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Debonding of composites on a curved masonry substrate: Experimental results and analytical formulation

Marialaura Malena, Gianmarco de Felice *

Department of Engineering, University Roma Tre, Rome, Italy

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ABSTRACT

Externally bonded mortar based composites have become a popular technique for strengthening masonry arches and vaults. The effect of the curved substrate on the bond properties is one of the key factors affecting their structural behaviour. This paper presents the results of an experimental campaign of debonding tests on straight and curved substrates made of bricks assembled with mortar and strengthened either with Carbon Fibre Reinforced Cementitious Matrix (CFRCM) or Steel Reinforced Grout (SRG). The experimental results get insight into the failure mechanisms that take place in mortar based composites and disclose the effect of the substrate curvature on the interfacial strain distribution and on the load–displacement response. The experimental results are compared with the outcomes of a predictive model, proposed in this work, which provides a closed-form analytical solution to the debonding process of a thin plate on a rigid substrate with constant curvature. The model, which is based on an interface cohesive law, coupled in the tangential and normal directions, as a consequence of the curvature, is able to predict the decrease in bond stiffness and strength for increasing curvature, as shown by experimental results.

1. Introduction

Increasing attention has been devoted in the recent years to the use of innovative materials, such as externally bonded reinforcement, for strengthening masonry constructions. Current applications concern walls [1–3], arches and vaults [4,5], or columns [6] for either increasing the load carrying capacity or improving the behaviour under seismic events. Besides the well-established use of fibre reinforced polymers (FRP), the application of composites with inorganic matrix is receiving greater attention in current research and practice [7–11] thanks to the advantages in terms of permeability, fire resistance, cost, easier application. Fiber Reinforced Cementitious Matrix systems (FRCM) appear particularly appropriated for application to architectural heritage because of theirs reversibility and chemical compatibility with the substrate [12].

For most strengthening systems, the bond between the masonry and the reinforcement plays a key role in ensuring the load transfer. Several experimental debonding tests have been carried out on FRP systems, with different setups, either on clay bricks [13–15], stone elements [16] or on masonry prisms [7,17,18]. Most of the experimental results show that failure generally takes place with the detachment of a thin layer of masonry substrate. The adoption of an inorganic matrix affects the failure process that usually takes place within the matrix due to its lower mechanical strength, either by debonding at the fibre/mortar interface or by sliding of the fibres inside the mortar [9,13,19,20].

An analytical solution to the debonding problem is usually provided in the framework of fracture mechanics: in [21] a prediction of the ultimate load and the effective bond length is given, while in [22,23] a closed-form solution of the debonding process is provided for a bilinear and an exponential interface law, respectively. The number of contributions offered toward the comprehension of the mechanical behaviour of curved substrates is small, even though in current practice an increasing number of structural elements like arches or vaults are strengthened with external bonded composites. Most of the experimental data available in the literature concern the structural behaviour of arches [4,5], but in such cases the local bond–slip law is hardly deducted from experiments. Direct shear bond tests on curved masonry prisms were described in [18] and simulated numerically in [24]. An analytical model for describing the interfacial stresses between a thin plate bonded to a curved substrate was proposed in [25] and in [26].

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* Corresponding author. Tel.: +39 0657336268; fax: +39 0657336265.
E-mail addresses: marialaura.malena@uniroma3.it (M. Malena), gianmarco.defelice@uniroma3.it (G. de Felice).

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The present work aims at covering this gap, by studying the behaviour of externally bonded fibre-reinforced systems embedded in an inorganic matrix and applied on brickwork specimens. To this purpose, an experimental campaign comprising bond tests with two reinforcement systems, either with straight or curved substrate, has been carried out. The tests provide the global load–displacements behaviour up to failure, as well as the shear stress–strain distribution along the bonded strip. The failure mode resulting from the experiments highlights the role played by the mortar matrix, which turns to be the weakest element in the debonding process and the effect of the substrate curvature.

Aiming at simulating the initiation of the debondig process taking place on a curved substrate, a predictive model is proposed which provides an analytical solution to the debonding of a thin plate glued to a rigid substrate with constant curvature. Moving from the formulation in [25], the interfacial behaviour is described by a cohesive law coupled in the tangential and normal directions, as a consequence of the curvature, such as to reproduce the decrease in bond strength and stiffness for increasing curvature. Eventually, the analytical results are compared with experimental data, showing to what extent the model is able to describe effective behaviour of two different composites for varying curvature radius.

2. Experimental results

2.1. Mechanical characteristics of masonry substrate and reinforcement

The brickwork specimens manufactured for the experimental tests are made by bricks 230 mm long, 120 mm wide and 55 mm thick, assembled with hydraulic lime mortar joints with 10 mm thickness. Their mechanical properties have been estimated by means of compression tests and the average properties of brick and mortar are, respectively: compressive strength 55 MPa and 2.3 MPa, Elastic Modulus 7600 MPa and 4800 MPa.

Two reinforcement strips have been tested, namely, Steel Reinforced Grout (SRG) and Carbon Fibre Reinforced Cementitious Matrix (CFRCM), both embedded in the same hydraulic mortar matrix.

The steel reinforcement system is made by high tensile strength steel filaments, with a micro-fine brass coating, inter-twisted in cords and assembled in a strip with high flexibility, denoted as 3SX-12-12 and produced by HardWire LLC. The strip has a density of 12 cord per inch (see Fig. 1a); each cord is made of three filaments winded around an axis and a fourth filament, with a lower section, wound around the other tree, inserted to improve the bond with the matrix. The cords are welded on a non-structural glass net to make the strip easy to work. The geometrical and the mechanical characteristics of steel filament, cord and strip, provided by the producer, are indicated in Table 1.

The carbon reinforcement system is made by carbon bands 4 mm wide, spaced by 10 mm in two orthogonal directions (see Fig. 1b), named X MESH C10 and produced by the Ruredil SpA. The geometrical and mechanical characteristics of carbon reinforcement provided by the producer are summarised in Table 2.

The inorganic matrix is made by a pozzolanic mortar with synthetic polymeric fibres named X MESH M25 and produced by Ruredil SpA, whose mechanical properties provided by the producer are: compressive strength 38 MPa, tensile bending strength 7.5 MPa, elastic modulus 15 GPa.

2.2. Tensile testing of reinforcements

Tensile tests have been carried out on both reinforcement systems, in order to determine the stress–strain response, including the ultimate strain and stress and the tensile modulus of elasticity before and after cracking of the matrix. In whole, four specimens of each reinforcement have been tested, as shown in Fig. 2. The specimens have been cut from the reinforcement strip in order to include either 18 steel cords (see Fig. 1a) for a width of 38.1 mm and an overall steel area of 9.77 mm^2, or four carbon bands (see Fig. 1b) for a width of 40 mm. In this latter case, three layers of carbon reinforcement have been superposed and embedded in the mortar matrix, for a whole reinforcement area of 5.64 mm^2. The specimens were 600 mm long and 6 mm thick, with both free ends glued between two aluminium tabs (100 × 50 mm) such as to avoid damage in the gripping area and ensure uniform transmission of load. Axial strains have been recorded by strain-gauges and by an extensometer.

The experimental results are reported in Table 3 for all tested specimens. The specimens display cracks in the matrix at the very early stage of the test (below 15% of the maximum load) and from that stage, apart from a slight stiffening effect, the behaviour is almost linear, with an elastic modulus similar to that of the reinforcement only. Failure is elastic perfectly brittle in the case of carbon reinforcement, while a non-linear behaviour with a limited ductility of about 1.4 occurs in the case of steel reinforcement. It is worth noting that the tensile strength and ultimate strain of carbon reinforcement obtained by the tests, are lower than the values

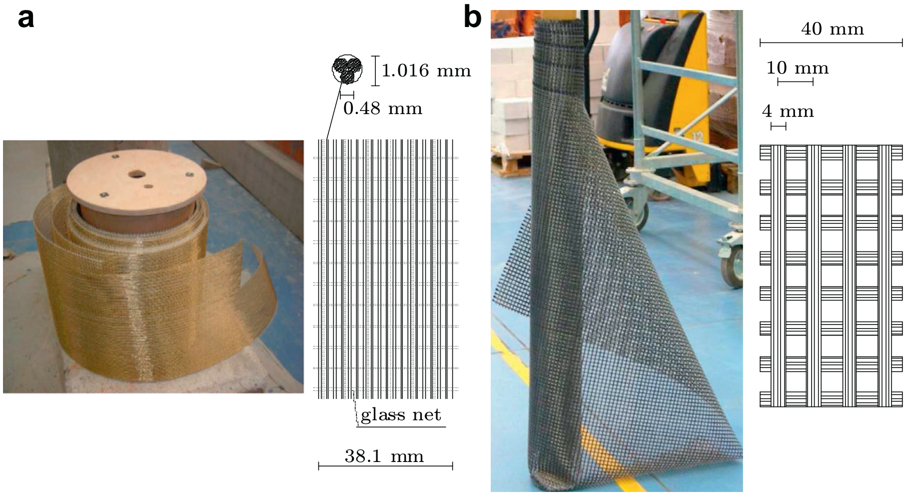

Fig. 1. (a) Steel strip and (b) carbon strip.