Journal of Asian Concrete Federation
Vol. 3, No. 2, pp. 98-104, December 2017
ISSN 2465-7964 / eISSN 2465-7972
https://doi.org/10.18702/acf.2017.12.3.2.98

Technical Paper

Blast-resistance of ultra-high strength concrete and reactive powder concrete

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(Received: August 15, 2017; Accepted: November 14, 2017; Published online: January 5, 2018)

Abstract: Recent advances in nanotechnology research have been applied to improve the durability, serviceability, and safety of ultra-high performance concrete (UHPC). Furthermore, improvements in the compressive strength of concrete have allowed concrete structural member size and self-weight to be significantly reduced, which has in turn resulted in cost reduction and structural aesthetic enhancement. Among many UHPCs currently available on the market, the most representative ones are ultra-high strength concrete (UHSC) and reactive powder concrete (RPC). Even though UHSC and RPC have compressive strengths of over 100 MPa, their safety has been questioned due to possible ultra-brittle failure behavior and unfavorable cost-to-performance efficiency. The blast-resistant capacities of UHSC and RPC were experimentally evaluated to determine the possibility of using UHSC and RPC in concrete structures susceptible to terrorist attacks or accidental impacts. In addition, ANFO blast tests were performed on reinforced UHSC and RPC panels. Incidental and reflected pressures, as well as maximum and residual displacements and the strains of rebar and concrete were measured. Blast damage and failure modes of the reinforced panel specimens were recorded. The maximum displacement ratio of UHSC-NSC and RPC-NSC are 0.57, showing that UHSC and RPC have better blast resistance than NSC.

Keywords: ultra-high performance concrete (UHPC), ultra-high strength concrete (UHSC), reactive powder concrete (RPC), blast-resistant capacity, ANFO blast charge.

1. Introduction

The recent construction trends of building super-span bridges and mega-height high-rises mandate the use of ultra-high performance concrete (UHPC) due to its outstanding safety, serviceability, durability, and economical advantages [1,2]. Among many UHPCs available in the market, the most representative ones are Ultra High Strength Concrete (UHSC) using reinforcing steel with additives and Reactive Powder Concrete (RPC) using steel fibers with reactive mineral addition [1,3]. This study was performed to evaluate the blast resistance capacities of UHSC and RPC to determine whether these materials are suitable for use in structures susceptible to terrorist attacks or accidental impacts. In 2009, the Korean Building Code was modified to require terror-resistant designs for any high-rises located within the city limits of Seoul with an above-ground height of over 200 m or 50 or more floors above ground [4,5]. This code regulation reflects the public concern regarding possible terror attacks on buildings and structures in Korea. Because of the ultra-high strengths and energy absorption capacities of UHSC and RPC, they seem to be optimal materials for use in structures that are potential targets of terror attacks or accidental impacts. Therefore, in this study, the evaluation of the blast-resistant capacities of UHSC and RPC are carried out.

2. Specimen details

The panel dimensions were 1,000 × 1,000 × 150 mm. Two layers of D10 mesh reinforcements with 82-mm spacing in both directions were placed in the NSC and UHSC panel specimens. The yield and ultimate strength of the D10 reinforcement was 400 and 600 MPa, respectively, with a nominal cross-sectional area of 71.33 mm^2 and a unit weight of 0.56 kg/m. The reinforcement ratios of NSC and UHSC specimens were the same, whereas 2% volume of special short steel fibers were used in the RPC specimens. The selected mix proportions of

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NSC, UHSC, and RPC are tabulated in Tables 1, 2, and 3, respectively. In Table 1, S1 is regular sand and S2 is micro-silica sand. Due to the patent copyright of the developer of the materials, the mix proportions of RPC and UHSC are listed as range values. The specific mixture contents are reported in the Korean patent. UHSC and RPC were steam-cured for 3 days at 90℃. Average compressive strength of NSC, UHSC, and RPC are 25.6, 202.1, and 202.9 MPa, respectively, as shown in Fig. 1 [9]. Compressive strength of UHSC and RPC is approximately 7.9 folds greater than that of NSC. Average elastic modulus of NSC, UHSC, and RPC are 16,300, 53,143, and 50,511 MPa, respectively, as shown in Fig. 1 [10]. Elastic modulus of UHSC and RPC is approximately 3.09~3.26 folds greater than that of NSC. As shown in Fig. 2, average split tensile strength of NSC, UHSC, and RPC are 2.2, 9.2, and 21.4 MPa, respectively. RPC have a higher resistance to split tensile strength than that of UHSC [11].

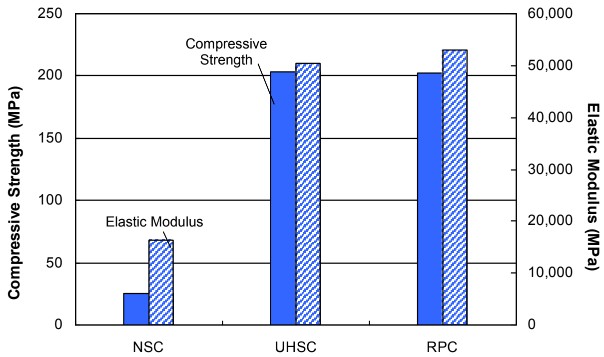


Fig. 1 – Average compressive strength and elastic modulus of NSC, UHSC, and RPC

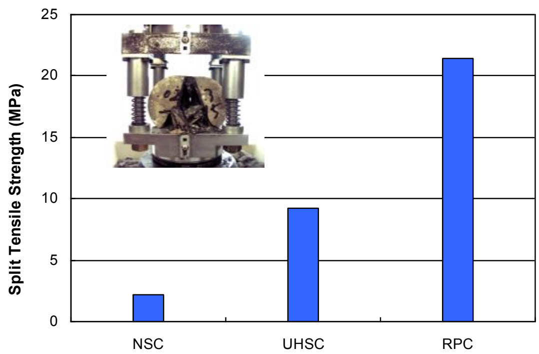


Fig. 2 – Split tensile strength of NSC, UHSC, and RPC

Table 1 – Mix proportion design of normal strength concrete (NSC) [7]

Max. size of coarse aggregate (mm)	Target strength (MPa)	Slump (mm)	W/B (%)	S/a (%)	Unit water (kg)	Unit binder (kg)		Unit fine aggregate (kg)		Unit coarse aggregate (kg)	AE admixture (kg)
						Cement	Fly-ash	S1	S2		
25	24	100	49.8	47.7	163	294	33	616	264	957	2.45

Table 2 – Mix proportion design of ultra-high strength concrete (UHSC) [7]

W/B (%) less than	S/a (%) less than	Unit water (kg) less than	Unit binder (kg) less than	Unit fine aggregate (kg) less than	Unit coarse aggregate (kg) less than	AE admixture (%) range of
20	39.1	140	1300	450	700	1 to 3

Table 3 – Mix proportion design of reactive powder concrete (RPC) [7]

W/B(%) less than	Cement (kg) less than	Unit water (kg) greater than	Silica fume (%) range of	Unit fine aggregate (kg) range of	Filler (2.2~200 ㎛) (kg) greater than	Admixture (%) range of	Steel fiber (%)
20	800	200	10 to 30	800 to 1000	200	1 to 3	2

3. Blast-resistant capacity

The blast-resistant capacity of reinforced UHSC and RPC panels under ammonium nitrate/fuel oil (ANFO) blast loading is evaluated [12]. The experiments were carried out at the test site of the Agency for Defense Development of Korea located near the Military Demarcation Line (MDL).

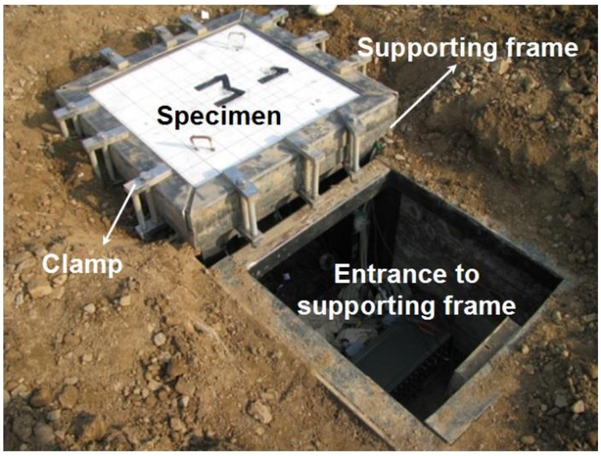
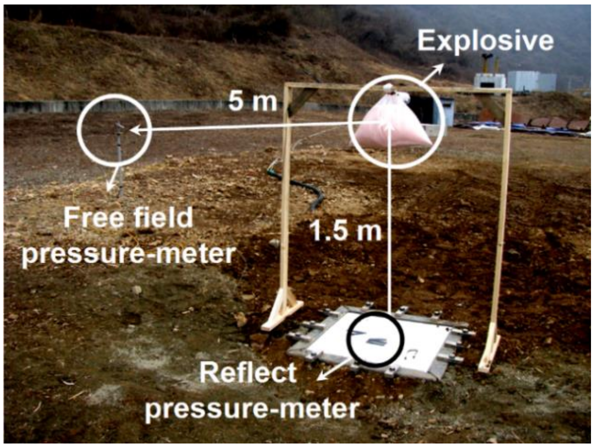
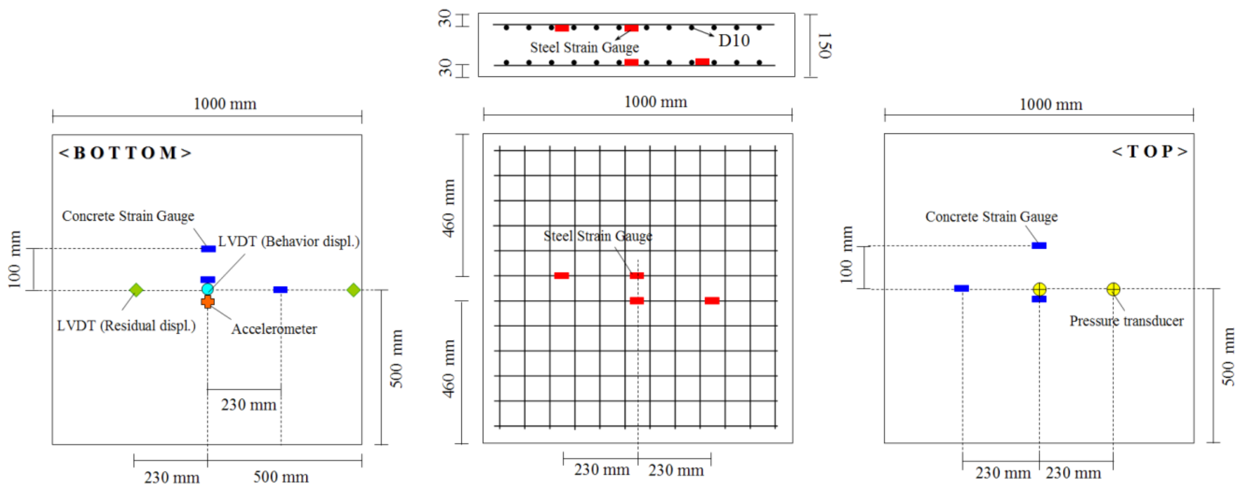


Fig. 3 – Configuration photo of buried supporting frame



(a)



(b)

Fig. 4 – Measurement sensor locations: (a) pressure-meter placement setup photo, (b) strain gauge locations [7]

15.88 kg of ANFO and a standoff distance of 1.5 m were selected from the trial test before main test.

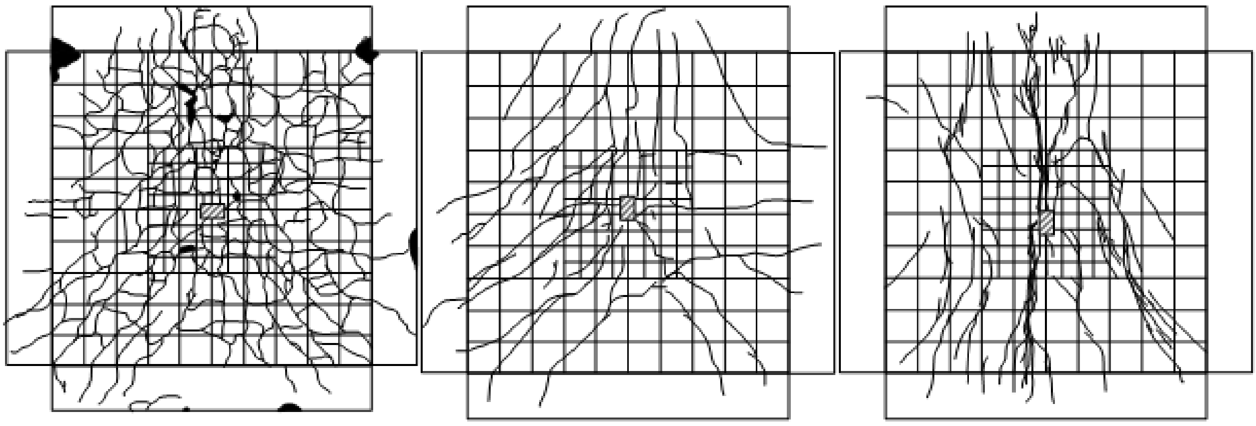
3.1 Blast test details

As shown in Fig. 3, a steel frame is buried in the ground for the placement of the specimen to eliminate the ground reflection effect [4-7]. The supporting steel frame made using SM520 with 7-mm thickness were attached with stiffeners at 250 mm spacing to prevent the frame distortion during blast loading. The clamp was provided to prevent uplifting of the test specimen. Free-field incident pressure and reflected pressure were measured at distances of 5 m and 1.5 m away from the center of the blast charge, respectively, as shown in Fig. 4(a). The reflected pressure transducers were placed on the top surface of the specimens, at the center and at 230 mm from the center, 1/3 of the diagonal distance from the center to the corner as shown in Fig. 4(b). To measure wave impact acceleration, an accelerometer was attached on the top center of the specimens and linear variable differential transformers (LVDTs) were placed on the bottom surface to measure maximum and residual vertical displacements.

3.2 Blast test results

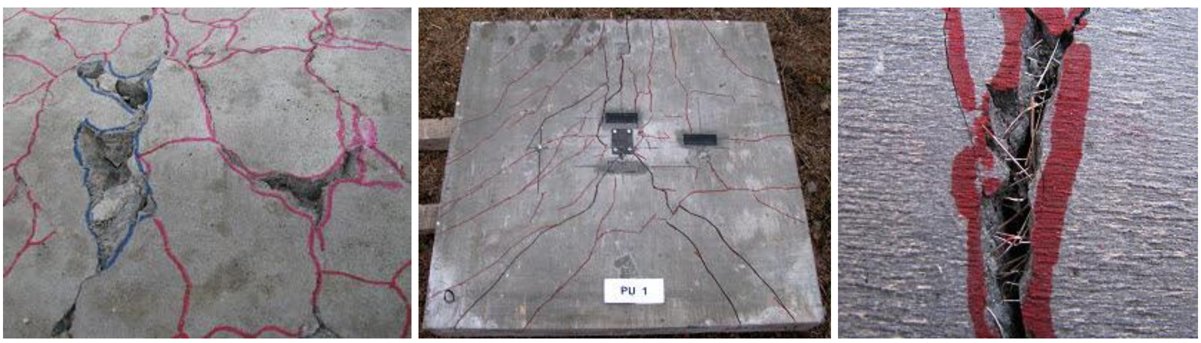
3.2.1 Surface examination and crack patterns

Schematic drawings of the bottom surface crack patterns of NSC, UHSC, and RPC panel specimens are shown in Fig. 5. One-directional multiple medium length macro-cracks bisected the middle of the RPC specimens. This crack pattern was expected for RPC, because RPC is a cement mortar reinforced with short steel fibers; crack control by the fibers prevented catastrophic macro-crack propagations, resulting in the formation of medium length macro-cracks only in the direction perpendicular to the principle tensile strain direction as shown in Fig. 6(c). The macro-crack means visually observable crack.



(a) (b) (c)

Fig. 5 – Bottom surface crack patterns of blasted specimens: (a) NSC (b) UHSC (c) RPC



(a) (b) (c)

Fig. 6 – Photos of bottom surface of the blasted specimens: (a) NSC, (b) UHSC, (c) RPC

Because both UHSC and RPC specimens failed due to macro-cracks, it is safe to assume that they failed in a quasi-brittle manner even under the flexure mode because of their ultra-high compressive strengths. The lack of shear cracks on the specimens led to a conclusion that the shear capacities of UHSC and RPC are sufficient to withstand blasts. In summary, the failure patterns of UHSC and RPC indicate that they are much more resistant to blast loading than NSC and have superior blast-resistant capacities. Furthermore, because relatively fewer cracks were found in these specimens than in the NSC specimens, it would require less effort and cost to repair blast-damaged UHSC and RPC members than NSC members.

3.2.2 Blast pressure measurements

The pressure comparison results are shown in Fig. 7. The second peak pressure obtained from the experiment of USHC and RPC were approximately 18% and 30% less than the first peak pressure predicted by ConWEP, respectively. ConWEP software is an analytical program used to calculate the blast loadings of blast pressure, fragmentation, surface impact, etc. based on Unified Facilities Criteria (UFC) 3-340-01 [13]. These results indicated that reflected pressure is highly dependent on experimental variabilities and environmental conditions, validating the implementation of a magnification factor in the ConWEP calculation [5,8]. The experimental data were inconsistent due to experimental variations and environmental conditions (i.e., charge shape, charge angle, wind velocity, humidity, etc.). A second peak pressure followed the first peak overpressure at the center of the specimen for both reflected and free field pressures. This could be ascribed to the finite time duration of the explosion of an ANFO charge, resulting in a relatively slower detonation speed. Due to the continuous explosion characteristics of an ANFO charge, the reflected and re-reflected pressures are combined, creating different applied pressures and several peak overpressures as shown in Fig. 7.

3.2.3 Deflection measurements

The center point deflection histories of NSC specimens with a 15.88 kg ANFO charge are shown in Fig. 8(a), while the center point deflection histories of the UHSC and RPC specimens with an ANFO charge of 15.88 kg are shown in Fig. 8(b) and Fig. 8(c), respectively. The maximum and residual deflections of the NSC, UHSC, and RPC specimens from the 15.88 kg ANFO charge were 18.57 and 5.79 mm, 15.238 and 5.65 mm, 10.73 mm

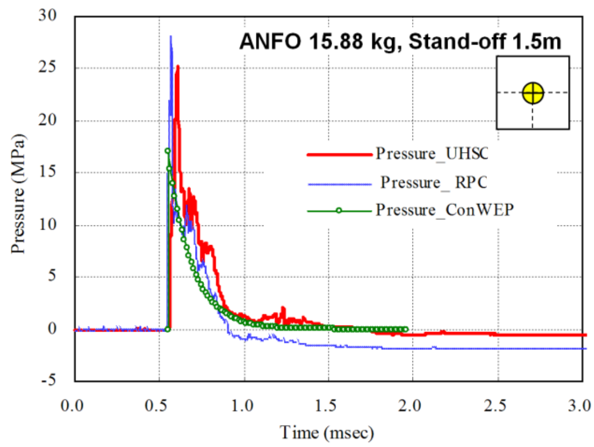


Fig. 7 – Reflected pressures versus time measurements at the center from the main test (15.88 kg ANFO)

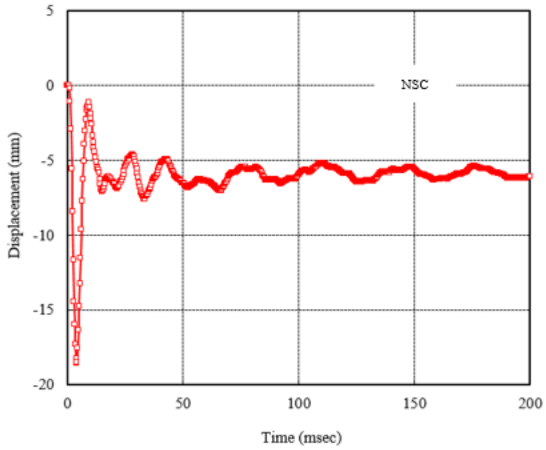
and 3.202 mm, respectively, as shown in Fig. 8. These results indicate that RPC has the best blast-resistant capacity followed by UHSC and then RPC. This is a reasonable result, because the blast resistance of RPC is significantly enhanced by the presence of short steel fibers, which provide improved crack-bridging characteristics and energy absorption capacity.

3.2.4 Strain measurements

The strains measured in this study are shown in Fig. 9. Because RPC specimens do not have reinforcing bars, steel strain measurements were only obtained from the NSC and UHSC specimens. The strain data indicate bottom reinforcement yielding in all specimens, with higher strains occurring in the reinforcements towards the center of the specimen. The maximum strains measured from bottom reinforcement of the NSC and UHSC specimens were approximately 28,000 and 6,500 με, respectively, as shown in Fig. 9. These results indicated that smaller displacements occurred in the UHSC specimens than in the NSC specimens, confirming that UHSC has better blast-resistant capacity than NSC.

4. Conclusions

In this study, the blast-resistant capacities of ultra-high strength concrete and reactive powder concrete were experimentally evaluated. The results showed that they have outstanding blast-resistant capacities. The conclusions of this study are summarized as follows:



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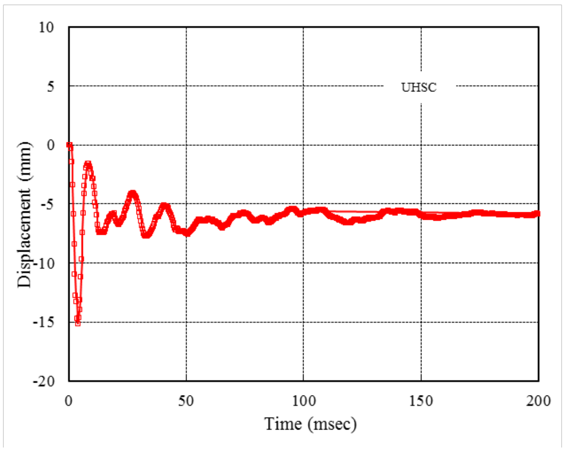
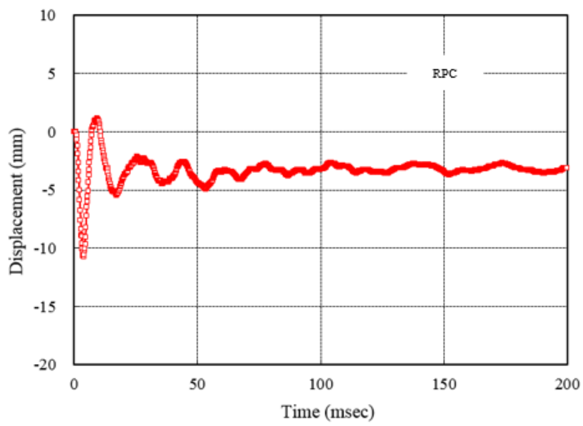
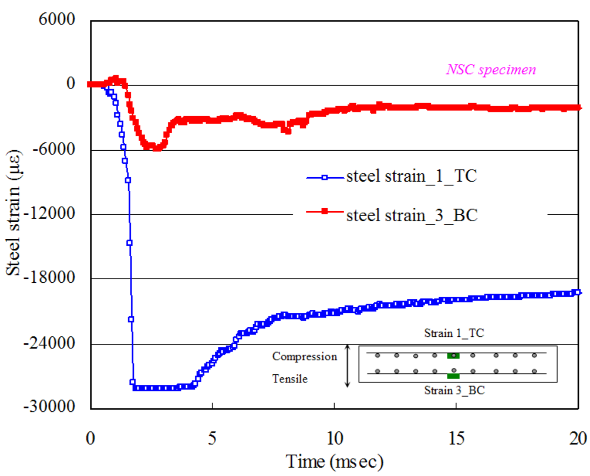
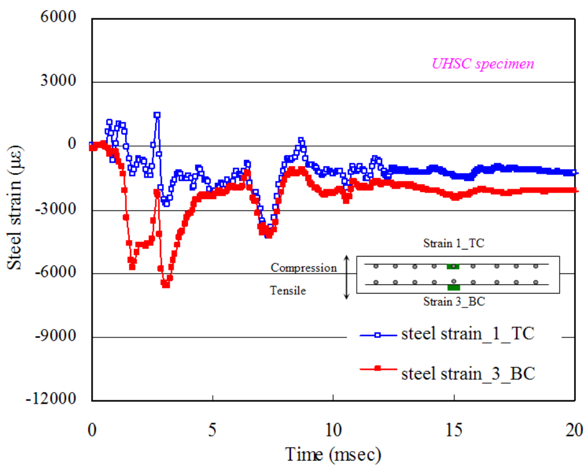




(b) (c)

Fig. 8 – Center displacement versus time measurements from 15.88 Kg ANFO blast loading: (a) NSC, (b) UHSC, (c) RPC





(a) (b)

Fig. 9 – Reinforcement bar strain versus time measurements from blast loading: (a) NSC, (b) UHSC

1) The blast-resistant capacities of UHSC and RPC were verified by blast tests using a 15.88 kg ANFO charge with a 1.5 m standoff distance, applying a blast load with strain rate of 278~457 s^{-1}. Pressure, deflection, and strain from theblast tests revealed that UHSC and RPC panel specimens have higher blast-resistant capacities than NSC specimens.

2) Rebar and short steel fibers used in the UHSC and RPC specimens, respectively, negate the brittle material characteristics of UHSC and RPC members, provide sufficient ductility, and confer outstanding energy absorption and crack controlling capacities to these materials.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science and ICT) (No. 2017M2A8A4056624) and also by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2016R1A2B3009444).

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