MECHANICS OF BOND BEHAVIOR OF THE EMBEDDED THROUGH-SECTION FRP BAR SHEAR-STRENGTHENING METHOD

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Abstract

A new shear-strengthening technique recently developed for concrete structures is the use of FRP bars embedded through pre-drilled holes into the concrete core. This so-called “embedded through section (ETS) method” uses an adhesive to bond the FRP rods to the concrete. In this study, a finite element model is developed for analyzing the interfacial behaviour for fibre reinforced polymer (FRP) bars bonded to concrete prisms by the ETS method and subjected to direct shear. To capture the interfacial behaviour, the FRP bar/concrete interface is modelled using discrete truss elements oriented above and below the FRP bar connecting the two substrates. These interface elements incorporate a constitutive model that is developed based on the CMR model for FRP reinforced concrete beams. Comparisons between the finite element results and available experimental data in terms of loading capacities and bond force–slip relationships are presented. In addition, the stress in the FRP bars, and the interfacial slip distribution along the interface are investigated.

Keywords: ETS method; nonlinear finite element analysis; FRP/concrete interfacial behaviour; interface elements; bond force–slip relationships.

1. Introduction

The strengthening of concrete structures by means of externally bonded (EB) fibre-reinforced polymers (FRP) is now routinely considered to be an effective method for enhancing the load-carrying capacity of existing structures. External bonding of FRP sheets and near-surface-mounted (NSM) rebars are the two techniques most widely used to strengthen deficient reinforced concrete (RC) structures. However, with these techniques, there is often a concern that premature failures may occur as a result of debonding of the FRP from the concrete. As a contribution to avoid such problems, a new shear-strengthening technique recently developed for concrete structures is the use of FRP bars embedded through previously drilled holes into the concrete core. This so-called embedded through-section (ETS) method uses an adhesive to attach the FRP rods to the concrete [1]. The method is characterized by many advantages such as rapid installation with simple hand tools, absence of the need for specialized labour skills, excellent confinement leading to improved bonding performance, and lack of need for surface
preparation. The method can also be considered as an attractive solution to increase fire resistance and reduce vandalism when FRP materials are applied to shear-strengthen deficient concrete structures.

Although the debonding phenomenon of the ETS technique has been investigated experimentally [2], a finite element model on the FRP/concrete interfacial behaviour has not been developed. An appropriate numerical model with particular emphasis on the interfacial behaviour is required for a better insight look into the debonding phenomenon. In this study, a nonlinear finite element model is developed to address the FRP/concrete interfacial behaviour of the ETS strengthening technique. The finite element formulation of the concrete, FRP bars and FRP/concrete interface is presented. The accuracy of the finite element model is assessed through comparisons of predicted results with experimental data. Based on this accuracy, information on the FRP bar stress and interfacial slip distribution along the interface is obtained.

2. Finite element model

The finite element analysis presented here is a 2-D plane stress analysis that simulates the problem of a direct shear test of the ETS method. A three-dimensional (3-D) finite element model is computationally demanding since a two-dimensional model can represent the behaviour accurately. The finite element package ADINA 8.5.4 [3] is used to carry out the finite element analysis. Nonlinear material behaviour of the plain concrete, FRP bars and FRP/concrete interface are simulated with appropriate constitutive models. The quality of this model is assessed by comparing numerical results with experimental data.

2.1 Material modelling

2.1.1 Concrete and FRP bars

The constitutive model used for the concrete corresponds to that provided in the ADINA software. A brief description of the main features of the model is presented below. It is characterized by a hypoelastic phenomenological model. It combines three features to simulate the basic characteristics of the concrete. These features are a nonlinear stress–strain relation to allow for the strain softening behaviour of the material under increasing compressive stresses. In addition, a failure criterion for concrete is used to define the cracking stress in tension and the failure envelope in compression. The failure envelopes account for multiaxial stress conditions and a fixed smeared crack model is used to describe the post-cracking behaviour of the concrete. The tensile behaviour of concrete takes into account cracking, shear modulus degradation, fracture energy and tension stiffening. Tension stiffening is modelled as a linearly descending branch in the stress–strain relationship after the peak point at which concrete has cracked. For the finite element implementation, the values of the compressive strength \( f’_c \) (MPa) and tensile strength \( f_t \) (MPa) are taken from the relevant set of experimental data. The elastic modulus \( E_c \) (MPa) is approximated based on the following CSA [4] equation:

\[
E_c = 3300 \sqrt{f’_c} + 6900 \quad \text{(MPa)}
\]  

(1)

Additional details regarding the concrete model are provided in the ADINA [5] software.

A linear elastic tensile model until failure is assumed to represent the FRP composites. A rupture point on the stress–strain relationship defines the maximum stress and strain of the FRP composites.

2.1.2 FRP/concrete interface

The FRP bar/concrete interfacial behaviour had a significant effect on the overall response of
the ETS tested specimens. Experimental results showed that a relative slippage occurs between the two components. As a result, assuming a full-contact bond is not realistic and is likely to produce misleading results. This assumption can lead to an overestimation of the FRP strain and overall stiffness. One effective way of modelling the FRP/concrete interface of the direct shear problem using the finite element model is to introduce interface elements. The constitutive law of these elements represents the interfacial behaviour of the joint. Use accurate constitutive is the key feature to obtain accurate results.

In this study, a constitutive model based on the Cosenza, Manfredi, and Realffonzo model (CMR model) proposed for FRP reinforced concrete beams is used [6]. It should be emphasized that the bond stress–slip model for the FRP reinforced concrete is selected because their behaviour is close to that observed for the ETS strengthening technique. As well, this model is recommended by the fib [7] to calibrate the experimental bond stress–slip relationships for the FRP reinforced concrete. In this model, a single equation is provided to describe the whole behaviour:

\[ \frac{\tau}{\tau_m} = (1 - e^{-s/s_r})^\beta \]  

where \( \tau \) and s are the bond stress and the corresponding slip, respectively; \( \tau_m \) is the peak bond stress; \( s_r \) and \( \beta \) are parameters based on curve fitting to experimental data. Initial prediction of the curve-fitting parameters was carried out by Godat et al. [2], who reported mean values for the curve-fitting parameters to describe the FRP/concrete interfacial behaviour of ETS strengthening technique. The values reported vary depending on the bar type. For the CMR model, \( s_r \) and \( \beta \) were set to 0.035 and 0.2, respectively, for smooth-surfaced bars and to 0.028 and 0.33 for sand-coated bars.

### 2.2 Geometrical modelling

It is necessary to emphasize that the interfacial behaviour and the bond strength of an FRP/concrete joint is independent of the length and height of the concrete prism. In fact, only a zone of a few millimetres inside the concrete adjacent to the interface contributes to the overall interfacial behaviour. In addition, since the concrete prism is already supported from movement in the loading direction, its dimensions are not very relevant. For this analysis, the length of the concrete prism was chosen to be 350 mm to cover the various embedded lengths investigated in this study, as it will be explained later. The height selected was 190 mm typical to the experimental tests.

#### 2.2.1 Concrete and FRP bars

To represent the concrete, quadrilateral four-node plane stress elements with two degrees of freedom at each node were used. The concrete elements at the interface are fine meshed in order to properly capture the interfacial response. A mesh size of 5 x 5 mm is considered appropriate for the analysis. The FRP bars are modelled using two-node truss elements with two degrees of freedom at each node.

#### 2.2.2 FRP/concrete interface

*Figure 1* shows a typical geometrical representation of the direct shear test along with the different elements employed at the interface. Discrete truss elements are employed to represent the FRP concrete interface. Based on a study carried out by [8], this truss element is an appropriate element to present the FRP interfacial behaviour. Each element has two nodes, each with two degrees of freedom. As shown in *Fig. 1*, the discrete truss elements are oriented above and below the FRP bar to connect the bar to the two sides of the concrete. The internal deformation of these elements represents the interfacial slip and the axial stress represents the
shear stress. It is necessary to mention that interface elements do not directly represent the adhesive. They rather represent the overall concrete/FRP interfacial response, which depends on the concrete, the FRP, as well as the adhesive. Full strain compatibility is assumed between the FRP nodes and the concrete nodes in the normal direction by enforcing suitable constraint equations. The area of each interface element represents the interfacial shear area between the FRP and the concrete within the length of an interface element. As shown in the figure, the constraint equations are enforced in the shear direction between the first interface Node $NI(i)$ and the concrete Node $NC(i)$ and between the second interface Node $NI(i+1)$ and the FRP Node $NF(i)$. If the displacements $\Delta$ are constrained in the horizontal direction at Nodes $NF(i)$ with those of $NI(i+1)$, and at Nodes $NI(i)$ with those at Nodes $NC(i)$, the constraint conditions can be represented as follows:

$$\Delta_{NF(i)} = \Delta_{NI(i+1)}$$  \hspace{1cm} (3)

$$\Delta_{NI(i)} = \Delta_{NC(i)}$$ \hspace{1cm} (4)

The displacement in an interface element that joins Nodes $NI(i)$ and $NI(i+1)$ is:

$$\Delta = \Delta_{NI(i+1)} - \Delta_{NI(i)}$$ \hspace{1cm} (5)

Hence, the differential displacements between concrete nodes and FRP are equal to the slip values. Subsequently, the interfacial shear stresses causing these differential slips are equivalent to the stresses in the truss elements. The aforementioned technique of simulating the interface overcomes certain problems arising from using elements with continuous interpolation functions.

2.3 Specimens investigated

The experimental tests of Godat et al. [2] will be used for investigating the numerical predictions. These tests encompassed many parameters such as the FRP bonded length, the hole diameter, the concrete strength and the bar type and diameter. The finite element model and the bond stress–slip model are general in a way that can accommodate all the variations in the test characteristics and parameters. Table 1 provides the geometrical characteristics and strengthening details. The specimen designations correspond to those used in the original references. The nonlinear load–deformation behaviour of the structure is simulated under displacement-controlled loading conditions. The configuration details of the specimens is shown in Fig. 2.

3. Finite Element Results

The results presented in the following sections are given in terms of ultimate load carrying capacities and bond force–slip relations. In addition, the results will be discussed in more detail in terms of the FRP/concrete interfacial response. The stress profiles in the FRP bar along the bonded region are also examined in this study.
3.1 Load carrying capacities and bond force–slip relations

The numerical predictions and experimental results of the various specimens are summarized in Table 1. From the table, it can be observed that there is a very good agreement between the theoretical and experimental results for the entire group of specimens in terms of ultimate bond force. The average numerical/experimental ratio is 1.034, with a standard deviation of 0.058. In Table 1, the discrepancy between the numerical and the experimental bond force is high for specimen C2-1.50d-9.5S-5.0d, while the discrepancy is small for the other specimens.

Table 1. Strengthening configurations, numerical and experimental ultimate load capacities.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Concrete strength (MPa)</th>
<th>Bar diameter (mm)</th>
<th>CFRP type</th>
<th>Hole diameter (mm)</th>
<th>Embedded length (mm)</th>
<th>Exp. load (kN)</th>
<th>Num. load (kN)</th>
<th>% Pnum/Pexp</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-1.50d-9.5B-15d</td>
<td>20.7</td>
<td>9.5</td>
<td>Pultrall sand coated</td>
<td>15 (1.50d)</td>
<td>143 (15.0 d)</td>
<td>35.7</td>
<td>32.3</td>
<td>90.4</td>
</tr>
<tr>
<td>C1-1.50d-12.7B-15d</td>
<td>20.7</td>
<td>12.7</td>
<td>Pultrall sand coated</td>
<td>15 (1.50d)</td>
<td>143 (15.0 d)</td>
<td>57.0</td>
<td>61.3</td>
<td>107.5</td>
</tr>
<tr>
<td>C2-1.25d-9.5S-15d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>12 (1.25d)</td>
<td>143 (15.0 d)</td>
<td>80.4</td>
<td>82.8</td>
<td>103.0</td>
</tr>
<tr>
<td>C2-1.30d-9.5S-15d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>143 (15.0 d)</td>
<td>91.2</td>
<td>93.8</td>
<td>102.9</td>
</tr>
<tr>
<td>C2-2.00d-9.5S-15d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>19 (2.00d)</td>
<td>143 (15.0 d)</td>
<td>78.5</td>
<td>80.7</td>
<td>102.8</td>
</tr>
<tr>
<td>C2-1.50d-9.5S-5.0d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>48 (5.0 d)</td>
<td>35.6</td>
<td>40.2</td>
<td>112.9</td>
</tr>
<tr>
<td>C2-1.50d-9.5S-7.5d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>71 (7.5 d)</td>
<td>57.4</td>
<td>60.1</td>
<td>104.7</td>
</tr>
<tr>
<td>C2-1.50d-9.5S-10.0d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>95 (10.0 d)</td>
<td>63.4</td>
<td>67.8</td>
<td>106.9</td>
</tr>
<tr>
<td>C2-1.50d-9.5S-12.5d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>119 (12.5 d)</td>
<td>71.0</td>
<td>69.0</td>
<td>97.2</td>
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<tr>
<td>C2-1.50d-9.5S-17.5d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>166 (17.5 d)</td>
<td>100.7</td>
<td>95.9</td>
<td>95.2</td>
</tr>
<tr>
<td>C2-1.50d-9.5S-20.0d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>190 (20.0 d)</td>
<td>102.4</td>
<td>107.4</td>
<td>104.9</td>
</tr>
<tr>
<td>C2-1.50d-9.5S-25.0d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>238 (25.0 d)</td>
<td>114.7</td>
<td>113.7</td>
<td>99.1</td>
</tr>
<tr>
<td>C2-1.50d-9.5S-30.0d</td>
<td>42.7</td>
<td>9.5</td>
<td>Sika smooth</td>
<td>15 (1.50d)</td>
<td>285 (30.0 d)</td>
<td>128.3</td>
<td>126.9</td>
<td>98.9</td>
</tr>
</tbody>
</table>

Figure 2. Test specimen and test setup.

The proposed numerical model successfully simulates the debonding failure of the tested specimens. At the stage of significant stress transfer from the concrete to the bonded FRP bar, the debonding initiated at the first interface elements towards the applied load.
removing the debonded interface elements, the analyses were continued and the load increased. As the load was further increased, the debonding continued toward the unloaded end. The debonding progressed until failure of the specimen.

**Figure 3. Comparison between numerical and experimental bond force–slip relations.**

*Figures 3a* and *3b* present the representative results for the comparison between the experimental and numerical results in terms of load force–slip relations for the tested specimens. *Figure 3a* corresponds to specimens tested to investigate the influence of the hole diameter on the bond behaviour (Specimens C2-1.25d-9.5B-15d and C2-1.5d-9.5B-15d). Small discrepancies in the bond force–slip relations are observed between the experimental and numerical results. In the numerical bond force–slip relations, the initiation of debonding is shown by sharp change from ascending to flat plateau. Similar behaviour is obtained in *Fig. 3b* for the specimens used to investigate the response of the embedded FRP bar length.

### 3.2 FRP/concrete interfacial profiles

*Figures 4a* and *4b* show the slip profiles along the FRP/concrete interface; these profiles can be very useful for understanding the interfacial behaviour between the FRP and the concrete. On each figure, the slip values are obtained at various load levels. The profiles are shown for specimens with different embedded lengths: 10d (*Fig. 4a*) and 25d (*Fig. 4b*), which correspond to specimens C2-1.5d-9.5S-10d and C2-1.5d-9.5S-25d. At a certain load level, the interfacial slip reaches a peak value near the loaded end. As the load is further increased, the location of the peak value on the interfacial slip curve moves towards the unloaded end of the FRP bar. The attainment of a peak in itself indicates that the load is being transferred starting at that point forward at that particular load value. At the onset of debonding, the location of the removed interface elements showed zero interfacial slip values, thus indicating the initiation of debonding. The peak interfacial slip value moves along the bonded length up to the failure.

From *Fig. 4a*, it can be concluded that the bond length for specimens C2-1.5d-9.5S-10d (95 mm) is not sufficient for the load to be transferred from the FRP bar to the concrete. This fact is obvious since (i) the length with low interfacial slip values is small at load level close to the failure load, and (ii) the slope of the descending part of the curve is mild. The slope of the descending part for specimen C2-1.5d-9.5S-25d (*Fig. 4b*) is steeper than that for the other specimen. The variation of the interfacial slip profiles can easily be easily used to verify the optimum embedded length of the different specimens. It is necessary to mention that the for the specimen with short embedded length (10d), the interface elements along the bonded length debonded quickly and the debonding propagates towards the unbounded end at very close load iterations, whereas the interface elements along the bonded length show less propagation towards failure at longer load iterations for long embedded length (25d).
3.3 FRP bar stress profiles

In this study, the FRP bar stress profiles are plotted for the same specimens used for the interfacial slip profiles. The stress values in the FRP bars along the bonded length are shown at different load levels to draw credible conclusions. As can be observed in Figs. 5a and 5b, for a given load level the stress profiles in the FRP bars decrease progressively along the length of the bonded area. This indicates that the load is being transferred from the FRP laminate to the concrete. With the load increase, the locations where the interface elements were debonded show constant FRP bar stress values. At the locations where the interface elements are removed, the stress (σ) in the FRP bar can be calculated by (σ = P/A); where P is the applied load and A is the FRP bar cross-section area (75 mm²). Similar as that observed for the FRP/concrete interfacial behaviour, the FRP bar stress profiles can be used to determine the optimum embedded length. This indicates that the FRP bar stress profiles are consistent with the interfacial slip profiles.

4. Conclusions

In this paper, a finite element model was developed to investigate the interfacial behaviour of the ETS method for FRP–concrete joints subjected to direct shear loadings. Numerous experimental data were used to calibrate the model. A key feature of the numerical model is the implementation of discrete truss elements to simulate the FRP/concrete interfacial behaviour. From this investigation, the following conclusions can be drawn:

- The comparisons between the finite element predictions and the experimental results showed that the numerical model can effectively simulate the interfacial behaviour of
the ETS method for FRP–concrete joints;
- The decay in the stress profile in the FRP bar indicated how the load was transferred between the FRP and concrete;
- The use of either the FRP/concrete interfacial slip profiles or the FRP bar stress can successfully predict the optimum bond length. The both profiles showed consistent results;
- The FRP/concrete interfacial slip profiles were greater at the loaded end and descend progressively towards the unloaded end.

5. Acknowledgements

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6. References


