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Evaluation of Long Carbon Fiber Reinforced Concrete to Mitigate Earthquake Damage of Infrastructure Components

by

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16. Abstract

The proposed study involves investigating long carbon fiber reinforced concrete as a method of mitigating earthquake damage to bridges and other infrastructure components. Long carbon fiber reinforced concrete has demonstrated significant resistance to impact and blast loading. The carbon fibers will potentially reduce spalling and the degree of cracking during an earthquake event as well as increase the overall structural capacity. The scope of the research project includes testing of carbon fibers, development of a fiber-concrete composite material, and dynamic testing to evaluate the response of the material.

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Technical Report

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Chapter 1

Introduction

The objective of this research was to develop coatings and manufacturing processes that would allow the use of “long” carbon fibers within conventional reinforced concrete, resulting in significantly improved dynamic resistance of the material. The ideal fiber is both resilient, so it can withstand the harsh environment of the mixing process, and disperses well with proper alignment. In the past, attempts to use “long” carbon fibers have failed due to “balling” (agglomeration) and poor dispersion of the fibers. Fibers showing improvements on dispersion and alignment would allow a longer fiber option that could be used more effectively, with a reduction in cost and easier handling during placement.

Chapter 2

Development of Fibers

The first product, which consists of a 48K tow twined around a stiffer polypropylene backbone, referred to as Fiber B1, is shown in Figure 2.1. During the manufacturing process, a light coating of thermally activated epoxy was applied to the polypropylene immediately prior to twinning with the carbon fiber tow. Once twined, a heat treatment process partially bonded the carbon fibers to the polypropylene core. The end result was a more traditional concrete fiber shape, although appreciably longer in length, with significantly improved resiliency.

The second fiber, referred to as Fiber B2, shown in Figure 2.2, used the same materials as Fiber B1, a 48K carbon fiber tow and a polypropylene support system. However, the polypropylene was placed around the carbon fiber tow versus being twined, forming a jacket that provided the necessary fiber resiliency. A heat treatment process partially bonded the carbon fibers to the polypropylene jacket. The fibers were sectioned into 4 in. (102 mm) lengths.

The third fiber, referred to as Fiber B3, shown in Figure 2.3, consisted of a 48K carbon fiber tow twined around a stiffer polypropylene backbone, then weaved together with cotton string and sectioned into 4 in. (103mm) lengths. The weaving allowed for additional stability, kept the fiber from breaking apart during mixing, and allowed the cement paste to thoroughly coat the carbon fiber tow.

Figure 2.1. Fiber B1

Figure 2.2. Fiber B2

Figure 2.3. Fiber B3

Chapter 3

Development of “Long” Carbon Fiber Reinforced Concrete

3.1 Introduction

The next step in the design process involved developing the optimal mix proportions for the “long” carbon fiber reinforced concrete. The correct mix design is critical in creating a material with usable fresh and hardened properties. High fiber percentages are advantageous in that it would result in better performance for blast and impact resistance. However, as fiber percentage increases, the workability of the fresh concrete decreases. If the fresh concrete cannot be placed and consolidated in the formwork, then the structural element is unbuildable and the benefits of the fibers are unrealized. This chapter discusses the work developing the optimal mix proportions for “long” carbon fiber reinforced concrete (LCFRC).

3.2 Preliminary Concrete Mix Design

In general, fiber addition to concrete reduces the workability of the mixture. The carbon fibers developed in this research project magnify this effect due to the increased surface area. The increased surface area, along with a sponge effect created by the carbon fiber tow, requires significantly more paste in the concrete mix. However, there is a practical limit on the amount of paste in a concrete mix, as excessive paste leads to increased shrinkage. A lower coarse aggregate content also increases workability. The combination of increased paste content and decreased coarse aggregate content should result in a mix with sufficient workability for the “long” carbon fibers.

The research team investigated a series of potential mix designs, eventually arriving at the mix proportions shown in Table 3.1. This mix provided the maximum paste content and workability while still maintaining adequate resistance to segregation. The materials consisted on Type I cement, crushed limestone coarse aggregate (3/4 in. maximum (19 mm)), natural sand fine aggregate, a water-cement ratio of 0.38, and a high range water reducer (HRWR). In addition to the high paste content and lower coarse aggregate content, the HRWR provided increased workability at the relatively low water-cement ratio. The low water-cement ratio was required to reach the target compressive strength of 7,500 psi (51.7 MPa). The HRWR selected was Gelenium 3030, produced by BASF, at a dosage rate of 1.1 ounces per hundred lbs. of cement (32.5 mL per 45 kg).

The research team performed fresh and hardened property tests on this base (control) concrete mix without any fibers present. The results are shown in Table 3.2. The compressive and flexural strength values in Table 3.2 represent an average of three (3) replicate specimens. Based on this mix design, the researchers proceeded to the next step, optimizing the fiber lengths and fiber content (percentage) for the LCFRC.

Table 3.1. Base (Control) Mix Proportions

Materials	Material Weights lb/cu. yd. (kg/cu. m)
Cement	1019 (605)
Coarse Aggregate*	1320 (783)
Fine Aggregate*	1320 (783)
Water	388 (230)

*Saturated surface dry condition

Table 3.2. Fresh and Hardened Properties of Control Mix

Property	Test Result
Slump	9 in. (229 mm)
Density	143 pcf (2291 kg/m^3)
Compressive Strength	7420 psi (51.2 MPa)
Flexural Strength	791 psi (5454 kPa)

3.3 Fiber Mix Optimization

The LCFRC can be tailored to the specific application by varying the fiber length and fiber content (percentage). To investigate this potential, Fiber B1 was sectioned into lengths of 2, 4, and 6 inches (51, 102, 152 mm). A preliminary mix test with each of the three lengths indicated problems with the 2 and 6-in.-long (51 and 152 mm) fibers. The 2 in. (51 mm) fibers appeared to be too light to uniformly mix with the heavier constituents as they formed into bunches during the mixing process. The 6 in. (152 mm) fibers mixed well, distributing in a fairly random and uniform manner. However, these fibers tended to wrap around the 6x6 in. (152x152 mm) mesh reinforcement typically used in blast resistant structures. The 4 in. (102 mm) fibers mixed well and did not wrap around the mesh reinforcement. For these reasons, the 4-in.-long (102 mm) fiber was chosen for subsequent testing.

The next variable to investigate was the fiber content (percentage), sometimes referred to as the fiber fraction, which is the ratio of volume of fibers to total volume of concrete, expressed as a percentage. The highest possible fiber volume, while still able to be placed and consolidated into a form containing traditional reinforcing steel, is ideal for this application. As noted previously, as the amount of fiber increases, the workability (flowability) decreases. A valuable test method to evaluate workability (flowability) of fiber-reinforced concrete is ASTM C995, “Standard Test Method for Time of Flow of Fiber-Reinforced Concrete through Inverted Slump Cone.” The test, shown in Figure 3.1, evaluates the time for the fiber-concrete sample to flow out of an inverted traditional slump cone after placing a standard vibrator into the mix. With a fiber length of 4 in. (102 mm), the research team varied the fiber percentage for Fiber B1 and performed the ASTM flow cone test at fiber volumes of 1, 1.5, and 2 percent. The fibers had a very pronounced effect on workability, so much so that at a dosage rate of 2 percent, the fiber-concrete did not complete the flow cone test. Consequently, a dosage rate of 1.25 percent was included, and the results for the flow cone tests are presented in Figure 3.2. As expected, as the fiber percentage increased, the flow time increased, but unexpectedly the time increased exponentially, indicating a substantial effect on workability as the fiber volume increased.

A series of flexural strength tests were also performed on fiber reinforced concrete containing Fiber B1 at 4-in.-long (102 mm) with fiber volumes of 1, 1.25, and 1.5 percent. The test procedure followed ASTM C78, “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading),” with a loading rate of 150 psi/min (1034 kPa/min). The beams measured 18 in. long (457 mm) with 6-in.-square (152 mm) cross sections. The results are shown in Figure 3.3. However, the results did not follow the expected outcome – increased strength for increased fiber percentage – but were very nearly identical for each fiber volume, differing by less than 5 percent. This result indicated no additional benefit in terms of flexural strength beyond 1 percent fiber volume.

Consequently, since the workability decreased exponentially as the fiber volume increased, and since there was no additional benefit in terms of flexural strength beyond 1 percent fiber volume, the optimal solution was a 4-in.-long (102 mm) fiber at a dosage rate of 1 percent by volume for Fiber B1.

Figure 3.1. ASTM C995 Fiber- Concrete Flow Cone Test

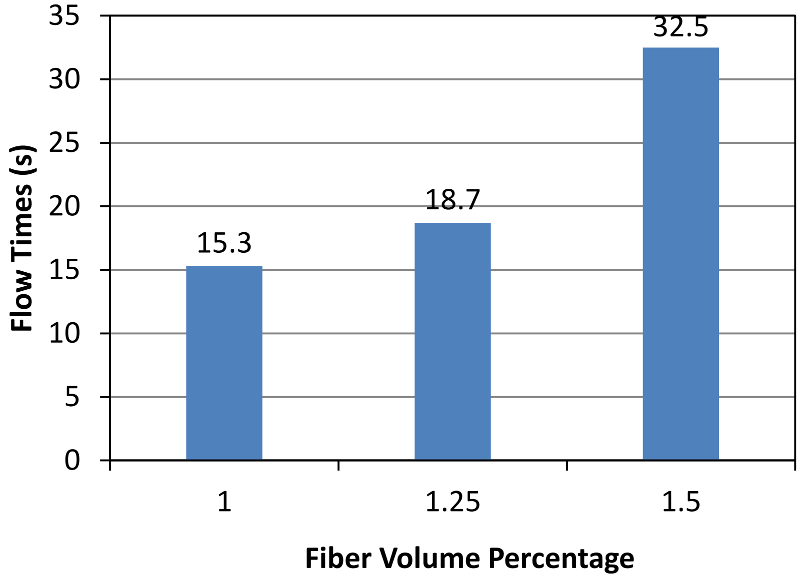

Figure 3.2. Flow Cone Test Results (ASTM C995)

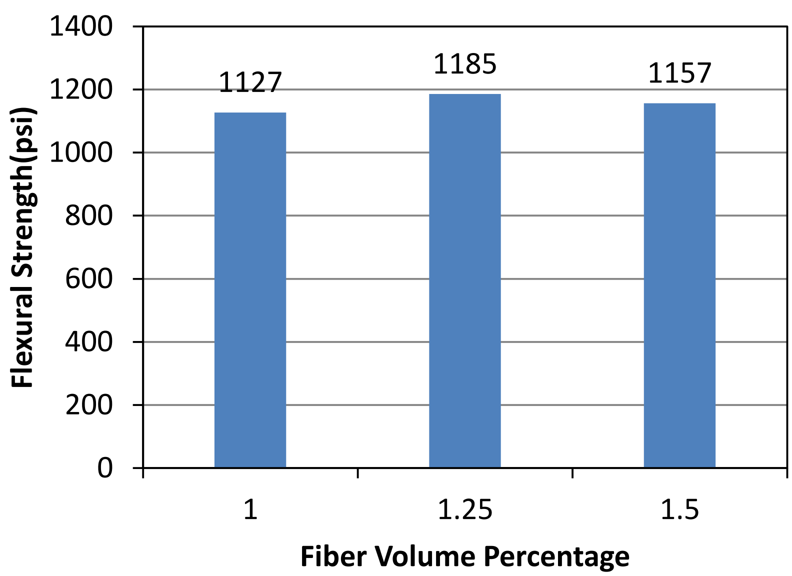

Figure 3.3. Flexural Strength Test Results (ASTM C78)

3.4. Conclusions

Based on the results of the above investigation, the following conclusions were developed:

- The mix design, as detailed in Table 3.1, should be used for concrete batching throughout the remainder of this study.
- The 4-in.-long (102 mm) fibers mixed well and did not wrap around the mesh reinforcement.
- Fiber addition had a very pronounced effect on workability.
- There is no additional benefit in terms of flexural strength beyond 1 percent fiber volume for Fiber B1.
- The research should proceed with the Fiber B1 measuring 4-in. (102 mm) in length at a 1 percent by volume addition to the concrete for impact testing.

Chapter 4

Impact Testing

4.1 Introduction

Drop-weight impact tests allowed the researchers to observe the dynamic response of concrete reinforced with “long” carbon fibers before performing the full-scale blast tests. This small-scale specimen testing was a useful way for the researchers to determine the efficacy of long carbon fiber reinforced concrete (LCFRC) versus plain concrete panels (no reinforcement) and panels reinforced with welded wire reinforcing (WWR). In essence, the drop-weight impact tests serves as a proof-of-concept and allows the researchers to more accurately predict the LCFRC blast resistance.

The drop weight impact test included a total of 14 specimens, each measuring 4-foot-square (1220 mm) in plan, with a thickness of 2 inches (51 mm), and simply supported on all four sides. The specimens included two plain concrete panels (no reinforcement), two panels reinforced with welded wire reinforcing (WWR), two panels reinforced with Fiber B1, four panels reinforced with Fiber B2, and four panels reinforced with Fiber B3. The tests involved increasing drop heights until failure of the specimen and recording the height at which cracking first occurred, the height at which failure occurred, and the permanent deflection. The panels were also instrumented to record load and deflection response. The load was collected by a load cell placed under the impactor at the center of the panel, and the deflection was obtained by a linear motion potentiometer placed under the slab.

4.2 Procedure

The researchers constructed a total of 14 specimens, each measuring 4-foot-square (1220 mm) in plan, with a thickness of 2 inches (51 mm). The specimens included two plain concrete panels (no reinforcement), two panels reinforced with welded wire reinforcing (WWR), and two panels reinforced with Fiber B1, four panels reinforced with Fiber B2, and four panels reinforced with Fiber B3. All 14 panels were constructed with the same concrete mix, shown in Table 4.1. Because the workability of the concrete is severely diminished when fibers are added to the cementitious matrix, a high-range water reducer (HRWR) was added to each mix. The HRWR used was Gelenium 3030 at a dosage rate of 1.1 ounces per hundred pounds of cement (32.5 mL per 45 kg). For consistency, the concrete mix for all six panels included the HRWR. All six panels were cast in identical wooden forms, with a 5/8-in.-thick plywood (16 mm) base and 1.5 in. thick framing studs (38 mm) for sides, as shown in Figure 4.1. Prior to casting, a form release agent was applied to the wood form to allow for easy panel removal, which allowed for the wooden forms to be reused.

Table 4.1 Concrete Batch Weights

Material	Material Weights, lb/cu. yd., (kg/m3)
Cement	1019 (605)
Coarse Aggregate*	1320 (783)
Fine Aggregate*	1320 (783)
Water	388 (230)

* Saturated Surface dry condition

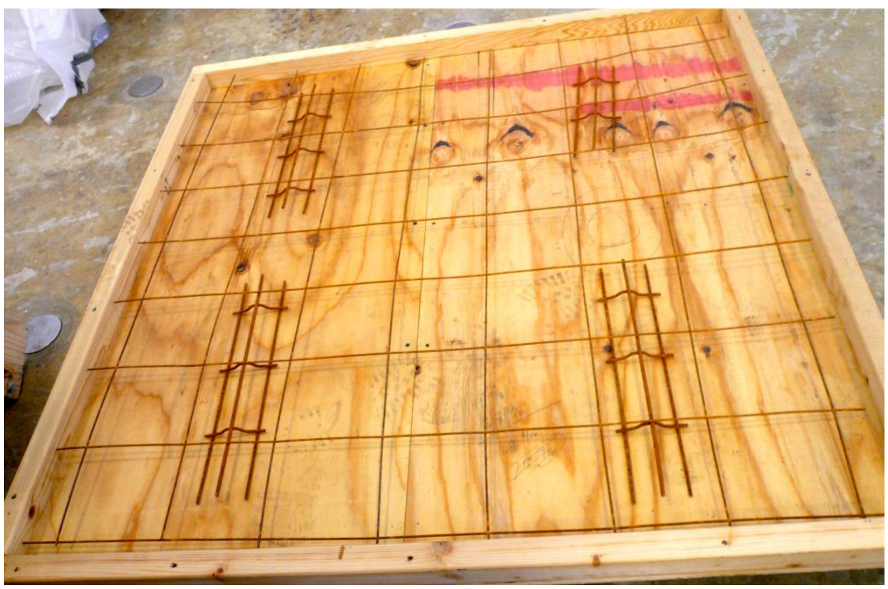

Figure 4.1: Impact Panel Formwork

The 14 panels were cast in pairs, with two plain concrete panels containing no reinforcement, two panels reinforced with 6 x 6 -W1.4 x W1.4 WWR placed at mid-height, two panels reinforced Fiber B1 at a dosage rate of 1 percent by volume, two panels reinforced with Fiber B2 at a dosage rate of 1 percent by volume, two panels reinforced with Fiber B2 at a dosage rate of 1.5 percent by volume, two panels reinforced with Fiber B3 at a dosage rate of 1 percent by volume, and two panels reinforced with Fiber B3 at a dosage rate of 1.5 percent by volume The WWR mesh was supported using 1-ft.-long (305 mm), 1-in.-high (25 mm) steel strip chairs, as shown in Figure 4.1. The 1 percent by volume dosage rate of the “long” carbon fibers correlates to 24.7 lb/cu. yd. (14.7 kg/m^3). The workability of the LCFRC was reduced compared to the concrete used in the plain and WWR mesh reinforced panels. To aid in construction of these panels, the researchers used form vibrators to consolidate the LCFRC effectively. Construction of the LCFRC impact panel is shown in Figures 4.2, 4.3, and 4.4.

Figure 4.2. LCFRC Mixing

Figure 4.3. LCFRC Impact Panel Construction

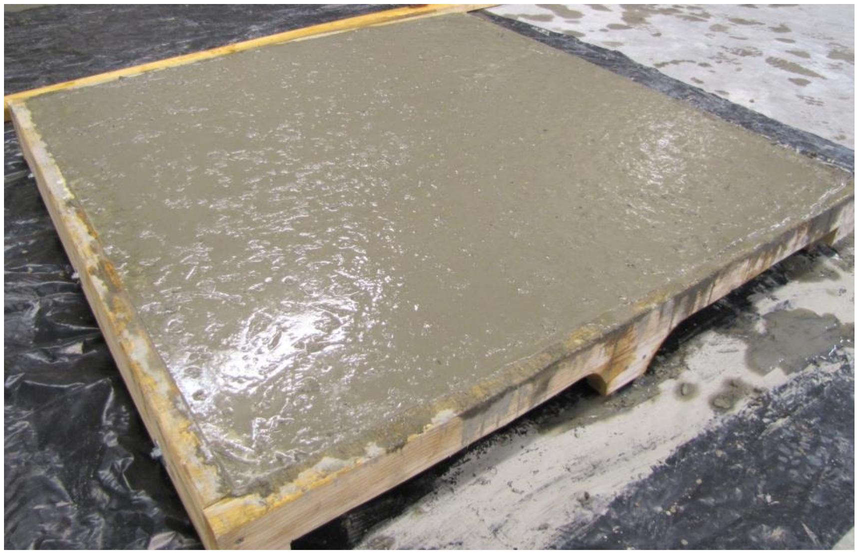

Figure 4.4. Completed LCFRC Impact Panel In Formwork

Each panel was cured for a minimum of 28 days prior to testing at a temperature of 73 ± 5°F (23 ± 3° C). Each panel was subjected to a seven-day moist cure using wet burlap and plastic followed by 21 days under ambient air conditions. The average compressive strength of the concrete used in casting the impact panels was 7600 psi (52.4 MPa).

The impact test setup is shown in Figure 4.5. Each panel was supported on a level, rigid steel frame with a 2-inch (51 mm) bearing support along each edge. The panels were unrestrained horizontally and upward vertically. Centered on the panel was the dynamic load cell to measure the load subjected to each panel by the drop weight.

The dynamic load cell was specially constructed using four individual dynamic load cells, built by PCB Piezotronics and shown in Figure 4.6, and machined steel plates. By combining the four individual 20 kip (89kN) capacity dynamic load cells, the researchers were able to measure loads up to 80 kips (356kN) of force. To reduce excessive vibrations of the load cell after impact, the researchers placed a 1/8-inch-thick (3.2 mm) neoprene square under the load cell. To measure deflection, a linear motion potentiometer with a 2-in.-stroke (51 mm) was secured under the panel, as shown in Figure 4.7. In order to measure rebound of the panel, the potentiometer was installed with an initial 1/2-in. deflection (12.7 mm).

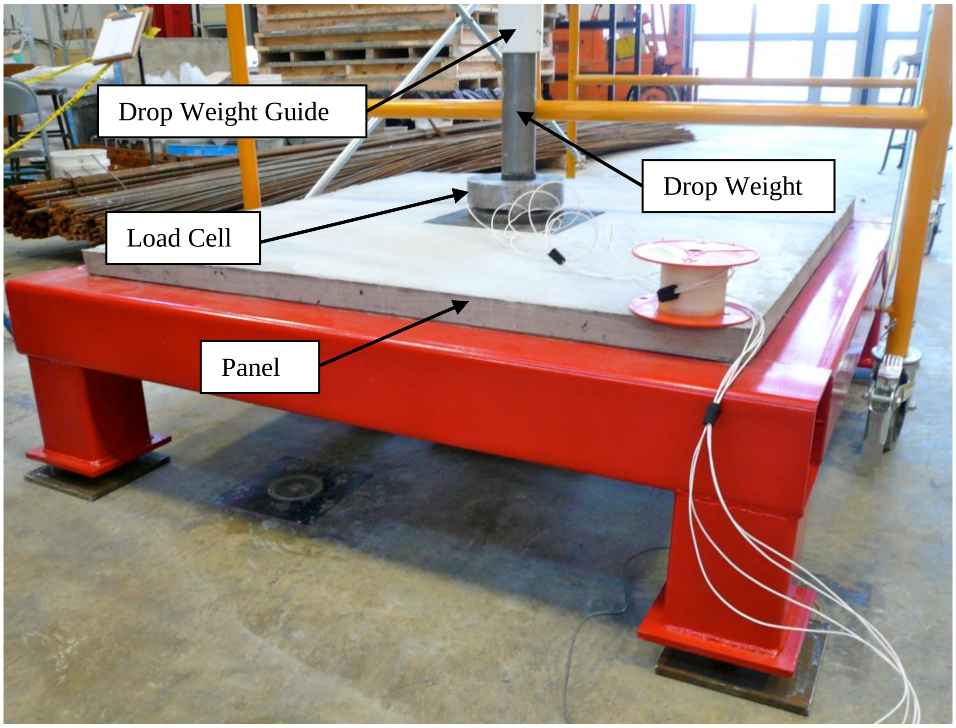

Figure 4.5: Drop-Weight Impact Test Setup

Figure 4.6: 20 kip (89kN) Dynamic Load Cell (courtesy of PCB Piezotronics)

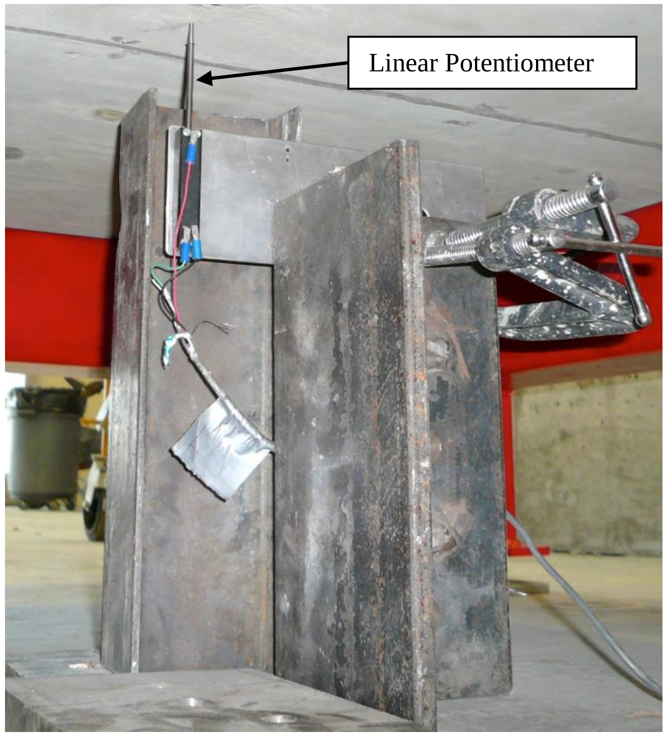

Figure 4.7: Linear Motion Potentiometer Setup

The researchers impacted the panels with a 50-pound (23kg), 2-3/4 in. (70 mm) steel rod drop weight, guided by a 15-ft.-tall (4570 mm) section of PVC pipe, as shown in Figure 4.5, at incremental heights until panel failure. To further reduce impact vibrations after the weight impacted the load cell, a 1/2-in.-thick (12.7 mm) section of high durometer neoprene was affixed to the striking end of the rod. For testing, each series began with a drop height of 3 in. (76 mm). The drop height increased by 3 in. (76 mm) for subsequent drops until a drop height of 24 in. (610 mm) was reached. From 24 in. (610 mm) until failure, the drop height increased by 6 in. (152 mm) each time. A Synergy Data Acquisition System recorded the load and deflection for each drop. When the panels neared failure, all instrumentation was removed to prevent the possibility of having it damaged.

4.3. Results

The results of the impact testing are summarized in Table 4.2. All of the LCFRC panels clearly outperformed the plain concrete panels. Although the LCFRC exhibited a higher average cracking height, the WWR panels outperformed the Fiber B1 and B2 panels in failure height. The Fiber B3 panels at a 1.5 percent dosage rate outperformed the WWR panels in failure height, exhibiting great potential. As expected, the plain concrete panels did not exhibit any visual cracking prior to failure. Figures 4.8 and 4.9 depict the cracking and failure heights graphically.

Table 4.2 Drop-Weight Impact Test Results

Panel, dosage rate (%)	**Cracking Height (in.)**	**Failure Height (in.)**
Plain Concrete No. 1	15	15
Plain Concrete No. 2	18	18
WWR No. 1	24	132
WWR No. 2	18	120
Fiber B1_1, 1.0	24	78
Fiber B1_2, 1.0	30	66
Fiber B2_1, 1.0	12	36
Fiber B2_2, 1.0	12	54
Fiber B2_3, 1.5	12	48
Fiber B2_4, 1.5	9	48
Fiber B3_1, 1.0	24	84
Fiber B3_2, 1.0	36	90
Fiber B3_3, 1.5	30	138
Fiber B3_4, 1.5	48	144

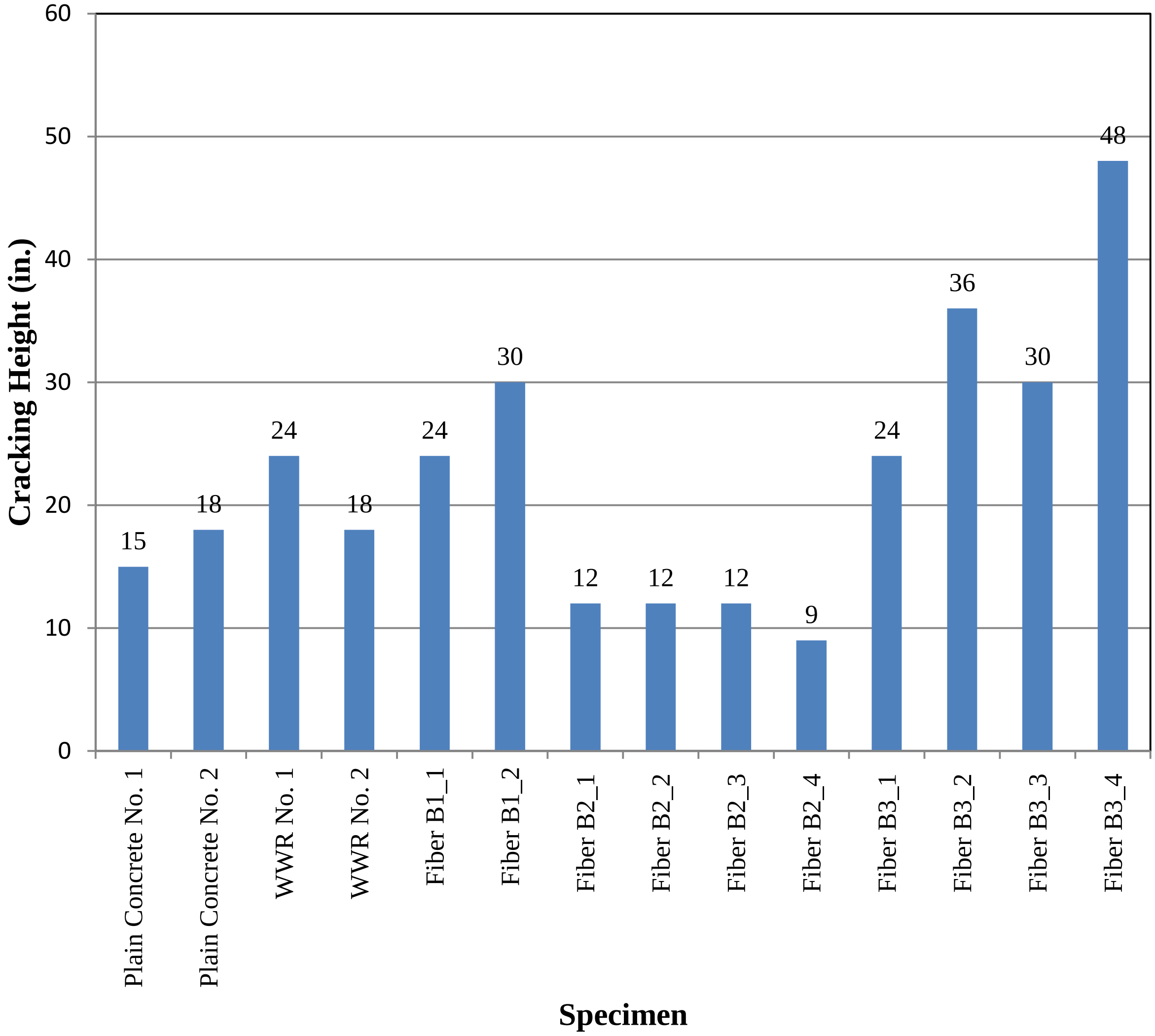

Figure 4.8: Summary of Cracking Heights for Drop-Weight Impact Testing

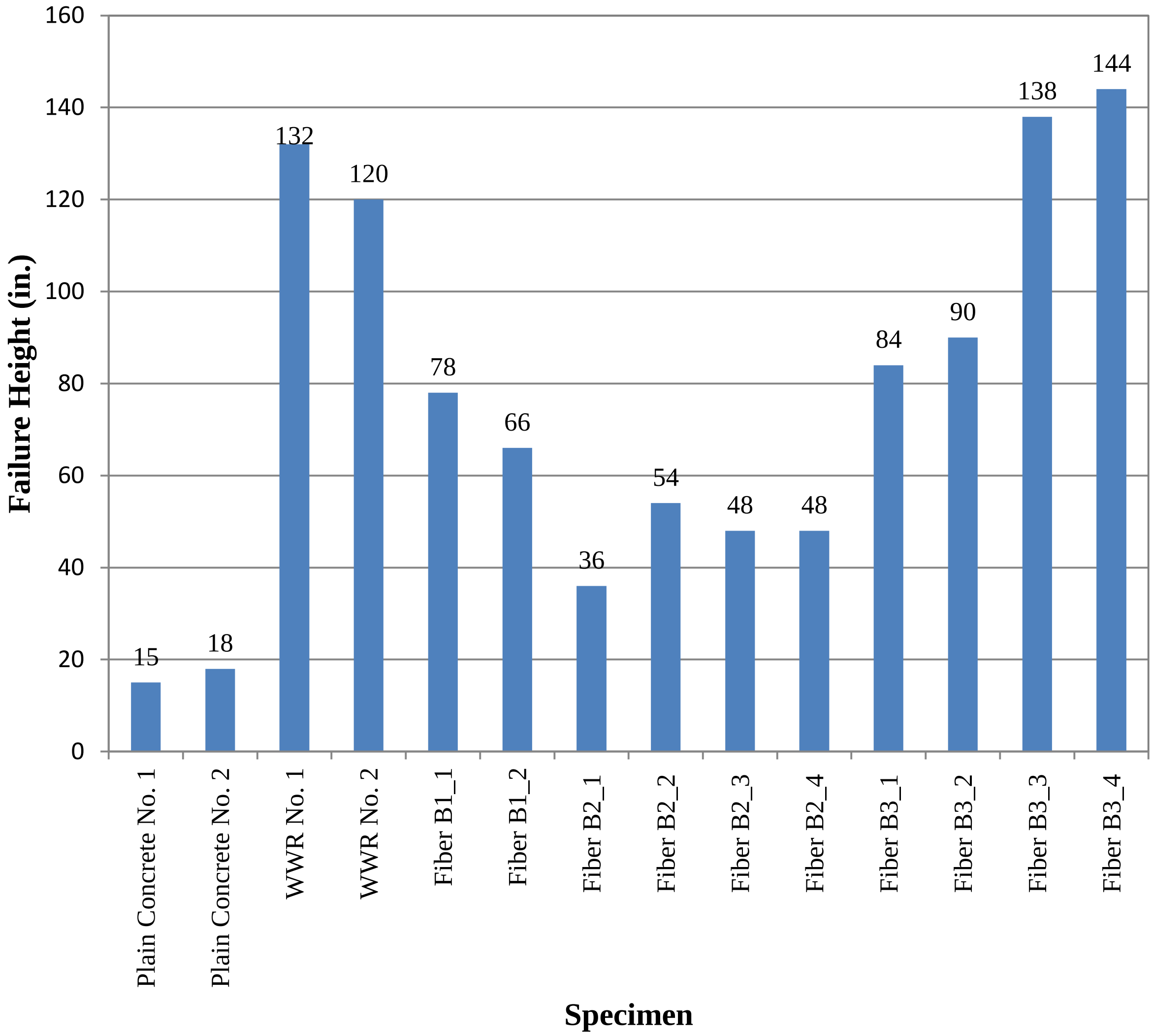

Figure 4.9: Summary of Failure Heights for Drop-Weight Impact Testing

Qualitative analysis of the panel impact damage is also a very important measurement of how well the panels performed and their potential blast resistance. Both plain concrete panels exhibited sudden failure with similar cracking patterns, with four cracks spreading out from the center to the middle of each of the four panel sides, as shown in Figure 4.10. The sudden failure of the two plain concrete panels was expected and evidences why reinforcement, either mild steel and/or fibers, is necessary in the concrete matrix.

A visual comparison of the WWR panels and LCFRC panels offers clues as to how the fiber reinforced concrete will respond to a blast event. The WWR panels failed at higher heights than the Fiber B1 and Fiber B2 panels. However, the WWR panels displayed significantly more damage that would be extremely harmful in a blast event. As shown in Figures 4.11, 4.12, and 4.13, the WWR panels had a significant amount of spalling (fragmentation) and cracking compared to the LCFRC panels. The improved dynamic response of the LCFRC can be attributed to the energy absorbed by the “long” carbon fibers by pullout and the ability to maintain post-crack continuity. Both of these attributes should significantly improve the blast resistance of the LCFRC. An example of crack bridging of the fibers and fiber pullout is shown in Figures 4.14 and 4.15, respectively.

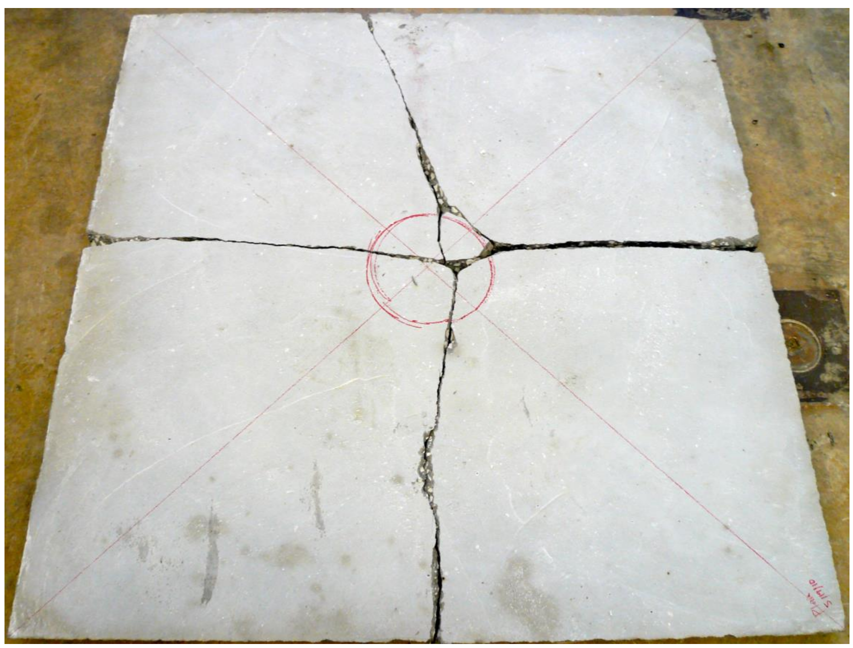

Figure 4.10: Typical Top of Plain Concrete Panel Failed Specimen

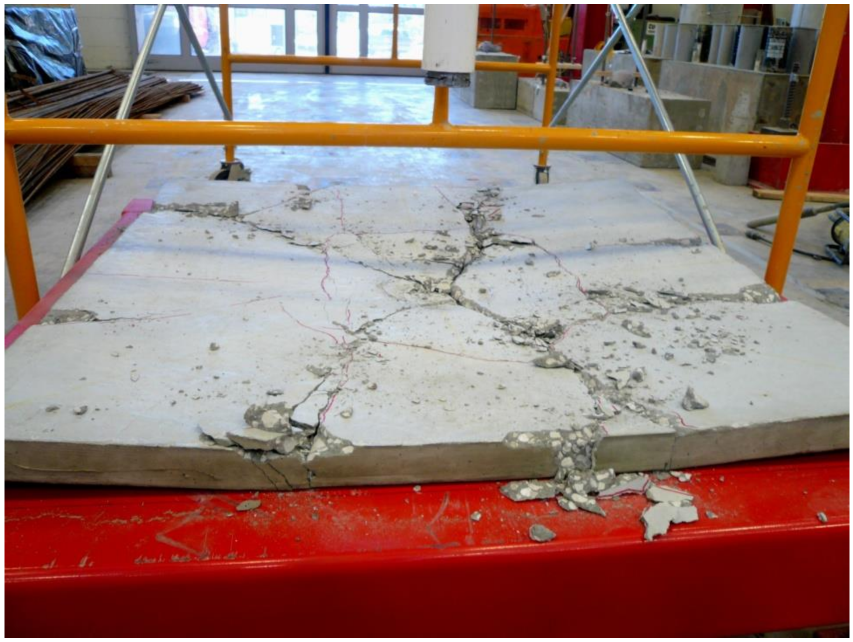

Figure 4.11: Typical Top of WWR Panel Failed Specimen

Figure 4.12: Typical Top of Fiber B1 Panel Failed Specimen

Figure 4.13: Typical Top of Fiber B3 Panel Failed Specimen

Figure 4.14: Carbon Fiber Bridging Crack along Bottom of Panel

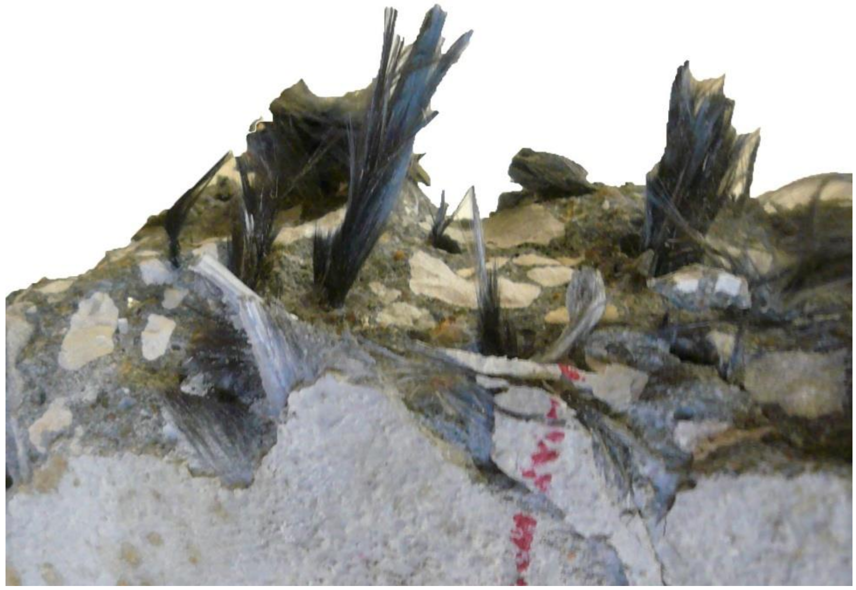

Figure 4.15: Carbon Fiber Pullout from LCFRC Panel Impact Test

4.4 Conclusions

Based on the results of the above investigation, the following conclusions were developed:

- The addition of “long” carbon fibers significantly increased the impact resistance of the panels as compared to the plain concrete panels.
- The WWR panels displayed significantly more damage, both in terms of spalling (fragmentation) and the extent of cracking than the LCFRC panels.
- The addition of “long” carbon fibers, which distribute throughout the specimen, provide superior spalling (fragmentation) resistance when exposed to impact loading.
- The results suggest that a hybrid system that utilized both “long” carbon fibers and mild reinforcement will provide the highest degree of failure and spalling (fragmentation) resistance.