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Application of digital image correlation in investigating the bond between FRP and masonry

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ABSTRACT

Full characterization of the bond behavior between Fiber Reinforced Polymers (FRPs) and masonry in externally bonded reinforcement (EBR) technique is crucial at the design stage or structural performance prediction. In this regard, a full-field assessment technique seems to be valuable for an adequate characterization of the bond behavior.

The digital image correlation (DIC) and feature tracking techniques have been used in this study for investigating the evolution of strains and deformation during uniaxial tensile tests and shear debonding tests in FRP-masonry systems. The results show that the DIC is a valuable technique for characterization of the bond behavior and investigating its three-dimensional aspects. The DIC was also found applicable for following the matrix crack development in Steel Reinforced Grout (SRG) specimens. Feature tracking method was used for monitoring the strains development on the steel fibers in SRG specimens during tensile tests.

1. Introduction

Composite materials such as Fiber Reinforced Polymers (FRPs) or Steel Reinforced Grouts have been extensively used for external strengthening of masonry structures. The effectiveness of this strengthening technique is intrinsically dependent on the bond performance between the composite material and the masonry substrate. As the bond is a key mechanism in transferring the stresses from the structural element to the composite material, any bond loss leads to deterioration of the strengthening system and possible premature failure. Therefore, complete understanding of the governing bond mechanisms is necessary for design and quality control purposes.

Significant progress has been achieved in the last years regarding experimental and computational investigation of the debonding mechanism and damage in FRP-strengthened masonry elements [1–6]. However, aspects such as failure initiation, effective bond length, distribution of interfacial strains, the role of mortar joints and three-dimensional nature of the bond behavior require further investigation. A comprehensive bond-slip model, for numerical modeling approaches, is also missing for FRP-masonry systems. The bond-slip law can be experimentally obtained during the debonding tests from the distribution of strains, obtained from the strain gauges attached to the FRP's surface, along the bonded length [2]. However, the measurements are limited to the location of the strain gauges [2] and the bond behavior cannot be investigated precisely.

Use of a full-field measurement technique seems to be valuable in better understanding the above mentioned aspects of the bond behavior. This paper addresses the applicability of the optical measurement techniques for characterization of the tensile and bond behavior in FRP-masonry systems. For this reason, uniaxial tensile tests and shear debonding tests have been performed on previously prepared specimens and the evolution of strains on the specimens' surfaces has been measured with digital image correlation (DIC) and feature tracking methods. These methods have been widely used for measurement of displacements or strains in different fields of solid mechanics [7–9]. However, only a few studies can be found using these techniques for investigating the interfacial bond behavior, e.g. [10,11]. To the knowledge of authors, existing studies have been devoted to FRP-strengthened concrete elements and information on full-field assessment of bond in FRP-strengthened masonry has not been attempted.

Uniaxial tensile tests were performed here on Glass Fiber Reinforced Polymer (GFRP) and Steel Reinforced Grout (SRG) specimens. GFRP composites, compared with other conventional FRP materials, have lower axial stiffness which makes them more suitable for masonry structures. SRG has been chosen as a composite

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material with inorganic matrix that can be advantageous for strengthening masonry structures regarding compatibility and sustainability issues [2]. In GFRP composites, when prepared following the wet lay-up procedure, a complex strain distribution is expected along the specimen due to the non-uniform distribution of fibers along the width and length of the specimens. Information on strain distribution is useful for interpretation of the results obtained in debonding tests. In SRG composites, the interfacial strains do not seem to be transferred completely to the matrix (mortar) surface. Therefore, strain gauges attached to the mortar surface cannot provide a precise estimation of the interfacial strains. These issues have been investigated here with DIC and feature tracking methods.

In addition, single-lap shear bond tests have been performed on GFRP-strengthened brick specimens and the strain development along the bonded length has been investigated with the same technique. The full-field strain distribution on the FRP's surface and the three-dimensional aspects of the bond behavior have been also investigated. Specimens consisted of solid clay bricks strengthened with GFRP sheets following the wet lay-up procedure. Although recent studies have shown that the weak mortar joints can affect the bond behavior [4,5], this issue is not well known yet. Moreover, it seems that this effect varies with material (FRP and brick) and geometrical properties [4]. Therefore, the mortar joints are neglected in this study and it is assumed that the bond strength is fully utilized on the brick's surfaces. Meanwhile, characterization of the bond behavior between FRP and masonry pillar with the DIC method is being under investigation and the results will be presented and discussed elsewhere.

2. Digital image correlation

2.1. Principle

In the last decades, several interferometric and white-light optical methods have been proposed and developed in experimental solid mechanics [7,9]. These techniques contrast with conventional strain gauges or extensometers by the fact that they provide full-field data and are contact-free. Among these techniques, non-interferometric methods based on image processing, such as the DIC, have been increasingly used [12,13].

DIC-2D provides full-field displacements of a planar object by comparing the similarity between image features recorded at different mechanical states. The surface of interest must have a speckled pattern. Typically, this is obtained by spray or airbrush painting. A suitable balance between region of interest (ROI) and average size of white-to-dark spots must be achieved in order to enhance the displacement spatial resolution (small aperture) associated to the DIC measurements. In the DIC method, the displacement field is measured by analyzing the geometrical deformation of facets defined across the ROI. Therefore, the facet size defines the displacement spatial resolution. Typically, increasing the facet size improves the accuracy of the measurements but will degrade the spatial resolution.

2.2. Measurements

The specimens in the current testing program were prepared by applying a speckle pattern on the ROI, produced by applying a thin coating of white matt followed by a spread distribution of black dots using spray paint, see Fig. 1. The ARAMIS DIC-2D software by GOM was used in this work [14,15]. The measurement system was equipped with an 8-bit Baumer Optronic FWX20 camera coupled with a Nikon AF Micro-Nikkor 200 mm *f*/4D IF-EDlens (Table 1).

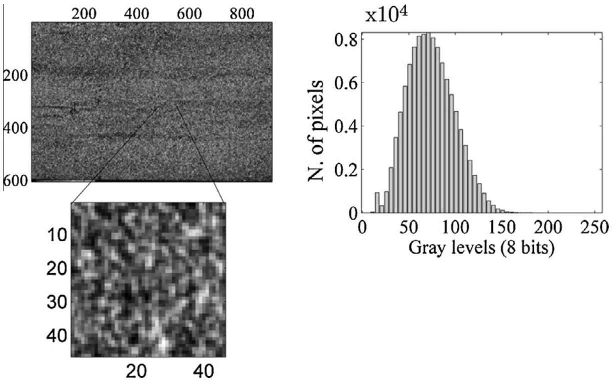

Fig. 1. Example of a speckle pattern and histogram of a GFRP coupon specimen.

In the test set-up, the optical system was positioned facing the surface of the specimen. A laser pointer was used to guarantee the correct alignment of the camera with regards to the specimen. The working distance (defined between the target surface and the support of the cameras) was set about 1.8 m leading to a conversion factor of 0.037 mm pixel^{-1}, see Table 1. The aperture of the lens was completely open (minimum depth of field) in order to focus the image on the specimen's surface. The lens aperture was then closed to *f*/11 in order to improve the depth of field during the testing. The shutter time was set to 5 ms. The light source was finally adjusted in order to guarantee an even illumination of the target surface and to avoid over-exposition.

Regarding the size of the ROI, the optical system (magnification) and the quality of the granulate (average speckle size) obtained by the spray paint, a facet size of 15×15 pixels^2 was chosen in this study. The facet step was also set to 15×15 pixels^2 in order to avoid statistically correlated measurements. The in-plane displacements were then numerically differentiated in order to determine the strains field. The typical resolution of the measurements was in the range of 10^{-2} mm and 0.02–0.04% for displacement and strain evaluation, respectively.

3. Feature tracking method

In the feature tracking method, the displacements of several target objects on a surface of interest are determined by suitable

Table 1
Optical system components and measurement parameters.

CCD camera	
Model	Baumer Optronic FWX20 (8 bits, 1624 × 1236 pixels, 4.4 μm/pixel)
Shutter time	5 ms
Acquisition frequency	1 Hz
Lens	
Model	Nikon AF Micro-Nikkor 200 mm *f*/4D
Aperture	*f*/11
Lighting	LEDMHL10 (color temperature: 6000 K)
Working distance	1800 mm
Conversion factor	0.037 mm/pixel
Project parameter – Facet	
Facet size	15×15 pixel^2
Step size	15×15 pixel^2
Project parameter – Strain	
Computation size	7 × 7 facets
Validity code	55%
Strain computation method	Total
Image recording	
Acquisition frequency	1 Hz