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Reinforced concrete and fiber reinforced concrete panels subjected to blast detonations and post-blast static tests

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ABSTRACT

Results of an experimental study of reinforced concrete panels under blast detonations are presented. The primary purpose of the tests was to collect data for validating simulation methods for blast loads. The scaled distance ranged from 0.41 m/(kg)$^{1/3}$ to 0.57 m/(kg)$^{1/3}$ and hence the tests are close-in detonations. Four types of 1.2 m square panels were subjected to blast to investigate the performance of new walls: reinforced concrete (RC) panels; fiber reinforced concrete (FRC) panels without additional reinforcement; FRC panels reinforced with steel bars; and RC panels reinforced with glass fiber reinforced polymer (GFRP) bars. Another RC panel type was built which was retrofitted with external GFRP laminates on both faces. The performance of the panels is classified into three categories as medium protection, very low protection, and protection below antiterrorism standards. FRC panels reinforced with steel bars had the best performance for new construction. Panels that survived the blast detonation without sustaining a breach were tested under monotonic static loads to determine their static post-blast load resistance.

1. Introduction

Blast-resistant structures must prevent progressive collapse and catastrophic failure [1]. Research has been carried out to improve the blast resistance of new and existing reinforced concrete (RC) structures. The following techniques have been proposed for improving the blast resistance of RC or unreinforced masonry slabs or walls: (a) strengthening with fiber reinforced polymer composites [2–7] or steel plates [8]; (b) employing fiber reinforced concrete as the slab material [8–13]; (c) use of a sprayed-on polymer [14]; and (d) use of double-layered precast thin plates made of concrete or polyethylene fiber reinforced concrete with an air cavity between the two layers [15]. A state-of-the art review of research on the blast resistance of FRP or polymer strengthened RC and concrete masonry structures has been presented [2]; it was noted that there is a lack of in-depth research in understanding the fundamental behavior of FRP strengthened structures under blast loading; in addition, it was recommended that further research should be carried out on methods to determine static post-blast load resistance.

The research in this paper is concerned with the prevention of progressive collapse and catastrophic failure. The primary purpose of the tests was to collect data from benchmark problems for validating simulation methods and material models for blast events. The overall goal of the research was to establish and validate by experiment new methods and material parameters for simulating and enhancing the performance of critical concrete structures subjected to malevolent attacks and dynamic accident events. The results could extend the application of simulation results into regimes where large scale experiments are too costly or otherwise impossible to conduct.

Application of GFRP bars are used as non-magnetic or radio-frequency transparent reinforcement for magnetic resonance imaging medical equipment and specialized defense applications. No studies are known that examine the performance of GFRP bars used as reinforcement in concrete to mitigate blast. To develop further insight into the performance of various types of concrete panels with different reinforcement schemes, blast events were carried out to evaluate new construction and rehabilitation of existing RC wall panels with these variables: panel thickness, type of concrete (RC and FRC), internal and external reinforcement type, spacing, and reinforcement ratio including steel bars, internal GFRP bars, and external GFRP composite laminates used in retrofit. Glass FRP laminates were selected because they develop higher ultimate strains compared to carbon FRP, thus increasing the strain energy

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Nomenclature

A_w	contact surface area between blast wave and test specimen	S_x	spacing of the steel or GFRP bars in the x direction
A_{bx}	area of the steel or GFRP bars in the x direction	S_y	spacing of the steel or GFRP bars in the y direction
A_{by}	area of the steel or GFRP bars in the y direction	W	weight of charge expressed as a mass of equivalent TNT
h	panel thickness	Z	scaled distance
I_s	blast impulse	t_d	duration of the positive phase of the blast impulse
P_s	peak static overpressure in the near field	ρ	internal reinforcement ratio
R	standoff distance from the center of the charge	ρ_x	internal reinforcement ratio in the x direction
		ρ_y	internal reinforcement ratio in the y direction

capacity of the member. The static post-blast load resistance of panels surviving the blast without sustaining a breach was also investigated.

2. Experimental research

2.1. Materials and specimen details

Two types of concrete were used to build the 1.2 m square panels: thirteen reinforced concrete panels and seven FRC panels constructed with macro-synthetic fibers (Table 1). The fibers used were polymer fibers 50 mm in length with an equivalent diameter of 0.9 mm; the fibers had a specific weight of 0.91, a tensile capacity of 338 MPa, and a modulus of elasticity of 3.0 GPa. The FRC had 8.9 kg/m^3 of polymer fibers resulting in 1.0% of fibers by volume; the fibers were added to concrete during mixing using a mixing time of 5 min. The fibers had a unique sinusoidal wavelike shape that increased anchorage to concrete, as shown in Fig. 1; the average 28 day compressive strength of concrete was 51 MPa while that of FRC was 46 MPa. The average static tensile strength of concrete using a split cylinder test was 4.0 MPa and that of FRC 4.3 MPa. Steel and GFRP bars were used as internal reinforcement. Steel bars had a tensile strength of 420 MPa and a modulus of elasticity of 200 GPa. The ∅16 GFRP bars had a tensile strength of 717 MPa and an elastic modulus of 43 GPa; the tensile strength of ∅10 GFRP bars was 758 MPa and the elastic modulus 41 GPa.

Unidirectional GFRP laminate was adhered to both sides of Type E panels (Table 1) for the full panel area. The fabric had a tensile strength of 2276 MPa and a modulus of elasticity of 72 GPa. The fabric had a weight of 913 g/m^2 with a thickness of 0.35 mm. A high-modulus high-strength impregnating two part epoxy was used to attach the GFRP composite fabric to concrete. Two layers of fabric were applied to each side; the layers were applied perpendicular to each other, one at zero and one at 90° with respect to the panel horizontal axis.

Eighteen panels were tested under blast. A summary of each panel type including thickness, reinforcement, and type of test is shown in Table 1. The test specimens were 1.2 m square panels constructed using reinforced concrete or FRC. Type A panels were RC with steel reinforcement, Type B and CONB were plain FRC panels, Type C were FRC panels with steel reinforcement, Type D and COND were RC panels with internal GFRP reinforcing bars, and Type E were RC panels with steel reinforcement and externally applied GFRP laminates. Specimen details are shown in Fig. 2. Panels A4-14 and B4-14 with a 356 mm thickness were tested under

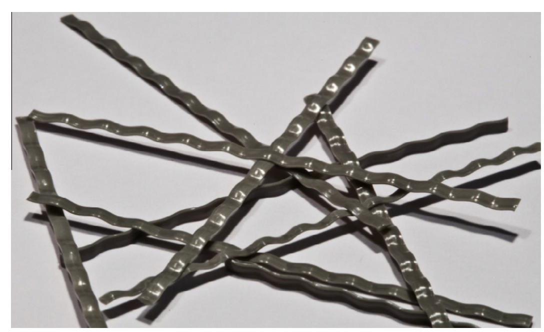

Fig. 1. Polypropylene macro-synthetic fibers.

Table 1
Description of panels and tests.

1.2 m × 1.2 m panels		Thickness, designation, and reinforcement		
Type	Description	152 mm	254 mm	356 mm
A4	RC (steel bars)	A4-6 ∅10 @ 305 mm	A4-10 ∅13 @ 305 mm	A4-14[b] ∅16 @ 305 mm
B4	FRC	B4-6 No Rebar	B4-10 No Rebar	B4-14[b] No Rebar
C4	FRC + steel bars	C4-6[a] ∅10 @ 152 mm	C4-10[a] ∅13 @ 152 mm	C4-14[a] ∅16 @ 152 mm
D4	RC (GFRP bars)	D4-6[a] ∅10 @ 152 mm	D4-10 ∅16 @ 229 mm	D4-14[a] ∅16 @ 152 mm
E4	RC (steel bars) + GFRP laminate	E4-6[a] ∅10 @ 305 mm	E4-10[a] ∅13 @ 305 mm	E4-14[a] ∅16 @ 305 mm
COND	RC (GFRP bars)	CON-1[a], CON-2, CON-3, CON-4 ∅16 @ 305 mm	N/A	N/A
CONB	FRC	CON-5 No rebar	N/A	N/A

RC = reinforced concrete; FRC = fiber reinforced concrete; GFRP = glass fiber reinforced polymer.
[a] Panels subjected to post-blast static load test.
[b] Panels tested only under static load test.