BLAST RESPONSE OF RC SLABS WITH EXTERNALLY BONDED REINFORCMENT UNDER TWO INDEPENDENT EXPLOSIONS

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ABSTRACT

The use of carbon fiber reinforced polymer (CFRP) as externally bonded reinforcement (EBR) for strengthening reinforced concrete (RC) structures that are loaded by a blast wave is confirmed as an efficient solution. This in addition to other advantages of CFRP such as high tensile strength, light weight and durability. This paper aims to investigate the blast response of reinforced concrete (RC) slabs retrofitted with carbon fiber reinforced polymer (CFRP) as externally bonded reinforcement (EBR) under two independent explosions. In order to achieve this objective, four simply supported slabs were tested using an explosive driven shock tube (EDST) to generate a reflected pressure equal to 3 MPa in the first explosion and a reflected pressure equal to 7.5 MPa in the second explosion. Digital image correlation (DIC) is used to measure the strain evolution in the concrete and the CFRP strips during the first explosion. The slabs retrofitted with increasing the quantity of fibers show a reduction in the residual deflection after two independent explosions. The results show that for the first explosion, EBR increases the flexural response and the stiffness of the RC slabs. In the second explosion, a total debonding of the CFRP strips occurs and initiates from the midspan of the slabs toward the supports. When the total debonding of the CFRP strips occurs, the strain distribution in the steel rebars are the same for all slabs regardless of the quantity of applied EBR.

INTRODUCTION

In recent years, terrorist attacks and industrial accidents have increased all over the world and nowadays, it's possible to have more than one explosion during the accident. However, existing structures lose their resistance after the first explosion [1] and collapse especially if they are not designed to resist to blast loads. The use of CFRP as EBR for strengthening existing structures has been a popular research area especially in static, seismic, impact and blast loads [2–6]. Due to their high strength, light weight and durability, CFRP are often used in diverse strengthening applications such as flexural retrofitting of reinforced concrete (RC) beams, slabs and walls or wrapping columns against impacts and earthquakes. However, the use of CFRP under two successive blast loading still not been investigated because of the lack of knowledge regarding the failure modes of the CFRP under high strain rate and the blast response of the retrofitted structures when the debonding occurs. It has been reported that the strengthened elements often failed due to brittle interface between the CFRP and the concrete substrate and implies the loss of bond between the two materials [7]. This paper presents experimental results of simply supported, RC slabs strengthened with CFRP strips under a second explosion where the debonding of the CFRP strips occurs. Maximum deflection at the midspan of the slab and the strain distribution in the steel and the CFRP are measured during the blast loading. This paper presents an experimental analysis of four simply supported RC slabs strengthened with CFRP strips under two independent explosions applied to the same target and where total debonding of the CFRP strips occurs. The primary objectives of this paper are to study the evolution of the strain in the steel reinforcement and CFRP strips during the first explosion and to investigate the effect of the blast wave on the debonding of the CFRP strips due to the propagation of the stresses through the materials during the second explosion. The reflected pressures, maximum deflection and the residual deflection are measured at the midspan of the slab as well as the debonding of the CFRP strips after the second detonation are recorded.

EXPERIMENTAL ANALYSIS

Four RC slabs are examined with the following dimensions: length 2.3 m, width 0.3 m and thickness 0.06 m. The main reinforcement is composed of 6 bars of 6 mm diameter. The steel has a design characteristic yield strength of fy =500 N/mm2 a Young's modulus of Es=210,000 N/mm2. The average compressive strength is fcm = 53 N/mm2. Only one type of CFRP strip is used for all slabs to be reinforced; it has a length of 1.96m, a thickness of 2.5 mm and a width of 15 mm. The tensile strength and Young's modulus of the CFRP (as reported by the manufacture) are 2800 N/mm2 and 165 000 N/mm2, respectively. Figure 1 shows the slab internal reinforcement details.

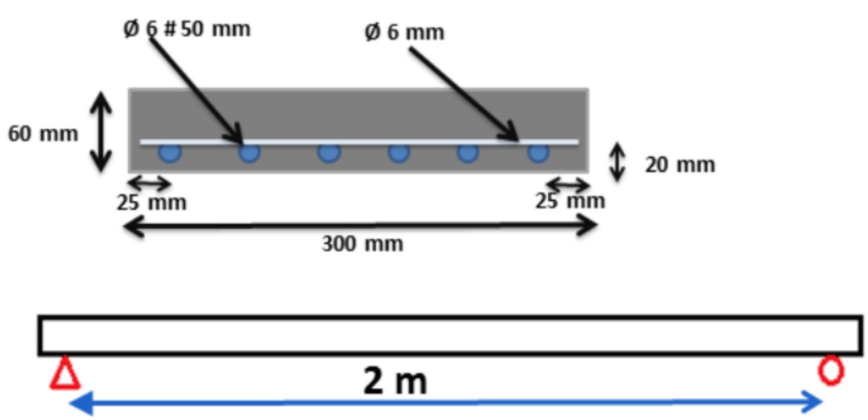


Figure 1. RC slab details

Four simply supported slabs with different EBR quantity are tested under two independent explosions but with the same bond contact surface. The slab A1 is used as a control specimen, the slabs A2, A3 and A4 are retrofitted with 1 CFRP strip, 2 CFRP strips and 4 CFRP strips respectively. Figure 2 shows the tested specimens.

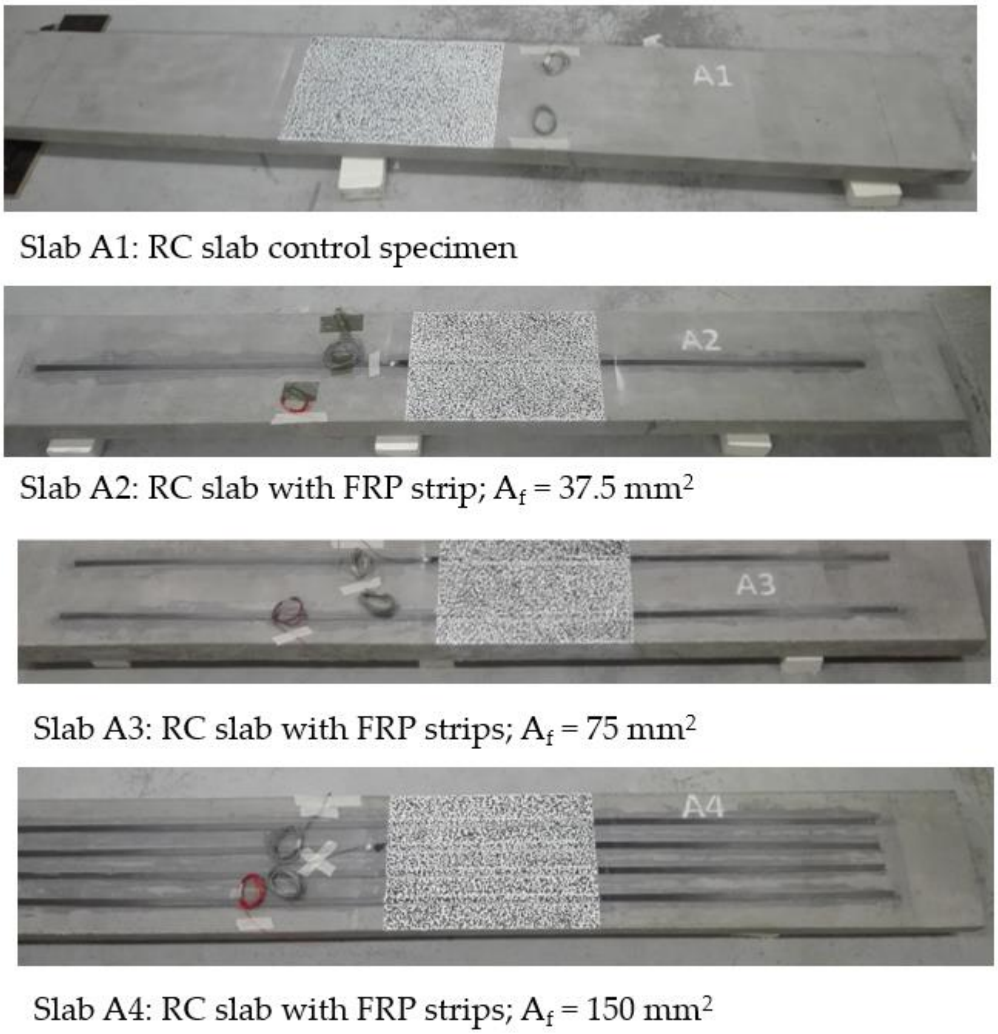


Figure 2. Specimens of RC slabs without and with EBR

EXPERIMENTAL SETUP FOR THE BLAST TESTING

An EDST with a square section, is used to generate a planar blast wave [8]. For the first explosion, the reflected pressure at the level of the slab is obtained by detonating 40 g of C4 at the entrance of the tube as shown in Figure 3. For the second explosion, the charge weight is increased to 50 g of C4 and fixed inside the tube at 30 cm from the entrance of the tube.

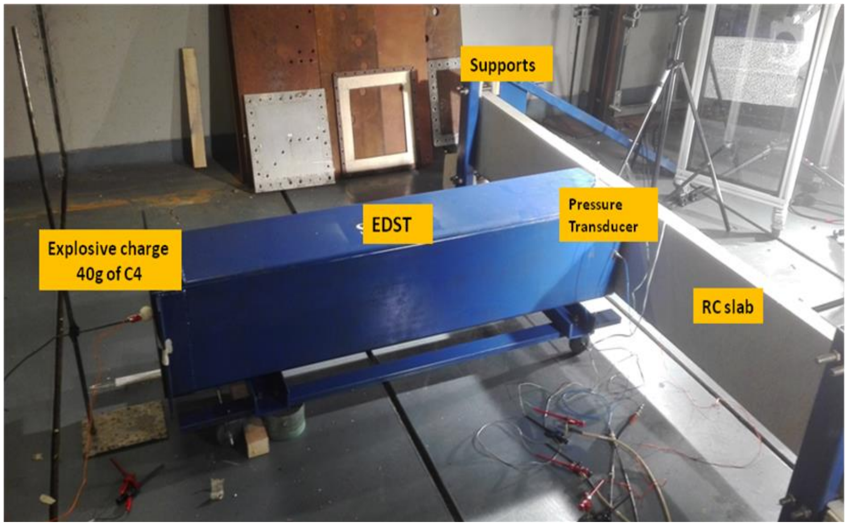


Figure 3. Experimental setup for blast tests

INSTRUMENTATION

Figure. 4 shows the experimental equipment used in the blast tests. DIC measurements are used to measure the maximum deflection and the strain evolution on the CFRP strips and the concrete at the mid span of the RC slab during the explosion. Also, three strain gauges of 10 mm length with a nominal resistance of 120 Ω are used. Two of them are bonded on the steel reinforcement at 0.1m from the mid span of the slab before casting the concrete and the other strain gauge is glued on the CFRP strip at 0.1 m from the mid span of the slab. To measure the incident pressure at the end of the tube of each experiment, two pressure transducers are fixed at the end of the tube.

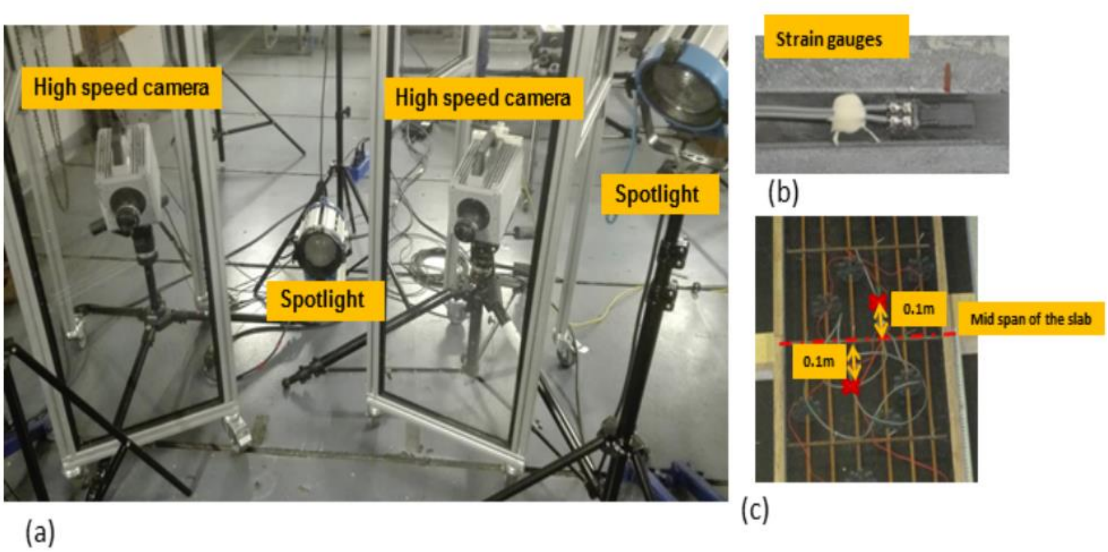


Figure 4. (a) Stereo vision setup of two high speed camera for DIC measurements; (b) strain gauge bonded on CFRP strip; (c) strain gauges glued on steel rebars before casting the concrete.

RESULTS OF THE FIRST EXPLOSION

Maximum deflection at the mid span of the slab

An experimental investigation is conducted to study the effect of EBR as a retrofit technique to improve the blast resistance of RC slabs. The results of this study confirm that EBR significantly increase the flexural strength and stiffness of the RC slab. In all the tests, a reduction in the maximum displacement for all specimens retrofitted with EBR is observed (a reduction of 41% to 47 % for Slabs retrofitted with 2 strips, 4 strips respectively) as shown in Figure. 5 .

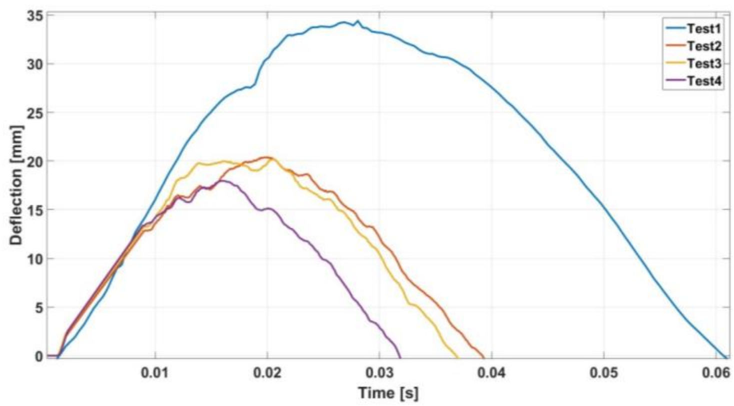


Figure. 5. Deflection time histories for experimental tests with DIC measurement.

Strain distribution in the steel reinforcement and CFRP strips

Increasing the amount of CFRP as EBR, decrease the strain on the steel rebars. A reduction of 48% and 62% of the strain in the steel reinforcement for test 3 and test 4 are recorded. Fig.7 shows the evolution of the strain in the CFRP strip is higher than the strain in the steel rebars during the explosion.

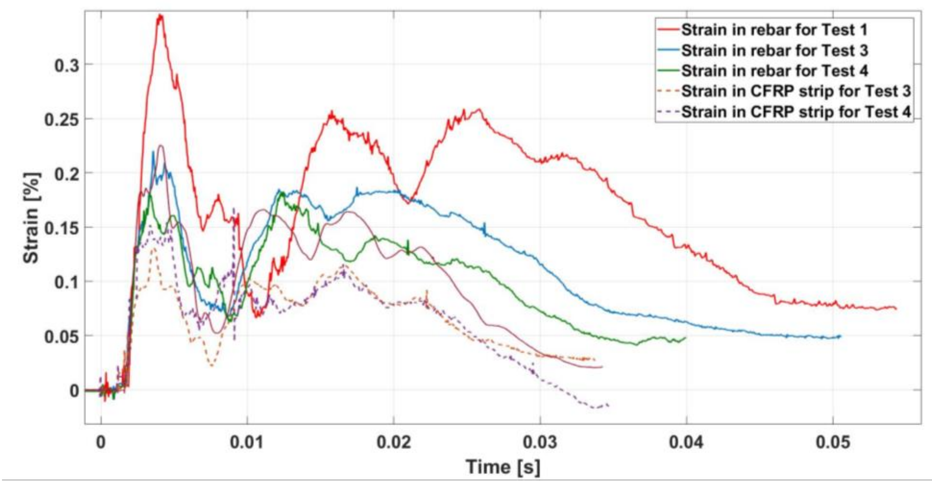


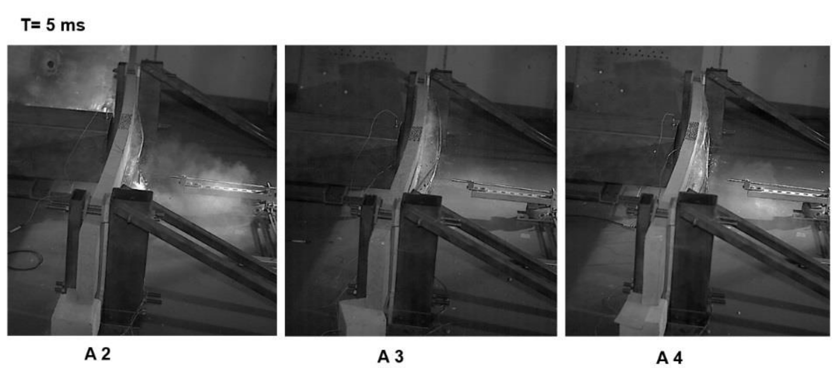
Figure 6. Evolution of the strain in the steel rebars and in CFRP strips during the inbound phase

The measurements confirm that EBR significantly increases the blast resistance and the stiffness of RC slabs and reduces the displacement of the slabs under blast loading. In all the tests, a reduction in the maximum displacement for all specimens retrofitted with EBR is observed. For example, the retrofitted slab A4 has a deflection of 18 mm while the control slab A1 has a deflection of 34 mm. The maximum deflection is decreased by 47 %. Moreover, increasing the amount of CFRP as EBR leads to a decrease of the strain in the steel rebars. A reduction of 32 % and 56 % of the strain in the steel reinforcement are recorded for the slabs A3 and A4, respectively.

RESULTS OF THE SECOND EXPLOSION

Debonding process

Using a high-speed camera, images are required to record the debonding process during the second explosion. The recorded images show that the total debonding of the CFRP strips occurs at 5 ms after the explosion for all the retrofitted RC slabs and the RC slabs reach the maximum deflection after 27 ms. This is shown in Figure 7.



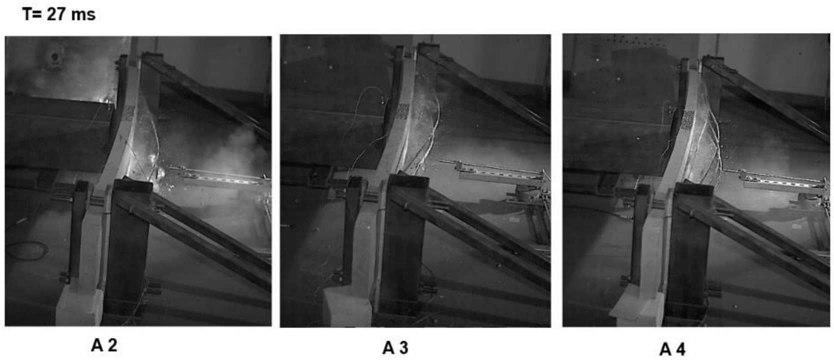


Figure 7. Debonding of CFRP strips during the second explosion

Deflection history at mid span of the specimens

Bonding CFRP strips on the RC slabs provides stiffness to the specimens and changes the blast response of the retrofitted slabs [5]. But when the total debonding of the CFRP strips occurs, all the retrofitted RC slabs experience the basic mechanisms composed by yielding of the steel and cracking of the concrete such as for the control specimen. Figure 8 shows the blast response of the RC slabs under a second explosion. The same maximum deflection is recorded for all the slabs during the inbound phase.

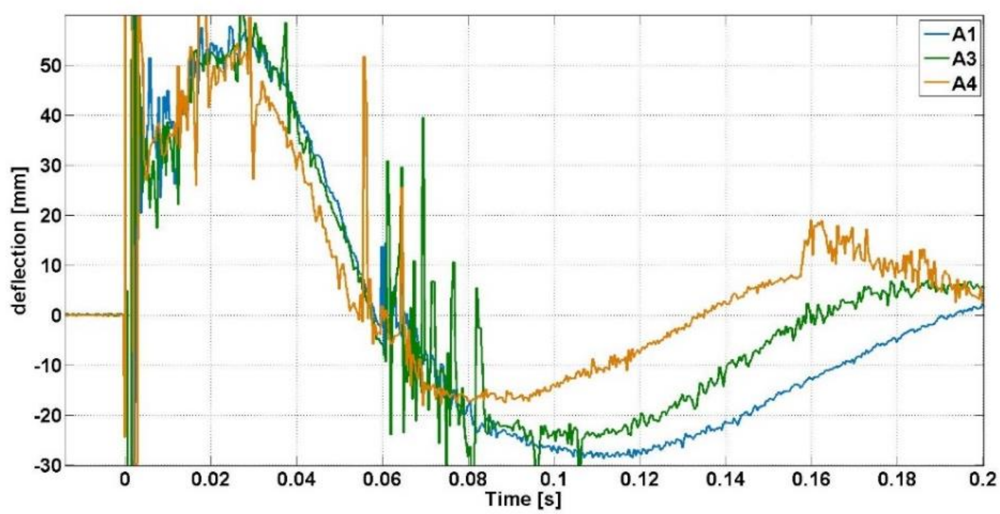


Figure 8. Deflection time history of RC slabs under a second explosion

Strain evolution in the steel reinforcement

Figure 9 shows the same evolution of the strain in the steel reinforcement during the inbound phase of the second explosion when the total debonding of the CFRP strips occurs. An average of maximum strain equal to 0.16% is recorded at t = 0.027 s for all the tested specimens when the RC slabs reach a maximum deflection.

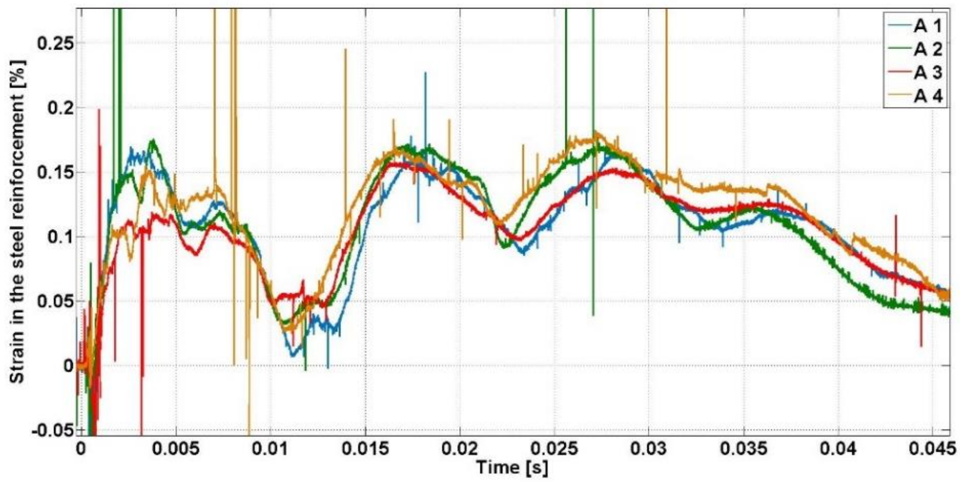


Figure 9. Strain distribution in the steel rebars under the second explosion during the inbound phase

CONCLUSION

This paper presents experimental results of simply supported RC slabs retrofitted with EBR under two successive independent explosions where the total debonding of CFRP strips occurs in the second explosion. Externally bonded CFRP is efficient to enhance the blast resistance of RC slabs. During the second explosion, total debonding of the CFRP strips runs from the midspan of the RC slabs towards the supports in a brittle and sudden manner and when the total debonding occurs, the retrofitted slabs behave as the control specimen without EBR (yielding of the steel and cracking of the concrete).

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