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The influence of the joint thickness on the adhesion between CFRP reinforcements and masonry arches

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Abstract

The effectiveness of Carbon Fiber Reinforced Polymers (CFRP) reinforcements bonded to masonry structures is demonstrated by the several interventions made on existing buildings as well as by the numerous studies presented in the scientific literature. In practical strengthening interventions, CFRP sheets are being used to reinforce both plane and curved structural elements. Contrariwise, research in the scientific literature are mainly devoted to the analysis of the effectiveness of such reinforcements bonded on plane surfaces. For this reason, the experimental program described in this paper concerns the analysis of the mechanical behavior of portion of masonry arches reinforced by CFRP sheets. The experimental results allowed to analyze the effectiveness of such reinforcements applied at intrados or extrados, loaded by actions tangent to an end of the reinforcement itself. The influence of the mortar joints thickness on the performance of such reinforcements has been also analyzed in the experimental program.

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1. Introduction

The use of composite materials to reinforce both plane and curved masonry structures have seen a considerable increase in the recent decades. Several experimental investigations (Valluzzi et al. 2012; Fagone and Ranocchiai 2016; Fagone and Ranocchiai 2017) demonstrated the effectiveness of externally bonded (EB) fiber-reinforced systems, like Carbon Fibers Composite Polymers (CFRP) sheets, as structural strengthening systems. The interest of the technical and scientific communities on the use of these materials in the structural field is justified by the excellent mechanical performance of CFRP reinforcements, combined with lightness and simplicity of application. CFRP sheets can be effectively used to improve the structural behavior of different masonry structural elements. In particular, CFRP sheets properly bonded at the intrados or extrados of masonry arches, in the zones subjected to tensile stresses, can drastically modify the structural behavior, increasing the load bearing capacity. This occurs thanks to the reinforcement-substrate adhesion, which plays a crucial role in the effectiveness of the reinforcements, as extensively analysed in the literature with reference to CFRP reinforcements bonded to plane masonry structural elements and loaded by actions parallel to the plane of the CFRP sheet. In that case, failure generally occurs in the substrate, a few millimeters below the bonding surface. The load is transferred to the substrate mainly through shear stresses, mostly concentrated in a limited portion of the reinforcement whose length is called “effective bond length”. This represents a limit length: longer bond lengths do not lead significant increases of the peak load. Such reinforcements generally exhibit brittle failure modes, occurring at a load level lower than the load bearing capacity of the carbon fiber fabric. Several systems have been proposed in the literature to prevent such brittle behaviour. Among these, spike anchors demonstrated to be able to increase both the load bearing capacity and the ductility of the reinforcement (Caggegi et al. 2014; Fagone et al. 2014; Fagone et al. 2015; Ceroni 2017; Briccoli Bati et al. 2015).

Moreover, the load bearing capacity of CFRP reinforcements, as well as their structural behavior, is expected to be influenced by the geometry of the bonding surface that can be plane, as in the case of the strengthening of masonry walls, or curved (concave or convex) as in the case of masonry arches reinforced at the intrados or at the extrados. Despite the great interest of the technical and scientific community on the use of CFRP sheets as reinforcement of masonry arches or vaults (Fagone et al. 2016; Briccoli Bati et al. 2013; Cancelliere et al. 2010; Briccoli Bati and Fagone 2007; Pintucchi and Zani 2016; Foraboschi 2004), only a few research activities presented in the literature refers to the analysis of the sheet-substrate adhesion behavior in the case reinforcements bonded to curved surfaces (Basilio et al. 2014; Fagone et al. 2017; Grande and Milani 2016). The experimental program described in this paper represents a contribution in this field. In particular, it concerns specimens representing a portion of masonry arch, reinforced either at the intrados or at the extrados, loaded by actions tangent to an end of the reinforcement itself according to the so called Near End Supported Single Shear Test.

The experimental results highlighted the influence of the curvature and of the mortar joints thickness on the effectiveness of CFRP reinforcement sheets.

The paper layout is the following: the experimental program is described in the next paragraph; the mechanical properties of the materials used and the procedure followed to manufacture the specimens are described in section 3 and 4 respectively; the test setup and test procedure are described in section 5; results of the experimental campaign are reported in section 6 and final remarks conclude the paper.

2. Overall description of the experimental program

The experimental program described in this paper is aimed at analyzing the effect of both the curvature of the bonding surface and the mortar joint thickness on the mechanical behavior of CFRP sheet reinforcements applied to masonry specimens. In particular, masonry specimens, representative of portion of masonry arches having different mortar joint thickness, have been reinforced at the intrados or extrados and tested using the Single Lap Shear Tests (Rotunno et al. 2015; Valluzzi et al. 2012) scheme, as shown in Figure 1.

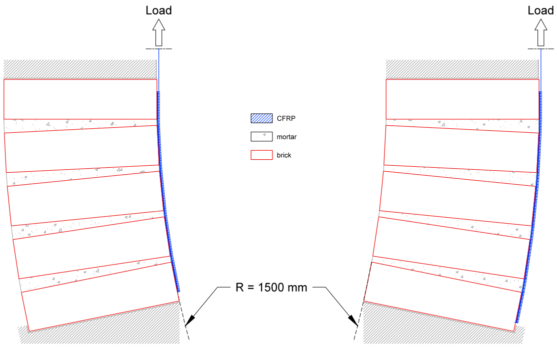


Figure 1: Test scheme

3. Material properties

The materials employed in the experimental program described in this paper are the same as those used in (Caggegi et al. 2014; Fagone et al. 2014; Fagone et al. 2015). The reader can refer to these papers for a comprehensive description of the tests performed to characterize the mechanical properties of the materials. Here, just the main mechanical parameters are summarized for completeness sake.

Soft mud bricks, also called solid pressed bricks, have been used to manufacture the specimens because their material structure resembles the one of traditional soft pressed bricks, used in most existing buildings (Briccoli Bati and Ranocchiai 1994). Brick specimens had average compressive strength equal to 20.1 MPa, average tensile strength of 2.5 MPa and Young modulus equal to 8712 MPa.

Ready mixed mortar, made with lime and cement as binder, was employed in manufacturing the specimens. Its average compressive and (bending) tensile strength, obtained according to (UNI EN 1015-11 2007), was respectively 5.2 and 1.9 MPa.

A composite material, made of a unidirectional carbon fiber fabric and epoxy resin, was used to realize the reinforcements. The reinforcement sheets were applied to the substrate using a wet lay up process (with a single layer of carbon fiber fabric), after surface preparation and primer application, according to the producer's guidelines. The main characteristics of the constituent materials, declared by the producer, are summarized in Table 1.

Table 1: Mechanical properties (declared by the producer) of the reinforcing system components.

	Nominal thickness	Tensile elastic modulus	Bending elastic modulus	Ultimate tensile strain	Characteristic tensile strength	Shear strength
	[mm]	[MPa]	[MPa]	[%]	[MPa]	[MPa]
Unidirectional carbon fiber fabric	0.165	240000	--	1.3	3200	--
Adhesive	--	--	2200	--	--	95
Primer	--	1200	--	--	> 20	--

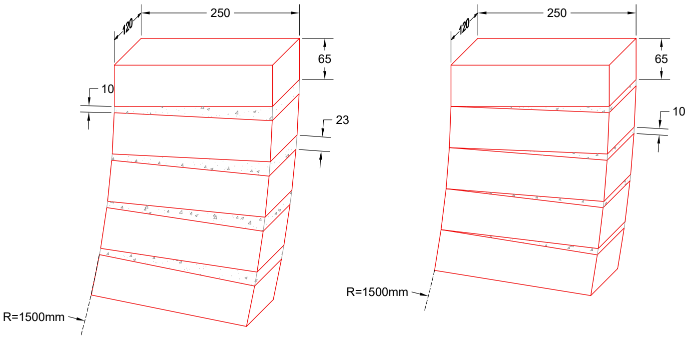
4. Specimens

Three different specimen's series have been considered in the experimental program as described in Table 2. The specimens consisted in portions of two types of double leaf masonry circular arches (type 1 and type 2 in Figure 2) having internal radius equal to 1500 mm. All the specimens were manufactured with five soft mud bricks having dimension of 65×120×250 mm; the mortar joint thickness ranges from 10 mm to 23 mm for type 1 and from 0 mm to 10 mm for type 2. Type 1 specimens have been reinforced at the intrados (CA-I-0 series) or at the extrados (CA-E-0 series), while Type 2 specimens have been reinforced only at the extrados (CA-E-0s series).

For each series, 5 specimens have been tested, each one identified by the label of the corresponding series followed by a number from 1 to 5. The CFRP sheet reinforcement length (equal to 382 mm for CA-E-0 series and 330 mm for CA-I-0 and CA-E-0s series) was higher than the effective length (leff=122 mm), evaluated according to (National Research Council 2013) with reference to sheet reinforcements bonded to plane surface. Of course, this estimation could not be reliable for curved surfaces, but can be considered at least to have a first dimensioning of the reinforcements considered in this paper, seeing the lack in the literature of specific design formulas. The bonded surface were smaller than the intrados or extrados surfaces (see Figure 3): it was not glued up to the surface borders in order to avoid stress concentrations during the tests.

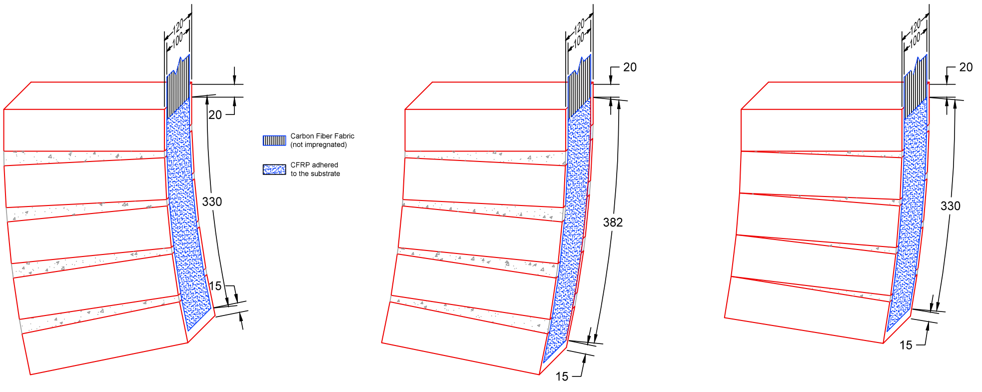
Table 2: Main characteristics of the specimen's series.

Series name	n. specimens	Specimen's brickwork (Figure 2)	Joint thickness range [mm]	Reinforcement position	Mortar joint thickness below the reinforcement [mm]
CA-I-0	5	Type 1	10÷23	Intrados	10
CA-E-0	5	Type 1	10÷23	Extrados	23
CA-E-0s	5	Type 2	0÷10	Extrados	10



(a) (b)

Figure 2: (a) type 1 and (b) type 2 specimen's brickwork (measures in mm)



(a) (b) (c)

Figure 3: Specimen's series considered in the experimental program (measures in mm): (a) CA-I-0; (b) CA-E-0; (c) CA-E-0s

The masonry specimens were cured for at least 28 days at room environment; then, the CFRP reinforcements were applied using a wet lay-up procedure, following the indications of the producer. First, the substrate surface was sanded and cleaned; then the primer was spread over the masonry surface to be reinforced; then, within twenty-four hours, a layer of epoxy resin was spread and the carbon fiber fabric was laid on it. At this point, a second layer of epoxy resin was spread as to form a composite having total thickness equal to 1 mm. Note that the total length of carbon fiber fabric was equal to the sum of the bonded part and 433 mm, left not impregnated and used to apply the load as described in next section. The specimens were tested after the hardening time of the CFRP reinforcement (minimum 24 hours, as indicated by the producer).

5. Test setup and procedure

The test fixture and the test instrumentation are schematized in Figure 4. The specimens were constrained by a steel plate at the upper base and by a steel wedge at the lower base. The steel wedge was used to properly constrain the lower base of the specimens. These steel elements were linked to each other by four steel bars that were pre-tensioned in order to give a little pre-compression to the specimens, necessary to stabilize them during the positioning and the test execution. Note that the steel wedge is provided of a little steel plate to constrain the specimen, preventing its rotation during the test.

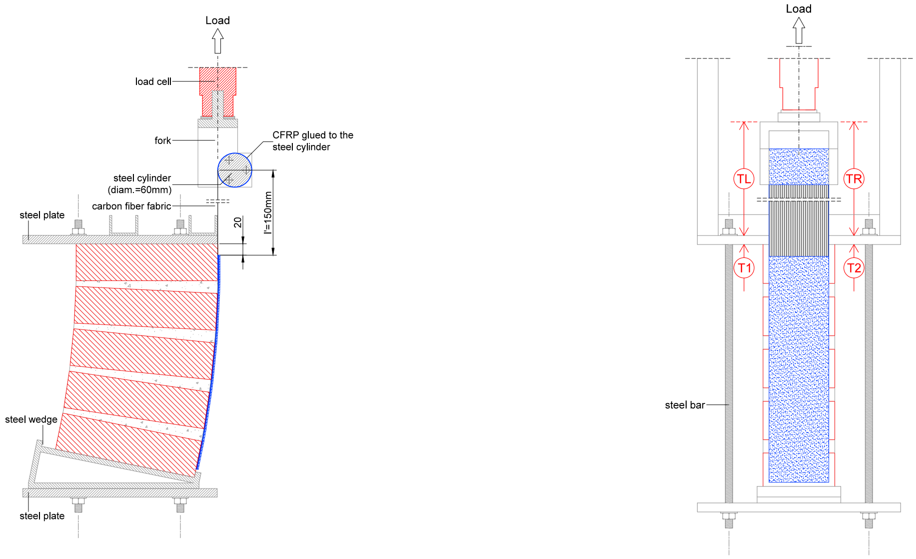


Figure 4: Test setup and instrumentation

The specimens were loaded imposing the vertical displacement of the upper grip consisting of a fork and a steel cylinder having a diameter equal to 60 mm. The final portion of the reinforcement fabric, outside the CFRP reinforcement (total length 433 mm), was impregnated with the same epoxy resin used for the reinforcement for a length of 283 mm (equal to 1.5 times the length of the circumference of the steel cylinder base) and wrapped and glued to the steel cylinder itself. The not impregnated part of the carbon fiber fabric, between the reinforcement sheet and the gripping system, had a length l=150mm. Compared with other methods, such as using jaws, the gripping system selected in the experimental program has the advantage that, by virtue of the curvature of the attachment surface, the load applied to the specimen increases the adhesion between the glued portion of the carbon fiber fabric and the steel cylinder. Moreover, the fabric was glued to the steel cylinder after the realization of the reinforcement sheet and before the specimen was placed in the test machine. At this stage it was possible to easily check that the threads of the fabric were well aligned orthogonally to the axis of the steel cylinder and to the upper face of the masonry specimens as to properly apply an action tangent to the reinforcement surface. Moreover, it was checked that the threads length was constant, in order to ensure that the load was evenly distributed across all the fabric.

The steel fork was connected in series to a load cell (50 kN) and then to a screw jack. In so doing, the tensile load was applied directly to the reinforcement sheet. Two displacement transducers (“TL” and “TR” in Figure 4) were placed at the bottom of the load cell and based on the contrast plate of the steel frame, so that they could record the relative displacement between the fork and the upper face of the brick. Moreover, two displacement transducers

("T1" and "T2" in Figure 4) measured the vertical displacement of the steel plate as a check of possible translations and rotations of the upper constraining plate of the steel frame.

The load was applied increasing monotonically the displacement, at a constant rate of 0.015 mm/s, up to the specimens' failure.

6. Experimental results

The main characteristics of the adhesion capacity of the CFRP reinforcements, bonded to the intrados or extrados of the portion of masonry arch, can be analyzed using the load-displacement diagrams reported in Figure 5. Note that, the displacement indicated in abscissa is the relative displacement between the rigid plate, constraining the upper specimen surface, and the load grip (measured by the transducers ''TL'' and ''TR'' indicated in Figure 4) minus the elastic deformation of the fiber fabric sheet out of the reinforcement bonding (having length equal to 150 mm), estimated using the elastic modulus and the nominal thickness declared by the producer (see Table 1). Note that the absence of detachments or slips between the glued part of the carbon fabric and the steel cylinder has been carefully checked after each test.

All the diagrams exhibit an initial quasi-linear stroke up to the first crack occurring in the masonry, close to the loaded extremity of the CFRP to substrate bonded joint. All the specimens showed very similar values of initial stiffness. At the end of the initial linear path, the load slightly decreased and a second, more scattered, branch was followed up to the specimen's failure. The mechanical behavior of the specimens within this second phase, as apparent from the shape of the diagrams, was very different between specimens reinforced at the intrados or at the extrados. This is related to the different effects of the bonding surface geometry on the stress distribution at the interface and, in general, in the specimens. Beyond the first linear branch, the load-displacement path is almost increasing up to failure for specimens reinforced at the extrados, while it increase up to the maximum load and then decreases up to failure for specimens reinforced at the intrados. Specimens of CA-E-0 and CA-E-0s series showed similar load-displacement diagrams, maximum load values and failure modes; so that it appears that the considered mortar joint thicknesses did not substantially affect the specimen's behavior. As expected, the load bearing capacity of specimens reinforced at the extrados (average values 25.9 kN and 26.0 kN respectively for CA-E-0 and CA-E-0s series) is higher than the one referring to specimens reinforced at the intrados (average value 15.9 kN). Note that, the values of maximum load within each series have low statistical dispersion, since the coefficient of variation ranges from 7.18 % to 13.67 %.

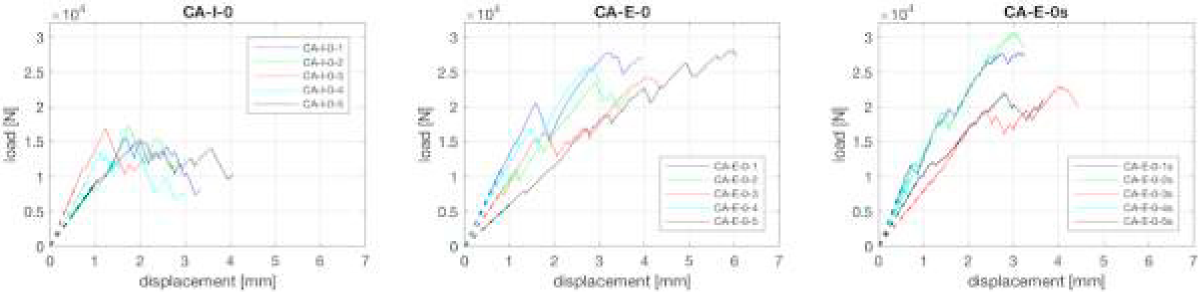
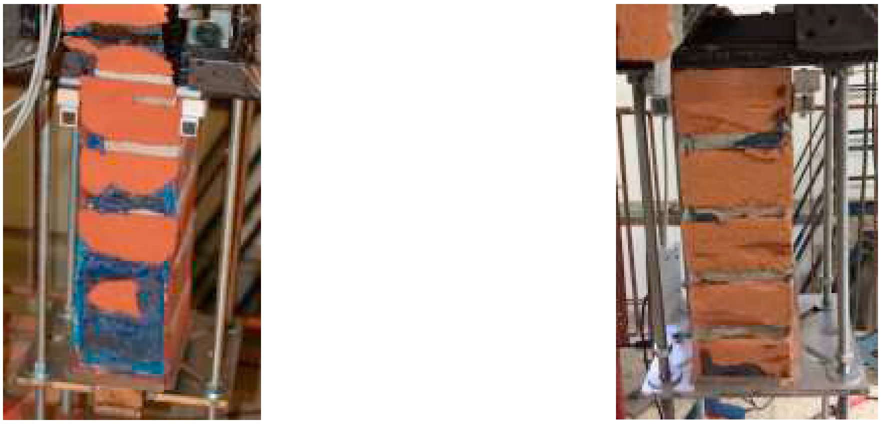


Figure 5: Load-displacement diagrams

The failure mode of specimens reinforced at the extrados mainly involved the substrate material since it was related to cracks occurring a few millimeters below the CFRP-masonry interface. Such failure mode, here referred to as "CF" (Cohesive Failure), is showed in Figure 6(b). One specimen of both CA-E-0 and CA-E-0s series failed because of the tensile failure of the dry carbon fiber fabric ("FF" – "Fiber Failure" in Table 2). Specimens of CA-I-0 series showed a "Mixed Failure" mode ("MF"), that is a combination of "CF" mode, occurred at the "upper" part of the reinforcement (close to the loaded end), and of the interface detachment of the CFRP reinforcement, occurred at the end part of the reinforcement.

Table 3: Maximum load (Fmax) and Failure Mode of the specimens

Specimen	F_{max} [N]	Failure mode	Specimen	F_{max} [N]	Failure mode	Specimen	F_{max} [N]	Failure mode
CA-I-0-1	15545	MF	CA-E-0-1	27805	CF	CA-E-0-1s	27822	CF
CA-I-0-2	17367	MF	CA-E-0-2	23583	CF	CA-E-0-2s	30600	FF
CA-I-0-3	16864	MF	CA-E-0-3	24169	CF	CA-E-0-3s	22913	CF
CA-I-0-4	14657	MF	CA-E-0-4	25773	FF	CA-E-0-4s	26838	CF
CA-I-0-5	15208	MF	CA-E-0-5	28145	CF	CA-E-0-5s	22006	CF
Mean	15928		Mean	25895		Mean	26036	
Co.V.	7.18%		Co.V.	7.97%		Co.V.	13.67%	



(a) (b)

Figure 6: Failure modes: (a) "Mixed Failure" (MF); (b) "Cohesive Failure" (CF)

7. Conclusions

A preliminary set of results emerged from an experimental campaign, devoted to the analysis of the influence of the curvature of the bonding surface (concave or convex) and of the mortar joints thickness on the mechanical effectiveness of CFRP reinforcement sheets, have been described in this paper. The experimental program involved specimens representing a portion of masonry arch, having different joint thickness, reinforced at the intrados or at the extrados. All the specimens exhibited similar behavior up to the occurrence of the first cracks, located behind the reinforcement, close to the loaded end. Then, specimens reinforced at intrados and extrados exhibited a very different behavior: beyond the first linear branch, the load-displacement path is almost increasing up to failure for specimens reinforced at the extrados, while it increase up to the maximum load and then decreases up to failure for specimens reinforced at the intrados. Moreover, as expected the load bearing capacity of specimens reinforced at the extrados is higher (+63%) than the one referring to specimens reinforced at the intrados. Finally, the experimental results showed that the mechanical behavior of specimens reinforced at the extrados was not substantially affected by the mortar joint thickness.

8. Aknowledgements

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