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Strain and shear stress fields analysis by means of Digital Image Correlation on CFRP to brick bonded joints fastened by fiber anchors

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HIGHLIGHTS

- An experimental study on brick reinforced by FRP and fiber anchor has been done.
- The displacement fields have been measured by means of Digital Image Correlation.
- Strains and stresses have been obtained after an interpolation of displacements.
- The product stiffness–thickness of the composite has been evaluated.
- The crack advancement during the debonding process has been described.

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ABSTRACT

Recent experimental analyses have shown the high performance of the "fiber anchor" applied over FRP to substrate bonded joints to avoid the premature debonding fracture of the reinforcement. In this study, an optical non-destructive measurement method, the Digital Image Correlation, was used to describe the debonding onto the FRP reinforced surface of 36 bricks subjected to Shear Test. A series of samples not-fastened was compared to some series fastened by fiber anchor. The fields data permitted to analyze the stress transfer zone and the effective bond length and to make several considerations about the product stiffness–thickness of the FRP strip.

1. Introduction

The strengthening of structural masonry elements by means of FRP sheet is a widespread reinforcement technique developed over the last decades. Usually the composite reinforcement is carried out in-situ bonding a carbon fabric onto the substrate to strength (FRP to substrate bonded joints). Experimental and numerical campaigns carried out by means of Shear Test [1,2] have showed the existence of an effective bond length l_e. The latter corresponds to the longitudinal extent of the stress transfer zone [3]; if the bond length is longer than l_e, no further increment of the maximal adhesion resistance is given to the reinforced system. The common failure mode of FRP to support bonded joints is the detachment of the composite from substrate at a much smaller load than the tensile strength of the FRP [1,2]. The use of mechanical anchors permits to improve the adhesion between the FRP sheet and the substrate increasing the efficiency of the reinforcement. Specifically, between the mechanical devices performed using the same fabric type of the reinforcement sheet, the "fiber anchors" (referred also as "FRP spike anchors") are among the efficient ones [4,5]. They are applied through the FRP reinforcement sheet; the cylindrical inferior part of each spike is inserted through the composite sheet in a predrilled hole (full of epoxy), the other extremity of the anchor is splayed in a fan-like shape and glued onto the FRP reinforcement. Few recent experimental studies have been carried out to test the performances of the anchors system applied onto CFRP sheet reinforcement varying the type of spike dowel, the fan angle,

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the number and the geometrical disposition of spikes; several experimental sessions have been carried out on concrete substrates [4,6–8], others researches concern the masonry [9–12].

In the majority of experimental studies, the strain fields onto the sample surface reinforced by FRP sheet and fastened by fiber anchor have been measured using strain gauges [6–8,13]. The latter permit to obtain only local values of deformation on the flat and smooth surface of the FRP sheet; in addition, the start of the brittle crack process could generate a malfunction of the strain gauges during the tests [7].

The evolution of the digital image technologies has permitted to develop an optical measurement method to obtain the displacements and strain fields on the surface of interest; the Digital Image Correlation (DIC) [14,15]. The DIC permits to calculate the displacement fields on the surface of interest matching digital grey level pictures of specimen taken by means of Charge-Coupled Device camera (CCD camera) [16]. The strain values can then be obtained after a derivation procedure of the displacements. The digital images carried out by the CCD camera are constituted by a chessboard of squares (pixels), each one characterized by a monochromatic color. The performances of DIC are related to the grey level characteristic of the pixel array. Specifically, the best results are obtained when local gray level fluctuations are present in the images to correlate. Usually, to obtain this optimal characteristic of the pixel array, a texture is carried out on the observed surface. First, the surface is covered with a homogeneous paint which is then coated with a random speckle pattern of paint. Frequently, to generate a high contrast, the support cover is black and the speckle is white (or inversely) [17–21].

The displacement field could be calculated matching the photos using a cross-correlation function that can be solved in physical space or in Fourier space [21–23].

DIC has been applied in several studies on debonding of CFRP to concrete bonded joint. Corr et al. [18] carried out an experimental study by NES Single Shear Test using the DIC to analyze the displacement and the strain field over the reinforced surface of the specimens. In [18] an equilibrium equation has been used to calculate the bond stress between the FRP sheet and the support. The relation proposed by Corr et al. [18] requires some assumptions; the substrate is rigid if compared to the reinforcement, the CFRP has an elastic behavior, the Young modulus and the cross section of the composite are constants. The results obtained in [18] shown the evolution of the stress transfer zone from the loaded side to the unloaded side of the specimen.

Carloni et al. [19] carried out an experimental study to obtain the through-thickness strains in the concrete reinforced by FRP during three Single Shear Tests. The tests of [19] show that the region of concrete substrate through the thickness of the sample involved in the stress transfer phenomenon is approximately 15 [mm]. Moreover, the strain distribution below the FRP is similar to the one obtained from the analysis of the composite surface. Some other studies on the FRP to concrete bonded joint have been carried out using DIC [20].

The work presented in this paper has been carried out to investigate deeply the behavior of the reinforced system constituted by a CFRP sheet bonded to a brick substrate and not fastened/or fastened by fiber anchor(s). Six different types of specimens, each one characterized by a different number of spike anchor, splay radius, splay opening and anchor placement, have been tested by means of Single Shear Tests (SSTs). The analysis of the maximal resistance and of the ductility of the sample types has been presented in [9,10]. Instead, the results obtained in this paper have been obtained using the DIC data collected during the 36 SST tests (6 for each type). Specifically, the objectives of the present work have been: (I) Analyze the debonding process defining the strain fields onto the reinforced surface of all the specimen series, (II) Define the tangential stress fields on the reinforced surface of specimens not fastened by anchor/s making some conclusion about the effective bond length, (III) Define the range of variation of the product "Et" (Young modulus "E" to cross section "t" of the composite) related to the series of test without anchor/s, (IV) Describe how the anchor affect the distribution of strain.

The experimental setup used to carry out the 36 Single Shear Test is described in the Section 2. In the latter they will be presented the boundary conditions reproduced, the materials and the geometrical properties of specimens and the testing apparatus. The algorithm and the parameters used to carry out the DIC will also be presented. The result processing procedure is deeply described in the first part of the Section 3 (the analysis of fields, the evaluation of product stiffness–thickness of composite and the analysis of the stress transfer zone). This "overview" is followed by some data obtained in the experimental session. Section 4 concerns the discussion on the results. Conclusions are collected in the last Section.

2. Experimental setup

2.1. Boundary conditions and specimen series

In the experimental session, the boundary conditions of the so called "Near-End Supported Single Shear Test" (NES-SST) (Fig. 1) have been reproduced to study the evolution of an "intermediate crack debonding" failure [1].

Thirty-six specimens, subdivided in six series, have been tested [9,10]. The reinforcement configuration of each series and the corresponding nomenclature are defined in Fig. 2.

All the specimens have been strengthened by CFRP, bonding a unidirectional carbon tissue by epoxy resin onto a brick substrate. The bond length of the CFRP has been designed to be longer than the optimal bond length to increase the ductility of the reinforced system and to permit the study of the crack advancement process. The effective bond length has been calculated using the equation proposed by the CNR DT200/2004 [24] and it is equal to 10.3 cm. In the loaded extremity of the specimen the carbon fabric was not attached to the substrate over a length of 2 cm to avoid a premature corner fracture.

The fiber anchors used to fasten the specimens have been designed according to the best design characteristics of literature in order to avoid the shear failure and the pullout of the composite nails [9–12]. The fiber anchors have been carried out using the procedure defined by Zhang et al. [6] for the "impregnated fiber anchor". Each anchor was made rolling a 20 cm width unidirectional carbon fiber fabric. The anchors were inserted inside predrilled holes in the substrate for a depth of 5 cm. The sharp edge of each cavity was rounded to prevent strain concentration.

The "T0" represents the series of reference and it is composed by specimens not fastened by anchors (Fig. 2). The series "T1", "T2", "T3" are fastened respectively by one, two and three carbon fiber anchor/s (Fig. 2). The specimens of series T1_25_V have been fastened by one anchor with a splay radius of 2.5 cm and an angle splay of 75°. The samples named T1_40_O are characterized by one anchor with a splay radius of 4 cm and an angle splay of 360°. The last series T1, the T1_40_V, is constituted by specimens fastened by one anchor with a splay radius of 4 cm and an angle splay of 75°. The specimens of series T2 are fastened with two anchors characterized by a splay angle of 75° and a fan radius of 4 cm. Finally, the specimens of series T3 are fastened by three anchors and present a splay angle of 75° and a 2.5 cm fan radius.

2.2. Materials

The specimens are constituted by brick "S. Marco" $12 \times 25 \times 6.5\ cm^3$ (made by terreal Italia group) reinforced by a CFRP composite. The brick substrate is characterized by a compressive resistance between 18.22 MPa and 22.17 MPa and a Young modulus of about 8700 MPa [11,12]. The composite has been carried out using the primer "MBRACE-primer", the epoxy resin "MBRACE-adesivo" and the carbon fibers "MBRACE-fibre high res." (Products of BASF chemical company). MBRACE-fiber is a

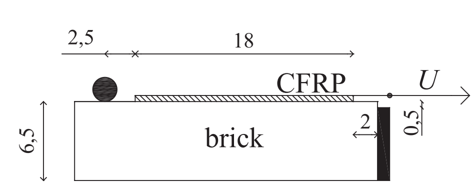

Fig. 1. Boundary conditions (measure in cm).