

Numerical analysis of retrofitted RC slabs with CFRP strips under blast loading

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Abstract

This paper investigates the effectiveness of carbon fiber reinforced polymer (CFRP) as externally bonded reinforcement (EBR) to improve the flexural resistance of reinforced concrete (RC) slabs under blast loads. Three simply supported RC slabs are subjected to blast loading using an explosive driven shock tube (EDST). The obtained experimental results of the RC slabs without and with EBR are presented and discussed with the aim of evaluating the influence of EBR on the blast response of the RC slabs. A numerical analysis is carried out using the finite element software LS-DYNA to complement the experimental results. The bond interface between CFRP strips and concrete is simulated with a specific contact algorithm including the normal and shear stresses at the interface with failure criteria. The numerical analysis shows good agreement with the experimental results for the maximum deflection at the mid span of the slabs and good prediction of the distribution of cracks. CFRP strips as EBR increase the flexural capacity and the stiffness of the slabs. A reduction in the blast induced maximum deflection is recorded for the slabs retrofitted with CFRP strips.

Keywords: RC slab, Blast loading, Carbon fiber reinforced polymer strips, Numerical analysis.

1. Introduction

Difficulties and challenges to model the bond between CFRP strips and concrete are reported in literature. The FRP-concrete bonding strength is significantly affected by epoxy strength, epoxy thickness, concrete surface preparation and quality of the workmanship. All these parameters are subject to some variability. Muszynski et al. [1] measured a bond strength between 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. Sayed-Ahmed [2] used 32 MPa and 29.4 MPa for normal and shear strength, respectively; for epoxy in a numerical analysis investigating the effect of bonding CFRP strips to steel I-beams under static loads. Mutalib et al. [3] compared different bonding strengths for numerical analyses of FRP-composite-strengthened 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. In this study, a quarter model of a RC slab is developed for blast analysis using finite element (FE) software LS-DYNA. Numerical analysis is performed using a specific contact algorithm to model the bond between CFRP strips and concrete. The numerical results are validated with previously conducted experiments [4].

2. Description of the blast tests

In order to verify the validity of the numerical model, the experimental tests of RC slabs retrofitted with CFRP strips performed by Maazoun et al. [4] are simulated. Three RC slabs are tested; the slab A1 is used as a reference specimen, the slabs A2 is retrofitted with 4 CFRP strips and the slab A3 is retrofitted at both sides with 2 CFRP strips. Fig. 1 shows the tested specimens. The material properties of the test specimen are reported in Table 1.

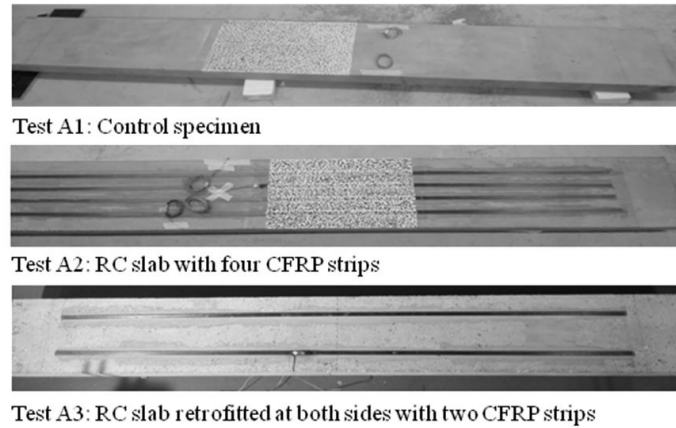


Fig. 1. Experimental specimens

Table 1 Material parameters used in the simulations

Concrete	Density (kg/m ³)	2400
	Compressive strength (MPa)	54
	Young's modulus (GPa)	36.4
	Poisson's ratio	0.2
Steel reinforcement	Density (kg/m ³)	7850
	Yield strength (MPa)	534
	Young's modulus (GPa)	208
	Poisson's ratio	0.29
CFRP strips	Density (kg/m ³)	1600
	Thickness (mm)	2.5
	Length (m)	1.98
	Tensile strength (MPa)	2800
	Young's modulus (GPa)	165
	Ultimate strain (%)	1.7
Epoxy	Compressive strength (MPa)	70 (after 7 days)
	Tensile strength (MPa)	30
	Young's modulus (GPa)	12.8
	Ultimate strain (%)	0.9

An explosive driven shock tube (EDST) is used to generate a reflected pressure and impulse equal to 3 MPa and 1150 Pa.s. A series of experimental tests are performed using the experimental setup shown in Fig. 2.

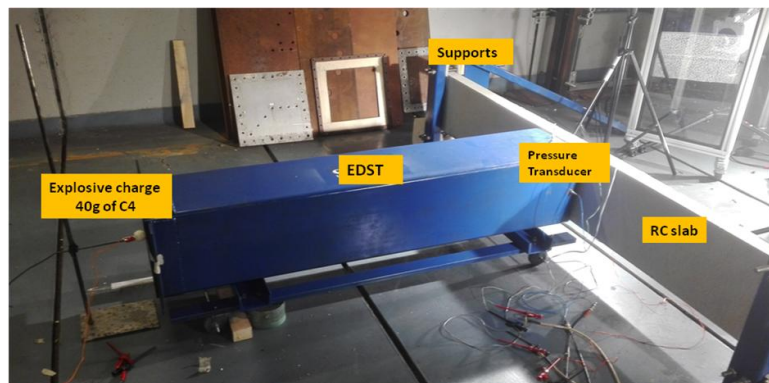


Fig. 2. Experimental setup for blast tests

3. Finite element analysis of reinforced concrete slabs

3.1 Finite element model

A three-dimensional (3-D) finite element model of the RC slab is developed in LS-DYNA; the analysis is performed using the LS-DYNA explicit solver. An eight-node solid element with integration scheme is used to model the concrete elements in the analysis. A two-node beam element is used to model the steel reinforcement in the concrete. The element formulation for the beam element is Hughes-Liu with cross-section integration. The RC slab has a thickness of 60 mm, width of 300 mm and length of 2000 mm between the supports. The reflected pressure recorded at the end of the tube is defined as a curve and applied at the mid span of the slab using the keyword "segment-set" to define the blast loaded area on the concrete.

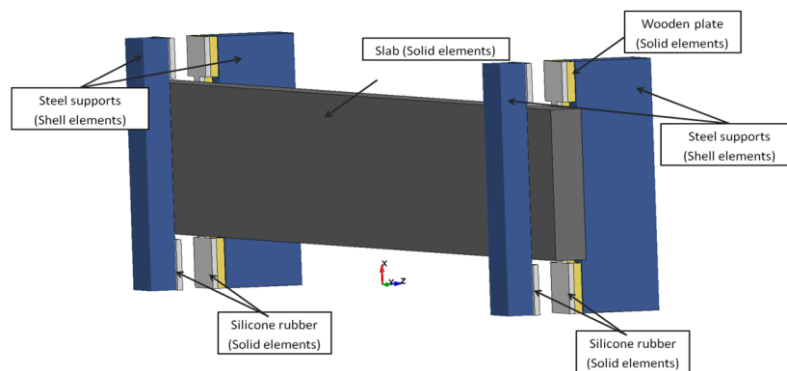


Fig. 3. A schematic representation for the numerical model of RC slab

3.2 Material models for concrete, steel and CFRP strips

Two material models for concrete are studied. The Winfrith concrete model 'MAT085' and the Concrete Damage Release 3 'MAT072R3'. The Concrete Damage Release 3 is a three invariant model that uses three shear failure surfaces and includes damage and strain rate effects, while the Winfrith model is a basic plasticity model with a constitutive model able for cracking, crushing and shear retention depending on crack width and aggregate size [5].

The steel rebars are modeled using a linear plastic model 'MAT024'. This material model represents steel reinforcement behavior, with plastic deformation, strain rate effects and failure [5].

The material model composite damage 'MAT054' is used to model the CFRP composite. The MAT054 is a progressive failure model which is designed to handle orthotropic materials [5] such as unidirectional laminate. The failure criteria of composite materials used in the analysis is the one proposed by Chang and Chang (1987) [6].

3.3 Tiebreak contact definition

In order to simulate the bond between the CFRP strips and the concrete, the tiebreak contact in LS-DYNA is used to model the adhesive. The command 'tiebreak contact' allows the modeling of connections which transmits both compressive and tensile forces, with the option to set a failure criteria and whereby the sliding between the elements is neglected [5]. This is a special contact option in which the variables **NFLS** and **SFLS** are the tensile and shear failure stresses of the interface, respectively. Failure of contact between the FRP composite and concrete surface occurs if:

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

in which σ_n and σ_s are the normal and shear stresses at the interface, respectively.

4. Validation of the FE models with experimental data

For the control specimen A1, a maximum deflection of 34.2 mm is measured and flexural cracks are observed at both sides of the slabs. The used material models of concrete are shown to be valuable for evaluating the blast response of test A1 (good prediction in the maximum deflection at the midspan of the slab). The crack distribution at both sides of the specimen A1 found by the Winfrith concrete model (Mat 85) is in good agreement with the experiments. Moreover, the damage evolution predicted by the Concrete Damage Release 3 (Mat 72R3) is shown also in Fig. 4.

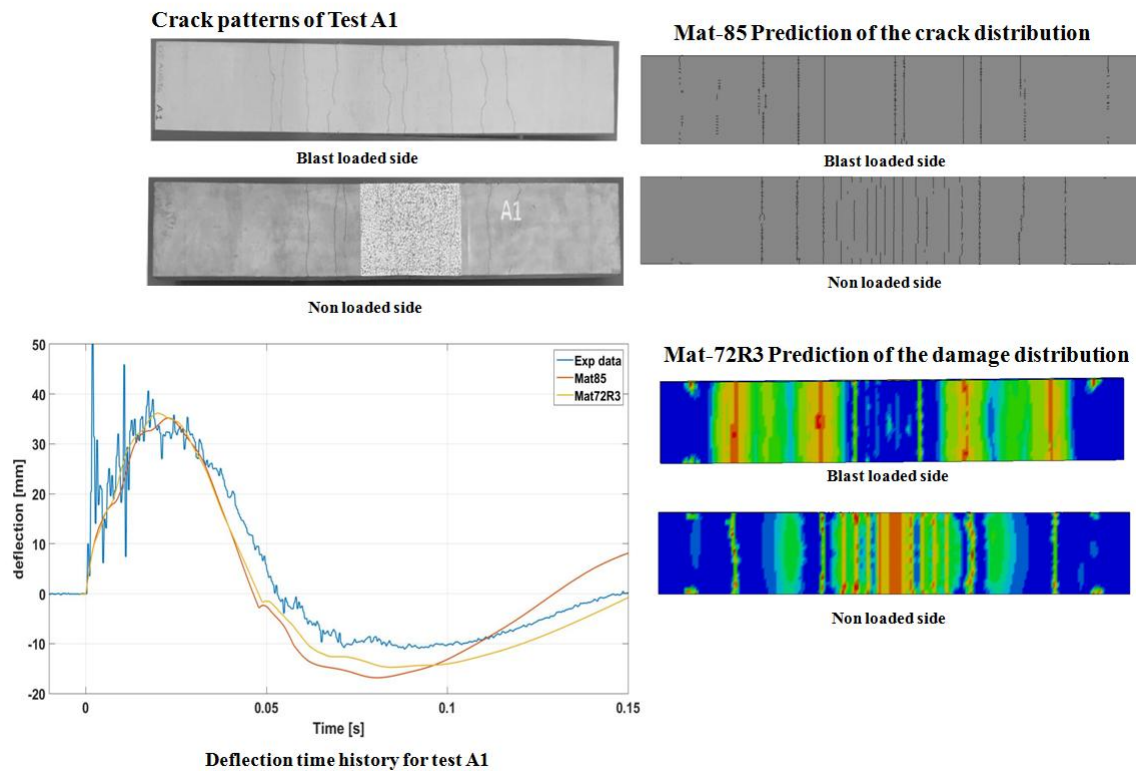
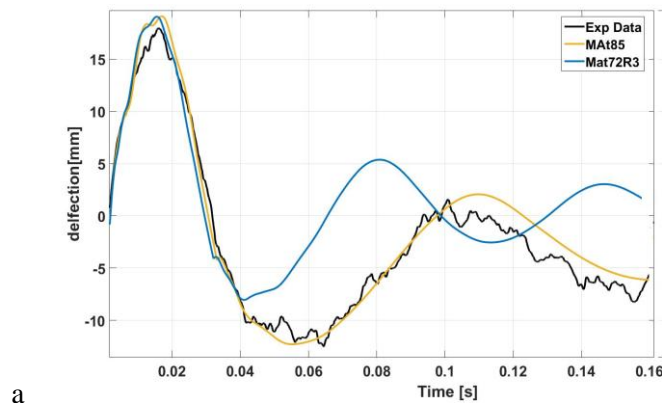


Fig. 4. Validation of the numerical models with experiments

For the specimens A2 retrofitted with four CFRP strips and A3 retrofitted at both sides with two CFRP strips, a reduction of 47% and 32% in the maximum deflection is recorded respectively. No cracks are observed on the non loaded side for the both blasted specimens. The Winfrith concrete model shows a better prediction of the blast response of the retrofitted specimen in comparison the concrete damage release 3 model which has a stiffer response as shown in Fig. 5.



a

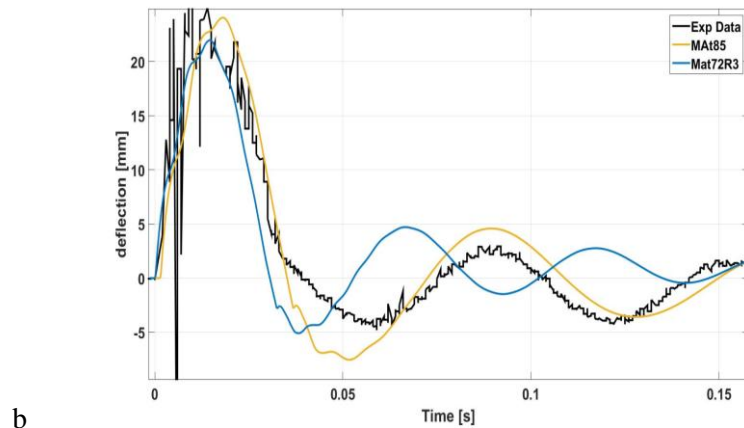


Fig. 5. (a) Deflection time history for specimen A2; (b) Deflection time history for specimen A3

5. Conclusion

A numerical model has been implemented for RC slabs retrofitted with CFRP strips under blast loads using a specific contact algorithm 'tiebreak contact' to model the interface between CFRP strips and concrete. The numerical analysis shows good agreement with the experimental results for the maximum deflection at the mid-span of the slabs and good prediction of the distribution of cracks. CFRP strips as EBR increase the flexural capacity and the stiffness of the slabs. A reduction in the maximum deflection is recorded for the slabs retrofitted with CFRP strips.

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