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The Bond Performance of Near Surface Mounted CFRP Strengthened Concrete Structure

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Abstract: The use of near surface mounted (NSM) fibre reinforced polymer (FRP) rods is proved to be a technology which can increase the flexural and shear strength of the deficient reinforced concrete (RC) members. Recently, considerable research has been directed to characterize the use of the FRP bars and strips as near surface mounted reinforcement. However, there are several methods in terms of modelling the bond stress-slip relationship, such as the "Tri-Linear" model, the "BEP" model, the "Modified-B.E.P." model, the "CMR" model, the "Naaman" model and the "Malvar" model. It is necessary that more experiment results are required to verify which of the models above are more accurate.

1. Introduction

In this paper the bond behaviour of the near-surface mounted FRP reinforcement that is in short-embedded-length is investigated. A total of four concrete cubes are used and four grooves with different dimensions are cut on each of them. Different embedded lengths are used in the grooves. Pull-out tests are carried out to evaluate the behaviours of the bonds and FRP reinforcements in different dimension of grooves with different embedded lengths. The experimental bond stress-slip curves are obtained from the experimental results. The obtained experimental stress-slip curves are used to verify which model is more accurate among the six stress-slip curve models mentioned above.

2. Theory of the Experiment - Short-embedded-length pull-out test

Since the short embedded length (the length of the reinforcement embedded in the concrete is a small multiple of the bar diameter) test is easy to carried out and the test results are very easy to interpret, this kind of test is adopted by most of the bond research [1-2].

For the short embedded length test, the variation of the slip along the embedded length is very small; as a result, the variation of the shear stress along the embedded length is very small too [3-5]. So, the average shear stress (τ_{AV}) which is the load applied to a single bar divided by the area of the reinforcement-concrete interface is sufficiently to describe the characteristics of the bond. For a single reinforcement of diameter $\o$ and embedded length ℓE, carrying a total load F, the average shear stress is [6]:

$$\tau_{AV} = \frac{F}{\pi \phi \ell_E} \tag{1}$$

The minimum practical embedded length is around $\ell_E \approx 4\phi$ [7]. Below this length, pull-out specimens are sensitive to imperfections and the position of the surface deformation relative to the end of the specimen. So equation (1) above allows the τ-s relationship to be plotted.

3. Experiment Details

Bond is of primary importance, since it is the means for the transfer of stress between the concrete and the FRP reinforcement in order to develop composite action; the bond behaviour influences the ultimate capacity of the reinforced element as well as serviceability aspects such as crack width and crack spacing [8]. Among large amounts of different types of bond tests that have be mentioned in the literature, the direct pull-out test and the beam pull-out test are the most common ones. In the experiment of this paper, the direct pull-out test was adopted [9].

In the direct pull-out tests a total of four concrete cubes with four bonds on each of the cubes (Figure 1) were used. The smooth surface CFRP rods (MBT MBAR®) which were bonded into the grooves are 8 mm in diameter. The bonds with different sizes of cross-sections and different embedded lengths were tested separately. The following variables were examined in the experimental test matrix:

• The embedded length (Table 1): There were four different embedded lengths which equal to 5, 10, 15 and 20 times the diameter of the CFRP rods.

• The size of the groove/bond (Table 1): Generally, specimens with four widths of grooves/bonds were tested.

Table 1: The sizes of the Grooves (Bonds) and The Embedded Length

	Groove Size		Embedded
Groove Number	Width (mm)	Depth (mm)	Length (mm)
1.1	16	21	80
1.2	18	20	80
1.3	14	20	160
1.4	18	20	120
2.1	20	20	160
2.2	23	20	120
2.3	24	19	80
2.4	25	20	40
3.1	21	20	40
3.2	19	19	160
3.3	20	20	160
3.4	20	20	80
4.1	19	22	40
4.2	18	19	40
4.3	15	20	120
4.4	20	20	120

3.1 Specimens

3.1.1 The concrete cubes

In the experiment of this paper, four concrete cubes with four grooves cut on each of them have been used; the dimension of each concrete cube is $250mm \times 250mm \times 250mm$, which allows the embedded length goes up to 160mm (20 times the diameter of the CFRP rods). The cubes in Figure 1 are those used in the experiment. To get the compressive strength of the concrete used to make the test specimens, compressive tests on three cubes (dimensions $25 \times 25 \times 25\text{mm}^3$) have been carried out one week after the pull-out tests are finished. The average compressive strength of the concrete obtained from the compressive tests is 2.24GPa.

Figure 1: The cubes used in the experiment

3.1.2 The fibre reinforced polymer rods

The fibre reinforced polymer rods are now widely used in the construction industry. The use of fibre reinforced polymer (FRP) rods is a technology which increases the flexural and shear strength of deficient reinforced concrete members. FRP is an alternative method which used in practical instead of metals in the application of concrete reinforcement where corrosion, service life, environment and other factors limiting the use of metals providing it is electromagnetic neutrality by the resistance from deicing salts and other corrosive agents [10]. Other features include relatively light weight (high strength to weight ratio), ease and fast of installation reducing traffic delays, versatility anti-seismic behavior, excellent durability and fatigue characteristics and fire resistance. With relatively unlimited material length availability make FRP materials an attractive solution for repairing and replacing damaged part of concrete structure.

In the experiment the smooth surface carbon fibre reinforced polymer rods (MBT MBAR®) [Figure 2] which is 8 mm in diameter were used as the near-surface mounted reinforcements. The properties of the MBT MBAR® are given in Table 2. These rods were bonded into different sizes of grooves using epoxy in different embedded lengths so that the influence of the groove size and embedded length on bond behaviour could be investigated.

Table 2: Properties of the CFRP rods

MBT MBAR®	
Typical tensile strength	2500MPa
Typical tensile modulus	165GPa
Diameter	8mm
Sectional area	46.6 mm^2
Ultimate deformation	1.50%
Fibre content	65%
Density	1.61g/cm^3
Inter Laminar Shear Strength	77MPa
Thermal Expansion (m/mm/ ℃)	6.00E-07

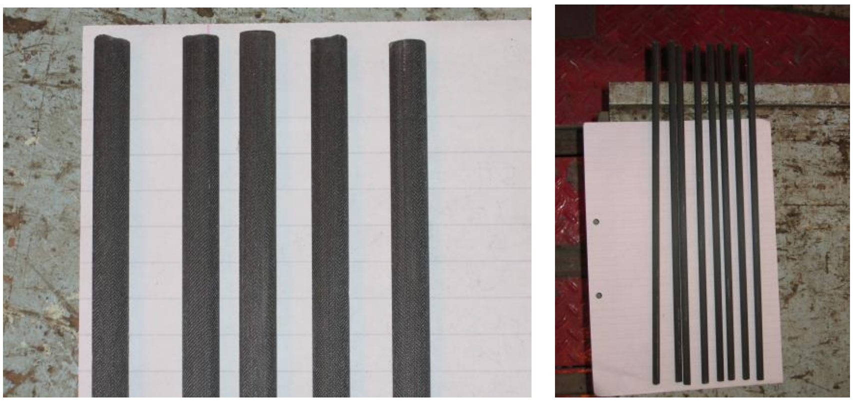

Figure 2: The CFRP rods used in the pull out tests

3.1.3 The epoxy

To bond the carbon fibre reinforced polymer rods into the grooves, some kind of epoxy paste was used. The epoxy paste was prepared by maxing two components in 1:0.564 proportion by weight. After finishing bonding the CFRP rods into the grooves, it takes at least a week (at the room temperature) for the epoxy paste to get hard enough to be tested.

3.2 The equipment

The equipment that was used to do the pull-out tests is called “Instron machine” (Figure 3 & Figure 5) which is controlled by computer while the tests were being carried out. After finishing a test, the computer can output all the data needed, such as the tensile load that the machine applied to the CFRP rod, the displacement between the CFRP rod and the concrete at the loaded and free end of the rod and the shear stress and strain. The plot of tensile load against loaded-end displacement (relative displacement between the rod and the bond) was sketched automatically in the computer while a test was being carried out so that people would be aware of what was happening (when the bond started to fail or at what time the CFRP rod was pulled out) in the bond during the test. The maximum load that the machine can apply to the CFRP rod is 100KN.

Figure 3: The “Instron machine”

3.3 Experimental procedure

3.3.1 Preparation of the specimens

3.3.1.1 Cutting of the grooves

To evaluate the bond characteristic and load transfer mechanism between near surface mounted CFRP rods and concrete, different sizes of grooves needed to be cut on the concrete cubes so that CFRP rods could be bonded into the concrete.

The grooves were created by saw-cutting two parallel slits at the desired distance and depth and chiselling off the material in between. And then, the powered concrete and dust that were produced by the cutting progress must be removed.

The concrete cubes in Figure 1 are those have been cut. Different sizes of grooves (Table 1) were used in the direct pull-out test so that the influence of groove size ton the load carrying capacity of the bond can be investigated.

3.3.1.2 Bonding of the carbon fibre reinforced polymer rods

The method used in applying the CFRP rods is as follows: a groove is cut in the desired direction into the concrete surface, the groove is filled halfway with epoxy paste, and then the CFRP rod is placed in the groove and lightly pressed. This forces the paste to flow around the rod and fill completely between the rod and the sides of the groove. Finally the groove is filled with more paste and the surface is levelled (Figure 4).

There are several cases which must be considered while the CFRP rod was being bonded into the groove:

- The inner-surface of the groove and the CFRP rod must be clean enough (no powered concrete and dust) to enable the epoxy works properly.
- The CFRP rod must be vertical to avoid bending moment being generated when the tensile load is applied vertically to the rod.
- The CFRP rod must be placed at the centre the groove so that the tensile strength of the bond around the rod is the same.

There are four embedded lengths which are 5, 10, 15 and 20 times the diameter of the rod and the bond length for each specimen is indicated in Table 1.

Figure 4: The cubes after bonding

3.3.2 Pull-out tests

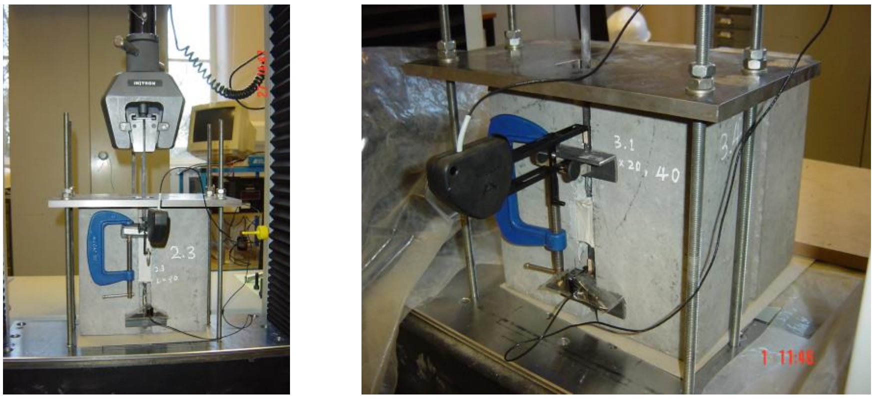

Figure 5: General layout of the test program

3.3.2.1 Setup of the test

The general layout of the directly pull-out test program is shown in Figure 5 above. The concrete cube on which the CFRP rods are bonded is placed under a thick steel plate which is fixed by four steel rods and the crosshead that applies tensile load to the CFRP rod is above the steel plate. While the pull-out test is being carried out, the crosshead holds the CFRP rod and pulls upward until either the concrete/bond cracks or the rod is pulled out through the bond and the tensile load applied to the rod is recorded by a load cell above the crosshead. To record the slip between the CFRP rod and the concrete/bond at the loaded end and free end of the rod, two strain gauges are set at both ends (the displacement arm of the top gauge is attached on the CFRP rod at a short distance ℓ_{TG} above the top end of the bond, so the reading of the top gauge needed to be corrected due to the effect of the tensile deformation of the rod). Steel angles/blocks have been attached on the surface of the concrete block first, so that the strain gauges can be set up. The range of the gauge used to record loaded end slip (top gauge) is from -1cm to 6cm, and the range of the gauge to record free end slip (bottom gauge) is from -1mm to 2mm. The rate at which the crosshead goes up holding the CFRP rod is 0.5 mm/min.

4. Test Results and - Average Shear Stress versus Loaded End Slip

During the test, the tensile load and the slip (relative displacement between the rod and bond) at the loaded and free end were recorded. The average shear stress is obtained from equation (1), which allows the relationship between the average shear stress (τ) and the slip of loaded end (s)

[reading of the top gauge] to be plotted. Figure 6 illustrates the relationship between τ and *s* for the serious of distinct embedded lengths (experimental τ-*s* curves).

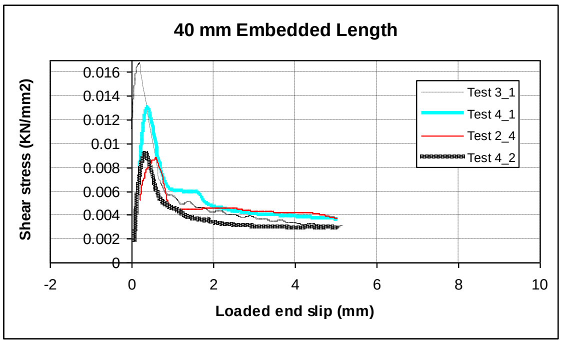

Figure 6 (a): τ-s curves for 40mm embedded length specimens

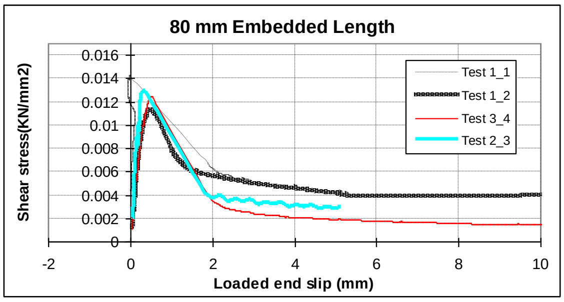

Figure 6 (b): τ-s curves for 80mm embedded length specimens

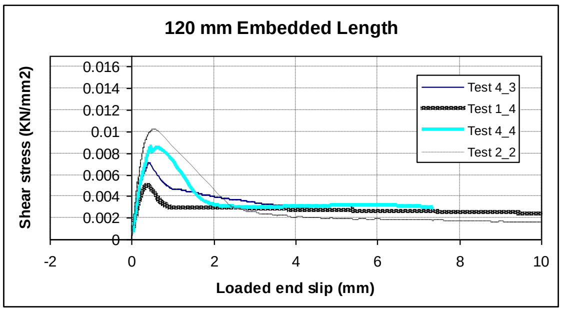

Figure 6 (c): τ-s curves for 120mm embedded length specimens

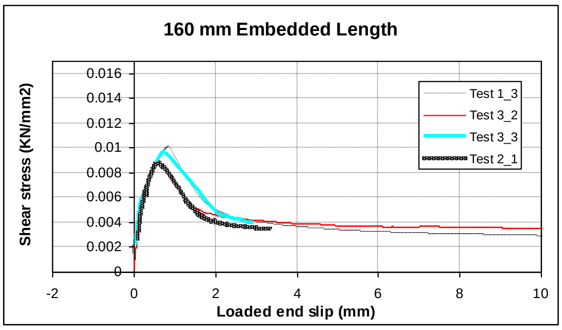

Figure 6 (d): τ-s curves for 160mm embedded length specimens

Figure 6: τ-s relationship for series of 40mm, 80mm, 120mm and 160mm embedded lengths (experimental curves)

5. Conclusions

In Figure 6, the experimental τ-s relationship curves have three different zones. For the first zone, shear stress goes up rapidly as the loaded end slip getting longer and the shape of the curve has tiny curvature. In the second zone, shear stress goes down rapidly as the loaded end slip getting longer and the shape of the curve is nearly linear. The curve of the third zone is nearly linear too, and the shear stress remains nearly constant as the loaded end slip getting longer. The general τ-s curve model (Figure 7) which most of the researchers suggested has primary bond mechanism (the primary zone), degradation of the primary bond mechanism (the degradation zone), and the secondary bond mechanism (the secondary zone). As can see, by comparison, the experimental τ-s curves fit well with the general τ-s model that most of the previous researchers suggest. Hope conclusion of this paper could provide further confidence for the design of the FRP structures and for the development of design standards.

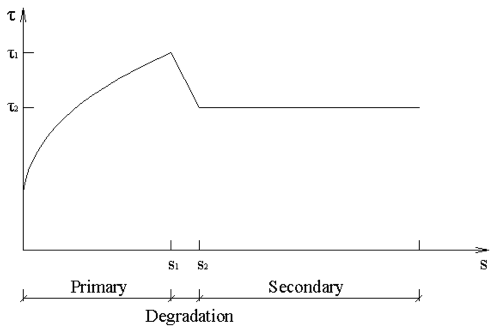

Figure 7: The general τ-s model

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