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NUMERICAL ANALYSIS OF DEBONDING BETWEEN CFRP STRIPS AND CONCRETE IN SHEAR TESTS UNDER STATIC AND BLAST LOADS

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ABSTRACT

The present paper deals with the finite element (FE) analysis of the bond slip between concrete and carbon fiber reinforced polymer (CFRP) strips in a single bond shear test under static loads and in a double bond shear test under blast loading. A plastic damage material model and an elastic material model are used to model the concrete prism and the unidirectional CFRP strip, respectively. The bond interface between concrete and CFRP strip is simulated using a cohesive bond model. For the static loads, the numerical model is validated with experimental tests available in the literature. The debonding failure mode, the delamination loads and the strain distribution along the CFRP strip are predicted. The numerical results show a good agreement with the experimental data using the cohesive bond model. For the blast loads, the validated cohesive bond model is used. A parametric study with respect to the width and the length of the CFRP is conducted. Moreover, the reflected pressure and impulse are varied to highlight the effect of the propagation of the blast wave in the debonding process under blast loads.

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1. INTRODUCTION

1.1. An overview of the previous studies

Difficulties and challenges to model the bond between carbon fiber reinforced polymer (CFRP) strips and concrete under blast loads are reported in literature. The bond strength is significantly affected by CFRP width, strength, thickness, adhesive properties, concrete strength, surface preparation and quality of the workmanship. All these parameters are subject to some variability. Muszynski et al. [1] measured a bond strength between fiber reinforced polymer (FRP) and concrete equal to 2.8 MPa when they tested two concrete structures retrofitted with composite materials subjected to 830 kg of TNT at a stand-off distance of 14.5 m. Mutalib et al. [2] compared different bonding strengths for numerical analyses of FRP-composite-strengthened reinforced concrete (RC) walls with or without additional anchors to examine the structural response under blast loads. They found that FRP strengthening increases the RC wall blast resistance capacity and the bond strength plays a significant role in maintaining the composite action between FRP and concrete. These previous studies show that some progress has been made to study the interface behaviour between concrete and CFRP strip under blast loads. However, the prediction of an accurate bond slip model under blast loads is still subject to improvement due the complexity of the problem. In this paper, a FE model is developed for blast analysis using nonlinear finite element (FE) software LS-DYNA. Numerical analysis is performed using cohesive elements to model the bond between CFRP strips and concrete. The numerical results are validated with previously conducted experiments under static loads and the validated FE model is applied to blast loads. Further experimental validation of the model by means of double bond shear tests under blast loads is work under progress [3].

1.2. Methodology of the research

This paper is divided into two parts. The first part deals with the FE analysis of bond slip between the concrete and the CFRP strip in a single bond shear test under static loads. The numerical model is validated based on experimental test results available from the literature [4]. The debonding failure mode, the delamination loads and the strain distribution along the CFRP strip are predicted and validated with the experimental results. In the second part, after the validation of the model under the static loads, the FE model is tested under blast loads and a parametric study is conducted with respect to the width and the length of the CFRP strip. Moreover, the debonding process under blast loads is discussed and the parameters that affect the bond strength under blast loads are highlighted.

2. BOND SLIP EVALUATION BETWEEN CFRP AND CONRETE UNDER STATIC LOADS

2.1. Experimental setup

Experimental tests of single lap bond shear tests have been performed by Mazzotti et al. [4]. Eight prisms strengthened with a CFRP strip are tested with varying width (b_f) and bond length (L) of the CFRP strip. Two strip widths (b_f =50mm and 80mm) and four bond lengths (L= 50mm, 100mm, 200mm, 400mm) are used. The concrete prisms are fixed with a steel frame to prevent vertical and horizontal displacement as shown in Figure 1. For more details on the experimental setup see reference [4].

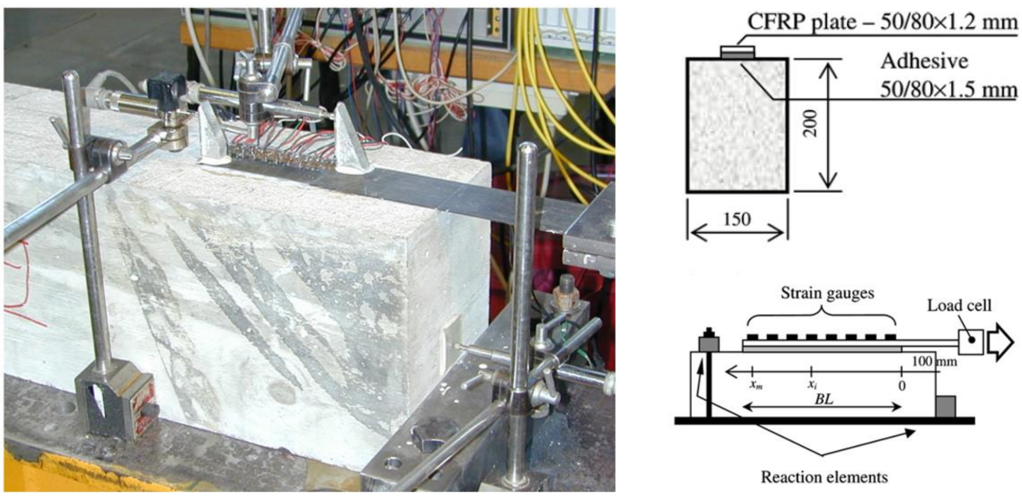

Figure 1. Experimental setup [4]

2.2. Finite elements modelling

2.2.1. Material models

A numerical analysis is conducted using FE modelling. The concrete and the CFRP strip are modelled 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 [5]. An elastic material model is used to model the unidirectional CFRP strip. The material properties of the concrete, the CFRP strips and the adhesive are shown in Table 1.

Table1. Static material properties of the concrete, CFRP strips and epoxy

Material	Young's modulus (MPa)	Compressive strength (MPa)	Tensile strength (MPa)	Thickness (mm)	Width (mm)
Concrete	30700	52.6	3.8	-	-
CFRP strips	195200	-	2800	1.2	50
					80
Epoxy	12840	30.2	70	1.5	50
					80

2.2.2. Modelling of the interface using cohesive elements

Previous experimental shear tests between the CFRP strip and the concrete under static loads have shown that usually debonding occurs at the adhesive-concrete interface with a thin layer of concrete remaining attached to the FRP [4,6,7]. Moreover, they concluded that the main parameters that affect the bond strength in a bond shear test are the concrete strength, the bond length, the FRP to concrete width ratio, the stiffness of the FRP and the adhesive as well as the strength of the adhesive. All these aspects are considered to model the interface between the concrete and the CFRP strip using cohesive elements. The behaviour of these cohesive elements can be based on the local bond slip model proposed by Obaidat et al. [8] based on the following formula:

$$\tau_{max} = 1.46 G_a{}^{0.165} f_{ct}{}^{1.033} \quad (1a)$$

$$k_0 = 0.16 \frac{G_a}{t_a} + 0.47 \quad (1b)$$

$$G_{cr} = 0.52 f_{ct}{}^{0.26} G_a{}^{-0.23} \quad (1c)$$

Where τ_{max} is the maximum shear strength at the interface, G_a is the shear modulus of the adhesive, f_{ct} is the tensile strength of the concrete, K_0 is the initial bond stiffness, t_a is the thickness of the adhesive and G_{cr} is the fracture energy. Figure 2 shows the numerical bond interface between concrete and CFRP strips using cohesive elements including the properties of the concrete and the adhesive.

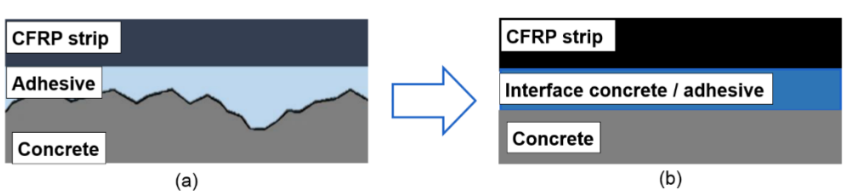

Figure 2. (a) real case of a bonded CFRP plate to concrete; (b) numerical modelling of the bonded CFRP plate to concrete using cohesive elements

The cohesive model defines surfaces of separation and describes their interaction by defining a bilinear traction displacement softening law [9]. The advantage of using this cohesive model is that the damage of the interface is considered as a mix mode of two different modes; mode I (tensile), mode II (shear) as shown in Figure 3.

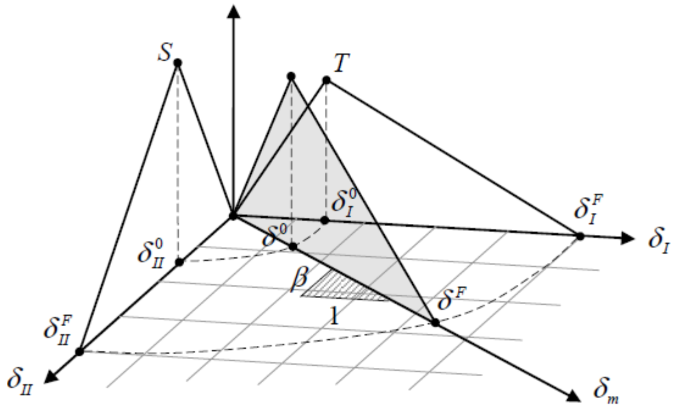

Figure 3. Mixed mode traction-separation law [9]

Where T and S are the tensile and the shear stresses of the concrete for mode I and mode II and δ^0 and δ^F are the initial relative displacement and ultimate relative displacement at failure. A 3D finite element model of a pull-out test using cohesive elements to model the interface between the concrete and the CFRP strip is shown in Figure 4.

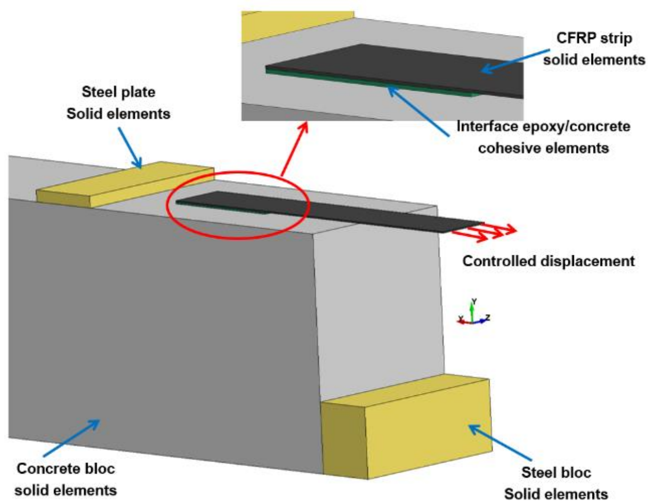

Figure 4. FE model of the pullout test

2.3. Validation of the FE model

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. The delamination loads found by the numerical model are in close agreement with the experimental data.

Table 2. Comparison between the experimental and numerical delamination loads

Specimens		Exp data P_u(kN)	Num data P_u(kN)	Ratio (Num/Exp)
b_f= 50mm	L=50mm	14.0	16.4	1.17
	L=100mm	22.3	23.8	1.06
	L=200mm	19.8	24.2	1.22
	L=400mm	23.0	25.4	1.10
b_f = 80mm	L=50mm	22.0	25.2	1.14
	L=100mm	30.5	29.5	0.96
	L=200mm	33.0	33.2	1.01
	L=400mm	37.0	38.2	1.03

Moreover, the distribution of the longitudinal strain along the bonded length are predicted by the FE model and compared to the experimental data as shown in Figure 5. Increasing the bonded length of the CFRP strips makes the debonding process less brittle and the distribution of strain along the bonded area uniform until the debonding. Also, a plateau of strain is observed when the bonded length exceeds the effective bonded length. These results are also reported in other studies [6,10,11].

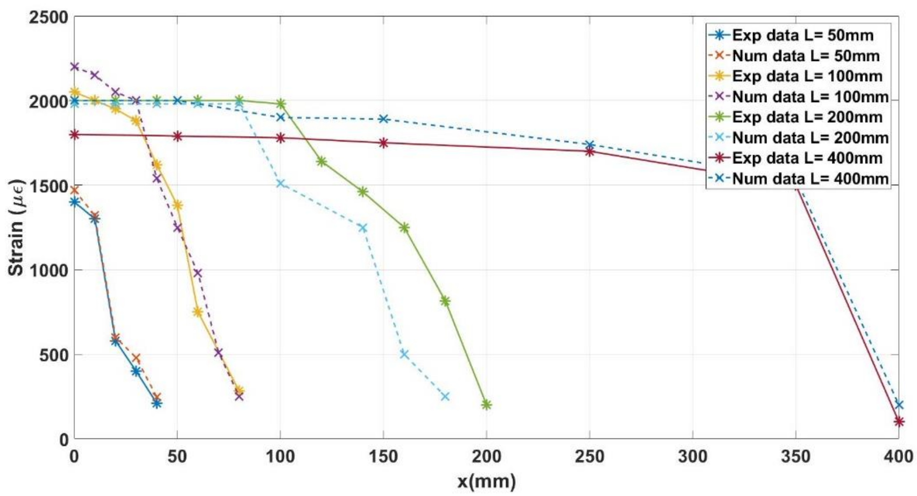

Figure 5. Evolution of the strain in the CFRP strip (b_f= 50mm) for different bond lengths at the delamination stage

2.4. Debonding process under static loads

The debonding of the CFRP strip starts from the fixed end to the free end of the CFRP strip in a brittle and sudden manner. Increasing the load at the fixed end of the CFRP strip generates a high concentration of shear stress at the interface between the CFRP strip and the concrete. Figure 6 shows the debonding process at different time stage using the cohesive elements for the concrete prism with a bond length L= 400mm and a width b_f= 50mm. Where the damage evolution index (D_{ei}) is shown at different level of loading. Three damage levels are considered: low damage ($0.33 < D_{ei} \leq 0.67$); moderate damage ($0.67 < D_{ei} \leq 1.3$); heavy damage ($1.3 < D_{ei} \leq 2$).

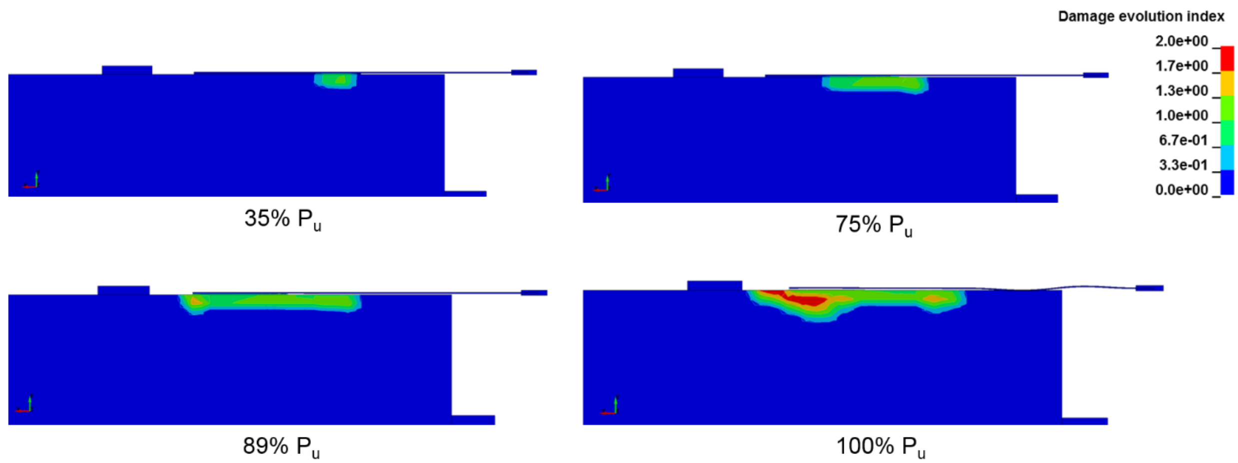

Figure 6. Evolution of the damage at the interface during the debonding process (b_f= 50mm; L= 400mm)

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3. NUMERICAL INVESTIGATIONS UNDER BLAST LOADING

3.1. Finite element model of double bond shear test under blast loads

After the validation of the FE modes under static loads, the FE models is tested under blast loads using the same contact to model the interface between the CFRP strip and the concrete (see section 2.2.2). To consider the effect of the propagation of the blast wave at the interface between the CFRP strip and concrete, the CFRP strips are modelled using solid elements to include the out of plane stresses. A uniform distribution of the reflected pressure is assumed on the steel plate fixed at the centre of the concrete prism as shown in Figure 7.

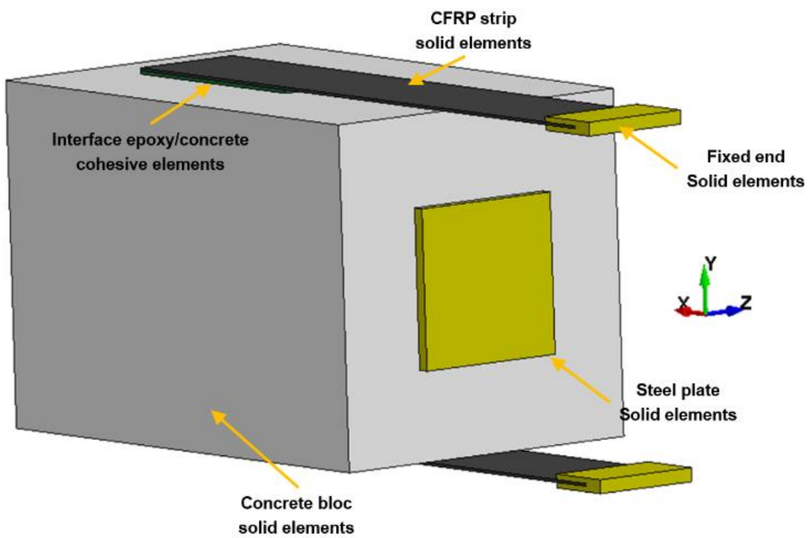

Figure 7. FE model of a double bond shear test under blast loads

3.2. Parametric study

A parametric study is conducted with respect to the width and the length of the CFRP strips with increasing reflected pressure and impulse to reach the debonding. The delamination load is predicted by the FE model and compared to the static loads. For increasing width and length of the CFRP strip, the delamination loads increase under blast loads. Moreover, increasing the bond length of the CFRP strip adds stiffness to the retrofitted specimens to better resist to the blast loads due to the increase of the active zone that resist to the dynamic stresses caused by the displacement of the concrete prism. A dynamic increase factor is observed between the delamination loads under static loads and dynamic loads as shown in Table 3.

Table 3. Numerical prediction of the delamination loads with different width and length of the CFRP strips

FE models		Static data P_u (kN)	Reflected pressure P_r (MPa)	Reflected impulse I_r (Pa.s)	Blast data P_u (kN)	Ratio (blast/static)
b_f= 15mm	L= 50mm	5.5	10.0	2000	5.9	1.07
	L= 100mm	6.5	13.8	2250	6.7	1.04
	L= 200mm	6.9	13.8	3500	7.4	1.06
b_f= 50mm	L= 50mm	16.4	13.8	4500	21.9	1.33
	L= 100mm	23.8	23.8	6250	26.6	1.11
	L= 200mm	24.2	50.0	8750	25.3	1.04

3.3. Debonding process under blast loads

Under static loads, bond slip tests between concrete and CFRP strip are mainly governed by mode II (in plane shear). However, for blast loads the two different modes should be included as the propagation of the blast wave within the concrete causes out of plane stresses at the interface between the concrete and the CFRP strip. When the energy released by the explosion exceeds the fracture energy at the interface, debonding occurs [12]. Due the blast response, the concrete prisms are moving and vibrating, creating dynamic stresses at the interface between concrete and CFRP strips [13].

4. CONCLUSIONS

This paper is divided into two parts. The first part deals with a numerical investigation of the bond behaviour between concrete and CFRP strip under static loads. The numerical model is compared with experimental tests conducted by Mazzotti et al. [4]. The debonding failure mode and delamination loads are predicted using cohesive elements to model the interface. The FE model based on Obaidat et al. approach [8], which considers both the concrete and the adhesive properties, is in good agreement with experimental results in terms of ultimate loads and failure mode.

Under blast loading, increasing the width and the length of the CFRP strips increases the delamination loads. The debonding between CFRP strip and concrete occurs due a combined effect. Mainly, concentration of the shear and normal stresses caused by (1) the propagation of the blast wave within the concrete and (2) the displacement of the concrete prism. As such, fracture energy under mixed mode (normal and shear stresses) is governing. Despite the more complex interface stresses under blast loads, a dynamic increase factor is observed.

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