Fracture Mechanics of Concrete and Concrete Structures -
High Performance, Fiber Reinforced Concrete, Special Loadings and Structural Applications- B. H. Oh, et al. (eds)


# Blast loading response of ultra high performance concrete and reactive powder concrete slabs

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ABSTRACT: In recent years, there have been numerous explosion-related accidents due to military and terrorist activities. Such incidents caused not only damages to structures but also human casualties, especially in urban areas. To protect structures and save human lives against explosion accidents, better understanding of the explosion effect on structures is needed. In an explosion, the blast load is applied to concrete structures as an impulsive load of extremely short duration with very high pressure and heat. Generally, concrete is known to have a relatively high blast resistance compared to other construction materials. However, normal strength concrete structures require higher strength to improve their resistance against impact and blast loads. Therefore, a new material with high-energy absorption capacity and high resistance to damage is a better material for blast resistance design. Recently, Ultra High Strength Concrete (UHSC) and Reactive Powder Concrete (RPC) have been actively developed to significantly improve concrete strength. UHSC and RPC can improve concrete strength, member size and weight reductions and workability improvement. High strength concrete usages in better earthquake resistance and increase a building height and bridge span. Also, UHSC and RPC can be implemented for blast resistance design of infrastructure due to terror or impact such as 9.11 terror attack. Therefore, in this study, the blast tests are performed to investigate the behavior of UHSC and RPC slab subjected to blast load. Blast wave characteristics, including incident and reflected pressures as well as maximum and residual displacements and strains in steel and concrete surface are measured. Also, blast damages and failure modes were recorded for each specimen. From these tests, UHSC and RPC are shown to effectively resist blast explosions compare to normal strength concrete.

## 1 INTRODUCTION

In recent years, there have been numerous explosion-related accidents due to military and terrorist activities. Such incidents caused not only damages to structures but also human casualties. Especially, in metropolitan areas which are exposed to terror attack, these severe loading related accidents can cause great human causalities, economical losses, and public infrastructure destructions, and civilian structure collapses. To protect structures and save human lives against explosion accidents, better understanding of the explosion effect on structures is needed. In an explosion, the blast load is applied to structures as an impulsive load of extremely short duration with very high pressure and heat.

Generally, concrete is known to have a relatively high blast resistance compared to other construction materials. However, normal strength concrete structures require higher strength to improve their resistance against impact and blast loads. Therefore, a new material with high-energy absorption capacity and high resistance to damage is a better material for blast resistance design. Recently, Ultra High Strength Concrete (UHSC) and Reactive Powder Concrete (RPC) have been actively developed to significantly improve concrete strength. UHSC and RPC can improve concrete strength, reduce member size and self-weight, and improve workability. Commonly, UHSC and RPC produce compressive strength greater than 150MPa and sometime up to 180~200MPa. High strength concrete are used to improve earthquake resistance as well as constructions of high-rises and long span bridges. Also, UHSC and RPC can be implemented to blast resistance design of infrastructure against terror or impact (ASCE 1999, Baker 1973).

The Korean building code has been modified in year 2009 where any high-rises located in the city of Seoul with the height of over 50 above ground floors or 200m, the terror resistant design has to be incorporated. This code regulation reflects the keen public interest on blast resistance and protective design concepts. However, since UHSC or RPC has been recently developed, their blast resistant capacities have never been studied. In order to properly and efficiently incorporate UHSC and RPC into protective design scheme, an in-depth research on blast resistance behavior on UHSC and RPC is urgently needed at this time (Kim 2009, Zineddin et al. 2007).

Therefore, in this study, the blast tests are performed to investigate the behavior of UHSC and RPC slabs subjected to blast load. Blast wave characteristics including incident and reflected pressures as well as maximum and residual displacements and strains in steel and concrete surface are measured. Also, blast damages and failure modes were recorded for each specimen. From these tests, UHSC and RPC are shown to effectively resist blast explosions compared to normal strength concrete. Based on these test results, the blast design procedure will be suggested.

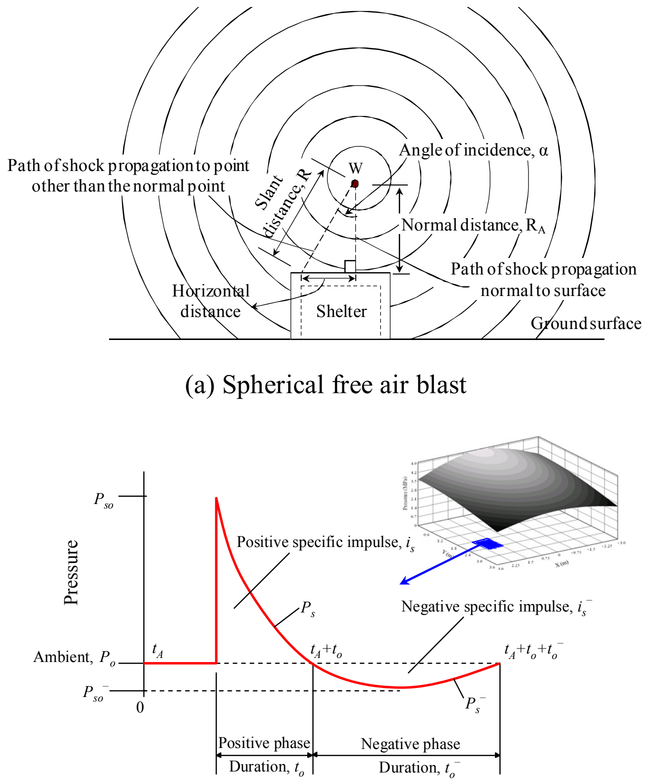
## 2 LITERATURE LEVIEW

### 2.1 *Characteristic of blast load*

An explosion is a very fast chemical reaction producing transient air pressure waves called blast waves. For a free-air burst, the blast wave will travel away from the source as a spherical wave front as shown in Figure 1(a). The peak overpressure and the duration of the overpressure vary with distance from the explosives. The magnitude of these parameters also depends on the explosive materials from which the explosive compound is made. Usually the size of the explosive compound is given in terms of a TNT weight. Explosive behavior depends on a number of factors: ambient temperature, ambient pressure, explosive composition, explosive material properties, and the nature of the ignition source type. Additional factors include type, energy, and duration of the events as well as geometry of surroundings (i.e., confined or unconfined). When a condensed high explosive is initiated, explosion reaction generates several additional characteristics such as blast wave of very high pressure, fragmentation from the explosive case or structural elements, hot gas with a pressure from 100 up to 300 kilobar, and a temperature of about 3,000~4,000℃. The main blast effect is impulsive pressure loading from the blast wave as shown in Figure 1(b) (Baker 1973, Mays & Smith 1995).

After a short time, the overpressure behind the shock front drops rapidly and becomes smaller than that of the surrounding atmosphere as shown in Figure 1(b). This pressure domain is known as the negative phase. The front of the blast wave weakens as it progresses outward and its velocity drops toward the velocity of sound in the undisturbed atmosphere.

The characteristics of a blast wave resulting from an explosion depend mainly on the physical properties of the source and the medium through which blast waves propagate. To create reference blast experiments, some controlled explosions have been conducted under ideal conditions. To relate other explosions with non-ideal conditions to the reference explosions, blast scaling laws can be employed. The most widely used approach to blast wave scaling is that formulated by Hopkinson, which is commonly described as the cube-root scaling law. The scaled distance, Z, is defined using the Hopkinson-Cranz's cube root law as (ASCE 1999):




(a) Spherical free air blast



(b) Pressure-time history

Figure 1. Spherical free air blast (TM5-1300 1990, Kim et al. 2007).

$$Z = R / E^{1/3} \ or \ Z = R / W^{1/3} \qquad (1)$$

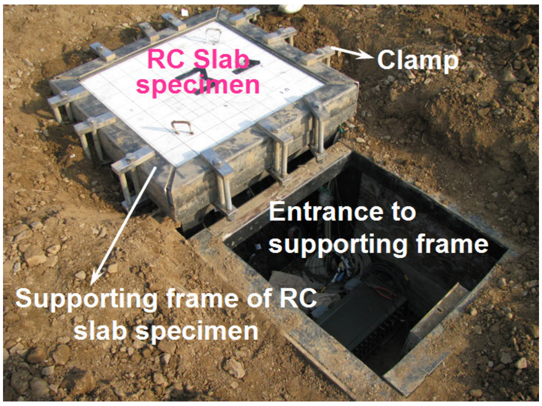
where, Z is scaling distance; R is stand-off distance from the target structure; E is total explosive thermal amount of energy; W is charge weight of equivalent TNT amount. The scaling distance is used for evaluation of blast wave characteristics.

### 2.2 *Research trends*

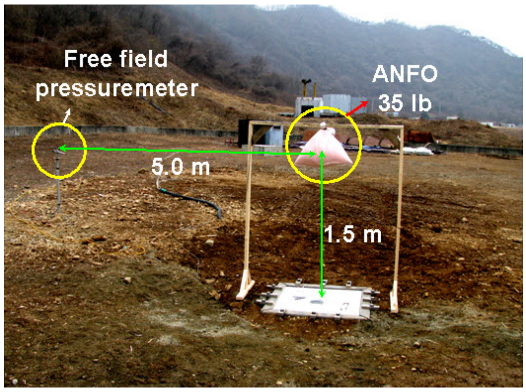
Concrete is generally known to have a relatively high blast resistance capacity compared to other construction materials. However, concrete structures, which were not designed to have blast protective capacity, require retrofitting during their service life to improve their resistance against blast loads. Retrofitting method of attaching extra structural members or supports to increase the blast resistance is inefficient in the perspective of additional construction cost and eliminating useable space. Also, since this method does not greatly improve the overall structural resistance against blast load, a more feasible method of retrofitting to improve blast resistance would be to use Ultra High Strength Concrete (UHSC) or Reactive Powder Concrete (RPC). UHSC and RPC would also be very effective in new constructions since they can be used for concrete materials in reinforced concrete members.

In fact, beams and plates constructed using high strength concrete (HSC) showed better impact resistance capacity than ones made using normal strength concrete (NSC) in past researches. However, due to social and governmental constraints, this type of comparison study has not been carried over to blast resistance capacity study, resulting in insufficient database of HSC's role as blast resisting material (Kim 2009).

Recently, several researchers have pursued static and impact capacity studies on fiber reinforced concrete members under time-dependent loading conditions. The reference study has shown that the impact and blast loaded UHSC or RPC study results are non-existing and blast loaded HSC study results are scarcely existing at best (Habel et al. 2008).



(a) Buried supporting frame



(b) Explosive charge and specimen

Figure 2. Overview blast setup.

## 3 BLAST TEST DETAILS

In this paper, the failure behaviors of reinforced UHSC and RPC slabs under blast loading are studied. The tests were performed as 2 step process of preliminary and main tests at Agency for Defense Development of Korea's testing sight. In the preliminary test stage, TNT 35lbs was used as blast load on control specimens (NSC specimen). After the trial tests, ANFO 35lbs was selected as the blast explosive charge to be used for the main test stage.

### 3.1 *Blasting test setup*

In this study, in order to eliminate the 3-D effect, RC slab specimens are placed at a same level as ground surface(Razaqpur et al. 2007). A steel frame is constructed and buried in the ground as shown in Figure 2(a). For preventing the supporting frame distortion during blast loading, the stiffeners with 250mm spacing are installed on wall surface of supporting frame. Rubber pads of the same width and length as the steel angle legs were placed between the angles and test specimen to ensure uniform support conditions. The explosive used for the test was spherical ANFO, which was held by wooden horizontal bar. Figure 2(b) shows the test specimen setup with the 35lbs ANFO (28.7lbs TNT) explosive charge. The 1.5m standoff from specimens to explosive middle point is consistently maintained.

### 3.2 *Specimen manufacturing and details*

For the relative and absolute comparisons between the specimens casted with UHSC, RCP, and NSC RC slabs with the dimensions of 1,000×1,000×150mm and D10 (71.33mm$^2$) mesh type reinforcements with 82mm spacing are used. The steel ratio of the reinforced NSC and UHSC specimens is same as the 2 volume % of short steel fibers used in RPC specimen. The mix proportions for NSC, UHSC, and RPC are tabulated in Table 2, 3, and 4, respectively. The 100×200mm cylindrical specimens are prepared for compressive and tensile strength tests performed at Hyundai Institute of Construction Technology. The number of specimens tested for NSC, UHSC, and RPC are 2, 4, and 4 specimens, respectively. The average compressive strength of NSC, UHSC, and RPC are 25.6, 202.0, and 203.0 MPa, respectively. The compressive strengths with a deviation over 15% are eliminated from consideration. The tensile strength of RPC is approximately 2.3 times greater (21.4MPa) than NSC (2.2MPa) and UHSC, (9.21MPa), respectively, due to the addition of 2 vol.% of short steel fibers in RPC.

### 3.3 *Measurement outline*

The free field incident pressure was measured at 5m from the center of the test slab specimens where reflected pressure on concrete specimen was measure at the center of the top surface of the specimen and

Table 2. Mix proportion of normal strength concrete (NSC).

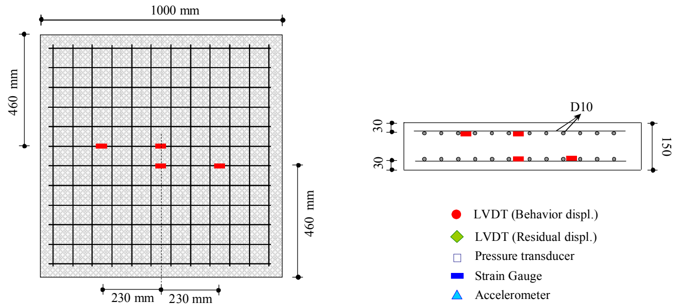
| Max. Size of Coarse Aggregate (mm) | Target Strength (MPa) | Slump (mm) | W/B (%) | S/a (%) | Water (kg) | Binder (kg) | | FA (kg) | | CA (kg) | AE (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Cement | Fly-ash | S1 | S2 | | |
| 25 | 24 | 100 | 49.8 | 47.7 | 163 | 294 | 33 | 616 | 264 | 957 | 2.45 |

Table 3. Mix proportion range of Ultra High Strength Concrete (UHSC).

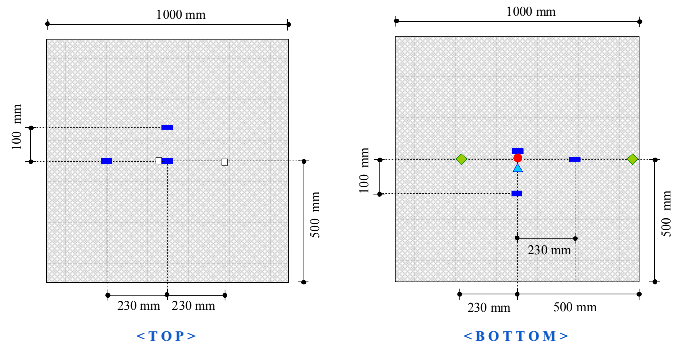
| W/B (%) | S/a (%) | Water (kg) | Binder (kg) | FA (kg) | CA (kg) | AE (%) |
|---|---|---|---|---|---|---|
| < 20 | < 39.1 | < 140 | < 1300 | < 450 | < 700 | 1~3 |

Table 4. Mix proportion range of Reactive Powder Concrete (RPC).

| W/B (%) | Cement (kg) | Water (kg) | Silica Fume (%) | FA (kg) | Filler (2.2~200㎛) | Admixture (%) | Steel Fiber (%) |
|---|---|---|---|---|---|---|---|
| < 20 | < 800 | > 200 | 10~30 | 800~1000 | 200kg ~ | 1~3 | 2 |




(a) Steel strain gauge




(b) Gauges on concrete surface

Figure 3. Location of measuring sensor.

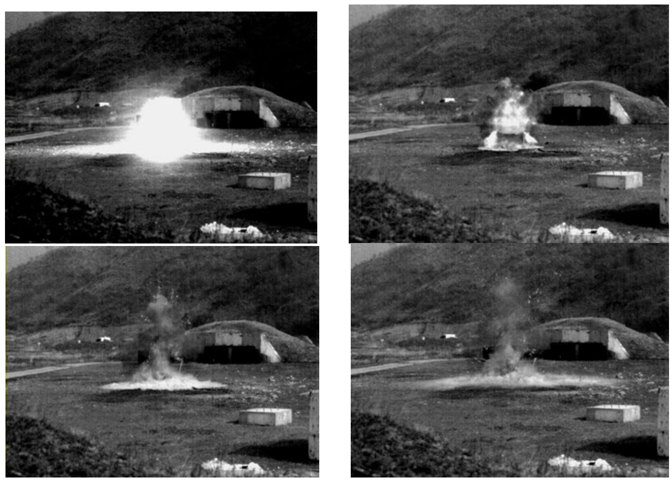
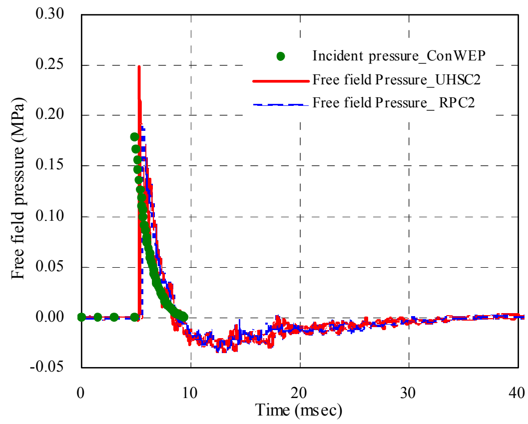


Figure 4. Explosive scene by ANFO 35lbs.

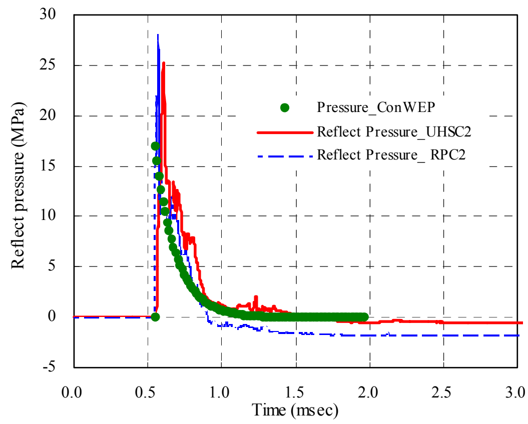
230mm from the center. (e.g., 1/3 point of specimen diagonal length). To measure strain, 6mm strain gauges are attached on reinforcing steel at tensile region and 30mm strain gauges are attached on concrete top and bottom surfaces as shown Figure 3. In case of retrofitted specimen, FRP strain gauges are attached instead of concrete strain gauges on bottom surface. Also, LVDTs on the specimen center are used to measure the maximum and residual displacements.

## 4 BLAST TEST RESULTS

UHSC and RPC RC slabs are blast loaded to analyze their resistance performance. In the preliminary testing stage, NSC RC slab was tested to estimate the blast cracking behavior and the required explosive charge weight for the main tests.




(a) Free field pressure




(b) Reflect pressure

Figure 5. Measured pressure on specimens (ANFO 35lbs).

## 4.1 *Blasting tests*

When ANFO 35lbs was used as the explosive charge, extreme wave of high pressure, temperature, noise, and energy dispersed out radially. The photos in Figure 4 are ANFO 35lbs detonation photos. Since ANFO detonation produces debrisless explosion, giving a more of pure pressure type of explosion loading, ANFO explosive charge is used for the main tests.

## 4.2 *Measured blast pressure results*

Due to the exploded metal debris of TNT steel container impacting and damaging the pressure gauge installed in the center–top surface of the specimen, the compressive blast pressure data was not obtained in the preliminary stage. The measured free field and reflected pressures of ANFO 35lbs are shown in Figure 5. And the other data are tabulated in Table 6. The measured data are inconsistent due to the variations in experimental and environmental conditions (i.e., charge shape, charge angle, wind velocity, humidity, etc.). However, the obtained blast pressure data seem to agree well with ConWEP data.

## 4.3 *Tested specimen examination*

When the testing is completed and the safety is insured for the inspectors, the surface examination of the specimen was performed. Figure 6(a), 6(b), and 6(c) are the schematic drawings of NSC, UHSC, and RPC slab bottom surface crack distributions after ANFO 35lbs blasting, respectively. The NSC specimens had a well dispersed turtle back type crack pattern. The crack lines followed the cone prism type of plastic yield line from the center to the 4 corners, indicating a 2D membrane plastic failure mode. However, UHSC specimen's crack pattern showed mostly macro-cracks concentrated near or on the yield lines. The RPC specimens showed predominantly one directional, center bisecting type, macro-cracks. Since RPC specimen is made using cement mortar with short fibers, it tended to be brittle but the crack bridging effect of short fibers resisted crack propagation where the macro-cracks form only in the direction perpendicular to the principle tensile strain direction as shown in Figure 6(c)

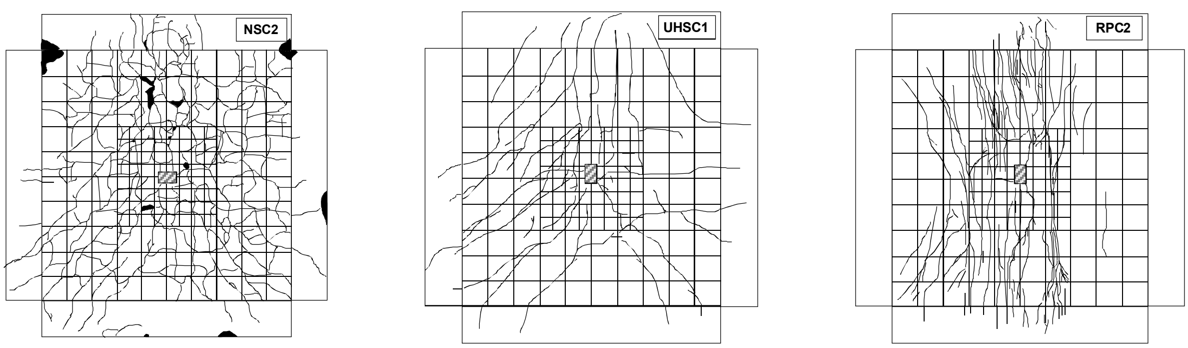
## 4.4 *Deflection measurements from blast tests*

The incidental and residual deflections are measured from the blast test. Both deflection results of maximum and residual measurements are tabulated in Table 7. In the preliminary tests using TNT 35lbs, the maximum measured deflection at the center of the specimen was beyond 25mm measurement capacity of the LVDT. The specimen center deflection-time histories for NSC-TNT 35lbs, which exceeded LVDT measuring capacity, and NSC-ANFO 35lbs are shown in Figure 7. As shown in Table 7, the maximum and residual deflections from ANFO 35lbs for NSC, UHSC, and RPC are 18.57mm and 9.03mm, 12.83mm and 3..86mm, and 11.91mm and 4.31mm, respectively. In case of maximum retrofit effect, the RPC (35.85%) have more effective than UHSC (30.90%). But in case of residual effect, the UHSC (57.23%) have more effective than RPC

Table 6. Measured blast pressure.

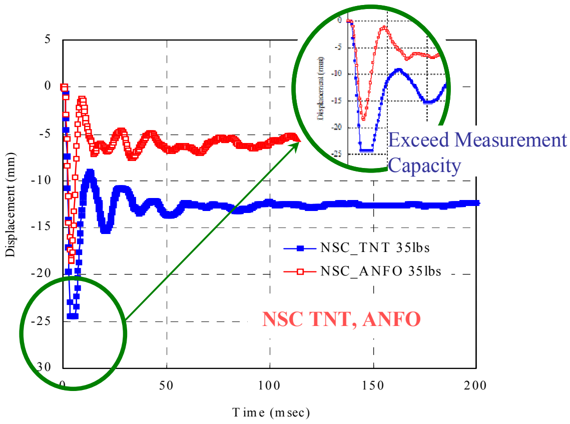
| SPECIMEN | | ConWEP | NSC2 | UHSC1 | UHSC2 | RPC1 | RPC2 |
|---|---|---|---|---|---|---|---|
| Charge | | ANFO 35lbs | ANFO 35lbs | ANFO 35lbs | ANFO 35lbs | ANFO 35lbs | ANFO 35lbs |
| Environment | Temp. | - | 5 | 8 | NR | -9 | NR |
| | Humid (%) | - | up 51 | 56 | NR | 39 | NR |
| Reflect Pressure | Center (MPa) | 17.02 | NR | NR | 16.92 | NR | 21.99 |
| | Impulse (MPa-msec) | 2.42 | NR | NR | 3.87 | NR | 2.83 |
| | 230mm (MPa) | 16.53 | 26.58 | NR | 18.76 | 22.62 | 22.1 |
| | Impulse (MPa-msec) | 2.38 | 3.26 | NR | 3.02 | 2.03 | 22.41 |
| Free Field | Peak overpressure | 0.170 | 0.161 | 0.249 | 0.191 | 0.16 | 0.191 |
| Pressure | Impulse (MPa-msec) | 0.205 | 0.23 | 0.191 | 0.23 | 0.229 | 0.21 |

* NR : Not Record
* NSC : Normal strength concrete(control specimen)
* UHSC : Ultra High Strength Concrete
* RPC : Reactive Powder Concrete

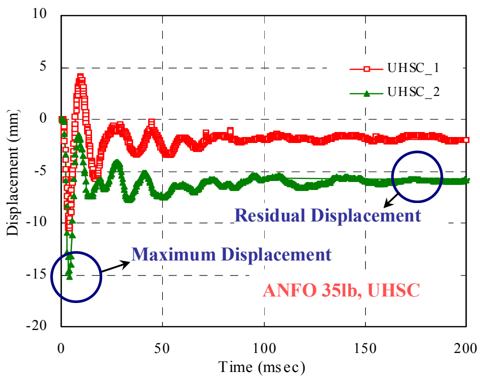


(a) NSC (b) UHSC (c) RPC

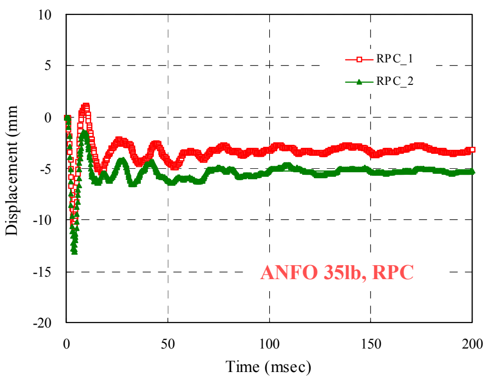
Figure 6. The crack pattern of blasted specimens (bottom side).



(a) NSC

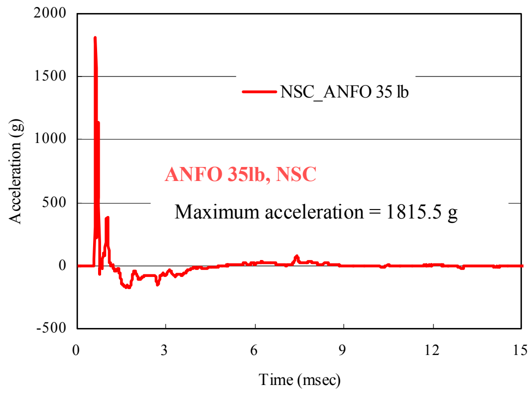


(b) UHSC

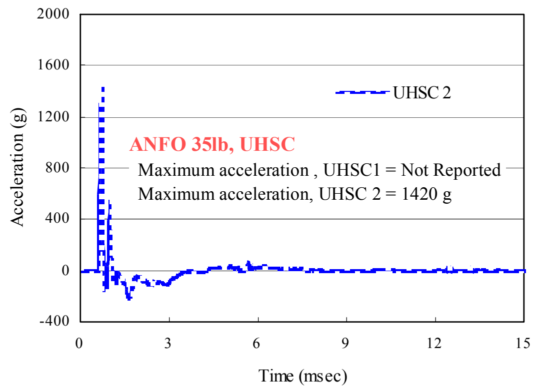


(c) RPC

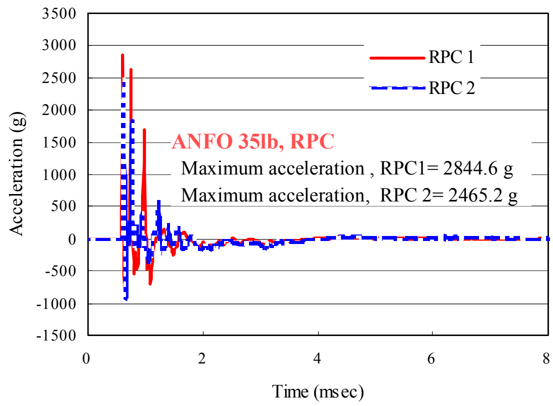
Figure 7. Displacement behavior of concrete specimen center point under blast loading.



(a) NSC



(b) UHSC



(c) RPC

Figure 8. Specimen acceleration under blast loading.

(52.29%).

As shown in Table 7, the bottom center concrete strains were over 16,000με for NSC and UHSC specimens. However, when the strain measurements and displacements for NSC, UHSC, and RPC specimens are compared, RPC data at the specimen center tend to be less than those of NSC and UHSC specimens. It means RPC specimens have more blast resistance capacity than others. This result is probably

Table 7. Measured blast test results.

| SPECIMEN | | NSC1 | NSC2 | UHSC1 | UHSC2 | RPC1 | RPC2 |
|---|---|---|---|---|---|---|---|
| Charge | | TNT 35lbs | ANFO 35lbs | ANFO 35lbs | ANFO 35lbs | ANFO 35lbs | ANFO 35lbs |
| Max. displacement (mm) | | Over 25 | 18.565 | 10.517 | 15.14 | 10.73 | 13.09 |
| Average of max disp.(mm) | | 18.565 | | 12.829 | | 11.910 | |
| Retrofit Effect (%) | | - | | 30.90 | | 35.85 | |
| Residual displacement (mm) | | 12.260 | 5.790 | 1.860 | 5.86 | 3.202 | 5.41 |
| Average of residual disp.(mm) | | 9.025 | | 3.860 | | 4.306 | |
| Retrofit Effect (%) | | - | | 57.23 | | 52.29 | |
| Strain | Steel up | 16012 | 5964 | 2796 | 2832 | - | - |
| | Steel bottom | 15998 | 28113 | 6711 | 7553.6 | - | - |
| | Concrete up | NR | 11848 | 4502 | 12821 | 11198 | 24214 |
| | Concrete bottom | 16007 | NR | 16025 | 18081 | NR | 4903 |

* NR : Not Record

* - : Non-attached gauge

due to the short steel fiber reinforcing in RPC specimen where the fibers restrained crack opening by crack bridging and controlling effect.

## 4.5 *Acceleration measurements from blast test*

Generally, specimen blast behavior can be analyzed based on data obtained from LVDT and accelerometer. If LVDT data are unusable or imprecise, specimen acceleration data can be alternatively used. Figures 8(a)~(c) show the specimen acceleration measurements for NSC, UHSC, and RPC specimens. As shown Figures 8(a)~(c), the accelerations ranging from 1,000~2,500g have occurred. However, these acceleration measurements are combined values of both specimen acceleration as well as the impulse acceleration. Also, for UHSC 1 specimen, the sensor was detached from concrete surface when blast pressure was applied, causing imprecise noise. Therefore, the data were considered unfit for analysis. Also, RPC specimens have extreme high frequency vibration due to no reinforcement. Therefore, the reinforcement can be affect to specimen behavior under blast load.

## 4.6 *Blast design and analysis process*

Based on the blast tests for NSC, UHSC, and RPC in this study, the blast design and analysis process are suggested. Most importantly the building and owner requirements are needed for determination of blast resistance capacity of a targeted structure. To evaluate the building requirements, the blast loading on each component and resistance capacity can be derived from test results or research reports.  If materials and structural system are selected, determination of deformation limit using analysis method such as HFPB (High Fidelity Physics Based) and SDOF, MDOF, etc. is selected for the blast analysis. The details of design will be accompanied with satisfaction of the deformation limit based on the analysis results.

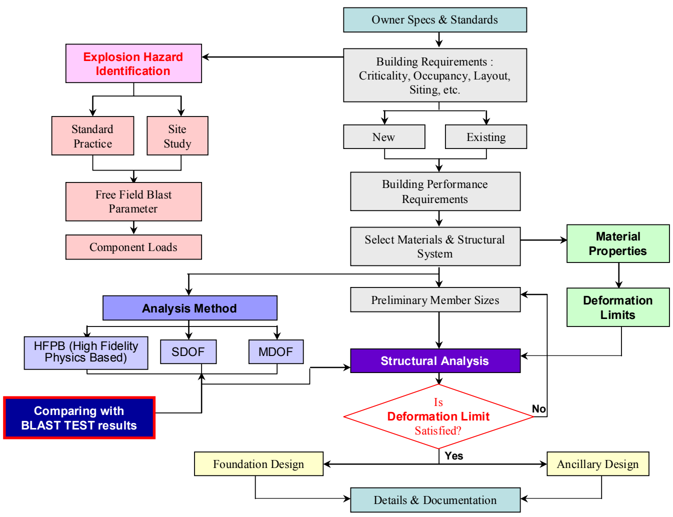



Figure 9. Blast design and analysis process.

## 5 CONCLUSION

From this study, Ultra High Strength Concrete (UHSC) and Reactive Powder Concrete (RPC) RC slabs' response induced by explosive of blast wave pressure are evaluated to understand the blast resistance capacity blast resisting repair materials and retrofitted structure. The reflected blast pressure and impulse values calculated using the ConWEP were in reasonable agreement with the experimental data. The performance comparison of UHSC and RPC specimens to NSC control specimens subjected to blast loads of ANFO 35 lbs has shown the high blast resistance capacity of about 30.9~35.9% increase with respect to average maximum displacement. An average of residual displacements was smaller than normal strength concrete specimen's residual displacement, even though there was no consistent trend due to variations in environmental conditions. Therefore, to evaluate the damage under blast load, failure mode must be considered. From the test results, the failure patterns of both UHSC and RPC indicate that they are much more resistant to blast loading and have higher blast resistance capacity than NSC.


## ACKNOWLEDGMENTS

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