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Performance of RC and FRC Wall Panels Reinforced with Mild Steel and GFRP Composites in Blast Events

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Abstract

The structural integrity of reinforced concrete structures in blast events is important for critical facilities. This paper presents experimental data generated for calibrating detailed finite element models that predict the performance of reinforced concrete wall panels with a wide range of construction details under blast loading. The test specimens were 1.2 m square wall panels constructed using Normal Weight Concrete (NWC) or Fiber Reinforced Concrete (FRC). FRC consists of macro-synthetic fibers dispersed in NWC. Five types of panels were tested: NWC panels with steel bar reinforcement (Type A); FRC panels without additional reinforcement (Type B); FRC panels with steel bar reinforcement (Type C); NWC panels with glass fiber reinforced polymer (GFRP) bar reinforcement (Type D); and NWC panels reinforced with steel bar reinforcement and external bidirectional GFRP overlays on both faces (Type E). Three additional Type D panels were used as control specimens (CON). Each panel type was constructed with three thicknesses: 152 mm, 254 mm, and 356 mm. The panels were instrumented with strain gauges, and accelerometers; in addition, pressure sensors and high speed video were employed during the blast events. Panel types C and E had the best performance, whereas panel type B did not perform well. Preliminary dynamic simulations show crack patterns similar to the experimental results.

Blast loads; Concrete panels; Fiber reinforced concrete; Glass fiber reinforced polymer; Rehabilitation; Steel

1. Introduction

The dynamic behavior of concrete is well understood; as the strain rate of concrete increases so does its strength as reported by Ross et al. [1]. The properties that are not as well researched are how fiber reinforced concrete (FRC), glass fiber reinforced polymer (GFRP) rebar and GFRP overlays perform at the high strain rates experienced during blast loading. Coughlin et al. [2] determined that adding synthetic fibers increases the performance of concrete barriers during a blast, by keeping the damaged concrete more intact than the normal weight concrete (NWC)

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barriers. However, the research was limited to using contact charges placed directly on reinforced concrete barriers and using a mixture of synthetic and steel fibers. Lawver et al. [3] and Razaqpur et al. [4], have determined that the use of GFRP overlays can increase the performance of reinforced concrete when subjected to an explosion. Lawver et al. [3] considered bridge decks and a blast from below the deck, while Razaqpur et al. [4] used GFRP overlays crossing the entire panel in a crucifix form in both directions. The studies listed here and others in the open literature summarize various techniques to improve the performance of reinforced concrete subjected to blast loading.

This paper describes an ongoing project being conducted by the Idaho National Laboratory and the University of Utah. A primary project goal is to investigate and validate new materials subjected to explosive attacks or dynamic impact events. Various types of reinforced concrete panels were constructed and tested by detonating an explosive charge near the panel. The data collected from the project is being used to improve dynamic simulation methods and material models for predicting the blast performance of concrete structures.

2. Experimental Investigation

2.1. Test Design

The concrete test panels were arranged in a square pattern with a centrally located charge, as shown in Fig. 1A. One panel was placed on each of three sides of the layout, while the fourth side was left open for working space. The layout provided an equal standoff distance of 1 m from the center of the explosive to the face of each panel. The panels were placed on the ground and large concrete blocks were placed one on each side behind the specimens to provide a simply supported structure, as shown in Fig. 1B. A chain was attached to the blocks and wrapped around the top half of the panels to prevent additional damage following the blast. The charge (C4 or ANFO) was placed on a small wooden table at the center of the test layout with the height adjusted to position the explosive at the mid-height of the specimen. A mylar break screen, located at the bottom of the table acted as the trigger for the data acquisition system.

A series of nine blast tests were carried out. Blasts varied in charge size (expressed here as equivalent weight of TNT) depending on the thickness of the panels being tested. A charge weight of 6.1 kg was used to test 152 mm thick panels. A charge weight of 12.8 kg was used to test 254 mm and 356 mm thick panels allowing evaluation of the effect of changing the panel thickness.

2.2. Data Acquisition System

The data acquisition system consisted of National Instruments data recording hardware and software with power supplied using portable generators and an uninterruptable power supply. Additional hardware was available to record pressures, accelerations, and strains. Data from accelerometers and pressure transducers was digitized simultaneously at 10^5 per second with record lengths up to 3 seconds. Data for strain gauges was digitized simultaneously at 10^4 per second with record lengths up to 5 seconds.

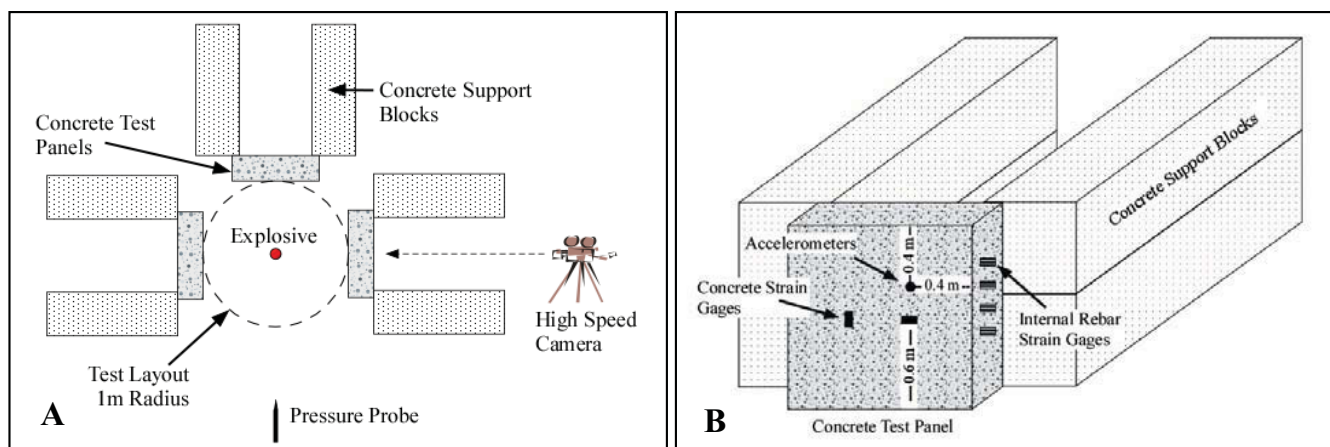


Fig. 1. (A) Test layout plan view (B) Instrumentation details. Note that the concrete strain gages and accelerometers were installed on the back face (with respect to the blast) of the concrete test panel. The internal rebar strain gauges were installed during casting of the concrete.

2.3. Materials

Specimens were built from NWC concrete, steel rebar, GFRP bars, macro-synthetic fibers and GFRP overlays. Two types of concrete mixes were produced: (i) NWC and (ii) concrete with the addition of macro-synthetic fibers referred to herein as FRC. Seven kilograms of fibers per cubic meter of concrete was used in the FRC mixture. The 28 day compressive strength of NWC was 51 MPa, and that of FRC was 45 MPa. The reinforcing steel had a tensile yield strength of 414 MPa and a modulus of elasticity of 200 GPa. The GFRP bars had a tensile strength of 655 MPa, and modulus of elasticity of 41 GPa. The sinusoidal shaped macro-synthetic fibers were 50 mm long and 0.9 mm in diameter, and had a tensile strength of 337 MPa and a modulus of elasticity of 3.0 GPa. The GFRP overlay had a tensile strength of 2.3 GPa and a modulus of elasticity of 72 GPa. The GFRP overlay was made using a unidirectional fabric; two layers were applied externally to each side of a specimen after the concrete had cured; one layer of fibers in the horizontal direction and one layer in the vertical direction.

2.4. Specimen Details

Eighteen 1.2 m square wall panels were tested under blast loading with various reinforcement types and thicknesses. The reinforcement was selected based on whether the panel simulated an existing structure or new construction. An existing structure would contain steel rebar and could be retrofitted with GFRP overlays to add extra protection from an explosion. New construction could be built using FRC or could contain GFRP bars as reinforcement.

Five different types of panels were constructed: Type A panels were NWC and contained steel rebar, Type B panels were only FRC, Type C panels were FRC with steel rebar, Type D panels were NWC reinforced with GFRP bars, and Type E panels were NWC reinforced with steel rebar and two layers of GFRP overlays applied externally as a rehabilitation method on each side of the panel. Each panel type was constructed using three thicknesses: 152 mm, 254 mm and 356 mm. Three CON panels were constructed to calibrate the testing equipment and standoff distance. The CON specimens were 152mm thick Type D panels.

Rebar mats were constructed for each panel type, except panel Type B. Each panel contained two mats, with varied rebar spacing and rebar size. In panel types A, E and CON, the rebar was spaced at 305 mm on center; in panel types C and D the rebar was spaced at 152 mm on center. The clear cover to the mats was 25 mm.

Internal strain gauges were installed at the center of the rebar mat. On each mat, one gauge was installed in the horizontal and one in the vertical direction, for a total of four gauges per panel. In addition to the internal strain gauges, two external concrete strain gauges were installed on the exterior back face of each test panel, as shown in Fig. 1B.

3. Experimental Results

3.1. Data Analysis and Panel Behavior

Two panel types had the best performance: (1) FRC panels with 10 mm diameter steel rebar spaced at 152 mm (Fig. 2A), and (2) NWC panels with 10 mm diameter steel rebar spaced at 305 mm and external GFRP overlays (Fig. 2B). These panels exhibited significantly less damage when compared to the other panels; they fragmented less and cracking was minimal. Panel C4-6, in Fig. 2A, experienced very small cracking on the back face of the panel only. The maximum crack widths measured were: 1.0 mm, 1.6 mm and 1.3 mm for panels with respective thicknesses of 152 mm, 254 mm, and 356 mm. Panel E4-6, in Fig. 2B, experienced short cracks on the back face and minimal cracks on the sides of the panel. The maximum crack widths measured were: 3.2 mm, 6.4 mm, and 3.2 mm for panels with respective thicknesses of 152 mm, 254 mm, and 356 mm. The GFRP overlay that was bonded to the back of Panel E4-6 de-bonded from the whole back face of the panel, but the front facing GFRP overlay was still bonded to the panel. GFRP overlays and FRC internal reinforcement can be used in existing and new construction,

respectively. GFRP overlays can be used to rehabilitate older structures and provide additional protection. Macro-synthetic fibers can be used in new structures, in addition to internal steel rebar, to provide additional stiffness.

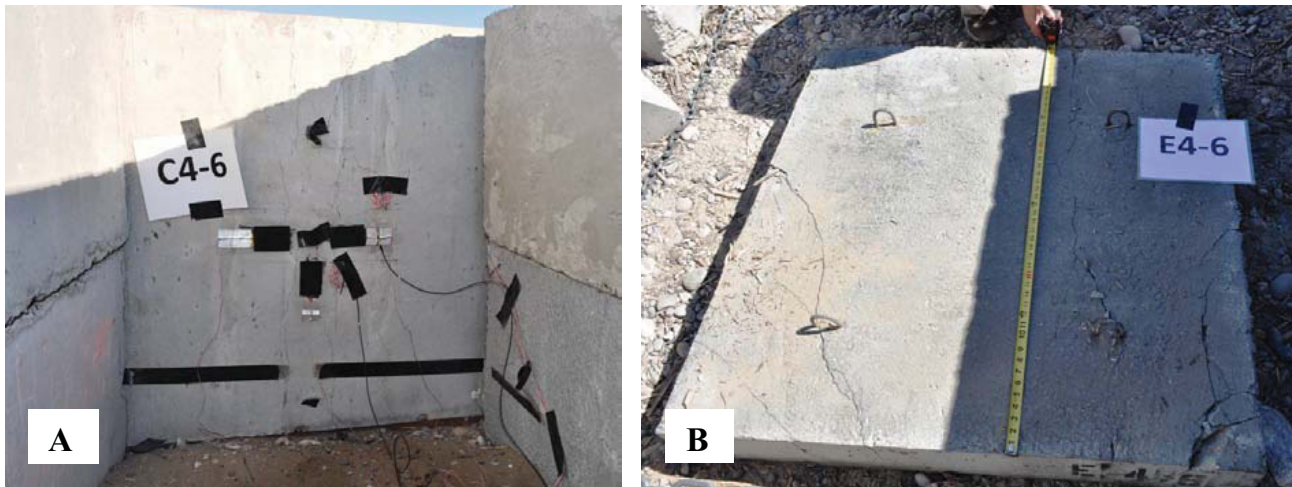


Fig. 2. (A) FRC panel C4-6 with steel rebar, (B) NWC panel E4-6 with steel rebar and GFRP overlays.

Panels made from NWC with internal steel rebar and NWC with internal GFRP bars had considerable structural damage, when compared to the entire data set. Panels A4-6 shown in Fig. 3A and CON-3 shown in Fig. 3B were chosen for comparison because they were tested during the same blast event. The only difference in the two panels was the reinforcement. Panel A4-6 was reinforced with 10 mm diameter steel bars spaced at 305 mm and panel CON-3 with 16 mm diameter GFRP bars at 305 mm. There is considerable structural damage in both panels. The panels show large flexural cracks that start in the middle of the panel and move outwards radially in all directions as shown in Fig. 3. Panel CON-3 has more fragments of concrete missing compared to Panel A4-6. Steel rebar is more ductile than GFRP bar which remains linearly elastic until rupture and generally exhibits brittle failure. Figures 4 and 5 show internal and external strain, acceleration, and pressure data for panels A4-6 and CON-3 respectively. Both panels experienced similar levels of pressure, strain and acceleration caused by the explosion. Panels made from FRC without any rebar were the worst performers. These panels generally fractured vertically into two pieces as a result of the blast.

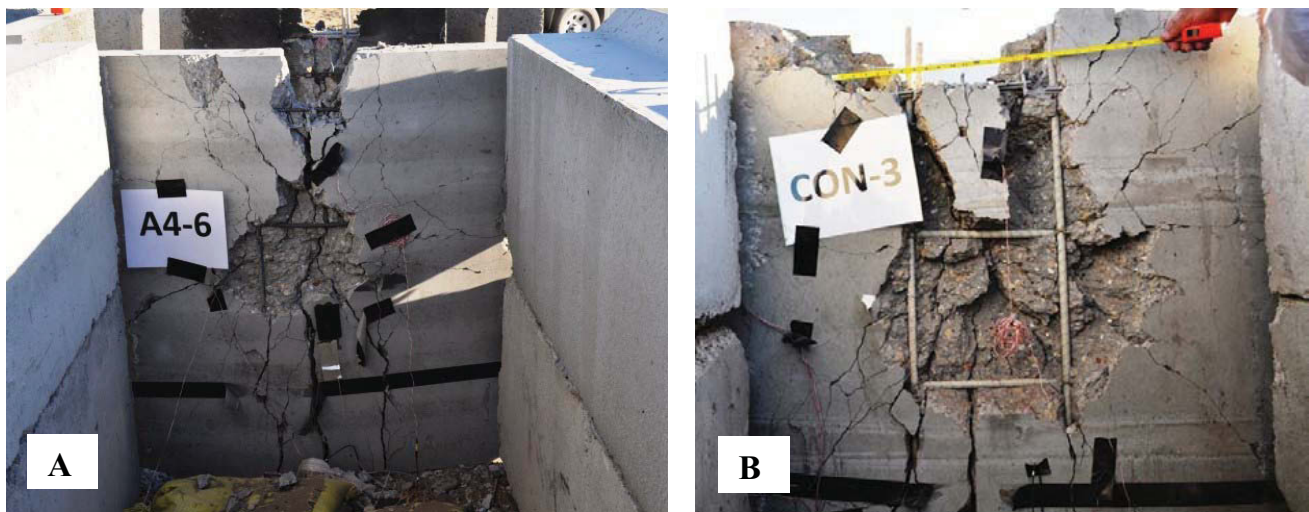


Fig. 3. (A) NWC panel A4-6 with internal steel rebar, (B) NWC panel CON-3 with internal GFRP bars.

3.2. Dynamic Simulations

Preliminary dynamic simulations of the panel tests were conducted using LS-DYNA [5] with Material 159—a smooth surface cap model for strain rates similar to vehicle impacts. Figure 6 shows results from a model of a 152 mm thick plain concrete panel with no reinforcement. Rigid elements shown in light grey represent the support structure used during testing. A conversion factor of 1.34 kg of TNT to 1 kg of C4 was used to simulate an air blast consisting of 4.54 kg of C4 explosive at a 1.0 m standoff from the center of the panel front face. Concrete strength data (compression and tension) from cylinder tests conducted within one week of the blast tests were used in this simulation.

Contours shown are a combination of brittle and ductile damage with elements removed when damage reaches a value of 1.0. While the crack and damage patterns are similar to those for the lightly reinforced test panels, the extent of damage predicted is in general larger in the simulations. Corrections in the material model are underway to account for the very high strain rates experienced by the concrete during blast loading.

4. Conclusions and Recommendations

This paper has presented an ongoing project on the performance of various types of reinforced concrete panels subjected to blast loading. Panels that performed the best were: (1) FRC panels with steel bar reinforcement and (2) NWC panels with externally bonded GFRP overlays. These panels showed the least amount of spalling and the narrowest crack widths when compared to

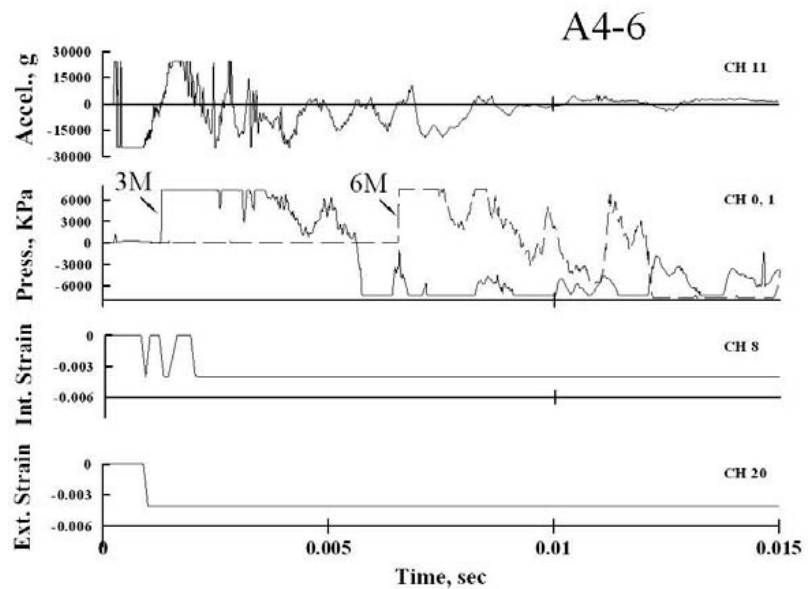


Fig. 4. Test data for concrete panel A4-6. Pressures were sampled at 3 m and 6 m from the blast.

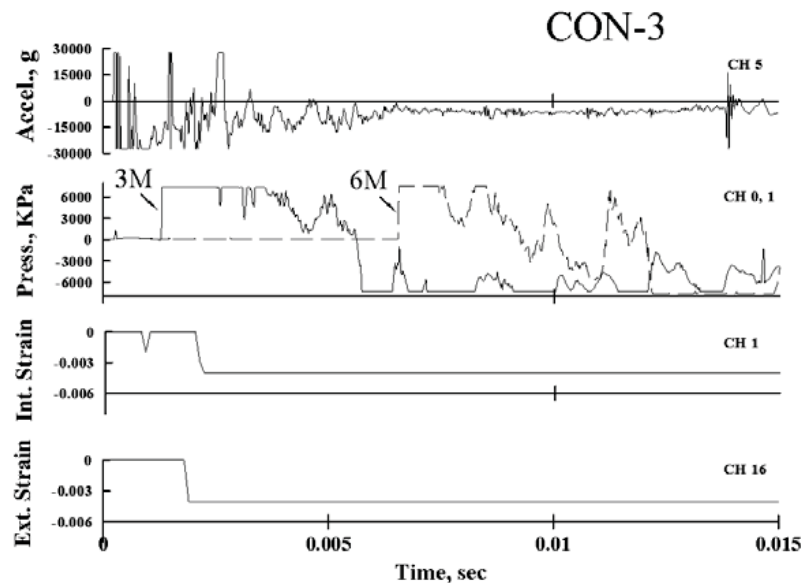


Fig. 5. Test data for concrete panel CON-3. Pressures were sampled at 3 m and 6 m from the blast.

other panel types. Panels made from NWC with steel rebar reinforcement and NWC with GFRP bars as reinforcement had considerable structural damage; the steel reinforced panels performed better than the GFRP reinforced panels in terms of overall damage. Panels that were made of only FRC without any internal steel rebar or GFRP bars performed the worst, with complete loss of structural integrity.

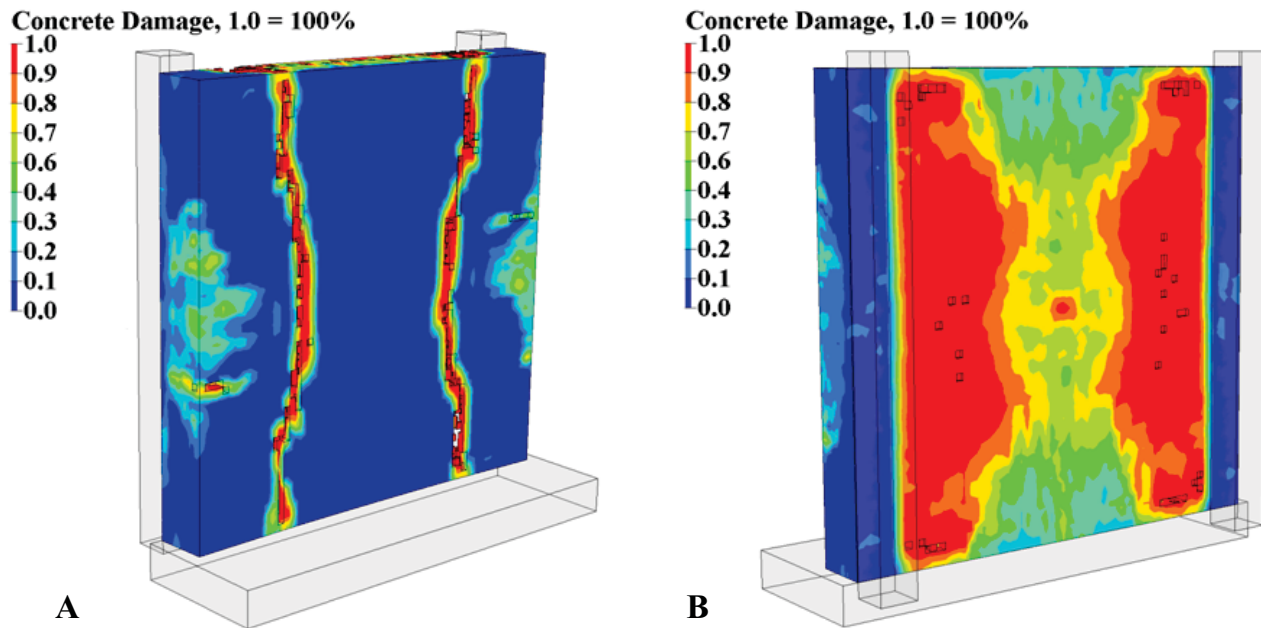


Fig. 6. (A) Preliminary front face LS-DYNA simulation (B) Preliminary back face LS-DYNA simulation. The support structure is modeled using rigid elements shown in grey.

It is recommended that further research be conducted for panels with FRC as internal reinforcement and internal steel rebar. Additional research is needed for reinforced concrete panels with GFRP overlays to study the different overlay configurations and anchorage, such as GFRP anchors or mechanical fasteners, to improve the bond of the GFRP overlays to the concrete. The results of this research will further the development of dynamic material simulation methods and materials models.

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