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Bond behavior in NSM-strengthened masonry

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A B S T R A C T

Near Surface Mounted (NSM) reinforcement is an interesting technique for seismic strengthening of masonry and historical structures. Despite having several advantages compared to conventional techniques, little attention has been given to understanding the involved mechanisms (such as bond behavior) in the performance of masonry components strengthened with this reinforcement technique. This study presents an experimental and analytical investigation on the bond performance of NSM-strengthened masonry bricks aiming at filling the existing gaps in the available experimental results in the literature. The main focus is on the effect of test setup and bond length, but attention has also been given to the groove size and loading regime effect on the bond performance. The accuracy of the existing bond strength prediction models is also assessed and the required modifications are proposed.

1. Introduction

Fiber reinforced polymers (FRP) have been extensively used for strengthening of masonry and concrete structures due to advantages such as low weight, ease of application, corrosion resistance and high durability. These composites are generally used for Externally Bonded Reinforcement (EBR) or Near-Surface Mounted (NSM) strengthening techniques. The disadvantages related to the EBR strengthening techniques (such as special requirement for surface treatment and susceptibility to aggressive environmental conditions), promotes the use of NSM technique. Additionally, the NSM reinforcement does not change the aesthetics of the structure which is a great concern when dealing with restoration of historical structures [1,2]. NSM systems are also more efficient due to their larger bonded area to cross section ratio in comparison with EBR systems. The available literature on strengthening of masonry structures using NSM technique have shown its notable effect on increasing the ductility and capacity of the structures [3]. Despite these advantages, the available literature on characterization and performance assessment of NSM-strengthened masonry is still limited, see e.g. [3–6].

The NSM technique involves introducing FRP laminates or bars into slits prefabricated on the tensile face of structural elements using an epoxy adhesive [7]. In these systems, the stresses are transferred from the substrate to the reinforcing material through the adhesive and the interfacial stresses. The adhesive-to-substrate and the FRP-to-adhesive bond performance are therefore critical mechanisms. Although the bond performance has been subject of several studies in case of NSM-strengthened concrete elements, see e.g. [8–15], little attention has been given to strengthened masonry components, see e.g. [2,16–18]. The effect of different parameters (including the dimensions and shape, the adhesive type, the mechanical strength of substrate, the groove dimensions and the bonded length have been deeply investigated in NSM-strengthened concrete components [1,2,8,19,20]. The available studies on NSM-strengthened masonry, has not yet fully covered all these parameters and is mostly devoted to the effect of bond length on limited types of substrate. The majority of available studies are devoted to large bonded lengths and the bond performance in short bonded lengths still remains unexplored.

This paper presents an experimental assessment of the bond performance in CFRP NSM-strengthened bricks with special attention to short bonded lengths to fulfill the current gap in the literature. Attention has also been given to the effect of test setup, groove dimensions and loading regime. Based on the produced experimental results and the available data in the literature, a survey is also performed on accuracy of the existing bond strength analytical models and suitable modifications are proposed.

2. Experimental program

2.1. Specimens

The specimens were composed of solid clay bricks with dimensions

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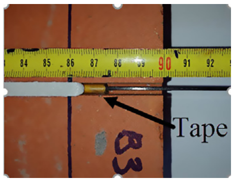

Fig. 1. Position of tapes inside the groove.

Table 1
Material properties.

	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
Masonry brick	14.5	1.6	–
Epoxy adhesive	–	22.0	7.2
CFRP laminate	–	–	165.0

of 200 mm × 100 mm × 50 mm strengthened with S&P® CFRP strips made of unidirectional carbon fibers. The strips had 10 mm width and 1.4 mm nominal thickness. A two-part epoxy adhesive (S&P resin 220) was used to bond the CFRP strips to the bricks following the near surface mounted (NSM) strengthening technique.

For preparation of the specimens, rectangular grooves were initially cut on the bricks' surfaces by an electrical saw with the desired width and depth. Then the bricks were washed, cleaned and dried in an oven for 24 h at 100 °C. After cooling in the laboratory environment, the dust was removed from the grooves using an air compressor. The grooves were then filled with the epoxy up to half of its depth. The CFRP laminates were then carefully inserted into the grooves and were covered with another layer of epoxy. The position of the laminate inside the groove was controlled by wrapping a tape around the laminate at both ends (outside of the bond area). The tapes also acted as a barrier to prevent penetration of the adhesive out of the bond zone, see Fig. 1. The exterior surface of the tape was greased with oil to minimize the friction with the groove's perimeter during the tests.

The laminates were applied with different bond lengths (from 30 mm to 150 mm). A 40 mm unbonded length was left at the loaded end to avoid compressive crushing of the bricks during the tests due to the edge effects, see Fig. 2. Two aluminum plates were glued at the end of the laminate to facilitate gripping of the specimens during the tests. The specimens were cured in laboratory conditions for two weeks as suggested in the technical datasheets provided by the manufacturer. The specimens are labeled according to the groove width (G) and bond length (B), throughout the paper.

2.2. Material properties

The compressive strength of the bricks was experimentally obtained as 16.7 MPa. The tests were performed on 40 mm × 40 mm × 40 mm cubes following the instructions given in ASTM C67 [21] and EN 772-1 [22]. The tests were conducted under force-controlled conditions at the rate of 150 N/min. To reduce friction, a pair of free-friction Teflon papers (with oil in the middle) was placed between the specimens and the compression plate. Even though, as some signs of shear stress were observed in the failure mode of the specimens, the correction factor proposed in ASTM C39/C39M [23] was also considered (factor of 0.87 for a height-to-length ratio of 1) that lead to a compressive strength of 14.5 MPa as presented in Table 1.

The epoxy adhesive had a 14 days tensile strength and elastic modulus of 22 MPa and 7.15 GPa, and the CFRP laminate had an elastic modulus of 165 GPa, respectively according to [24]. The summary of the materials' mechanical properties is presented in Table 1.

2.3. Test setup

As no standard test method is available for investigating the bond behavior in NSM-strengthened concrete or masonry specimens, various test setups have been employed by different researchers. A single-lap shear test scheme, by fixing the specimens to a supporting frame from the bottom and pulling the laminate from the top, is often used for this purpose. The specimens are fixed using a rigid restraining plate placed on top of the specimens which, after initial adjustments, is anchored to the supporting frame from the bottom. This leads to application of a pre-compression load to the specimens before starting the tests which can influence the experimental results [5]. Regardless of the advantages and disadvantages of this test setup, the specific geometry and size of the specimens did not allow to use such a system for performing the tests in this study.

The single-lap shear bond test setup developed in [25–27] for characterization of the bond behavior in EBR-strengthened bricks was thus used here, see Fig. 2. This test setup was not directly applicable for NSM-strengthened specimens due to the geometrical differences of the specimens compared to the EBR-strengthened specimens. In EBR strengthening technique, the FRP sheet is applied on the substrate's surface, while in NSM technique the laminate is inserted inside the specimen for few millimeters. The clamping and restraining systems were thus changed in two stages to optimize the test setup, see Fig. 3. In

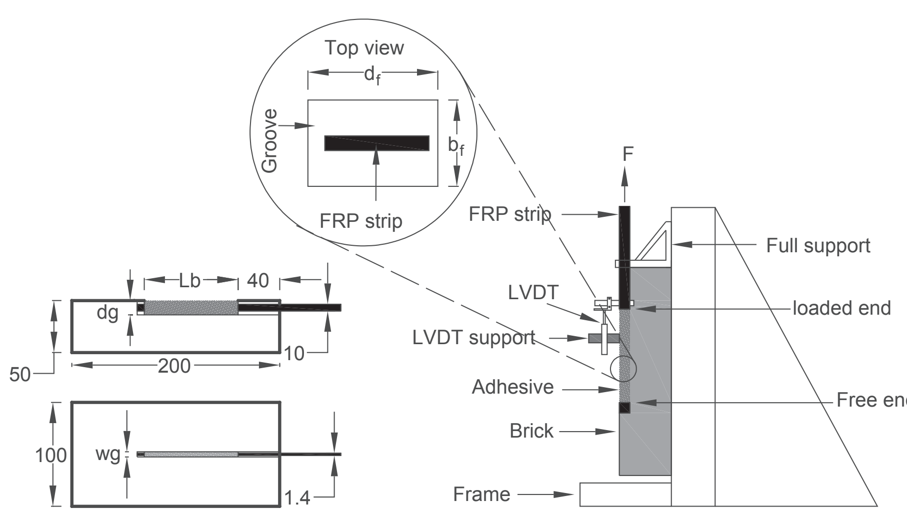

Fig. 2. Geometry of the test specimens and the test setup (dimensions are in mm).

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