would experience in field applications.

191 Tests were carried out using a Material Testing Systems (MTS) load frame (Figure 6). Load was applied by a
192 500kN hydraulic actuator under displacement control at 0.003mm/s rate, and recorded by a load cell
193 integrated in the testing machine. It was then distributed between the two sides of the specimen (i.e., between
194 the two SRG strips), proportionally to the strain recorded by the strain gauges. One LVDT and one
195 potentiometer were fixed with threaded bars on each side of the specimen, where SRG reinforcements were
196 applied. In addition, two potentiometers were also placed on the front and back faces, which measured over a
197 longer gage length (distance between the points where the device is fixed to the specimen). Data were
198 acquired at 10Hz sampling frequency in LabView environment.

199 LVDTs and potentiometers provided the relative displacement between the upper and lower prisms of the
200 specimen. Such displacement was the sum of three contributions; the slip between SRG and upper prism, the
201 slip between SRG and lower prism, and the opening of the cracks in the central joint. With LVDTs and
202 potentiometers, no information could be derived on each of these contributions taken individually. In order to
203 measure the slip between SRG and substrate in each portion of the specimen (upper/lower), two dimensional
204 Digital Image Correlation (2D-DIC) was used. DIC is a full-field contactless optical method based on the
205 correlation of the digital images taken during test execution that provides the displacement and strain fields
206 of the specimen surface [34]. To apply DIC, a speckle pattern made of randomly distributed black dots on a
207 white background was realized by means of spray painting (see [35,36] for details about specimen
208 preparation). During test execution, photographs were taken at 10s time interval, with two Nikon D610
209 digital cameras (one per side) positioned on stiff frames at 1.20m from the specimen, taking care of ensuring
210 correct alignment to minimize image distortions. Two LED spotlights per side were used to keep stable and

even illumination. Pictures had 6016×4016 pixels, which corresponds to a pixel size of 0.11mm. In the post-processing, a biquintic B-splines sub-pixel interpolation scheme on the displacement field led to a resolution in the order of 0.01mm [34,36]. The correlation analysis was limited to the central portion of the digital images, called Region of Interest (ROI), in which the full focus was ensured. The accuracy (i.e., correlation error between two consecutive pictures taken before the beginning of the test with no load applied) ranged between 0.023mm and 0.034mm, in the central and in the lateral zones of the ROI, respectively. Such difference is due to the optical distortion of the image in the zones at a larger distance from its centre [37]. In this case, the accuracy provide by DIC was considered satisfactory and no specific analyses were carried out to correct errors related to radial lens distortion.

Pictures were analysed to derive the relative displacement between reinforcement and substrate (slip) for the upper and lower portions, and for the left and right sides of the specimen. Therefore, in total, four slip values were calculated at each time instant (i.e., every 10s). Clearly, the two slip values (upper and lower) measured on one side were associated to the same load. To calculate each of these slip values, two points were selected, one on the reinforcement and one on the substrate (Figure 7), across the first crack starting from the loading plate, and their relative vertical displacement was measured. Since the crack pattern changed from test to test, the exact location of the measurement points was established after the end of the test based on the crack pattern, taking advantage of the possibility offered by DIC to select the measurement points in the post-processing phase. Concerning the measurement of the slip by DIC, the following remarks should be considered. First, DIC recorded only the outer surface of the specimen, while no information was provided on the steel cords embedded in the mortar matrix, because they were not visible. Therefore, in order to prevent the results from being affected by possible matrix-to-textile sliding, the measurement points on the SRG strip were chosen at a distance of at least 20mm from the cracks, which is a reasonable distance beyond which the displacement of the outer layer of mortar is expected to match that of the steel cords [35]. Second, being the measurement points very close to each other, the elastic elongation of the unbonded textile between them is negligible, so their relative displacement corresponds to the slip at the loaded end of the bonded area. Finally, to improve the reliability of the correlation, DIC does not correlated just two points (i.e., two pixels), but two circular subsets of pixels, centred at each point and having, in this case, 30 pixel radius. It should be

also noted that 2D-DIC shouldn't be applied to specimens with curved surface, because not all the points of the ROI are at the same distance from the digital camera (3D-DIC should instead be used to measure the strain field in a more reliable way). In this case, DIC was mainly used to measure the relative displacements of points that are in the middle of the specimen and close to each other, such that the reliability of slip data is not affected by surface curvature and, as said before, by aberration. On the other hand, the displacement fields provided over the entire specimen surface were not considered fully reliable and were used only to derive qualitative information, such as number, location and approximate spacing of cracks, which were detected by DIC even before they became visible to the naked eye.

Displacements provided by LVDTs and potentiometers used only to validate DIC measurements but they were not considered particularly useful to describe the SRG-to-substrate bond behaviour. Test results presented hereafter are therefore based on DIC measurements.



Figure 5. Manufacturing of the specimens: preparation of the surface of the brickwork substrate and positioning of the polyethylene frameworks (a), laying of the first layer of mortar matrix (b), installation of the steel textile (c) and laying of the top layer of mortar (d).

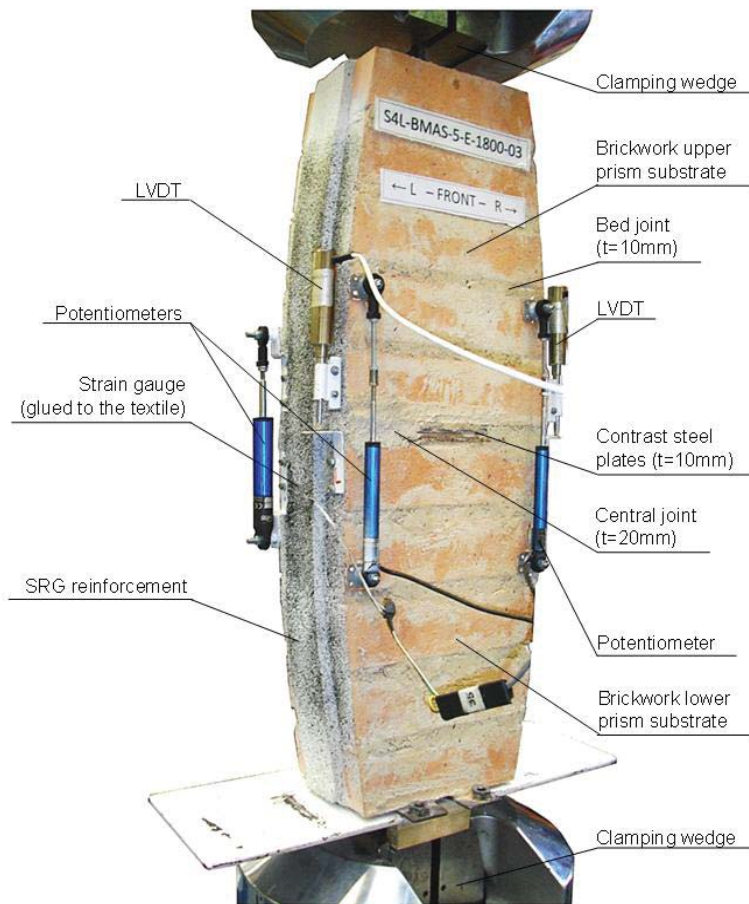


Figure 6. Experimental setup for laboratory tests.

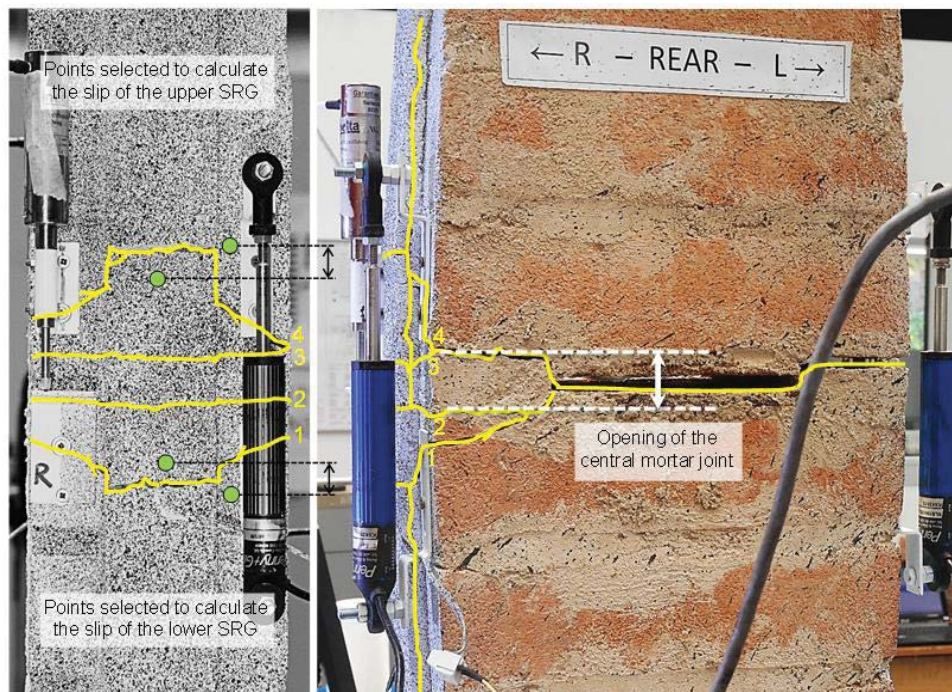


Figure 7. Identification of the cracks developed in the central portion of the specimen and selection of the points for calculating the slip with DIC.

3.2. Test results

The load-slip response curves of the shear bond tests carried out in the laboratory are shown in Figures 8 and 9. The slip (on the x-axis of the plots) was calculated for each bonded area with the Digital Image Correlation, while the load per unit width in the reinforcement (on the y-axis) was derived for each side as the load divided by the width of the steel textile (50.8mm). The specimens of Figure 8 have bond length $L_b=320\text{mm}$ and are collected by curvature radius of the substrate (R), namely R infinite (Figures 8a,b), $R=5000\text{mm}$ (Figures 8c,d), $R=2650\text{mm}$ (Figures 8e,f), and $R=1800\text{mm}$ (Figures 8g,h). For each specimen, four response curves were derived, one per each bonded area. Those referred to the lower prism are shown in plots a,c,e,g (with negative slip values), while those related to the upper prism are in plots b,d,f,h (positive slip). In each plot, there are three curves related to the left side (dotted line) and three curves related to the right side (solid line). Clearly, for each specimen and for each side (left/right) the load on the upper prism is equal to that of the lower prism. Finally, for each specimen, a round marker indicates where, among the four bonded areas, failure occurred. The specimens of Figure 9 have $R=1800\text{mm}$ and are gathered on the base of the bond length ($L_b=450\text{mm}$ in plots a,b,e,f and $L_b=580\text{mm}$ in plots c,d,g,h) and the type of steel textile (S4 in plots a-d and S12 in plots e-h).

All the specimens exhibited an initial uncracked behaviour, associated to a stiff response (Figures 8-9). The slip increased at the occurrence of a horizontal crack at the central mortar bed joint (between the two prisms, Figure 10a). A longitudinal crack, visible from the side of the mortar layer (Figure 10b) also appeared at the textile-to-matrix interface. Then, horizontal cracks developed, crossing the entire thickness of the SRG in correspondence with the bed joints of the masonry (Figure 10c), together with the propagation of the longitudinal crack. The occurrence of cracks was associated to load drops in the response curves (Figures 8-9). Despite the behaviour was never symmetric between the two portions (upper/lower) of the reinforcement, comparable slip values were generally measured. In some cases, however, the slip concentrated on one prism while remaining very small on the other one, which may be due to local imperfections or small detachments on the surface of one prism since the beginning of the test (promoting slip concentration) or grooves (improving adhesion and avoiding slip development). The difference between the slip values recorded on the

two sides of the specimen (sum of upper and lower ones) ranged between 2% and 154%. It may have been caused by a misalignment of the specimen and may have induced a bending effect, but, at this stage of knowledge, it is difficult to assess its influence on test results. Finally, in some cases (e.g., specimen #1 in Figures 8c,e) there is an initial increase and decrease of slip, which may be due to errors or noise in the displacement measurement provided by DIC.

Specimens with $R=1800\text{mm}$ and $R=2650\text{mm}$ exhibited less cracks than those with R infinite and $R=5000\text{mm}$, as revealed by the smaller number of load drops in the response curves (Figure 8) and by the fields of vertical displacements measured with the Digital Image Correlation, in which cracks are clearly identifiable by the jumps of displacement (Figure 11). In specimens with higher curvature, the slip concentrated in one crack near the loaded end of the bonded area, and was associated to the sliding of the textile within the matrix along the entire reinforcement (Figure 11d).

Failure always occurred by detachment at the textile-to-matrix interface (Figures 10e), with a sudden expulsion of the outer layer of mortar matrix in specimens with higher curvature ($R=1800\text{mm}$) and shorter bond length ($L_b=320\text{mm}$, Figure 10f). In 20/22 cases, failure occurred on the more loaded side, while in the other 2/22 cases detachment took place where the load was lower. It should be considered that the two sides could never be identical, such that, in these two cases, the weaker reinforcement, despite subjected to a lower load, may have failed before the stronger (and more loaded) one.

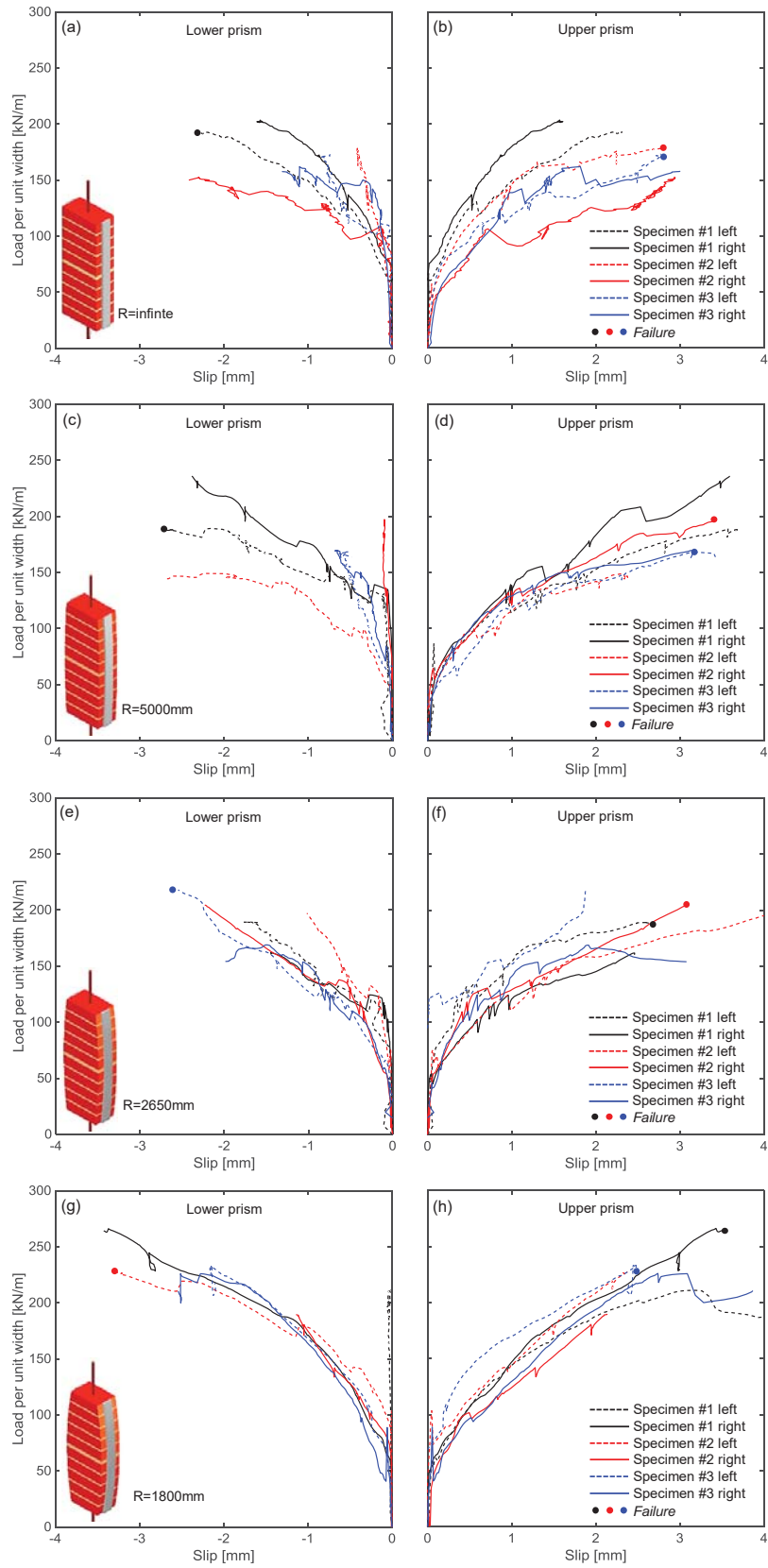


Figure 8. Load slip response curves for specimens with S4 textile, $L_b=320\text{mm}$, and curvature radius $R=\infty$ (plane surface, a,b), $R=5000\text{mm}$ (c,d), $R=2650\text{mm}$ (e,f), and $R=1800\text{mm}$ (g,h).

Table 1. Results of shear bond tests on specimens with S4 textile. F: failure.

R [mm]	L _b [mm]	Specimen	Right side			Left side			Stress at failure and exploitation ratio	
			F _{max} [kN/m]	s _L [mm]	s _U [mm]	F _{max} [kN/m]	s _L [mm]	s _U [mm]	σ _{max} [N/mm ²]	η [%]
Infinite	320	1	203.5	-1.57	1.59	193.3	-2.26 ^F	2.20	2301.2	71
		2	152.3	-2.29	2.93	178.9	-0.41	2.81 ^F	2129.8	66
		3	161.9	-1.10	1.81	173.1	-0.74	2.77 ^F	2060.7	64
5000	320	1	235.9	-2.38	3.59	189.3	-2.16 ^F	3.57	2253.6	69
		2	197.7	-0.10	3.28 ^F	149.2	-2.24	2.33	2353.6	73
		3	169.6	-0.65	3.13 ^F	168.5	-0.52	3.17	2019.0	62
2650	320	1	161.9	-1.45	2.46	189.2	-1.77	2.82 ^F	2252.4	69
		2	204.3	-2.22	3.06 ^F	197.2	-1.01	4.12	2432.1	75
		3	168.9	-1.49	1.90	217.9	-2.75 ^F	1.88	2594.0	80
1800	320	1	266.2	-3.37	3.43 ^F	212.9	-0.01	3.18	3169.0	98
		2	189.5	-1.14	2.14	227.3	-3.28 ^F	2.38	2706.0	83
		3	226.0	-2.28	2.74	233.4	-2.15	2.48 ^F	2778.6	86
	450	1	242.5	-5.90	5.41 ^F	220.5	-5.36	4.92	2886.9	89
		2	190.5	-4.28	3.02	240.8	-5.46 ^F	3.14	2866.7	88
		3	259.0	-4.65 ^F	5.46	226.1	-2.43	2.17	3083.3	95
	580	1	195.4	-0.83	2.64	265.3	-4.18 ^F	5.97	3158.6	97
		2	245.0	-1.20	6.49 ^F	189.3	-2.06	0.96	2916.7	90
		3	204.9	-2.54	1.79	254.8	-6.79 ^F	0.56	3033.3	94

305

306

Table 2. Results of shear bond tests on specimens with S12 textile. F: failure.

R [mm]	L _b [mm]	Specimen	Right side			Left side			Stress at failure and exploitation ratio	
			F _{max} [kN/m]	s _L [mm]	s _U [mm]	F _{max} [kN/m]	s _L [mm]	s _U [mm]	σ _{max} [N/mm ²]	η [%]
1800	450	1	158.8	-1.18	1.19	182.9	-0.93	1.09 ^F	720.1	25
		2	141.2	-0.47	0.84	157.5	-0.83 ^F	0.38	620.1	22
	580	1	173.3	-1.39	1.56	201.8	-1.55 ^F	1.11	794.5	28
		2	189.9	-1.54	0.94 ^F	157.2	-0.85	0.91	747.6	26

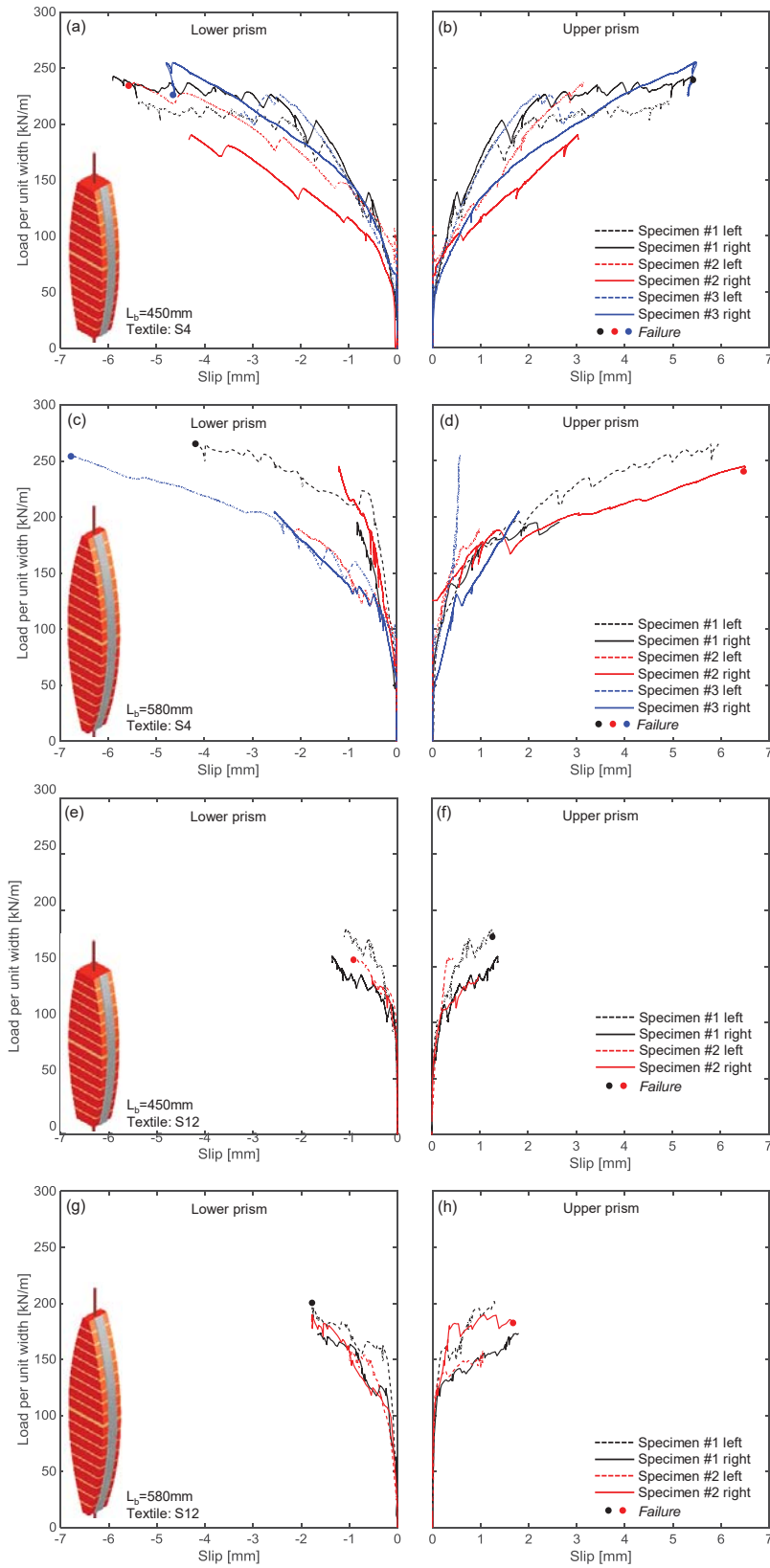


Figure 9. Load slip response curves for specimens with S4 (a,b,c,d) and S12 (e,f,g,h) textiles, $L_b=450\text{mm}$ (a,b,e,f) and $L_b=580\text{mm}$ (c,d,g,h) and curvature radius 1800mm.



Figure 10. Progressive damage development during laboratory shear bond tests: initial horizontal crack in the central bed joint (a), longitudinal crack at the textile-to-matrix interface (b), transversal cracks of the mortar matrix (c), sliding of the steel cords (d), failure mode by detachment at the textile-to-matrix interface (e), with expulsion of the top layer of matrix in specimens with $R=1800\text{mm}$ (f).

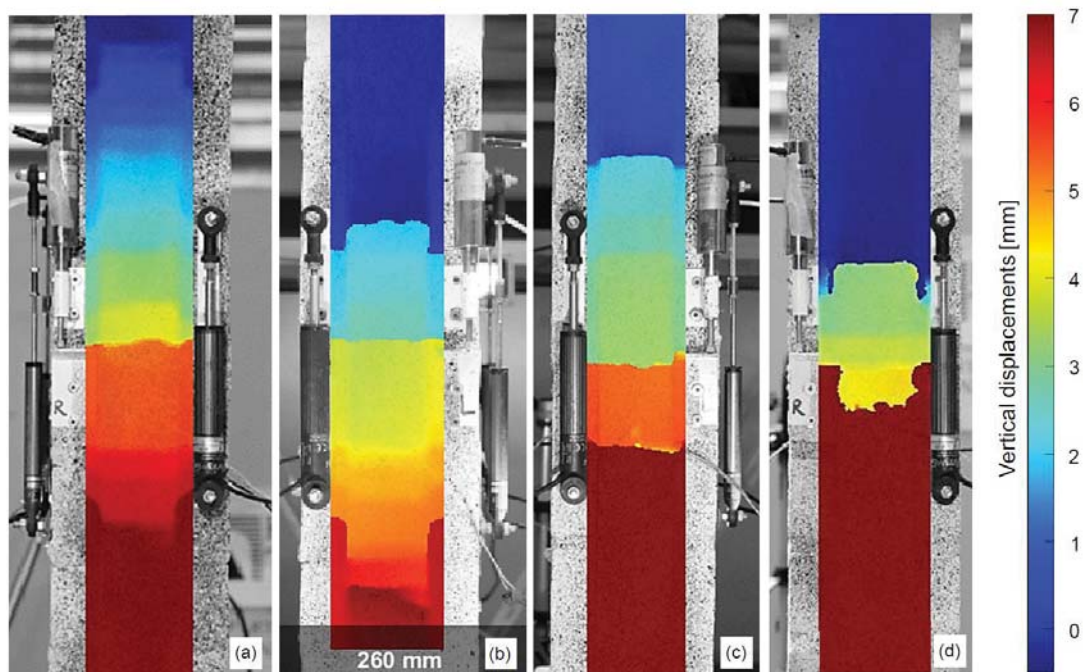


Figure 11. Field of vertical displacements recorded with the Digital Image Correlation on specimens with R infinite (plane surface, a), $R=5000\text{mm}$ (b), $R=2650\text{mm}$ (c), and $R=1800\text{mm}$ (d).

In the specimens with S4 textile and $L_b=320\text{mm}$, the maximum load attained at the bonded areas where failure occurred (F_{\max}) increased with the increase of curvature, ranging, on average, from 181.8kN/m (R infinite) to 242.3kN/m ($R=1800\text{mm}$), as shown in Figure 12a and reported in Table 1. Such gain in strength was due to the compressive normal stresses arising at the textile-to-matrix interface, associated to the tensile loading experienced by the reinforcement, as an effect of the convex curvature of the substrate. These normal stresses, in their turn, improved the cord-to-mortar bond and resulted in a friction contribution mobilized after the cords started sliding within the matrix. The effect of curvature was clearly identified for $R=1800\text{mm}$ and for $R=2650\text{mm}$, while no significant difference was found between R infinite and $R=5000\text{mm}$ (it should be considered that test results have a certain scatter and that only three specimens were tested for each configuration). The stress in the textile at failure (σ_{\max}) ranged between 2163N/mm^2 and 2884N/mm^2 and the exploitation ratios ($\eta=\sigma_{\max}/f_t$) between 67% and 89%. The gain in bond strength was also associated to an increase of the peak slip (s), i.e., the slip associated to F_{\max} , even if, in this case, the scatter is larger and the trend is weaker (Figure 12c).

The contribution of friction towards bond strength was investigated for different values of bond length, such as $L_b=450\text{mm}$ and $L_b=580\text{mm}$, by testing specimens with $R=1800\text{mm}$ (Figures 9a-d, Table 1). The maximum load increased from 242.3kN/m ($\sigma_{\max}=2884\text{N/mm}^2$, $\eta=89\%$) for $L_b=320\text{mm}$ to 247.4kN/m ($\sigma_{\max}=2946\text{N/mm}^2$, $\eta=91\%$) for $L_b=450\text{mm}$, and to 255kN/m ($\sigma_{\max}=3036\text{N/mm}^2$, $\eta=94\%$) for $L_b=580\text{mm}$ (Figures 9a-d and 12b). This trend is however quite weak, because the loads are very close to the tensile strength of the textile, which is clearly a threshold that cannot be crossed, and because test data are scattered, which is due to the difficulty of ensuring a proper alignment of the two brickwork prisms for long specimens. It is worth noting that, in the laboratory tests carried out in this research, the bond length did not affect friction as much as curvature, so other investigations would be needed with longer bond lengths to develop a deeper understanding of this issue and the field tests described in the following section of the paper aim at providing a first contribution. Finally, the increase of bond length entailed a longer portion of SRG subjected to elongation, resulting in higher values of the peak slip values, which grew from 3.06mm to 5.82mm (Figures 9a-d and 12d).

Since the exploitation ratios achieved in these tests were very close to 100%, it was decided to manufacture four specimens with $R=1800\text{mm}$, two with $L_b=450\text{mm}$ and two with $L_b=580\text{mm}$, using the steel textile with smaller cord spacing (S12). Despite the higher tensile strength, the denser textile had a weaker cord-to-mortar interlocking, reducing, with respect to S4, both the maximum load per unit width ($F_{\max}=170\text{--}196\text{kN/m}$, Figures 9e-f and 12b, Table 2) and the efficiency of the system ($\eta=23\text{--}27\%$). Failure occurred at the textile-to-mortar interface. The peak slip was smaller (between 0.83mm and 1.55mm) than that measured with S4 textile (Figures 9e-f and 12b, Table 2).

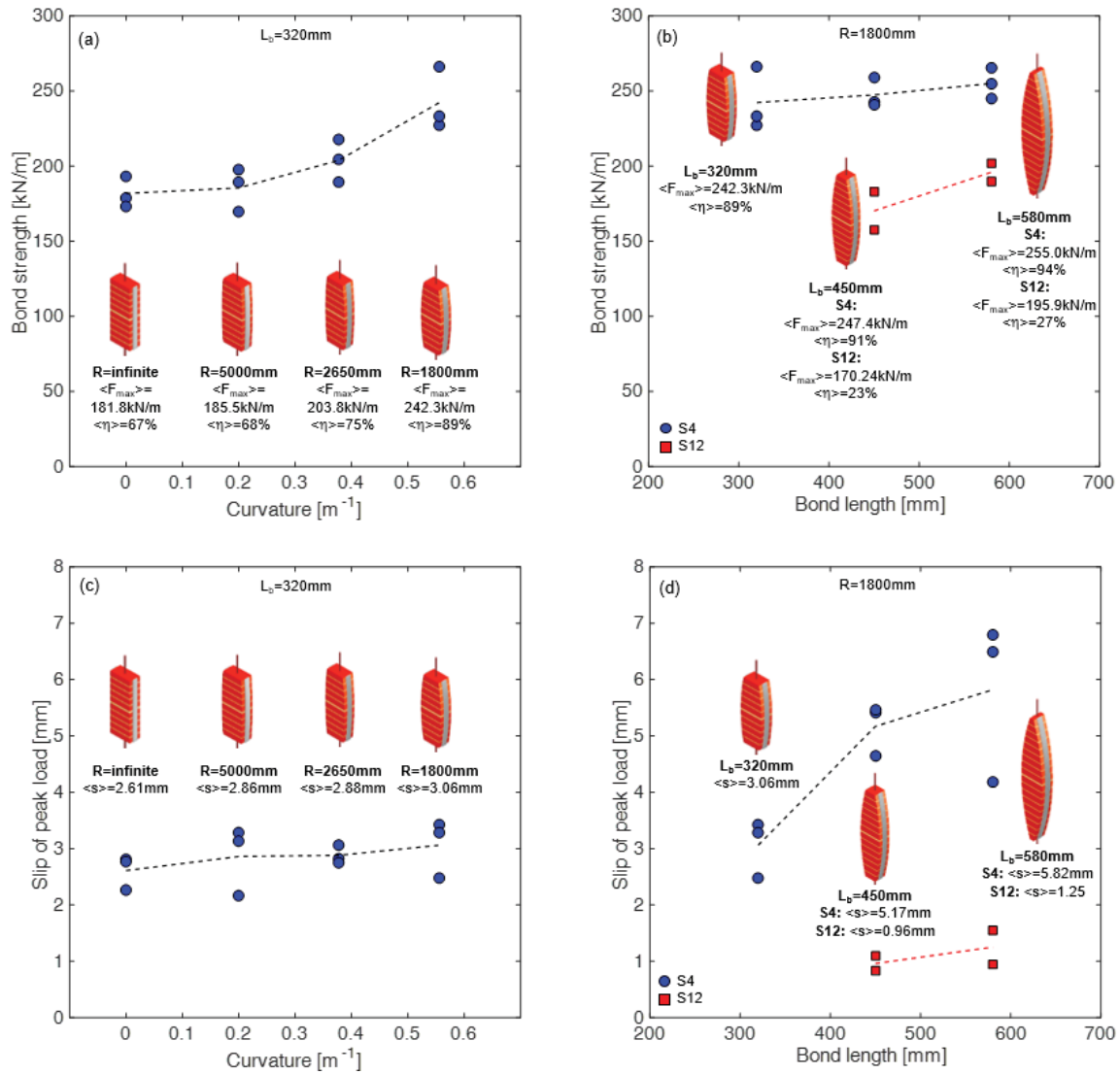


Figure 12. Bond strength (a,b) and peak slip (c,d) vs curvature (a,c) and bond length (b,d) for specimens with S4 textile and $L_b=320\text{mm}$ (a,c) and for specimens with S4 and S12 textile and $R=1800\text{mm}$ (b,d).

354 4. FIELD TESTS

355 4.1. Experimental setup

356 In-situ tests were performed on the bond behaviour of SRG applied to the extrados of a masonry vault. Tests
357 were carried out in an historic building in the city centre of L'Aquila, Italy, dating back to the XVIII
358 Century. The building was badly damaged by a strong earthquake in 2009, after which important
359 reconstruction and retrofitting works were undertaken that included the extrados reinforcement of the vaults
360 with SRG. The vault on which tests were performed has 4.64m span, 1.43m rise and 120mm thickness (one
361 brick head), it is built with clay bricks and has the profile of a three-centred arch, its curvature radius ranging
362 from about 1500mm (near the abutments) to 4500mm (in crown).

363 The experimental setup (Figure 13) aimed at reproducing a loading condition similar to the one that the SRG
364 reinforcement would experience if a crack developed at the extrados of the vault, due to the activation of a
365 collapse mechanism characterized by the development of alternate (intrados/extrados) hinges. The actual
366 stress state induced in the reinforcement may be, in fact, more complex due to the presence in the vault of a
367 wider crack pattern and of a combination of bending and shear stresses.

368 The steel textile with 12 cord/inch density (S12, Figure 2c) was applied to the extrados of the vault in one
369 direction (no orthogonal strips were installed). The strips had 150mm width and were bonded with the same
370 lime-based mortar used for the aforementioned laboratory tests. Before installation, the extrados of the vault
371 was slightly bush hammered, cleaned from dust and wet with water. The textile was bonded to half of the
372 vault for a length of 2.50m and connected to the side wall with an SRG connector, which was inserted in
373 inclined drilled holes and then injected with fluid grout. In correspondence with the crown of the vault, a
374 1.20m long portion of textile was left unbonded (and free of mortar) and subjected to a tensile load in the
375 direction tangent to the vault (Figure 13). To this purpose, the cords were clamped with two
376 250mm×60mm×5mm steel plates (Figure 14a), bolted with sufficient gripping pressure to avoid the slipping
377 of the textile during test execution. A Ø16 threaded steel bar, welded to the lower plate, was passed through
378 a hollow hydraulic actuator, and bolted to an end plate (Figure 14b). The actuator contrasted with two steel
379 IPE 240 girders anchored to the side walls (Figure 13a). The load was progressively increased under force

control up to the detachment of the SRG strip from the substrate, but before reaching pull-out failure of the end connector.

Clearly, the curing conditions at the construction site differed from those that can be ensured in the laboratory, as both temperature and humidity could not be controlled (apart from wetting with water) and may vary in a wider range during mortar hardening. With this in mind, field tests aimed at investigating if this could affect the SRG-to-substrate bond behaviour.

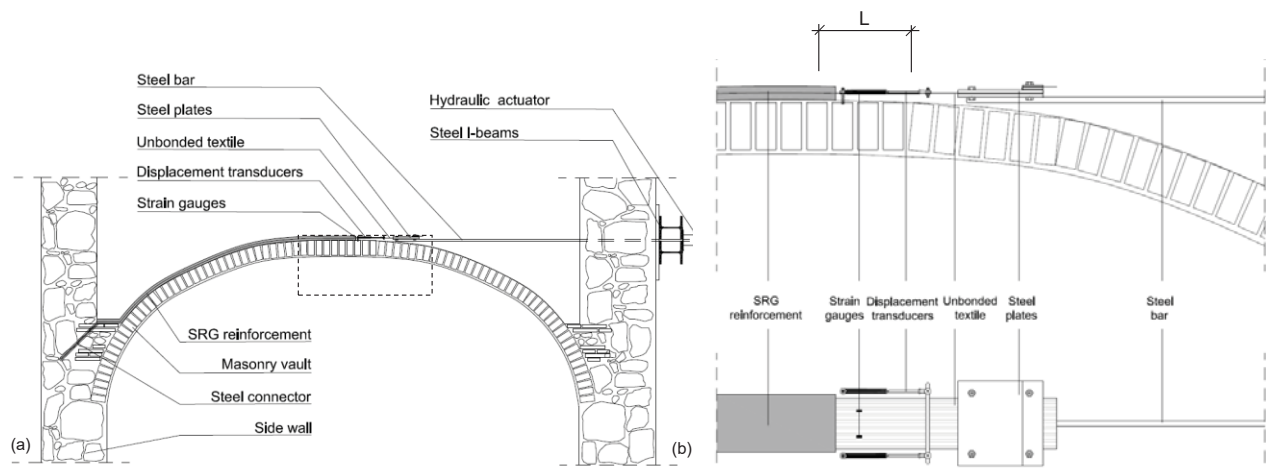


Figure 13. General view (a) and detail near the loaded (b) of the experimental setup for field tests.

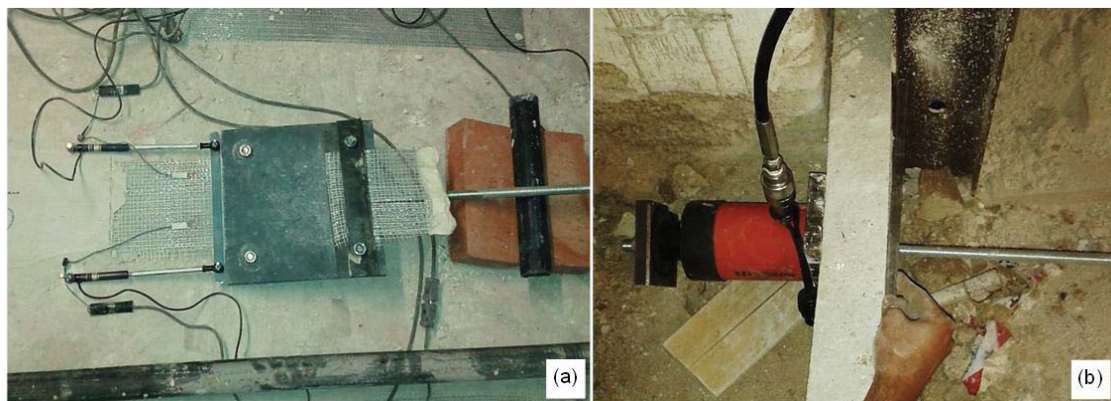


Figure 14. Details of the experimental setup for field tests: clamping of the textile (a) and hydraulic actuator (b).

The oil pressure in the actuator was provided by a hydraulic pump and measured by a manostat. The recorded pressure values were used to estimate the applied load. Two 10mm resistive gauges were also glued to the unbonded textile to record the strain (ϵ) and validate load data. The corresponding load per unit width and stress (conventionally referred to the cross section area of the dry textile) were then calculated. The relative displacement between SRG and substrate was measured by two linear potentiometers, fixed, on one

side, to the textile with metal plates (glued to the steel cords) and, on the other side, to the masonry with threaded bars (inserted in holes drilled into the vault and filled with epoxy resin). The slip (s) was calculated as $s=D-(\epsilon \times L)$, D being the average displacement recorded by the two transducers, and L being the distance between the loaded end of the SRG bonded area and the section of the textile where transducers were fixed (Figure 13b), to cleanse the measurement from the elastic elongating of the unbonded textile. All data were recorded at 10Hz sampling frequency with a portable acquisition system in LabView working environment. Three tests were carried out two months after the installation on nominally identical SRG strips realized on the same vault and completely independent from each other.

4.2. Test results

The load-slip response of the SRG extrados reinforcements tested in the field is shown in Figure 15. The curves display a good agreement, considering the variability of substrate local conditions and setup, which is unavoidable in field testing. The response was characterized by three stages with progressively reducing stiffness. The first stage was associated to the un-cracked behaviour of the reinforcement. The measured displacements were extremely small (i.e., negligible) and were related to elastic deformations and small settings. The second stage was related to the crack development in the matrix and the activation of the detachment of the reinforcement. The transition from the first phase to the second phase can be identified by the occurrence of the first crack and the increase of the slip. The load associated to this transition ranged between 40kN and 120kN/m. The large variability depends on the irregularities of the substrate and of those related to the test setup including possible misalignment of the loading system with the tangent to the vault at the crown, as well as potential lack of uniformly applied load along the textile width. Transversal cracks on the upper side of the SRG strip (Figure 16a) and longitudinal cracks on its side (Figure 16b) developed, starting from the loaded end of the reinforcement (i.e., its first bonded section). The crack pattern was influenced by the local properties of the substrate, such as depressions, imperfections, and small pre-existing cracks. Up to the end of Stage II, which could be identified at a load level of about 200-250kN/m, the bond behaviour of the SRG reinforcements applied to the vault was similar to that observed in laboratory tests on small-scale specimens, despite the different setups and specific properties of the substrate. Finally, in Stage

421 III, the debonding mechanism was activated at the textile-to-matrix interface and progressively moved from
422 the crown to the abutment (Figure 16c). As in the laboratory, at the end of the test, the entire outer layer of
423 the matrix, from the loaded end of the SRG strip to the connector, was spalled (Figure 16d). No cracks in the
424 masonry wall or slippage of the steel connectors were detected (Figure 16c).

425 In field tests, the combination of the two resisting mechanisms related to adhesion and friction was more
426 evident than in the laboratory. The resisting mechanism related to adhesion was initially activated over a
427 fully bonded portion of SRG near the loaded end. As debonding took place, the portion of the SRG resisting
428 by adhesion shifted, moving away from the loaded end. The friction contribution was mainly mobilized on
429 the detached portion of the reinforcement, as a result of the curvature of the vault, inducing normal
430 compressive stresses at the reinforcement-to-substrate interface. In Stage III, the component related to
431 friction displayed a linear increasing trend with the slip, and, since it was activated on the portion of SRG
432 that had already detached from the vault substrate, which was very long, significantly contributed to the
433 overall strength. It is worth noting that this could not be found in laboratory tests due to the smaller scale of
434 tested specimens, and that in field tests a minimum bonded length was always ensured by the presence of the
435 end connectors. As a result, the maximum load per unit width (F_{\max}) was, on average, 394kN/m
436 corresponding to a stress in the textile (σ_{\max}) of 1551N/mm². This latter was 53.5% of its tensile strength, as
437 reported in Table 3, in which η is the exploitation ratio of the tensile strength of the textile, and ε and s are
438 the strain in the textile and the slip at peak load, respectively. The presence of the end connectors, whose
439 contribution was not mobilized in the tests, could lead to an even higher strength.

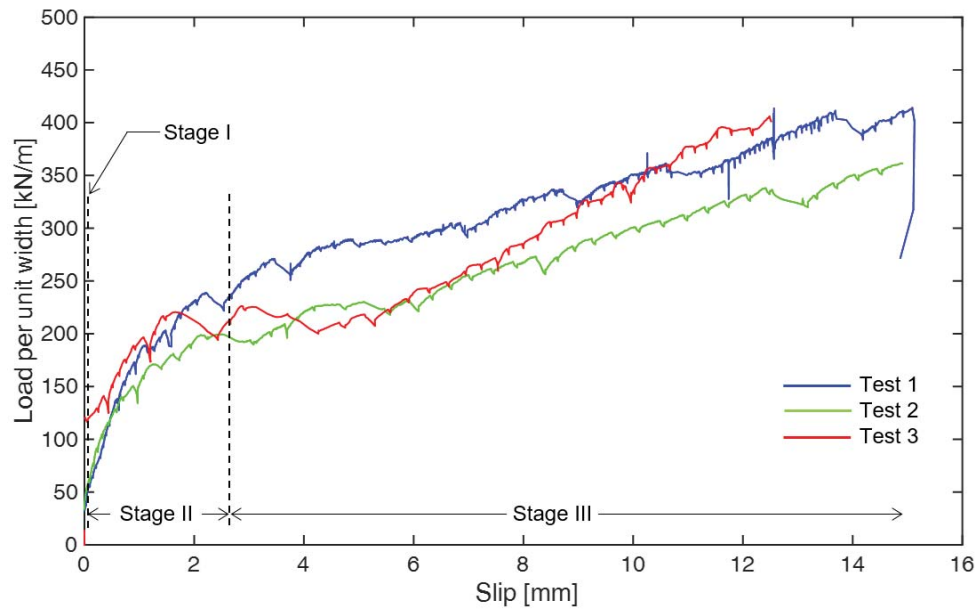


Figure 15. Load-slip response curves of field bond tests.

Table 3. Results of field tests.

Test	F_{\max} [kN/m]	σ_{\max} [N/mm ²]	η [%]	ε [10 ⁻³]	s [mm]
1	414.3	1631.2	56	5.63	15.1
2	361.6	1423.6	49	4.65	14.9
3	406.1	1598.9	55	4.91	12.5
Mean	394.0	1551.2	53	5.06	14.1



Figure 16. Progressive development of the crack pattern during field bond tests (for increasing applied load): first arched crack near the loaded end (a), cracks at the SRG-to-substrate interface developing on the side on the reinforcement strip (b), debonding of the entire SRG strip (c), and disintegration of the mortar matrix (d).

5. CONCLUSIONS

Laboratory and field tests provided experimental evidence of the bond behaviour of Steel Reinforced Grout (SRG) systems, comprising Ultra high Tensile Strength Steel (UHTSS) cords and lime-based mortar, applied to masonry substrates with a convex surface. The bond strength (F_{\max}) attained by SRG systems with a steel textile with 6.35mm cord spacing increased with the increase of both substrate curvature and bond length. In particular, F_{\max} ranged from 182kN/m on plane substrates to 242kN/m on convex surfaces with curvature radius $R=1800\text{mm}$ (both with bond length $L_b=320\text{mm}$), and reached 255kN/m for $L_b=580\text{mm}$ and $R=1800\text{mm}$. These loads correspond to values of stress in the textile (σ_{\max}) of 2164N/mm^2 , 2884N/mm^2 , and 3036N/mm^2 , and to exploitation ratios of the tensile strength of the textile (η) of 67%, 89%, and 94%. The

gain in strength, associated to an increase of the peak slip, is related to the compressive normal stresses arising at the textile-to-matrix interface, as an effect of the convex curvature of the substrate, which improve the cord-to-mortar bond and activates a friction resisting mechanism. The higher the curvature, the higher the compressive stress; the longer the bond length, the larger the area where the friction resisting mechanism is activated.

The use of a steel textile with smaller cord spacing (2.12mm) resulted in lower bond strength ($F_{\max}=170\text{kN/m}$ for $L_b=450\text{mm}$ and $F_{\max}=196\text{kN/m}$ for $L_b=580\text{mm}$, both with $R=1800\text{mm}$), exploitation ratios (23-27%) and peak slip (0.96-1.25mm). The smaller space between the cords impeded the proper protrusion of the mortar matrix which reduced cord-to-mortar interlocking, resulting in a lower efficiency of the reinforcement.

Full-scale field tests, carried out with the textile with 2.12mm cord spacing, provided further information on the effect of substrate curvature and bond length on the bond behaviour of SRG, taking into account the actual substrate preparation and mortar curing conditions at a construction site. The maximum load was $F_{\max}=394\text{kN/m}$, corresponding to $\sigma_{\max}=1551\text{N/mm}^2$ and $\eta=53\%$. The presence of the end connectors, whose contribution was not mobilized in the tests, could lead to an even higher strength. Three response stages were identified, associated to the un-cracked behaviour of SRG reinforcement (with negligible slip), crack development and debonding initiation, and progressive detachment along the bonded area with a significant contribution provided by the friction arising along the detached textile, thanks to the convex curvature of the substrate. In field tests, despite the less controlled installation and curing conditions, the SRG-to-substrate bond efficiency was higher than that detected in the laboratory (given the same cord spacing and curvature radius). The wider, and especially longer, bonded area increased the friction contribution and reduced the sensitivity to local imperfections.

In both laboratory and field tests, failure took place at the interface between textile and mortar, and not within the substrate as generally occurs in FRPs. Therefore, the bond behaviour of extrados SRG reinforcements appears independent from the mechanical properties (strength and stiffness) of the masonry substrate. On the one hand, this outcome makes the results of laboratory and field tests comparable, even if they differed in terms of setups (double lap/single lap) and brickwork substrates (properties of the masonry and surface roughness). On the other hand, due to the presence of a friction contribution, the bond strength

depends on the curvature of the vault and on the bond length, making the results of laboratory and field tests carried out in this study complementary.

Nevertheless, at the present state of knowledge, it still appears difficult to identify a relationships that bridges the gap between laboratory small-scale tests and full-scale field tests. This is due both to the limited number of available test results and to the difficulty of ensuring fully comparable conditions in terms of (i) scale (full-scale bond tests on curved brickwork substrates are hardly practicable in the laboratory), (ii) setup (only single-lap tests can be performed in the field, while the double-lap double-prism scheme offers a number of advantages for small scale specimens), (iii) boundary and stress state (the push-pull setup used in the laboratory induces a compression in the substrate, which is not experienced by the vault in the field), and (iv) installation and curing environment (temperature and humidity cannot be controlled in the construction site and are hardly reproducible in the laboratory).

The high performance of SRG reinforcements indicates that they can be installed in strips rather than on the whole surface of the vault, entailing lower costs and ensuring a better vapour permeability. On the other hand, as the employed textile is unidirectional, two orthogonal sets of strips may be needed to retrofit a vault with double curvature. Even if the sensitivity to installation, curing, and local phenomena seems higher in small scale tests, the performance of SRG, as well as that of most mortar-based strengthening systems, relies on the preparation of the surface of the substrate (whose roughness should be ensured), and on the curing conditions of the mortars (substrate and matrix should be kept wet for the first days after installation). The experimental results derived in this study still appears insufficient for a comprehensive understanding of the bond behaviour of SRG applied to convex substrates. A larger number of experimental results would be useful to calibrate numerical models and develop analytical relationships for the design of the extrados reinforcement of masonry arched members with SRG as well as for the assessment of the strengthened vault.

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512 REFERENCES

- 513 [1] Ochsendorf J. Guastavino Vaulting. The Art of Structural Tile. Princeton: Princeton Architectural
514 Press, 2010.
- 515 [2] Castori G, Borri A, Corradi M. Behavior of thin masonry arches repaired using composite materials.
516 Compos Part B-Eng 2016;87:311-321.
- 517 [3] Ramaglia G, Lignola GP, Balsamo A, Prota A, Manfredi G. Seismic strengthening of masonry vaults
518 with abutments using Textile Reinforced Mortar. Journal of Composites for Constructions
519 2016;21(2):04016079.
- 520 [4] Borri A, Casadei P, Castori G, Hammond J. Strengthening of brick masonry arches with externally
521 bonded steel reinforced composites. Journal of Composites for Constructions 2009;13(6):468-475.
- 522 [5] Triantafillou TC, Fardis MN. Strengthening of historic masonry structures with composite materials.
523 Materials and Structures 1997;30(202):486-496.
- 524 [6] Valluzzi MR, Modena C, de Felice G. Current practice and open issues in strengthening historical
525 buildings with composites. Materials and Structures 2014;47(12):1971-1985. DOI: 10.1617/s11527-
526 014-0359-7.
- 527 [7] Huang X, Birman V, Nanni A, Tunis G. Properties and potential for application of steel reinforced
528 polymer and steel reinforced grout composites. Composites Part B: Engineering, 2005;36(1):73-82.
- 529 [8] Papanicolaou CG, Triantafillou TC, Karlos K, Papathanasiou M. Textile reinforced mortar (TRM)
530 versus FRP as strengthening material of URM walls: In-plane cyclic loading. Materials and Structures
531 2007;40(10):1081-1097.

- [9] Ascione L, de Felice G, De Santis S. A qualification method for externally bonded Fibre Reinforced Cementitious Matrix (FRCM) strengthening systems. *Composites Part B: Engineering* 2015;78:497-506. DOI: 10.1016/j.compositesb.2015.03.079.
- [10] De Santis S, Carozzi FG, de Felice G, Poggi C. Test methods for Textile Reinforced Mortar systems. *Composites Part B: Engineering*. DOI: 10.1016/j.compositesb.2017.03.016.
- [11] De Santis S, de Felice G, Napoli A, Realfonzo R. State-of-the-art review on Steel Reinforced Polymer (SRP) systems for the strengthening of existing structures. *Composites Part B: Engineering*, 2016;104:87-110. DOI: 10.1016/j.compositesb.2016.08.025.
- [12] FIB, Fédération internationale du béton. Externally bonded FRP reinforcement for RC structures. *Fib Bulletin No. 14*. Lausanne, Switzerland, 2001.
- [13] American Concrete Institute. ACI 440.2R-08 Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. Farmington Hills, MI, USA, 2008.
- [14] American Concrete Institute. ACI 440.7R-10 Guide for the design and construction of externally bonded Fibre-Reinforced polymer systems for strengthening unreinforced masonry structures. Farmington Hills, MI, USA, 2010.
- [15] CNR, Italian National Research Council. CNR-DT200 R1/2013. Guide for the design and construction of externally bonded FRP systems for strengthening existing structures. Rome, 2013.
- [16] American Concrete Institute. ACI 549.4R-13 Guide to design and construction of externally bonded Fabric-Reinforced Cementitious Matrix (FRCM) systems for repair and strengthening concrete and masonry structures. Farmington Hills, MI, USA, 2013.
- [17] de Felice G, De Santis S, Garmendia L, Ghiassi B, Larrinaga P, Lourenço PB, Oliveira DV, Paolacci F, Papanicolaou CG. Mortar-based systems for externally bonded strengthening of masonry. *Materials and Structures* 2014;47(12):2021-2037. DOI: 10.1617/s11527-014-0360-1.
- [18] Razavizadeh A, Ghiassi B, Oliveira DV. Bond behavior of SRG-strengthened masonry units: Testing and numerical modeling. *Construction and Building Materials* 2014;64:387-397. DOI: 10.1016/j.conbuildmat.2014.04.070

- 558 [19] De Santis S, de Felice G. Steel reinforced grout systems for the strengthening of masonry. *Composite*
559 *Structures* 2015;134:533-548. DOI: 10.1016/j.compstruct.2015.08.094.
- 560 [20] Grande E, Imbimbo M, Sacco E. Investigation on the bond behavior of clay bricks reinforced with
561 SRP and SRG strengthening systems. *Materials and Structures* 2015;48(11):3755-3770.
- 562 [21] Ghiassi B, Oliveira DV, Marques V, Soares E, Maljaee H. Multi-level characterization of steel
563 reinforced mortars for strengthening of masonry structures. *Materials and Design* 2016;110:903-913.
- 564 [22] Bilotta A, Ceroni F, Nigro E, Pecce M. Experimental tests on FRCM strengthening systems for tuff
565 masonry elements (2017) *Construction and Building Materials* 2017;138:114-133.
- 566 [23] De Santis S, Ceroni F, de Felice G, Fagone M, Ghiassi B, Kwiecień A, Lignola GP, Morganti M,
567 Santandrea M, Valluzzi MR, Viskovic A. Round Robin Test on tensile and bond behaviour of Steel
568 Reinforced Grout systems. *Composites Part B: Engineering*. DOI: 10.1016/j.compositesb.2017.03.052.
- 569 [24] Malena M, de Felice G. Debonding of composites on a curved masonry substrate: experimental results
570 and analytical formulation. *Composite Structures* 2014;112:194-206. DOI:
571 10.1016/j.compstruct.2014.02.004.
- 572 [25] Valluzzi MR, Valdemarca M, Modena C. Behaviour of brick masonry vaults strengthened with FRP
573 laminates. *Journal of Composites for Construction* 2001;5(3):163-169. DOI: 10.1061/(ASCE)1090-
574 0268(2001)5:3(163).
- 575 [26] Foraboschi P. Strengthening of masonry arches with fiber-reinforced polymer strips. *Journal of*
576 *Composites for Construction* 2004;8(3):191-202. DOI: 10.1061/(ASCE)1090-0268(2004)8:3(191).
- 577 [27] Borri A, Castori G, Corradi M. Intrados strengthening of brick masonry arches with composite
578 materials. *Composites Part B: Engineering*, 2011;42(5):1164-1172. DOI:
579 10.1016/j.compositesb.2011.03.005.
- 580 [28] Garmendia L, San-José JT, García D, Larrinaga P. Rehabilitation of masonry arches with compatible
581 advanced composite material. *Construction and Building Materials*, 2011;25(12):4374-4385. DOI:
582 10.1016/j.conbuildmat.2011.03.065.

- 583 [29] Girardello P, Pappas A, da Porto F, Valluzzi MR. Experimental testing and numerical modelling of
584 masonry vaults. In: Proceedings of Int. Conf. on Rehabilitation and Restoration of Structures Chennai,
585 India, 2013.
- 586 [30] D'Ambrisi A, Focacci F, Caporale A. Strengthening of masonry-unreinforced concrete railway bridges
587 with PBO-FRCM materials. *Composite Structures* 2013;102:193-204. DOI:
588 10.1016/j.compstruct.2013.03.002.
- 589 [31] Alecci V, Focacci F, Rovero L, Stipo G, De Stefano M. Extrados strengthening of brick masonry
590 arches with PBO-FRCM composites: Experimental and analytical investigations. *Composite*
591 *Structures* 2016;149:184-196. DOI: 10.1016/j.compstruct.2016.04.030.
- 592 [32] De Santis S, de Felice G. Tensile behaviour of mortar-based composites for externally bonded
593 reinforcement systems. *Composites Part B: Engineering* 2015;68:401-413. DOI:
594 10.1016/j.compositesb.2014.09.011.
- 595 [33] de Felice G, Aiello MA, Bellini A, Ceroni F, De Santis S, Garbin E, Leone M, Lignola GP, Malena M,
596 Mazzotti C, Panizza M, Valluzzi MR. Experimental characterization of composite-to-brick masonry
597 shear bond. *Materials and Structures* 2015;49(7):2581-2596. DOI: 10.1617/s11527-015-0669-4.
- 598 [34] Blaber J, Adair B, Antoniou A. Ncorr: Open-Source 2D Digital Image Correlation Matlab Software.
599 *Experimental Mechanics* 2015;55(6):1105-1122.
- 600 [35] Tekieli M, De Santis S, de Felice G, Kwiecień A, Roscini F. Application of Digital Image Correlation
601 to composite reinforcements testing. *Composite Structures* 2017;160:670-688. DOI:
602 10.1016/j.compstruct.2016.10.096.
- 603 [36] Pan B, Qian K, Xie H, Asundi A. Two-dimensional digital image correlation for in-plane displacement
604 and strain measurement: a review. *Measurement Science and Technology* 2009;20(6):062001.
- 605 [37] Pan B, Yu L, Wu D, Tang L. Systematic errors in two-dimensional digital image correlation due to
606 lens distortion. *Optics and Lasers in Engineering*, 2013;51(2):140-147.
- 607