Numerical modelling of the debonding between CFRP strips and concrete in shear tests under static loads using different approaches

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Abstract

The present paper deals with the finite element (FE) analysis of bond slip between concrete and carbon fiber reinforced polymer (CFRP) strips in a single pull-out test under static loads. The commercial software LS-DYNA is used to simulate the test set-up using a plastic damage material model and an elastic material model for the concrete prism and the unidirectional CFRP strip, respectively. The bond interface between the concrete and the CFRP strip is simulated following three different approaches using a perfect bond model, a cohesive bond model and contact algorithms based on recently developed proposed bond slip models. The numerical model is validated based on experimental test results available from literature. The debonding failure mode and the delamination loads of the CFRP strip are predicted. The numerical results show a good agreement with the experimental data using the cohesive bond model. The perfect bond model gives an overestimation of the delamination loads and of the damage distribution in the concrete prism.

Keywords: Carbon fiber reinforced polymer; cohesive bond model; debonding issues; FE analysis

Nomenclature

P_u ultimate bond strength
E_p the young's modulus of the CFRP strip
t_p the thickness of the CFRP strip
b_p the width of the CFRP strip
b_L the bonded length of the CFRP strip
L_e the effective bond length
E_c the young's modulus of the concrete
b_c the width of the concrete prism
f_c the compressive cylinder strength of the concrete
f_{ct} the tensile strength of the concrete
G_a the shear modulus of the adhesive
t_a the thickness of the adhesive
K_0 initial bond stiffness
τ_{max} maximum shear strength at the interface,
G_{cr} fracture energy

1. Introduction

Using CFRP strips as externally bonded reinforcement (EBR) in civil engineering has been demonstrated as a very efficient technique for strengthening reinforced concrete structures [1–7]. However, the prediction of the failure mode of the CFRP strips which often happens in a brittle and sudden manner is, still a challenge of this technique. Thus, it's necessary to study the bond between the CFRP strip and the concrete using bond slip tests. Several bond slip models have been developed in the last few years [8–12].

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In 1997, Maeda et al. [8] develop an empirical model based on experimental data to predict the ultimate bond strength (P_u) of the bond tests between concrete and CFRP strips, considering an effective bond length:

$$P_u = (110.2 * 10^{-6} E_p t_p) L_e b_p \tag{1}$$

with $L_e = e^{6.13-0.580 ln E_p t_p}$

In 1998, khalifa et al. [7] improve this model by including the concrete properties:

$$P_u = (110.2 * 10^{-6} \left(\frac{f'_c}{42}\right)^{\frac{2}{3}} E_p t_p) L_e b_p \tag{2}$$

with $L_e = e^{6.13-0.580 ln E_p t_p}$

Moreover, in 2001, Chen and Teng [8] found this model is invalid when $L < L_e$ and indicated that the width of the bonded strip to the concrete member is another parameter that affect the ultimate bond strength and that should be included in the bond slip model. They proposed a new model, as follows:

$$P_u = 0.427 \beta_w \, \beta_L \sqrt{f'_c} \, b_p \, L_e \tag{3}$$

Where β_L is a coefficient related to the real bond length L and β_w is a size factor related to the width of the bonded strip to the concrete prism

$$\beta_L = \begin{cases} 1 & \text{if } L \geq Le \\ sin\left(\frac{\pi L}{2L_e}\right) & \text{if } L < Le \end{cases} \qquad L_e = \sqrt{\frac{E_p t_p}{\sqrt{f_c'}}} \qquad \beta_w = \sqrt{\frac{2 - b_p / b_c}{1 + b_p / b_c}}$$

In 2005, Lu et al. [9] proposed a new equation for implementation in FE models:

$$\tau_{max} = 1.5 \beta_w f_{ct}$$

$$k_0 = \frac{1.5 \beta_w f_{ct}}{0.0195 \beta_w f_{ct}}$$

$$G_{cr} = 0.308 {\beta_w}^2 \sqrt{f_{ct}} \tag{4}$$

However, the numerical model is setup, assuming a plane stress state using a 2D model and neglecting the out of plane mode of the local bond slip model. In 2011, Obaidat et al. [13] developed a 3D finite element model including the adhesive properties in the local bond model and they proposed the following new formula:

$$\tau_{max} = 1.46 {G_a}^{0.165} {f_{ct}}^{1.033}$$

$$k_0 = 0.16 \frac{G_a}{t_a} + 0.47$$

$$G_{cr} = 0.52 {f_{ct}}^{0.26} {G_a}^{-0.23} \tag{5}$$

These previous studies show that some progress has been made to study the interface behavior between the concrete and the CFRP strip. However, the prediction of an accurate bond slip model is still in improvement due the complexity of the problem. This paper presents a 3D FE model of a bond slip test between a CFRP strip and the concrete. The debonding failure mode and the ultimate load are predicted and validated with experimental data from the literature. A comparison is made when implementing different approaches for the bond interaction is the 3D FE model.

2. Description of the experimental tests under static loads

Experimental tests of single lap bond shear tests have been performed by Mazzotti et al. [14]. Eight prisms strengthened with a CFRP strip are tested. The concrete blocks are fixed by a steel frame to prevent vertical and horizontal displacement as shown in Figure 1. For more details on the experimental setup see reference [14].

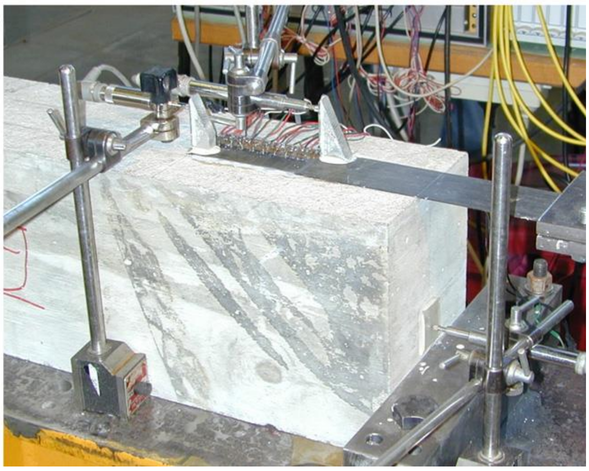


Figure. 1. Experimental setup [14].

3. Numerical analysis

A numerical analysis is conducted using the finite element software LS-DYNA. The concrete and the CFRP strip are modeled using constant stress solid elements. A plastic damage model is used to model the concrete. This material model is a three invariant model that uses three shear failure surfaces and includes damage [15]. An elastic material model is used to model the unidirectional CFRP strip. To model the interface between the concrete and the CFRP strip, cohesive elements are used based on the local bond slip model proposed by Obaidat et al. [12] as shown in Figure 2.

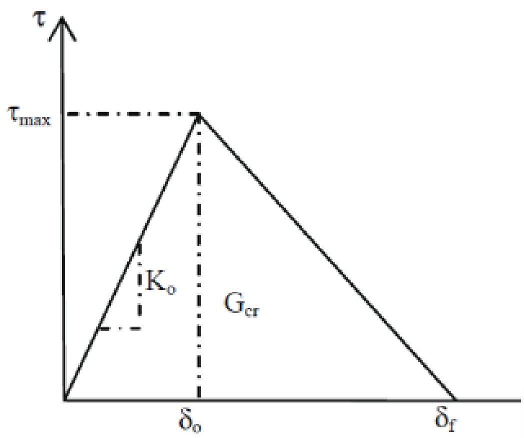


Figure. 2. Local bond slip model

The cohesive model defines surfaces of separation and describes their interaction by defining a bilinear traction displacement softening law [16]. The advantage of using this cohesive model is that the damage of the interface is considered in three different modes; mode I (tensile), mode II (shear) or mode III (out of plane tearing) as shown in Figure 3.
Implementing the cohesive elements, for mode I a bilinear law in relation to the concrete tensile strength and fracture energy is considered with values………………
For the mode II law, the model of Figure 2 is considered with values………… following [12].

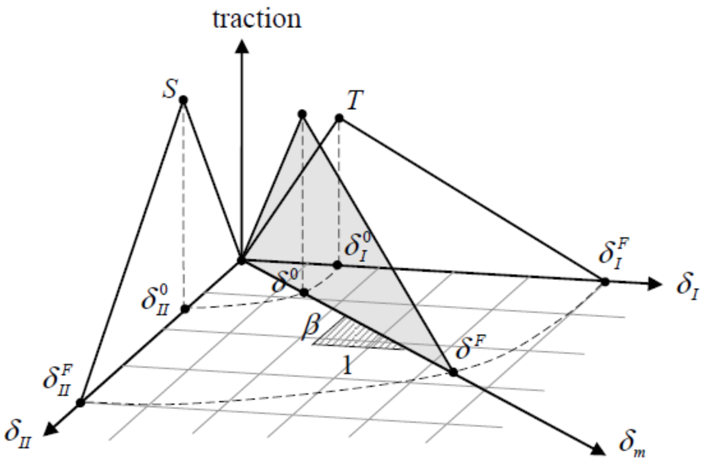


Figure. 3. Mixed mode traction-separation law [16]

The initiation of debonding occurs when the normal and shear tractions attained their respective tensile or shear strength respectively and the interface stiffness is then gradually reduced to zero when the complete fracture occurs at δ_F [16].

A 3D finite element model of a bond shear test using cohesive elements to model the interface between the concrete and the CFRP strip is shown in Figure. 4.

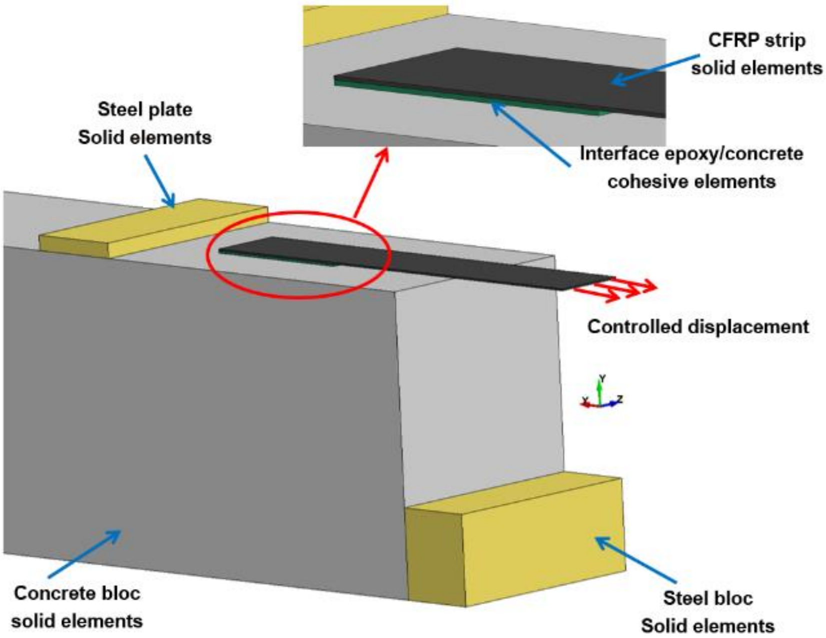
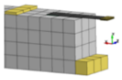
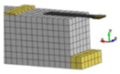
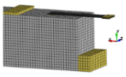
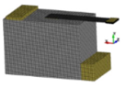


Figure. 4. FE model of the pullout test

A convergence mesh study is carried out. The delamination load is predicted and compared. It shows that the simulation converges with a mesh size of 10 mm as shown in Table 1.

Table 1. Convergence mesh study

	Mesh size (mm)	*Elements*	*Run time (minutes)*	*Ultimate load (kN)*
	50	221	1	0.8
	25	1289	5	21.4
	10	18 755	46	16.4
	5	75 040	120	16.25

4. Comparison of the FE models with the experimental data from the literature

During the experimental tests, a load cell is used to measure the applied force until the debonding of the CFRP strips. A comparison between the experimental data of the delamination loads and the numerical results for different bond lengths are shown in Table 2 and Figure 5. The delamination loads found by the numerical model are in a good agreement with the experimental data.

Table 2. Experimental and numerical delamination loads

Specimens		Exp data P_{max} (kN)	Num data P_{max} (kN)	Ratio (Num/Exp)
Bp = 50 mm	BL = 50	14	16.4	1.17
	BL = 100	22.3	23.8	1.06
	BL = 200	19.8	24.2	1.22
	BL = 400	23	25.4	1.10
Bp = 80 mm	BL = 50	22	25.2	1.14
	BL = 100	30.5	29.5	0.96
	BL = 200	33	33.2	1.01
	BL = 400	37	38.2	1.03

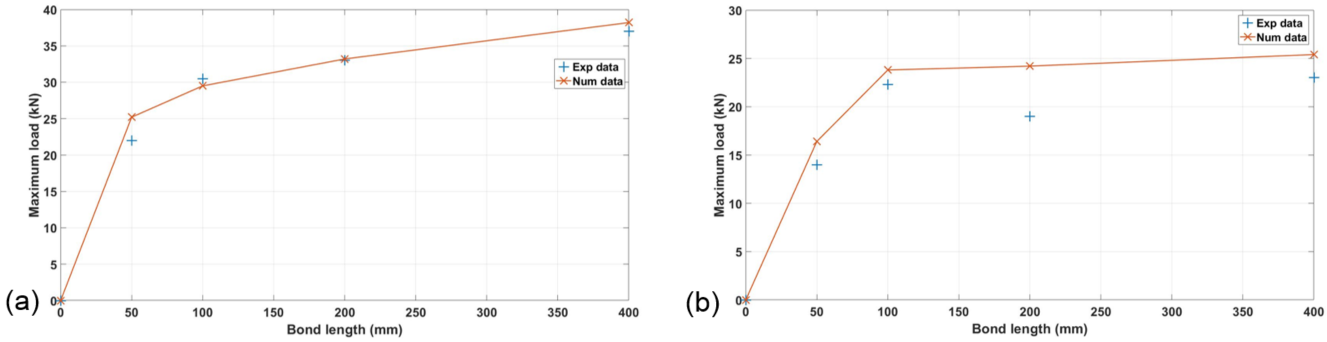


Figure. 5. (a) Delamination loads vs. bonded length for bp = 50 mm; (b) Delamination loads vs. bonded length for bp = 80 mm

5. Several approaches to model the interface between concrete and CFRP strip

To model the interface between the concrete and the CFRP strip, three approaches are used. As a first approach, a perfect bond is assumed between the concrete and the CFRP strip which means that the CFRP strip has perfect and permanent bond to concrete without any failure. For the second approach, the cohesive elements are used as discussed in section 3 based on the Lu et al. equation [11].
The final approach is using tiebreak contact based on the Cheng and Teng equation [10]. The command tiebreak contact allows the modeling of connections which transmits both normal and shear stresses with a failure criteria [16]. Failure of contact between the FRP composite and concrete surface occurs if:

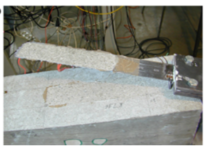
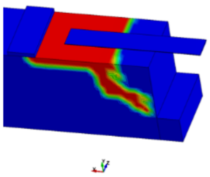
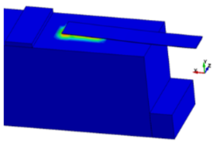
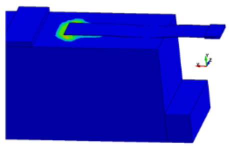
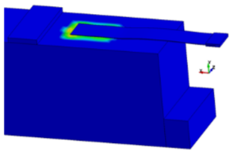
$$\left(\frac{|\sigma_n|}{NFLS}\right)^2 + \left(\frac{|\sigma_s|}{SFLS}\right)^2 \geq 1$$

This is a special contact option in which the variables **NFLS** and **SFLS** are the tensile strength of the concrete and ultimate bond strength based on the Cheng and Teng equation (see equation 3), respectively. σ_n and σ_s are the normal and shear stresses at the interface.

6. Debonding process under static loads

The debonding of the CFRP strip starts from the fixed end to the free end of the CFRP in a brittle and sudden manner. Table 3 summarizes the delamination loads and the failure modes predicted by the different approaches. The perfect bond algorithm cannot predict the debonding of the CFRP strip and should be used only in the ascending branch of the local bond slip model (elastic behavior without prediction of failure). Moreover, the perfect bond gives an overestimation of the delamination loads. The tiebreak contact calibrated with Chen and Teng formula (see equation 3) behaves as a perfect bond until the failure criteria is reached based on the shear and normal stresses implemented in the FE model. An accurate lower bond prediction of the failure load is obtained, the cohesive elements based on the fracture energy of the bond interface gives also an accurate prediction, especially with the bond model of Obaidat et al. [12].

Table 3. Comparison of the delamination loads using several bond slip models

Exp data [10] P_{max}	Perfect bond	Tiebreak contact using Chen and Teng approach	Cohesive elements using Lu et al. approach	Cohesive elements using Obaidat et al. approach
22.3 kN	27.4 kN	20.7 kN	25,3kN	23.8 kN
				
Debonding	No debonding	Debonding	Debonding	Debonding

7. Conclusions

This study presents a numerical investigation of the bond behavior between concrete and CFRP strips under shear tests. The numerical models are compared with experimental tests conducted by Mazzotti et al. [14]. The debonding failure mode and the delamination loads are predicted using different contact approaches. Using a perfect bond contact between concrete and CFRP gives an overestimation of the delamination loads and of the damage distribution in the concrete prism. This contact algorithm is not able to predict the debonding. Using cohesive elements to model the interface, the predicted delamination loads based on Lu et al. [11] formula is higher than the experimental data. This is due to the overestimation of the bond shear strength τ_{max} based only on the concrete properties. However, the Obaidat et al. approach [13] is in good argument with experimental results in terms of ultimate load and failure mode.

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