FINITE ELEMENT MODELLING OF SHEAR STRENGTHENED
REINFORCED CONCRETE BEAMS

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ABSTRACT

This research aims at creating precise finite element models for FRP shear strengthened concrete beams. It is inspired by the fact that the determination of the structural behaviour of the shear strengthened beams requires advanced numerical methods of which results are substantiated by credible experimental findings. The models are developed here to assess the shear and interfacial types of behaviour of beams strengthened using the hybrid externally bonded (EB)/mechanically fastened (MF) fibre-reinforced polymer (FRP) systems. The interfacial behaviour between the hybrid EB/MF-FRP and the concrete is accounted for, here, using specially developed interface elements. A user-defined subroutine for the microplane constitutive law for the concrete material is incorporated in the model. Results are presented in terms of the ultimate load carrying capacities, load–deflection relationships, and interfacial stress/slip distributions. Numerical results are validated against available experimental results and show reasonable agreement.

KEYWORDS

FRP, RC beams, hybrid MF/EB strengthening, interfacial stresses, finite element method.

INTRODUCTION

Recently, researchers have shown an increased interest in developing numerical tools based on the finite element analysis for determining the interfacial behaviour between the FRP systems and the concrete substrate in attempts to better understand such a complex behaviour when these systems are used for strengthening reinforced concrete (RC) beams (Abdel Baky et al. 2007; Ebead and Saeed 2013a; Kotynia et al. 2008; Neale et al. 2006) and slabs (Ebead and Marzouk 2005; Ebead and Saeed 2010; Elsayed et al. 2007). This is due to the fact that the interfacial behaviour is difficult to be accurately determined using physical experiments. Externally bonded (EB) FRP strengthening technique has proven great success when used for shear capacity enhancement of RC beams. However, a major problem with such a strengthening technique is debonding. End anchorage of the FRP plates or strips is a common remedy for mitigating debonding leading to an increase in the load capacity of shear strengthened RC.

A strengthening technique that is characterized by its ductile behaviour and uses mechanically fastened (MF) FRP strips with closely spaced nails/fasteners has been introduced for concrete structures (Bank and Arora 2007; Lamanna et al. 2004; Lamanna et al. 2004). This technique utilizes simple tools to attach pultruded FRP strips to the concrete. In the work done by Lamanna and coworkers a powder-actuated type of fasteners was used to attach the FRP strips to the concrete (Lamanna et al. 2004; Lamanna et al. 2004). In other contributions, small diameter threaded fasteners were utilized for the flexural (Ebead 2011) and shear (Ebead and Saeed 2013b) strengthening of RC beams, for the strengthening of RC two-way slabs with and without cut-outs (Elsayed et al. 2009), and for the direct shear application (Elsayed et al. 2009).

The hybrid EB/MF-FRP system is in essence a combination of the externally bonded and the mechanically fastened systems. The advantage of the relatively closely spaced fasteners is the fact that these fasteners act as anchorages; therefore mitigate debonding. The experimental results indicated that the hybrid EB/MF strengthened specimens consistently showed better strength performance than those strengthened using the MF strengthened specimens and better deformational and ductility performances.
than those strengthened using the EB system for both the shear (Ebead and Saeed 2013b) and flexural (Ebead 2011) applications. Numerical finite element models have been also created and verified for the flexural application of reinforced concrete beams strengthened using the three aforementioned strengthening systems (Ebead and Saeed 2013c).

Finite element packages have been employed to model the structural behaviour of both passive as well as externally bonded FRP shear strengthened concrete beams where the bond between the FRP composites and the beams is accounted for (Chen et al. 2012; Godat et al. 2012; Godat et al. 2012; Godat et al. 2007).

In this study, special interface elements to represent the interfacial behaviour between the concrete and the FRP composites (at the bonded and mechanically fastened locations) are implemented in the models. Results are presented here in terms of the ultimate load carrying capacities, load–deflection relationships, FRP strains and interfacial stress distributions. Experimental results of RC beams strengthened using the EB-, MF- or hybrid EB/MF-FRP strengthening systems (Ebead and Saeed 2013b) are used to validate the models in terms of the ultimate load capacities and deformational characteristics. In order to enrich the discussion on the interfacial bearing stress distribution, numerical models for hypothetical cases are also created for additional MF-FRP strengthened beams. Details of the experimental work can be found in the work completed by the authors (Ebead and Saeed 2013b). Configuration of the experimentally tested strengthened beams is shown in Figure 1.

FINITE ELEMENT MODELLING

Material Modelling

The M4 version of the microplane model is used here to define the concrete constitutive behaviour (Bažant et al. 2000; Caner and Bažant 2000). The concrete characteristics obtained experimentally (Ebead and Saeed 2013b) have been used in the model. The longitudinal and transverse steel reinforcement bars are modelled as bilinear elastic-plastic materials, with the tangent modulus in the strain-hardening zone taken to be 1/100 of the elastic modulus. Properties of the steel reinforcement and the FRP strips are based on the original experimental work (Ebead and Saeed 2013b). The yield stresses for the steel reinforcement bars as given in the original reference are 522 MPa, 516 MPa, and 410 MPa for the bars of diameters of 14 mm (for the main reinforcement), 8 mm (for the top reinforcement), and 6 mm (for the transverse reinforcement), respectively. The average FRP modulus of elasticity, $E_{FRP}$, and tensile strength, $f_{FRP}$, have been taken as 72.02 GPa and 1003.4 MPa,
respectively. The FRP strip widths are 102 mm for the wide strips and 51 mm for the narrow strips and the thickness is 3.2 mm. A linear elastic orthotropic constitutive relation was assumed for the FRP composites. The elastic modulus in the direction perpendicular to the fibres was assumed to be one tenth of that in the direction of the fibres. For the FRP/concrete interface, two different interfacial models are employed in this work. The first model is the interfacial shear stress–slip model for the EB-FRP system. The second model is applied at the locations of fasteners in the MF-FRP and hybrid EB/MF-FRP system and is referred to as the bearing stress–slip model. Details of the interface models for both the externally bonded and mechanically fastened locations can be found in (Ebead and Saeed 2013c). Figure 2a and 2b show the interfacial shear stress-slip relationship adopted for EB FRP locations of the strengthened specimens and the interfacial bearing stress-slip slip relationship adopted for MF FRP counterparts. The finite element package ADINA has been used in this study.

Figure 2. Interfacial stress-slip relationship adopted for (a) the EB FRP strengthened specimens and (b) the mechanically fastened FRP strengthened specimens

Geometrical Modelling, Loading and Boundary Conditions
For the shear application, building a 3D model is essential. Therefore, investigation the behaviour of shear strengthened beams is in general more challenging and complex as far as the models created are concerned as compared to those of the flexural strengthened specimens (Ebead and Saeed 2013a). 3-D finite element model used in this investigation for a 45-degree inclined FRP strengthened specimen is depicted in Fig. 3. Three-dimensional 27-node brick elements with three degrees of freedom per node are employed to define the concrete beams. Only one half of a beam specimen is modelled due to the geometrical symmetry with respect to a longitudinal place intersection mid-width of the beam, as per Fig. 3. The steel reinforcement bars in the longitudinal and transverse directions are represented using 3-node truss elements. Each element has two translational degrees of freedom at each node. The nodes of these truss elements have full constraint compatibility with the in-common nodes of the 3-D concrete elements, i.e., full bond between the concrete and the steel reinforcement is enforced. The different FRP configurations shown in Fig. 1 are modelled. Nine-node thin shell elements with three degrees of freedom at each node are used for the FRP strips. The orthotropic nature of the FRP composites is considered in the constitutive relation of the material. Truss elements aligned in the direction of the FRP longitudinal fibres are employed to represent the FRP/concrete interface as shown in Fig. 3. Each element has two nodes, each with two degrees of freedom. The internal deformation of an element represents the interfacial slip. The area of an interface element for the bonded locations is evaluated as the area that surrounds the element it represents. For the mechanically fastened locations, the area of the interface element is represented by the contact bearing area between the fastener and the FRP. This area is equal to the FRP strip thickness multiplied by the fastener diameter. In Detail 1 and Detail 2 in Fig. 3, the constraint equations are enforced in the FRP length 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).

Loading and boundary conditions
Displacement control loading is used in the model to capture the entire load–deflection plateau. The location of the applied displacement is as shown in Fig. 3 for the different specimens. The load that causes each displacement is evaluated as the summation of the vertical reactions associated with each load step at the support locations. Contact surface is used at the support location to avoid stress concentration and to simulate the actual supports in the experimental work.
NUMERICAL RESULTS AND DISCUSSIONS

Ultimate load capacities and deflections

The experimental results of 15 specimens have been used to validate the finite element models that have accurately predicted the ultimate load capacities for the simulated beams as shown in the comparisons in Table 1. The predictions ranged between 94% and 111% with an average of 104% and a standard deviation of 4.0%, which indicates a very good agreement between the numerical and the experimental load capacities, $P_{u,\text{num.}}$ and $P_{u,\text{exp.}}$, respectively.

The graphs in Fig. 4a through Fig. 4f depict the entire load–deflection scatter for tested specimen versus the finite element predicted plateau for these specimens of Groups 1 to 3 reported in the experimental study (Ebead and Saeed 2013b). It is shown from Fig. 4a that the model accurately predicted the load–deflection curves for the reference. In the graphs of Fig. 4b through 4f the model accurately predicted the load–deflection plateau for the strengthened specimens of different configurations and schemes.

Table 1. Characteristics of specimens and experimental results

<table>
<thead>
<tr>
<th>Designations</th>
<th>Description</th>
<th>Spacing, mm</th>
<th>Width, mm</th>
<th>Num.</th>
<th>Orientati on</th>
<th>Strengthening technique</th>
<th>$P_{u,\text{exp.}}$, kN</th>
<th>$P_{u,\text{num.}}$, mm</th>
<th>$P_{u,\text{exp.}}/P_{u,\text{num.}}$</th>
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<tbody>
<tr>
<td>R</td>
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<tr>
<td>G1-BM-4W-P1-V</td>
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<td>119</td>
<td>124</td>
<td>1.02</td>
<td></td>
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<td></td>
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<tr>
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<td>115</td>
<td>121</td>
<td>1.04</td>
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<td>87</td>
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<tr>
<td>G1-B-4W-V</td>
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<td>109</td>
<td>116</td>
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<tr>
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<td>143</td>
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<tr>
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<td>G2-BM-8N-P2-V</td>
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<td>105</td>
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<tr>
<td>G3-B-6N-I</td>
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<td>111</td>
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<td>1.03</td>
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Figure 4. Experimental versus numerical comparisons of the load-deflection plateaus for specimens

**FRP/concrete interfacial behaviour**

The graphs in Figs. 5a through 5e show the interfacial shear slip profiles at failure for the hybrid EB/MF specimen. The focus here is on the effect of using the fasteners along the bonded FRP strips on the interfacial shear stress distribution. It is useful to compare Fig. 5e (for example) with Fig. 5f for the EB counterpart. This is to assess the effect of the fasteners on the interfacial shear stress distribution within the bonded locations. Hybrid EB/MF specimens consistently show lower interfacial shear stresses at the ultimate load than those for the associated EB specimens. This is in fact an indication that the fasteners in the EB/MF specimens decreased possibilities of debonding by acting as locations of anchorage.

Figure 5. Interfacial shear-slip relationships for hybrid EB/MF strengthened specimens.

**CONCLUSIONS**

Finite element models for RC beams shear strengthened using hybrid EB/MF-FRP FRP composites were created in this study. Available experimental results were used to verify the models. Discrete interface elements were used at the bonded and the mechanically fastened locations. These elements accommodated the vertical and inclined FRP strips using appropriate constraint equations. The predictions of the ultimate load capacities were fairly accurate when compared to the available experimental results for 15 specimens; those include a reference
as well as strengthened specimens. The average numerical to experimental ultimate load ratio is 1.04 with a standard deviation of 4%. This indicates the prediction quality of the model in estimating the load capacity with reasonable accuracy. In addition, the model fairly accurately predicted the entire load–deflection plateaus. In the analyses, interfacial shear stress–slip and interfacial bearing stress–slip models were successfully used to define the constitutive behaviour of the discrete interface elements to properly simulate the FRP/concrete interfacial behaviour. The main conclusions out of the comparisons among the interfacial behaviour for the different simulated beams are that: (1) fasteners provided anchorage along the bonded length that led to a profound improvement of the bond behaviour; and (2) the ductile nature of the hybrid EB/MF-FRP system allowed for high interfacial slips for the strengthened specimens. This indicates an effective utilization of the EB/MF system for beam shear strengthening.

REFERENCES


