Performance of UHPFRC Plates under Repeated Impact Load

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Abstract:

An experimental investigation has been conducted to collect fundamental data and to develop more understanding of the dynamic response of UHPFRC plates. Six reinforced plates with identical dimensions are tested using multi-impact technique by dropping a 475 kg (1047.20 Ib) steel weight from a clear height of 4.15 m (13.60 ft). Three parameters are investigated: concrete type; fibers volume content; and steel reinforcement ratio. The results of this investigation have confirmed that UHPFRC plates exhibited superior damage control characteristics compared to high-strength concrete (HSC) plate. Increasing the fiber content was shown to improve the dynamic performance of the UHPFRC plates, resulting in reduced peak and residual displacements at same impact loads and an increase in the specimen ability to sustain increased impact energy capacity before failure. The test results showed that steel reinforcement played an important role in specimens overall behavior and increasing impact capacity.

Keywords: Drop-weight impact; UHPFRC; reinforcement ratio; steel fiber content; Impact energy; crack pattern**.**

1. Introduction

UHPFRC is a relatively new generation of fiber cementitious composites which has been developed to give significantly higher material performance than other concrete classes. UHPFRC exhibits outstanding mechanical, and durability properties. Such properties include: ultra-compressive strength exceeding 150 MPa (22 ksi), enhanced tensile strength, ductility, flexibility, toughness, dimensional stability, durability, impermeability, corrosion resistance, abrasion resistance, and aggressive environment resistance. Such superior properties have been achieved through the use of an optimized combination of materials which include cement, fine sand, micro-silica, super-plasticizer, very low water content, and fibers.

Low-velocity high mass impact loading conditions with velocities up to 10 m/s (32.8 ft/s) is the most common impact scenarios for civil engineering structures. Typical low-velocity impact scenarios include transportation structures subjected to vehicle collisions, and offshore structures subjected to ice and/or ship impact. Additionally, loading arising from natural hazards such as earthquakes and tornadoes are also related to low-velocity impact (CEB-FIP). Several experimental investigations at material level have demonstrated that UHPFRC exhibits excellent dynamic properties (E. Parant, P. Rossi, E. Jacquelin; Habel and Gauvreau; Millard et al.). However, experimental investigations on the dynamic response of UHPFRC structural members (i.e. beams and slabs) are limited. Additionally, Most of available data in literature are related to extreme loading conditions such as blast loading (Cavill, Rebentrost, and Perry; Ngo, Mendis, and Krauthammer; Yi et al.) and high-velocity impact simulation using shock tube (Ellis et al.). In summary, all these investigations have confirmed that UHPFRC shows improved performance and superior damage control properties under extreme load conditions compared to conventional concrete. However, there is no available data in literature related to the behavior of UHPFRC members subjected to low-velocity impact load with velocities up to 10 m/s (32.8 ft/s).

In general there is no standard test technique to assess the impact resistance of concrete members. ACI Committee 544 proposed a repeated drop-weight impact test for testing FRC materials (ACI Committee 544), in which the number of drops necessary to cause prescribed levels of damage in the specimen is the main parameter and the drop-height is kept constant. Relative impact resistance of specimens with identical dimensions casted using different materials can be evaluated using this technique. Therefore in this investigation, all plates are subjected to multi-impact tests by dropping a steel mass of 475 kg (1047.20 Ib) from a fixed height of 4.15 m (13.60 ft). The objectives of current investigation are: to develop a fundamental understanding of the dynamic response of UHPFRC plates subjected to low-velocity impact load; and to investigate the effect of reinforcement ratio and fiber content on the impact resistance and failure mode of UHPFRC plates. It was observed in small-scale impact tests on prisms with dimension of 100×100×400 mm (3.9×3.9×15.8 in.) that the residual displacement reached 8 times the serviceability limit of displacement without any significant fragmentations. Therefore in this investigation, the impact testing was terminated when the cumulative residual mid-point displacement of repeated impacts exceeds the value eight times the serviceability limit (i.e. 65 mm [2.56 in.]) or severe punching damage took place with high probability of instrumentation damage.

2. Experimental Investigation

2.1 Test Specimens

Six reinforced concrete plates with identical dimensions are constructed and tested under drop-weight low-velocity impact test. The plates are 1950 mm (76.8 in.) square with a thickness of 100 mm (3.94 in.). All plates are doubly reinforced with equal top and bottom orthogonal steel reinforcement mats to resist the tensile stresses generated due to reverse moment after bounding. 10M CSA standard deformed steel bars of Grade 400 [24] are used as longitudinal reinforcement in all plates. Three parameters are considered in current investigation, namely: concrete matrix (HSC and UHPFRC); fibers volume content (1, 2, and 3%); and steel reinforcement ratio (0.47, 0.64, and 1.00% per layer/direction). A summary of studied parameters is presented in Table 1.

Table 1. Details of test plates

Series No.	Specimen*	Fiber Content v_f (%)	Reinforcement Ratio** (%)	Reinforcement Spacing (mm[in.])
1	HS_{100}	0	1.00	100 (3.94)
2	UF_1S_{100}	1	1.00	100 (3.94)
3	UF_2S_{100}	2	1.00	100 (3.94)
4	UF_3S_{100}	3	1.00	100 (3.94)
5	UF_2S_{158}	2	0.64	158 (6.22)
6	UF_2S_{210}	2	0.47	210 (8.27)

*Plates' identification: concrete matrix (H=HSC, U=UHPFRC); fibre content ($\mathbf{F_1}$=1%, $\mathbf{F_2}$=2%, $\mathbf{F_3}$=3%); Spacing ($\mathbf{S_{100}}$=100, $\mathbf{S_{158}}$=158, $\mathbf{S_{210}}$=210mm);** per layer; per direction.

UHPFRCs mixes used in this investigation is Ductal® specified by Lafarge North America (Lafarge-North America). All UHPFRC mixes in this investigation have identical mix proportions with exception of fiber volume dosage. Short straight steel fibers with different volume contents of 1, 2, and 3% are used in all UHPFRC mixes. Geometrical and mechanical properties of concrete materials and coupon test of steel reinforcement are tested and summarized in Table 2. Each data point in the table is averaged from three specimens. Compression and splitting tensile tests were conducted on cylinders with dimensions of 100×200 mm (3.9×7.9 in.). On the other hand, three-point flexural strength tests were conducted on 100×100×400 mm (3.9×3.9×15.8 in.) prisms with a clear span of 300 mm (11.8 in.).

Table 2. Material properties of HSC, UHPFRC, and steel reinforcement

<table>
<tr><td colspan="2">Concrete mix</td><td>Density kg/m³(Ib/ft³)</td><td>Compressive strength fc', MPa (ksi)</td><td>Elastic modulus E_c, GPa, (ksi)</td><td>Flexural strength f_r[*], MPa (ksi)</td><td>Splitting strength f_{tsp}, MPa (ksi)</td></tr>
<tr><td colspan="2">HSC</td><td>2,540 (159)</td><td>83.1 (12.05)</td><td>30.2 (4380)</td><td>8.0 (1.16)</td><td>3.6 (0.52)</td></tr>
<tr><td rowspan="3">UHP-FRC</td><td>1%</td><td>2,600 (162)</td><td>154.8 (22.45)</td><td>45.0 (6527)</td><td>8.5 (1.23)</td><td>7.3 (1.06)</td></tr>
<tr><td>2%</td><td>2,650 (165)</td><td>162.4 (23.55)</td><td>45.8 (6643)</td><td>19.2 (2.78)</td><td>11.1 (1.61</td></tr>
<tr><td>3%</td><td>2,710 (169)</td><td>158.7 (23.00)</td><td>46.3 (6715)</td><td>28.3 (4.10)</td><td>14.0 (2.03)</td></tr>
<tr><td colspan="2">Steel bar</td><td>Diameter mm (in.)</td><td>Mass kg/m (Ib/ft)</td><td>Yield stress f_y, MPa (ksi)</td><td>Ultimate strength f_{ult}, MPa (ksi)</td><td>Elastic modulus E_s, GPa (ksi)</td></tr>
<tr><td colspan="2">10M</td><td>11.29(0.44)</td><td>0.775 (0.52)</td><td>433.4(62.86)</td><td>621.7 (90.2)</td><td>201.1 (29,2)</td></tr>
</table>

2.2 Test Setup and Instrumentations

Schematic diagram of the drop-weight impact test setup is illustrated in Figure 1. The plates are tested under same loading and supporting conditions. The plates are subjected to hard impact at their mid-point and simply supported at their four corners.

The striking surface of the drop-weight is flat with dimensions of 400×400 mm. The supporting system has been designed to prevent the uplift of supports without creating any significant restraint moments using a special tie-down steel frame that allows a sufficient amount of rotation up to 5o (Figure 1).

The experimental test is equipped with sophisticated instrumentation. Two accelerometers with capacities range of ±20,000g are mounted to the drop-weight (g is is the Earth's gravitational acceleration). The reaction forces between the supports and specimen are measured using four quartz load cells with a capacity of 650 kN. Contact-less laser displacement sensor is used to measure the mid-point vertical displacement. All output data are recorded using a digital dynamic data acquisition system ECON model MI-7008 with sampling rate of 100 kHz. Impact tests are recorded by a digital camera with a rate of 240 frames/second and posterior analysis of recorded videos is performed using the image analysis software Tracker® (D. Brown). More details regarding the impact setup can be found in (Othman and Marzouk).

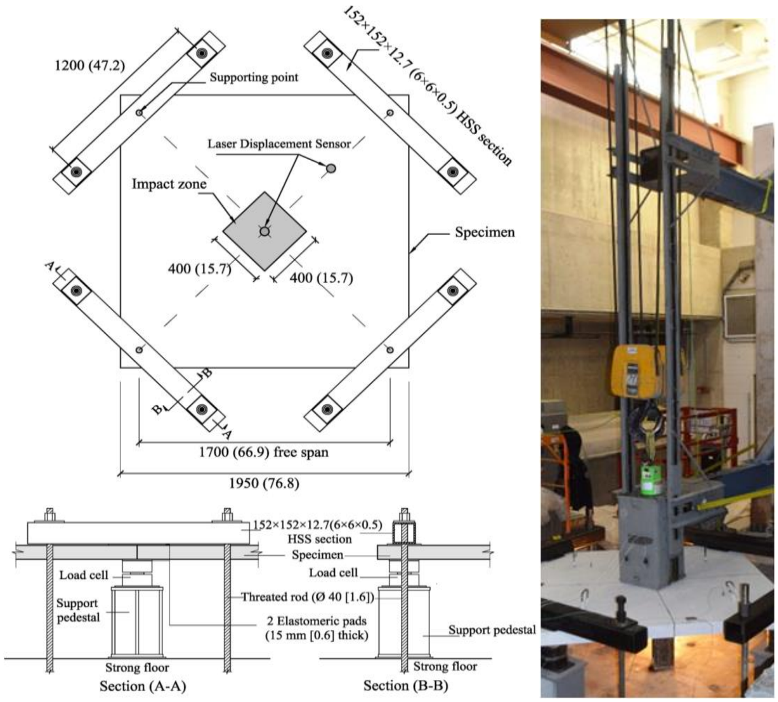


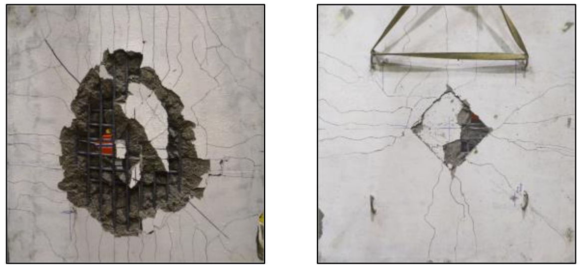
Figure 1. Drop-weight impact test setup (dimensions in mm[in.]) (Othman and Marzouk)

3. Results and Discussion

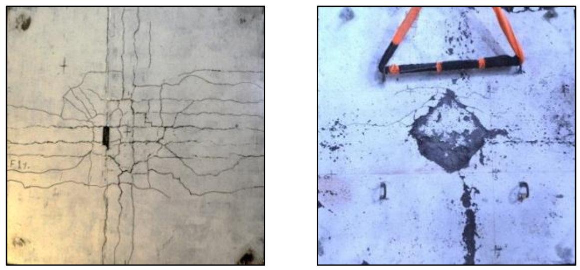
Selected results are presented in the following sections to characterize the responses of the plates and to illustrate the influence of main reinforcement ratio and steel fiber content.

3.1 Crack Patterns and Failure Modes

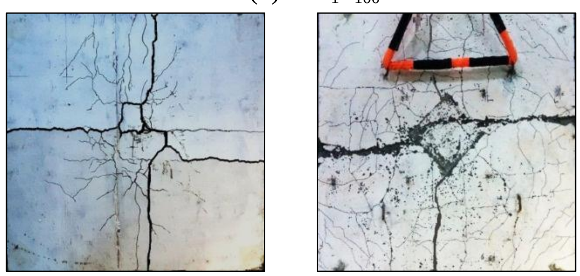
The final cracking patterns for tested plates are presented in Figure 2. Based on the observed damage in tested plates, the failure mode was found to be depending on the concrete material rather than reinforcement ratio and fiber content. HSC plate (HS_{100}) failed in punching shear mode and was terminated due to severe concrete ejection in impact zone with high probability of damage of instrumentation under additional impacts (Figure 2-a). On the other hand, all UHPFRC plates exhibit pronounced ductility and are typically failed in pure flexural mode. Under repeated impact tests, UHPFRC plates reach the specified cumulative residual displacement limit and only bending cracks are observed. Fibers failed due to pull-out at the fracture zone. UHPFRC plates showed enhanced damage control properties. No spalling, scabbing, and/nor significant large concrete fragmentations are observed under repeated impact tests. Even at failure, the fragments are in form of fine powder. Therefore, the use of UHP-FRC in such structural members can effectively eliminate the possibility of injury to occupants in case of accidental extreme loading scenario. A worth of mentioning here that steel reinforcement ratio is strongly influence the crack pattern. UHPFRC plates contain steel reinforcement ratio of 1% (UF_1S_{100}, UF_2S_{100}, and UF_3S_{100}) typically exhibit similar crack pattern. Multi-cracks aligned with steel reinforcement grids are developed in both directions on the bottom surface of plates regardless fiber volume content (Figure 2-b). On the other hand, the major damage of plates reinforced with steel reinforcement of ratios less than 1% (UF_2S_{158} and UF_2S_{210}) are typically concentrated in a single wide crack at mid-span and failure crack pattern consisting of four radial macro-cracks is generated (Figure 2-c). It should be mentioned that fiber content plays important role in limiting the extent of damage level. Increasing the fiber content led to an increase in the number of cracks and a reduction in the width of cracks formed.



(a) HS_{100}



(b) UF_1S_{100}



(c) UF_2S_{210}

Figure 2. Final crack patterns (left: bottom surface; right: top surface)

3.2 Impact capacity

previous study carried out by Kurihashi et al. (Habel and Gauvreau) showed that the impact capacities were the same for identical FRC plates subjected to two different low-velocity impact loading protocols (single impact or sequential impacts). Therefore, in current investigation, the total kinetic energy ($E_k = \Sigma 1/2\ mV_0^2$) imparted to each of the plates is used to provide an estimate of the impact capacity. Where: m is drop-weight mass (475 kg [1047.20 Ib]) and V_0 is the impact velocity calculated using image analysis of recorded videos. Figure 3 summarizes the impact capacities measurements of tested plates.

It is evident from Figure 3 that the use of UHPFRC material enhances the impact capacity significantly. Comparing the capacity of UHPFRCs and HSC plates that were constructed using identical steel reinforcement ratio, the total imparted energy to UHPFRC plates is being in range of 2.3 to 6.4 times the capacity of HSC plate. The increased capacities of UHPFRC plates are correlated to the steel fiber content. A worth of mentioning here that increasing of fiber content from 1 to 2% has limited effect on the impact capacity compared to increasing the fiber content from 2 to 3%. Additionally, the steel reinforcement ratio is found to have significant influence on the impact capacity.

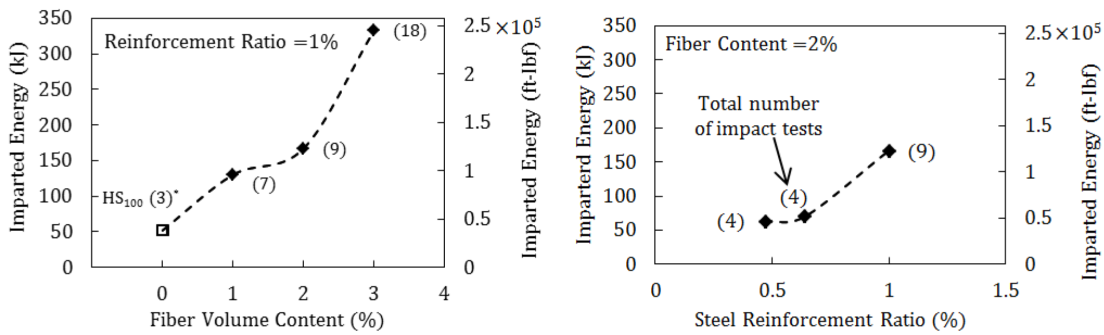


Figure 3. Impact capacities of HSC and UHPFRCs plates

3.3 Mid-point displacement response

Figure 4 shows the displacement response of plates HS_{100} and UF_1S_{100} for all preformed impact tests. It should be recalled that the two plates are identical with exception of concrete materials. The results of even impact tests of plate UF_1S_{100} are omitted for clear displaying purpose. The advantage of using UHPFRC in impact resistance structures shows up clearly in this comparison; HSC plate exhibits excessive damage as it is reflected on the displacement response in the form of permanent displacement offset and significant increase in natural time period after each impact test (Figure 4-left). On the other hand, UHPFRC plate (UF_1S_{100}) shows a pronounced ductility and enhanced elastic recovery response under subsequent impacts (Figure 4-right). It should be clear in this comparison that, UHPFRC plate (UF_1S_{100}) contains 1 % steel fibers is the lower-bound.

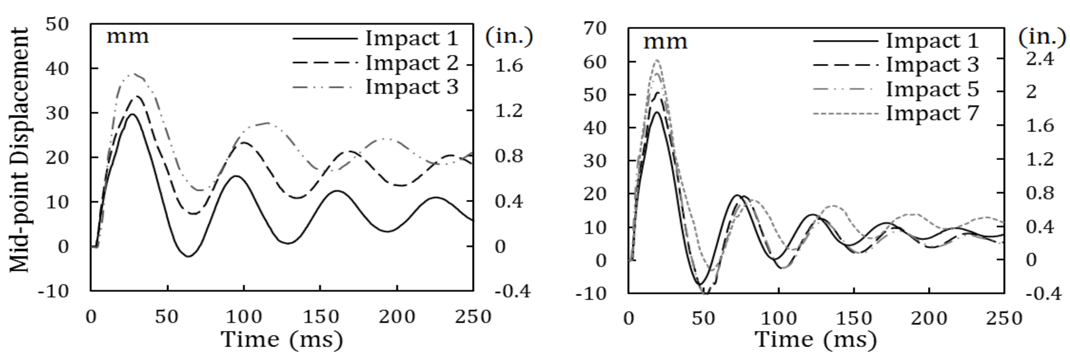


Figure 4. Mid-point displacement-time histories for plates (left: HS_{100}; right: UF_1S_{100}).

Figure 5 shows the influence of steel fiber content on displacement response for first and fourth impact tests. It is clearly illustrated that the increasing of fiber dosage reduced the peak and residual displacements. Also, the time period is decreased with the increase of fiber contents since plates with higher fiber contents have higher stiffness. Figure 5 can be used to demonstrate the effect of fiber content on controlling damage level; plate contains 3% fiber (UF_3S_{100}) exhibits no permanent displacement offset compare to plates contain 1 and 2% fibers (UF_1S_{100} and UF_2S_{100}). It should be mentioned that increasing fiber from 1 to 2% has limited effect on displacement response under first impact test (Figure 5-left). Additionally, same displacement response is observed in second and third impact tests. Both plates have almost similar response in terms of magnitude, time response, and residual displacement. Starting from fourth impact test

(Figure 5-right), the displacement histories of plates UF_1S_{100} and UF_2S_{100} show different peak and permanent displacement offset. The reason of such difference in displacement response may be return to the effect of fibers distribution on micromechanical behavior of UHPFRC matrix. The number of fibers per unit volume of plate UF_3S_{100} (v_f =3%) is sufficient to effectively arrest the propagation of any potential micro-cracks at early stage. As a result, the first crack limit is increased and there is no significant plastic deformation offset in displacement response (Figure 5-left). On the other hand, fibers spatial distributions of plates contain 1 and 2% fibers are not enough to stop the development of micro-cracks paths under first three impact tests. Under fourth impact tests, the size of developed micro-cracks is large enough to be arrested by fibers in plate UF_2S_{100} (v_f = 2%) and fibers start to be active. However at this level of damage, the micro-cracks size still small to be resisted by fibers in plate UF_1S_{100} (v_f =1%) and the plate suffer more plastic deformation offset (Figure 5-right). Based on the above observation, fiber content of 3% by volume has enough spatial distribution to resist the spreading of micro-cracks at its early stage.

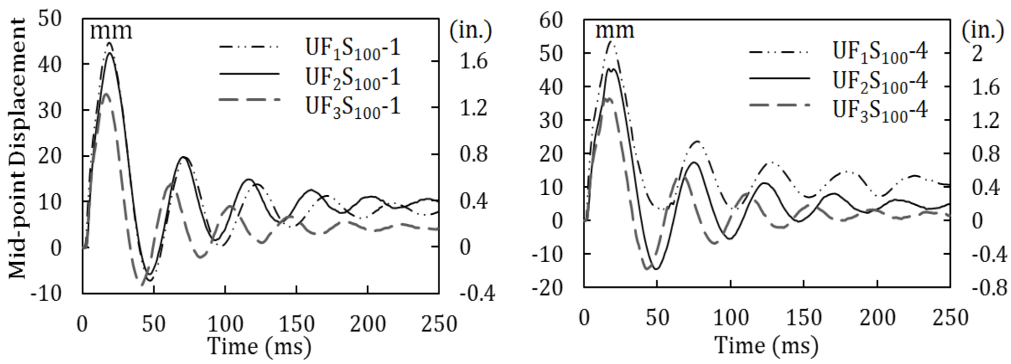


Figure 5. Influence of fiber content on mid-point displacement (left: 1st test; right: 4th test)

4. Conclusions

The following conclusions can be drawn from the experimental study that was conducted:

1. UHPFRC plates exhibited superior damage control characteristics under low-velocity impact loading conditions when compared to reinforced concrete plate cast using HSC concrete. No spalling, scabbing, and/nor significant large fragmentations are observed. Additionally, the fragments are in form of fine powder.

2. All UHPFRC plates were responded globally with pronounced ductility compared to HSC plate. Under repeated impact tests, all UHPFRC plates regardless of the fiber volume dosage and/or steel reinforcement ratio reached the target cumulative residual displacement and only bending cracks are observed without any significant punching shear cracks.

3. Increasing the fiber content was shown to improve the dynamic performance of the UHPFRC plates, resulting in reduced peak and residual displacements at same impact loads. A worth of mention, the use of fiber content of 3% is more significant in enhancing dynamic performance compared to other two steel fiber content of 1 and 2%. The reason may be return to fibers content of 3% has enough spatial distribution to resist the spreading of micro-cracks at its early stage. Additionally, Steel reinforcement ratio is found to have significant influence on the impact capacity of plates. Increasing steel reinforcement ratio led to less peak and residual displacements at same impact loads and higher impact energy capacity.

5. References

ACI Committee 544. *Measurement of Properties of Fiber Reinforced Concrete*. Vol. 85, 1988.

Cavill, B, M Rebentrost, and V Perry. "Ductal®: An Ultra-High Performance Material for Resistance to Blasts and Impacts." *1st Specialty Confrence on Disaster Mitigation (CSCE)*. Calgary, Canada, 2006. pp. 1–10.

CEB-FIP. *Concrete Structures under Impact and Impulsive Loading*. Lausanne, Switzerland, 1988.

D. Brown. "Tracker® V. 4.87 (video Analysis and Modeling Tool)." 2014.

E. Parant, P. Rossi, E. Jacquelin, and C. Boulay. "Strain Rate Effect on Bending Behavior of New Ultra-High-Performance Cement-Based Composite." *ACI Materials Journal* Vol. 104, 2007, pp.458–463.

Ellis, B.D. et al. "Experimental Investigation and Multiscale Modeling of Ultra-High-Performance Concrete Panels Subject to Blast Loading." *International Journal of Impact Engineering*, Vol. 69, 2014, pp. 95–103.

Habel, Katrin, and Paul Gauvreau. "Response of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) to Impact and Static Loading." *Cement and Concrete Composites* Vol. 30, No.10, 2008, pp. 938–946.

Lafarge-North America. "Lafarge North America." 2016, Available at www. ductal.com [cited Feb 1, 2016].

Millard, S G et al. "Dynamic Enhancement of Blast-Resistant Ultra High Performance Fibre-Reinforced Concrete under Flexural and Shear Loading." *International Journal of Impact Engineering*, Vol. 37, No. 4, 2010, pp. 405–413.

Ngo, Tuan, Priyan Mendis, and Ted Krauthammer. "Behavior of Ultrahigh-Strength Prestressed Concrete Panels Subjected to Blast Loading." Journal of Structural Engineering, Vol 133, No. 11, 2007, pp. 1582–1590.

Othman, H., and H. Marzouk. "An Experimental Investigation on the Effect of Steel Reinforcement on Impact Response of Reinforced Concrete Plates." *International Journal of Impact Engineering*, Vol. 88, 2016, pp. 12–21.

Yi, Na-Hyun et al. "Blast-Resistant Characteristics of Ultra-High Strength Concrete and Reactive Powder Concrete." *Construction and Building Materials*, Vol 28, No.1, 2012, pp. 694–707.

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