BOND BETWEEN NEAR SURFACE MOUNTED FRP RODS AND MASONRY IN STRUCTURAL STRENGTHENING

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Abstract

The structural strengthening of un-reinforced masonry walls (URM) is often a need. The successful use of near surface mounted fiber-reinforced polymer (FRP) bars for strengthening of concrete members has been extended, in this experimental program, to unreinforced masonry (URM) walls: glass FRP (GFRP) twisted sand-coated rods have been embedded in two different matrixes: a latex modified cementitious paste and an epoxy based paste. The results, in terms of bond behavior, are presented and discussed in this paper.

1. Introduction

There are a lot of causes which lead UMR structures to collapse: wrong design, structural weakness or overloading, differential settlements, dynamic vibrations, in-plane and out-of-plane deformations, environmental conditions. Previous investigations have shown that the use of fiber reinforced polymers (FRP) as rehabilitation and strengthening materials for masonry structures is a valid alternative to traditional strengthening techniques. The use of FRP materials offers to the designer an outstanding combination of advantages, including high strength and stiffness in the direction of the fibers, immunity to corrosion, low weight and a lot of different commercially available forms. Numerous investigations have explored the potential use of FRP on concrete, while much less has been reported about masonry.

Two are the alternatives offered by the FRP materials for strengthening of masonry structures: externally bonded laminates and near surface mounted (NSM) bars. The use of pultruded FRP bars consists in encapsulating them by means of a paste, into grooves cut onto the surface of the member being strengthened. Once the curing time is over, the paste has the function to transfer the stresses from the substrate of the strengthened member to the bar. Objective of this experimental program was to investigate the bond behavior between the NSM FRP rods and concrete masonry blocks by using two different embedding materials and by changing variables such the bonded lengths and the dimension of the groove.
2. Experimental Program

**Test Matrix.** Twelve specimens were tested: each of them consisted of two standard hollow concrete blocks. One NSM GFRP rod was applied to two faces of the blocks in the longitudinal direction, connecting the two blocks together. Only one block was the test region, with the NSM FRP rod having a limited bonded length and being unbonded in the remaining part. Length and position of the bonded part were the same for both faces of the test block. The rod was fully bonded on the other block, to cause bond failure to occur in the test region. In each block, the hole closer to the face where the load had to be applied was filled with Ash Grove pre-mixed concrete, so to prevent crushing of the block face before failure of the bond. The diameter of the rods used in the tests was 6.35 mm (2/8 in) and the sizes of the groove, which was square, were 9.52 mm (3/8 in) and 15.87 mm (5/8 in) (1.5 times and 2.5 the diameter of the bar respectively). These test parameters were chosen taking into account the dimensions of the standard concrete blocks: a groove size of 19 mm (3/4 in) is believed to be the largest that can be possibly adopted; so a maximum groove of 15.8 mm (5/8 in) was chosen to reduce the possibility of creating excessive damage in the blocks (Tumialan et al. 2000) [7]. Specimens with three different values of the bonded length were tested, equal to 127, 254 and 381 mm (5, 10 and 15 in). Strain gages were applied on the surface of the FRP rods to monitor the strain distribution along the rod during the test. They were placed within the bonded length and an additional one was applied in the unbonded region. No strain gages were applied to some specimens in order to see the influence of them on the bond behavior.  

Table 1 presents the test matrix indicating the designation that will be used to identify the specimens. The specimen designation refers to the following parameters: type of filling paste – bond length – dimension of the groove - use of the strain gages or not. As an example, C-5-SS refers to a specimen with latex modified cementitious paste as embedding material (“C”), having a bonded length of 127 mm (5 in) (“5”), a groove of 9.52 mm (3/8 in) (“S”) and strain-gages attached on the rod’s surface at the test region (“S”).

**Materials.** Tests were performed to characterize the engineering properties of the materials used in this investigation. The average compressive strengths of concrete masonry block, obtained from the testing of prisms (ASTM C1314), were 13.3 MPa (1934 psi). Splitting tensile test (ASTM C496) for both the embedding materials were performed since the most important mechanical properties that are used in design of NSM reinforcement are the tensile properties: the splitting tensile strength was found to be 3.58 MPa (0.518 ksi) after 7 days and 5.59 MPa (0.81 ksi) after 28 days in the case of latex modified cementitious paste, and 16.31 MPa (2.36 ksi) after 7 days and 18.54 MPa (2.7 ksi) after 28 days in the case of epoxy-based paste. By following the ASTM D 3916-94, the tensile properties of the rods were investigated, which are related to fiber content and not to composite area. GFRP twisted sand-coated bars having a diameter of 6 mm (2/8 in) presented a tensile strength of 825 MPa (120 ksi) and a modulus of elasticity of 40.8 GPa (52900 ksi).

**Test Procedure.** The test bed was a steel plate with dimensions 1.5 m by 0.6 m (5 ft by 2 ft) and thickness of 3.2 mm (1/8 in). Five steel angles were glued on the plate to delimitate the position where the concrete blocks had to be placed. The purpose of the plate was to avoid other movements during the test except the longitudinal movement. A plastic sheet was placed
between the plate and the bottom surface of the blocks, in order to minimize the friction between the two surfaces during testing. Figure 1 shows the test setup.

Load was applied by means of a 12-ton hydraulic jack connected to a hydraulic pump. The jack was placed horizontally between the two blocks. Load was recorded by means of a 50 kips Load Cell. Slip at the end of the FRP rods in the test region was measured using two LVDTs. Load, slip and strains were all recorded with a one-Hertz sampling rate by a LABTECH data acquisition system.

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![Test Setup](image)

**Figure 1. Test Setup**

### 3. Test Results

**Modes of Failure.** The test results, in terms of ultimate load applied to each rod, average bond strength, and failure mode are summarized in Table 1. The value of the ultimate load was obtained dividing by two the load registered by the load cell. The average bond strength was computed with the following equation:

\[
T_{bu} = \frac{T_u}{\pi \cdot d_b \cdot l_b}
\]

where \(T_u\) is the ultimate load, \(d_b\) the nominal diameter of the rod and \(l_b\) the bonded length. The specimens exhibited the following modes of failure: (1) cracking of the masonry unit by shear and (2) splitting of the embedding paste cover.

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Table 1. Test Matrix and Test Results

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At the beginning of loading, the main mechanism that resisted to the external load was the chemical adhesion and friction between the two materials. The radial component of the bond stresses induces circumferential tensile stresses in the material around the bar. Thus, as the load increased, the radiating bond forces had to be resisted by tensile strength of the embedding paste and the surrounding masonry.

The specimens having the epoxy paste as embedding material failed by shear of the masonry in the zone surrounding the groove (Figure 2(a) and 2(b)). A typical noise was audible with the increase of the load up to failure and revealed the progressive cracking of the epoxy cover. Vertical cracks formed in the epoxy paste and developed sloping to the concrete block getting wider until the failure occurred. Epoxy paste has typically a much higher tensile strength than the tensile strength of the masonry unit. Thus, even if the cover depth was around 1.6 mm (1/8 in), it was enough to offer resistance to splitting. The tensile strength of the masonry is, in this case, an important parameter: its value influences the ultimate load.

The failure by splitting was observed with the specimens having latex modified cementitious paste as filling material (Figure 2(c)). At failure, the cover split away and fractured in small pieces; some damages were observed in the zone surrounding the groove. In this case, even though from the splitting tensile test the modified cementitious paste was stronger than the concrete block, the embedding cover was not enough to avoid failure by splitting.

Even so, some differences may be noted from the results obtained by using a groove of 1.5 and 2.5 times the diameter. In the first case the cover was too thin, it did not allow high tensile stresses and consequently the reordered bond strengths were very low: as a matter of fact the
surface configuration of the rod was intact and completely clean after failure. In the other case, a bigger groove, which in terms means a bigger cover depth, allowed higher tensile stresses and thus better bond performances. A higher level of damage was observed at the sides of the groove in the masonry unit and the rod deformations were extensively damaged (Figure 2(d)). In this case the registered ultimate loads are comparable with the results obtained by using the epoxy paste.

![Figure 2. Specimens after Failure by Shear in the Masonry Block and ((a) and (b)) and by Splitting of the Embedding Paste Cover((c) and (d))](image)

**Influence of Different Bonded Length.** As found in similar previous tests [4], the experimental results show that the ultimate load was found to increase with the increase of the bond length while the bond strength decreased with the increase of the bond length. These results could be attributed to a non-uniform distribution of bond stresses on GFRP rods along the anchorage length. The bond stress is always an average of the maximum value over a short length, a reduced value over the portion where the slip has occurred, and, at lower loads, a zero stress over a portion of the length. This variation is very pronounced at low loads and increases with the bond length. The shorter the specimen, the more nearly the average bond stress approaches the ultimate value in adhesion; the longer the specimen, the lower is the average bond stress which can be obtained. At higher loads, the bond properties change in such a way as to approach a uniformly distributed bond stress. Therefore the bond strength decreased with the increase of the bonded length.
**Free-End Slip Data Analysis.** During the test, slip at the free-end of each rod was measured by means of an LVDT. Then, the overall slip has been computed from the average of the values given by LVDTs reading.

Figure 3 shows the Load vs. the Free-end Slip Chart for the specimens with the epoxy and with the latex modified cementitious paste. These graphs were plotted in order to check the overall behavior of the specimens during loading.

![Figure 3. Load vs. the Free-end Slip Chart](image)

It could be observed that twisted strand-coated GFRP bars presented a clearly frictional behavior with a constant plateau until about 5.3 kN (1.19 kips): that was registered for the specimens with the epoxy paste. The plateau found for the second series was until 4.8 kN (1.079 kips).

As the load increases, adhesion break down, some slip begins to be registered and the bond mechanism changes: at this stage, the bearing stresses from the bar deformations to the surrounding zone increase considerably: this is evident from the Strain vs Location Chart reported in Figure 4. The splitting resistance of the concrete surrounding the bar is decisive at this stage: specimens having the latex modified cementitious paste as embedding material and a minimum groove failed at this point.

If more resistance to splitting can be provided by the surrounding concrete and the cover (i.e. groove having a depth of 2.5 times the diameter of the rod), the load can be increased and more slip is registered. At this point the tensile strength of the concrete unit is reached and failure is immediate without presenting any ductile residual resistance.

**Strain in the Embedding Material.** Even if the strain in the embedding material has not been recorded during the tests, an important consideration may be drawn. In the case of specimens having epoxy paste as parent material, vertical cracks formed in the epoxy paste by loading and developed sloping to the concrete block and getting wider until the failure occurred. On the contrary, no cracks were visible on the outside surface of the modified cementitious paste until failure. This fact could be addressed to a different strain in the two filling materials at ultimate: the epoxy paste has a high strain-ability which may be traduced in a more pseudo-ductile behavior. On the other side, the latex modified cementitious paste...
presents a low strain-ability and its behavior is consequently much more brittle: once the cracks form, the failure is quite immediate.

**Analysis of Strain Data.** Strain gages were applied at various locations on the surface of the FRP rods in order to monitor the strain distribution along the rod during the test. A typical Load vs. Strain Diagram is shown in Figure 4(a). The strain gages are numbered starting from the zero in the unbonded region and proceeding toward the rod free end.

The data from the strain gages were used to plot Strain vs. Location graphs. In these graphs, the strain in the rod along the bonded length is plotted for different values of the load (Figure 4(b)): all points were obtained from the readings of the strain gages, except for the strain at the end of the bonded length, which was assumed to be equal to zero. The left end (location equal to zero) and the right end of the x-axis correspond to the loaded end and to the free end of the bonded length, respectively.

![Load vs. Strain Chart and Strain vs. Location Chart for Specimen C-10-SS](image)

From these charts, it may be observed that all the specimens experienced a similar behavior. The strain distribution along the bonded length is nonlinear at moderate load levels and tends to approach an almost linear shape as the applied load increases. This means that, as the load increases, the bond stresses become more evenly distributed along the bonded length as a result of changes in the nature of bond and the slopes of the lines become parallel between each other. The primary bond mechanism changes from chemical adhesion to mechanical interlocking as soon as the rod’s deformations are brought into bearing. Thus, the strain at the rod’s free end are close to zero at low load levels and, as the load increases, the peak of the strain shifts toward the free end and the whole bonded length contributes to resist the pulling force.

**Conclusions**

The following conclusions could be taken on from the results obtained in this experimental program:
Two different failure mode were observed: (1) cracking of the masonry unit by shear and (2) splitting of the embedding paste cover.

From the values of ultimate load, it could be said that the epoxy paste is more efficient then the cementitious paste when the rods are embedded in a minimum groove (1.5 times the diameter). This means that, in terms of design approach, the anchorage length has to be approximately more then 1.5-2 times. The results are much better when, by using the latex modified cementitious paste, the rods are embedded in a groove of 2.5 times the diameter. In this case the registered ultimate loads are comparable with the results obtained by using the epoxy paste.

The presence of the strain gages on the surface of the rod interrupts the bond and consequently decreased the ultimate load. The loss of capacity is related to the area covered by the strain gages.

Generally, the ultimate load increases with the increase of the bond length while the average bond strength decreases with the increase of the bond length as a results of a non-uniform distribution of the bond stresses.

Considering the results obtained from the bond tests, some previsions may be drawn about the behavior or masonry walls reinforced with twisted sand-coated NSM FRP bars:

- In case of flexural strengthening, during loading, once the tensile strength of the mortar joint has been reached, the bonded length will be equal to the height of the concrete block used (15-20 cm); this length could be not sufficient to develop enough bond by using a minimum groove; since the normal component of stress due to flexural behavior has to be added to the normal component of the bond stress, the stress in the cover could be to high and thus the effectiveness of the strengthening very low. On the contrary, better results are expected by using a cover depth of 2.5 times the rod’s diameter.

- In case of shear strengthening, the dimension of the groove is dictated by the thickness of the bed joint (minimum groove) but longer bonded lengths are possible. Thus, the low bond between GFRP rods and latex modified cementitious paste could be an advantage. It may allow some sliding and a better redistribution of the stresses in the system. In addition, the lower tensile strength of the latex modified cementitious paste than the epoxy paste, could generate a more homogeneous system.

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