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Experimental and numerical analyses of long carbon fiber reinforced concrete panels exposed to blast loading

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ABSTRACT

The addition of long carbon fibers to traditional reinforced concrete is proposed as a method to improve the blast spalling resistance of concrete. A series of tests was conducted to compare the blast resistance of panels constructed with either conventional reinforced concrete (RC) or long carbon fiber-reinforced concrete (LCFRC). Conventional reinforced concrete panels were tested as control specimens. Pressure sensors measured both the free-field incident pressure and the reflected pressure for each panel. Furthermore, a finite element model was created in LS-DYNA to replicate both a control panel and an LCFRC panel to observe whether or not the models could predict the observed damage. Each of the LCFRC panels exhibited less material loss and less surface damage than the control panels. The addition of long carbon fibers significantly increased the concrete's blast resistance and significantly reduced the degree of cracking associated with the concrete panels. The results were also compared to the existing damage level chart (UFC 3-340-02). A comparison of the results indicates that the finite element modeling approach adopted in this study provides an adequate representation of both RC and LCFRC experimental responses. The results can be used in blast modeling with a reasonable degree of accuracy.

1. Introduction

Events over the last 10 years, including the Oklahoma City bombing, the 9/11 World Trade Center attacks, and the war in Iraq, have brought the topic of structural blast and impact resistant materials to the forefront. Due to the extensive use of reinforced concrete in critical structures, technologies that improve the performance of concrete under dynamic loading have the potential to save many lives.

The concept of using fibers as reinforcement is not new. Fibers were used for structural reinforcement in ancient times. Research on the use of fibers to increase the strength of both blast and impact structures has typically been limited to steel fibers and, to a lesser degree, polypropylene fibers [1–8]. Carbon fibers, however, possess many potential benefits over other fibers, including higher strength and stiffness, as well as increased durability. Carbon fibers also offer an economical benefit as they are readily available as a waste product from the aerospace industry [9,10].

Short carbon fibers have been successfully used within concrete mixtures [11]. However, research in the area of carbon fibers more than 30 mm in length is virtually nonexistent. Because fibers used in this present research (100 mm long) are more than twice as long as other researched fibers, they are referred to here as long fibers.

Long carbon fibers have not been previously used because they tend to segregate within the mixtures and decrease workability. A proprietary coating is applied to the fiber yarn to form a stiff tape that overcomes these problems. This coating allows the fibers to be added directly into the concrete mixer, where they evenly distribute throughout the material. The concrete mixture to which the fibers are added has been established in previous work [12,13]. This project examined the properties of this material, focusing on the blast resistance.

The use of long carbon fibers within a concrete matrix can be an economical option for improving blast resistance with distinct advantages over other blast-resistant material options. The long carbon fibers will also reduce secondary fragmentation by improving the spalling resistance of the concrete, a critical property for protecting personnel and equipment during a blast and difficult to prevent with current materials. With the use of long carbon fibers, these improvements come with little to no modification of

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Nomenclature

CP	control panel
h_e	standoff distance of explosive from top of concrete
f_c'	compressive strength
HRWR	high-range water reducer
LCFRC	long carbon fiber-reinforced concrete
NEW	net equivalent weight (of TNT explosives)
RC	reinforced concrete
SDAS	synergy data acquisition system
SSD	saturated surface dry

current design practices, allowing implementation to occur quickly and easily.

Two types of long carbon fibers were investigated in this study and are referred to as Fiber Type A and Fiber Type B. Fiber Type A is a 3K (K refers to thousands of filaments in a strand), plain weave, 40% epoxy, preimpregnated fabric. This fiber has an optimized application of 100 × 10 mm fibers, at a dosage rate of 1.5% by volume, and a curing cycle of 121 °C for 45 min. Fiber Type B is a twined, 48K, polypropylene backbone carbon fiber with an optimized application of 100 mm long fibers and a dosage rate of 1% by volume [14]. Fig. 1 is a photograph of both fiber types.

The goal of this study was to compare the blast resistance of long carbon fiber reinforced concrete (LCFRC) panels with traditional reinforced concrete (RC). The panels' responses were compared in terms of both the loss of mass and the extent of surface damage. Additionally, the panel response was simulated numerically using the finite element code LS-DYNA [15]. Successful damage prediction using numerical methods allowed the concrete panels to be assessed further without the need for full-scale blast testing.

2. Experimental procedure & results

2.1. Specimen design & specifications

Seven panels were tested to determine their responses to blast loading: three conventional reinforced concrete control panels (CP), two reinforced concrete panels containing long carbon fiber Type A (LCFRC-A), and two reinforced concrete panels containing long carbon fiber Type B (LCFRC-B). All of the panels measured 1830 × 1830 mm with a thickness of 165 mm.

All panels were constructed using identical concrete mixtures and steel reinforcement. The panels were designed in accordance with UFC 3-340-02 [16] for a charge weight of 34 kg of TNT at a standoff distance of 1675 mm and zero angle of incidence. Details of both the steel reinforcement design and layout are illustrated in Fig. 2. The flexural and shear designs assumed a Type II cross section based on the scaled distance of the charge, which represented an intermediate-range blast [16]. Since the calculated response time of the structure was significantly greater than the duration of load, the panels were designed for the impulse generated by the blast with a yield line analysis to determine the panel resistance at a maximum support rotation of 2°. The shear design was based on an unlaced reinforced slab for both diagonal tension and direct shear and ignored any beneficial effect of the fibers. Based on the scaled distance and the use of a grid system of top and bottom flexural reinforcement, UFC 3-340-02 allows shear reinforcement in the form of single leg stirrups at alternate bar intersections in both directions. For the charge weight, standoff distance, and slab thickness selected for the test panels, the spall and breach parameters of UFC 3-340-02 indicated a strong likelihood of spalling. Furthermore, the McVay [17] prediction curves indicated the likelihood of severe spalling.

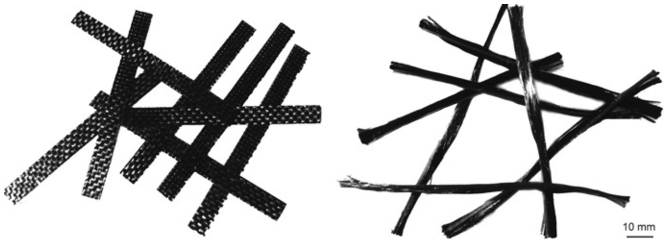

Fig. 1. Fiber Type A (left) and Fiber Type B (right).

Mix proportions for the specimens are given in Table 1. Carbon fibers were added at 1.5% and 1% by volume for Types A and B, respectively. A high-range water reducer (HRWR) was added to the mix to maintain consistency and workability after the fibers were added to the concrete. Properties for the specimens are listed in Table 2, which includes the compressive strength at time of testing, which varied from 28 to 30 days after casting. The compressive strength values represent the average of three replicate 150 × 300 mm cylindrical test specimens. The yield strength of the reinforcing steel was 407 MPa.

2.2. Blast test setup & procedure

The blast test setup is shown in Fig. 3. The panels were supported along all four sides by a frame constructed from high-strength steel tube sections filled with concrete. Ammonium nitrate/fuel oil (ANFO) was chosen for the explosive charge because it is easier and less expensive to produce and procure than TNT. Because it is also harder to detect, terrorists tend to prefer ANFO (e.g., Murray Federal Building, Oklahoma City, 1995). The charge used for the testing consisted of 38.5 kg of ANFO with four 0.45-kg pentolite boosters, corresponding to a net equivalent weight (NEW) of 34 kg of TNT (TNT equivalent weight factor 0.83 for ANFO [18] and 1.11 for Pentolite [manufacturer]). The charge was centered above each panel using prefabricated cardboard tubes (Sonotubes), which allowed refinements during the test procedure by adjusting the standoff distance.

The sensor setup is also shown in Fig. 3. Pressure transducers – referred to as PS1, PS2, and PS3 – were placed at the specimen's center as well as 430 mm and 860 mm away from the center, respectively. These distances were at approximately 1/3 and 2/3 of the diagonal distance from the center to the corner of the panel. Two free-field incident pressure sensors – referred to as FPS1 and FPS2 – were placed at a distance of 7420 mm from the center of the panel. General purpose ICP® (Integrated Circuit Piezoelectric) sensors, each rated up to 69 MPa with a usable range up to 103 MPa, were used to record the reflected pressure (PS1, PS2, and PS3). Pressure sensors rated up to 3.5 MPa were used for the free-field measurements (FPS1 and FPS2).

The blast testing was conducted in a two-step process at Test Range 27D, located at Fort Leonard Wood, Missouri. In the preliminary test stage, two control panels were subjected to the 34 kg NEW TNT charge at standoff distances of 1065 mm and 1370 mm, respectively, corresponding to previous ConWep [19] analyses.

Preliminary blasts produced shockwaves that spalled the concrete extensively, debonding much of the reinforcement without any readable data. Because pressures greatly exceeded the capacity of the sensors, all of the panel sensors were damaged and the synergy data acquisition system (SDAS) failed to record the free-field incident pressures. Thus, for the main test stage, a standoff distance of 1675 mm was selected. The specimens used for both the