New technique to protect RC slabs against explosions using CFRP as externally bonded reinforcement

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Abstract

In recent years, numerous explosions related to industrial accidents and terrorist attacks causing loss of life and severe damage to infrastructures have occurred all over the world. However, existing reinforced concrete (RC) structures are not designed to resist to blast loads and could collapse after the incident. As a consequence, the emerging challenge of critical infrastructure protection has been recognized and nowadays there is a desire to upgrade the blast resistance of existing RC structures. The present paper provides an experimental and numerical analysis of the efficiency of using carbon fiber reinforced polymer (CFRP) as externally bonded reinforcement (EBR) on RC slabs under blast loads in order to increase the flexural resistance of the structure. Moreover, the effect of the propagation of the blast wave within the retrofitted specimens and how it affects the bond interface between the CFRP strip and concrete during the blast loading is discussed.

Keywords: Carbon fiber reinforced polymer; Blast loading; Experimental analysis; Numerical simulation;

INTRODUCTION

Several experimental studies under blast loading report difficulties in getting reliable experimental results because of the generated light and the smoke of the explosion and generally experimental results yielded by these tests are qualitative in nature. In order to avoid this problem, an experimental setup using an explosive driven shock tube (EDST), digital image correlation (DIC) measurement and strain gauges is developed to record the maximum deflection, the evolution of strain in the steel reinforcement, concrete and CFRP strips simultaneously during the explosion. A detailed numerical model is developed to predict the blast response of the non-retrofitted and retrofitted RC slabs. After the validation of the finite element (FE) model, a parametric study with respect to CFRP width and thickness is performed in order to evaluate their effect on the blast response of the RC slabs.

EXPERIMENTAL ANALYSIS

An experimental program is performed in order to investigate the feasibility of strengthening RC slabs for blast loading by means of EBR and to study the blast response of the strengthened RC slabs. Five simply supported slabs with a span of 2 m between the axis of the supports are tested under an explosive charge. One of the slabs is used as a reference specimen and the remaining slabs were strengthened in flexure with different ratios of carbon fiber reinforced polymer (CFRP). Five specimens were casted in laboratory conditions with the following dimensions: length 2.3 m, width 0.3 m and thickness 0.06 m. Figure 1 shows the slab dimensions and reinforcement details

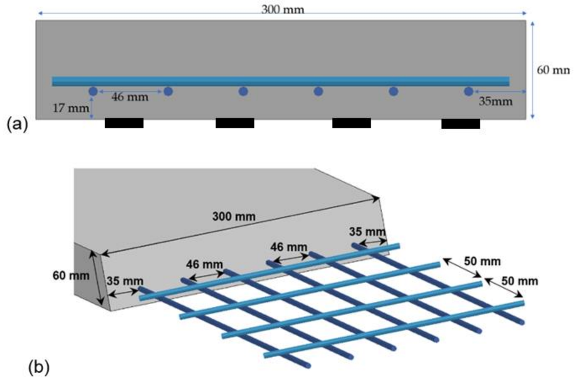

Figure 1. RC slab details

For the CFRP strips, unidirectional Sika CarboDur S1525 plates has been used with the following dimensions: length 1.96 m, width 15 mm and thickness 2.5 mm. According to technical data provided by the supplier, the CFRP strips have a density of 1500 kg/m^3 and a carbon fiber volumetric content equal to 70 %. Table 1 summarizes the static material properties of the steel reinforcement, the epoxy and the CFRP strips, as obtained from the manufactures.

Table 1.Static material properties

Type	Nominal dimensions (mm)	Yield strength (MPa)	Tensile strength (MPa)	Ultimate strain (%)	Young-modulus (GPa)
Rebars S500	Φ 6	500	570	10	210
Carbodur S1525	15x2.5x1960	-	2800	1.7	165
Sikadur-30	~ 1 mm thick	-	30	0.9	12.8

The concrete strength f_{cm} (average of 3 cubes with side length 150mm) at 73 days and 107 days age (moment of testing the slabs), is given in Table 2. Five RC slabs are tested: slab A1 is used as a reference specimen; slabs A2, A3 and A4 are retrofitted with 1 CFRP strip, 2 CFRP strips and 4 CFRP strips, respectively; and slab A5 is retrofitted at both sides with 2 CFRP strips. Figure 2 shows the specimens before testing. The blast load is applied on the opposite side where the CFRP is bonded. The application of the FRP is performed in accordance with the procedure described in fib [1] (see Appendix A). A first important aspect is the preparation of the concrete substrate which has been roughened using a diamond disc grinder, to expose the aggregates, providing an enhanced bond with the FRP and to activate the tensile strength of the concrete in an optimum way. Before the adhesion of the FRP strips, the strips are cleaned with acetone to remove any traces of grease and dust. The epoxy is mixed in the specified proportions. A thin layer of adhesive is applied on the roughened and cleaned concrete surface and a layer of adhesive is applied on the FRP strip in a dome shape, reducing the risk of forming voids. Then, the strip is placed on the concrete surface and a rubber roller is used to apply a pressure on the strip to ensure an intimate contact.

Table 2. Test parameters of RC strengthened in flexure

Spec	Type of strengthening	Age at test (days)	f_{cm} (N/mm^2)	ρ_s (%)	ρ_f (%)
Test A1	Reference	74	56.3	1.41	-
Test A2	Retrofitted with 1 CFRP strip	74	59.8	1.41	0.31
Test A3	Retrofitted with 2 CFRP strips	74	51.0	1.41	0.62
Test A4	Retrofitted with 4 CFRP strips	74	50.0	1.41	1.25
Test A5	Retrofitted with 2 CFRP strips at both sides	106	53.7	1.41	1.25

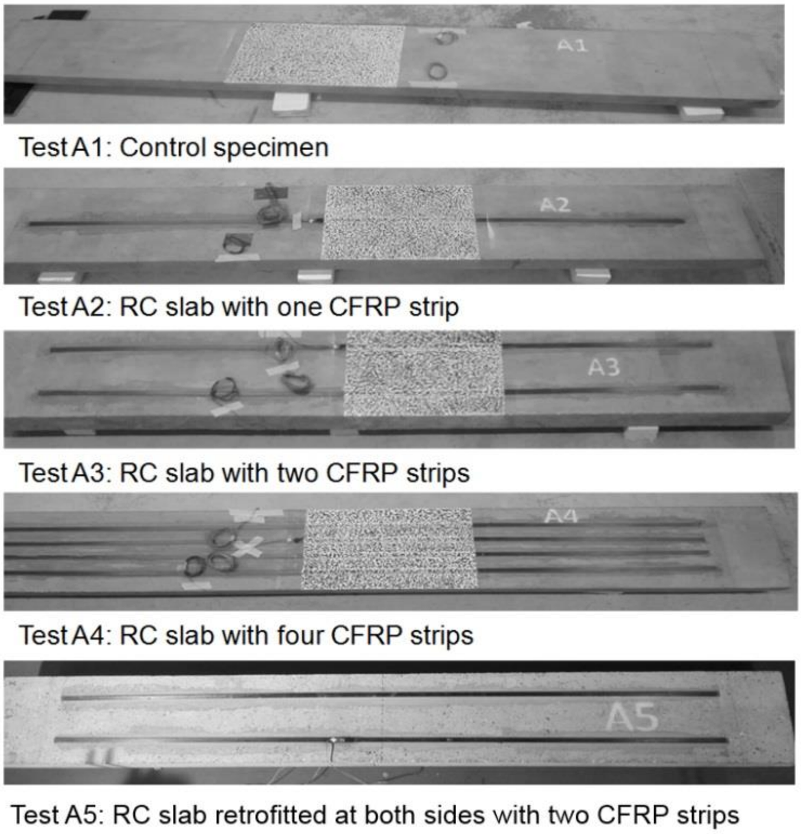

Figure 1. Experimental specimens

In this study an EDST is used with a square section; with side length 300 mm, the thickness of the tube wall is 5 mm, and the length is 1.5 m as shown in Figure 3. The end of the tube is positioned at 5 mm from the specimen. The tube is roller supported in back way, such that it is pushed aside for backwards deflections larger than 5 mm (in the rebound phase).

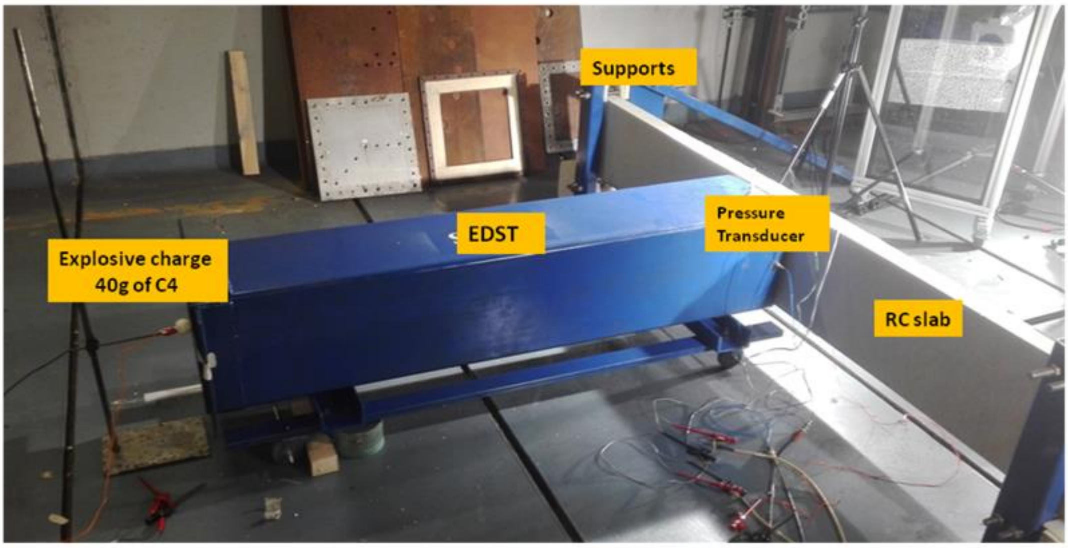

Figure 3. Experimental setup for blast tests

On the non-loaded side two high speed cameras are placed at 0.5 m from the specimen. DIC is used to obtain the out-off plane deformation of the slab (deflection) and the strain evolution in the CFRP strips and the concrete at the midspan of the RC slab during the explosion by means of two PhotronFastcam SA5 high-speed cameras as shown in Figure 4. The high-speed cameras are equipped with 50 mm focal length lenses, at a frame rate of 10.000 fps with a resolution of 896X840 pixels. The shutter speed is 50.000 /s. The initiation of the measurement is based on a light intensity trigger which is oriented toward the explosive charge. A third high-speed camera is fixed on the ceiling to record an out of plane displacement from above.

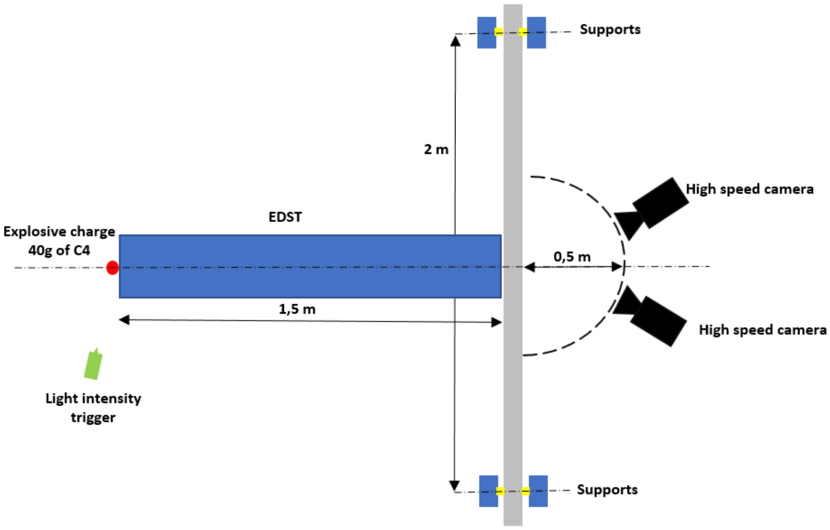

Figure 4. Schematic representation of the setup

NUMERICAL ANALYSIS

A three-dimensional (3-D) finite element model of the RC slab is developed. The analysis is performed using the LS-DYNA explicit solver. The slab is discretized into eight-node solid elements with constant stress solid element formulation. The steel reinforcement is discretized into beam elements. The element formulation for the beam element is Hughes- Liu with cross-section integration. The CFRP strip is discretized into shell elements with a fully integrated shell element formulation. Convergence tests are carried out. They show that the simulation converges when the mesh size is 10 mm. Therefore, a 10 mm mesh is used in the numerical model. The numerical model is analysed for 0.15 seconds which is the time sufficient for the blast wave to propagate throughout the slab. The RC slab and its motion under the blast load is modeled with the Lagrangian formulation. The slab has a thickness of 60 mm, width of 300 mm and length of 2000 mm between the axis of the supports. A schematic representation of a RC slab is shown in Figure 5.

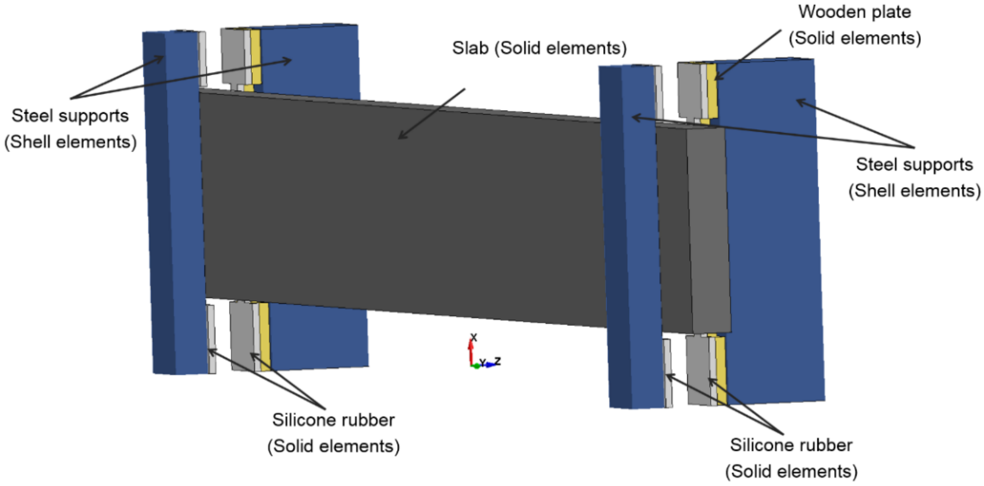

Figure 5. A schematic representation for the numerical model of RC slab

The concrete is modeled using the Winfrith concrete material model. The Winfrith model is a smeared crack model that is implemented in 8 node single integration point continuum elements [1] and uses a constitutive model able for cracking, crushing and shear retention depending on crack width and aggregate size. The model has a crack generation capability [2] and the prediction of the cracks is based on the approach of Wittman et al. [3].
The steel rebars are modeled using an elasto-plastic material model. This material model represent steel reinforcement behavior, with plastic deformation, strain rate effects, and failure[1]. Basic material properties used by the model are the yield strength 500 MPa, the Young's modulus 210 GPa and the Poisson's ratio 0.3.
The CFRP strips are modelled using the enhanced composite damage model (MAT54). This is a progressive failure model which is designed to handle anisotropic materials [1] such as unidirectional fiber reinforced polymer strips. The failure criteria for composite materials used in the analysis is the one proposed by Chang and Chang (1987) [1] based on the four failure modes including tensile fiber mode, compressive fiber mode, tensile matrix mode and compressive matrix mode. The parameters required to model the CFRP strips are based on the experimental tests provided by the manufacturer and the other missing parameters are taken from the literature based on the experimental studies conducted on CFRP strips by Chan et al [4].The input parameters used for the CFRP model are shown in Table 3.

Table 3. The material parameters of the CFRP strips [4].

Material properties of the CFRP strip	
Density ρ	1650kg/m^3
Longitudinal modulus E_1	138GPa
Transverse modulus E_2	9.65GPa
In-plane shear modulus G_{21}	5.24GPa
Out-plane shear modulus G_{23}	2.24GPa
Minor Poisson's ratio ν_{21}	0.021
Longitudinal tensile strength X_T	2800MPa
Transerve tensile strength Y_T	1440MPa
In-plane shear strength S	71 MPa
Maximum strain for fiber tension ε_t	1.7%
Maximum strain for fiber compression ε_c	1.15%

A tiebreak contact algorithm is used to model the contact between the concrete and the CFRP strip. This tiebreak command allows the modelling of connections which transmits normal and shear stresses with a failure criteria and neglects the sliding between the elements [1]. The failure of contact between the CFRP strip and the concrete surface occurs if:

$$\left(\frac{|\sigma_n|}{DIF*f_{ct}}\right)^2 + \left(\frac{|\sigma_s|}{DIF*f_b}\right)^2 \geq 1 \quad (1)$$

in which σ_n and σ_s are the normal and shear stresses at the interface, respectively. The variables f_{ct} and f_b are the tensile and shear stresses of the concrete under static loads. DIF is the dynamic increase factor.

RESULTS AND DISCUSSION

The measured deflection response is shown in Figure 6. For the specimens A2 and A3 only the inbound phase was recorded. Comparing the maximum deflection of the RC slabs, the experimental results confirm that the EBR significantly improves the flexural response and the stiffness of the slabs. A reduction in the maximum displacement for all specimens retrofitted with EBR is observed at the inbound phase, e.g. a reduction of 32 % and 47 % is recorded for slab A5 retrofitted at both sides with 2 strips and specimen A4 retrofitted with 4 strips (at one side).
For blast loads, the RC slab is submitted to a dynamic displacement in both directions and during the first inbound displacement phase, the kinetic energy of the retrofitted specimen is stored as elastic strain energy in the CFRP strips. All this elastic strain energy is violently released as kinetic energy during the rebound phase of the slab [5] and increases the deflection of the slab in the rebound phase. For specimen A4 compared to A1, the rebound deflection is increased by 21 % yet remained limited compared the inbound deflection as shown in Figure 4-13. In order to anticipate this behaviour, slab A5 was strengthened at both sides. For this specimen at the rebound phase, also a strong reduction of 63 % in the rebound deflection is observed (see Figure 6).

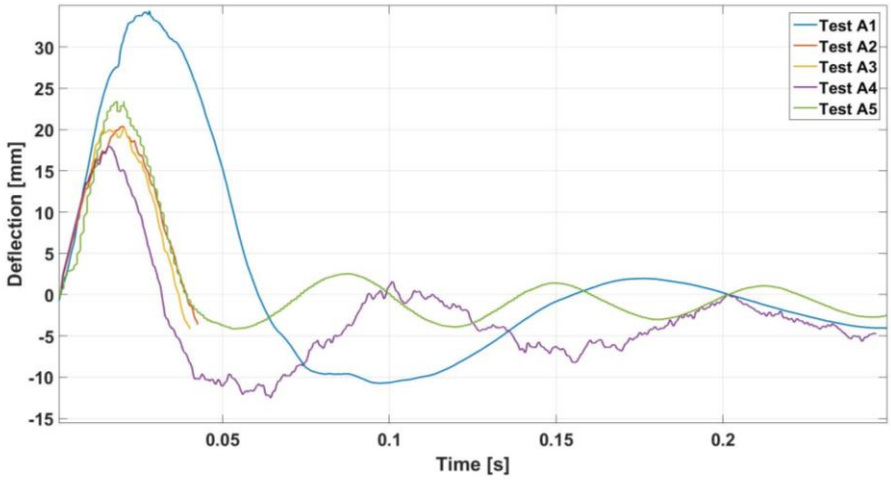

Figure 6. Deflection time history

The crack distribution on the non-loaded side of the specimen A1 found with the Winfrith concrete model is in good agreement with the experiments as shown in Figure 7.

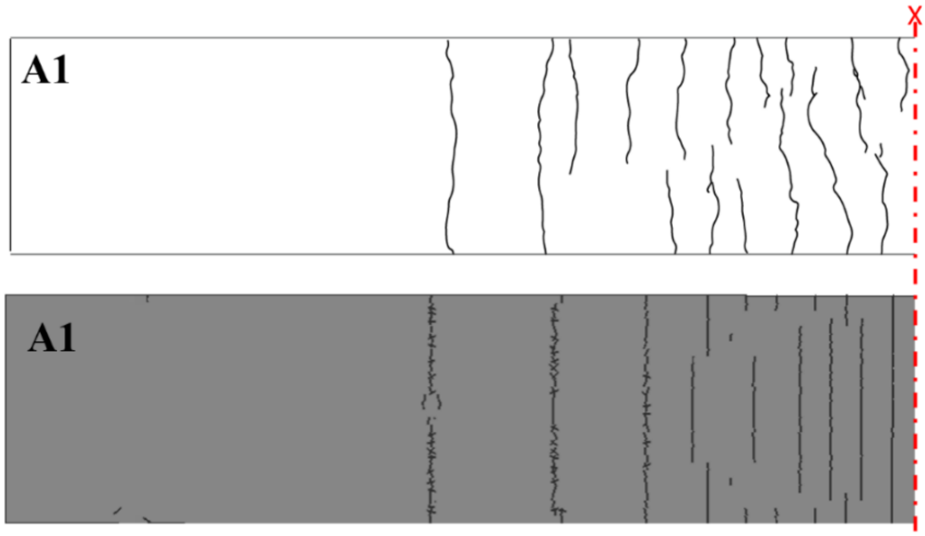

Figure 7. Comparison of the crack distribution of the numerical model with specimen A1

For the retrofitted specimens in the experimental tests, the formation of cracks is restrained as the CFRP strip effectively bridges the cracks and arrests the crack opening. This is also well predicted by the Winfrith concrete model as shown in Figure 8. Multiple tensile cracks with smaller widths are observed on the retrofitted slab A2 with one CFRP strip. No flexural cracks are recorded on the non-loading side for the specimens A3, A4 retrofitted with two and four CFRP strips, respectively.

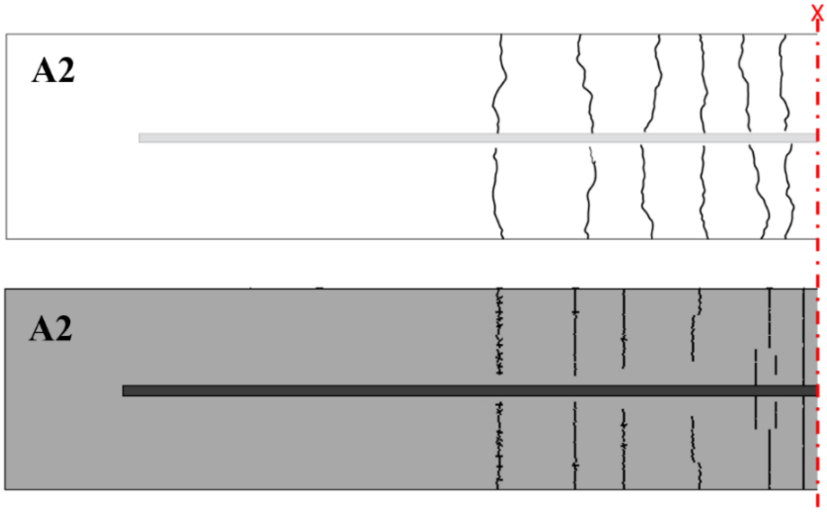

Figure 8. Distribution of the cracks in the specimens A2 predicted by the Winfrith concrete model

The maximum strain in the steel reinforcement and in the CFRP strips are selected when the slabs reach the maximum deflection and compared with the numerical predictions. The experimental and numerical results are given in Table 4. In all the experimental tests no debonding is observed as well as in the numerical results. The tiebreak contact algorithm used to model the bond between the CFRP strips and concrete, behaves as a perfect bond until reaches the failure criteria. This explains the overestimation observed in the numerical maximum strain in the CFRP strip. Moreover, the perfect bond assumed between the steel reinforcement and concrete gives a good agreement with the experimental data. Therefore, under blast loading due to the short duration of the loading the bond slip between steel reinforcement and concrete can be neglected. A good prediction in the maximum deflection at the midspan of the slab is obtained.

Table **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**. Comparison between the experimental and numerical results

Specimens	Max strain in the steel reinforcement			Max strain in the CFRP strips			Max deflection at midspan		
	Exp (%)	Num (%)	Ratio (Num/Exp)	Exp (%)	Num (%)	Ratio (Num/Exp)	Exp (mm)	Num (mm)	Ratio (Num/Exp)
A1	0.25	0.27	1.08	-	-	-	34.2	35	1.02
A2	0.18	0.17	0.94	-	0.26	-	21	23	1.09
A3	0.14	0.15	1.07	0.22	0.25	1.13	20	22	1.1
A4	0.11	0.12	1.09	0.17	0.20	1.17	18	19	1.05

CONCLUSION

This study presents experimental and numerical results of RC slabs with EBR, simply-supported, under blast loads. The following conclusions can be drawn:

1. The blast response of strengthened slabs can be effectively improved by means of FRP strengthening, although special consideration should be given to the inbound versus rebound phase of the response.

2. The impact of the blast wave on the retrofitted RC slabs generates high strains in the steel reinforcement, concrete and CFRP strips due to the propagation of the stresses through the materials.

3. CFRP strips as EBR increase the flexural stiffness of the slabs. A reduction of 32% and 47% in the maximum deflection (inbound phase) is recorded for slab A5 and slab A4, respectively.

4. The RC slab retrofitted at both sides with CFRP strips shows better flexural response than the control specimen, both in the inbound and rebound phase of the slab. No cracks are observed and a reduction of 63% in the rebound deflection is measured.

5. The numerical results are compared to experimental data. The maximum deflections, crack distribution and strain distribution in the CFRP strips found by these numerical analyses are in good agreement with the experiments. The Winfrith concrete model gives a good prediction of the blast response of the RC slabs with and without EBR and provides a valid prediction of the crack distribution.

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