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EXPERIMENT STUDY ON BLAST LOADING RESPONSE OF FRP-RETROFITTED RC SLAB STRUCTURES

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ABSTRACT

Recently, FRP usage for strengthening RC structures in civil engineering has been increasing. Especially, the use of FRP to strengthen structures against blast loading is growing rapidly. To estimate FRP retrofitting effect under blast loading, nine $1000 \times 1000 \times 150$ mm RC slab specimens, which were retrofitted with carbon fiber reinforced polymer (CFRP), basalt fiber reinforced polymer (BFRP), polyurea, and CFRP with polyurea were carried out. The applied blast load was generated by the detonation of 35lbs ANFO explosive charge at 1.5m standoff. The data acquisitions not only included blast waves of incident pressure, reflected pressure and impulse but also included central deflection and strains at steel, concrete, and FRP surfaces. The failure mode of each specimen was observed and compared with a control specimen. From the test results, it was determined that each FRP retrofitted concrete structures showed sufficient retrofit effect under severe damages. It also shows that each retrofit method can be applied to the targeted structures and protection level.

KEYWORDS

Blast loading, CFRP, BFRP, polyurea, retrofit effect, failure mode, blast test.

INTRODUCTION

In recent years, numerous explosion-related accidents due to military and terrorist activities have occurred all over the world. Such incidents cause not only severe damages to structures but also cause great human casualties, especially in urban areas (Mosalam and Mosallam, 2001). Generally, concrete is known to have a relatively high blast resistance compared to other construction materials. However, some existing concrete structures require retrofitting during their service period to improve their resistance against impact and blast loads. These concrete structures can be strengthened by steel plate or composite fibers to enhance the energy-absorbing capacity of the structures and to limit the structural damage in structural components. Retrofitting reinforced concrete (RC) structures subjected to blast loads using fiber-reinforced polymer (FRP) composite has distinct advantages over other retrofit materials because of the easeness of installation and inherent blending with the structures (e.g. Kim *et al.* 2007; Razaqpur *et al.* 2007).

Recently, the application of composite materials such as FRPs to enhance the ductility of concrete structures has been extended where strips or plates are attached to the surface for either repair or upgrade of the energy-absorbing ability. The use of FRP composite materials for retrofitting concrete structural members has been shown to be very successful in restoring or increasing the strength of the members (DTRA/TSWG Program, 1999). FRPs such as CFRP (carbon fiber-reinforced polymer), GFRP (glass fiber-reinforced polymer), polyurea, etc are most widely used as blast retrofit materials. These FRPs are able to increase the stiffness of the structures. However, if only stiffness is improved, the retrofitted member most likely will fail in a brittle manner. Thus, the determination of adequate retrofit materials and methods that can increase the stiffness as well as improve the ductility of the member is important. However, many researchers in Korea have depended on analysis using simulation techniques based on limited test results due to reasons of national securities and limited explosion sites. Therefore, in this study, the experimental studies have been carried out in ADD(Agency for Defence Development) in Korea to study about sufficient retrofit material under blast loading with various FRPs including CFRP, BFRP, polyurea, and CFRP with polyurea.

CHARACTERISTIC OF BLAST LOAD

An explosion comes from a very fast chemical reaction producing transient air pressure waves called blast waves. For an above-ground explosion, the blast wave will travel away from the source in the form of a hemispherical wavefront as shown in Figure 1(b). The peak overpressure (the pressure above normal atmospheric pressure) and the duration of the overpressure vary with distances from the explosive as shown in Figure 1(a). The maximum overpressure that occurs at the shock front is called the peak overpressure. As this wave moves away from the centre of the explosion, the overpressure in the shock front decreases steadily. The pressure behind the front also falls off exponentially. The magnitude of these parameters also depends on the explosive materials from which the explosive compound is made and the type of the detonation. 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, the composition of the explosives, the physical properties of the explosive material, and the nature of the ignition source. Additional factors include the type, energy, and duration of the events as well as the geometry of surroundings (confined or unconfined). Generally, explosive velocity is in the range of 4,000～8,400m/s. 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, and hot gas at a pressure of 100 up to 300 kilobar and at a temperature of about 3,000～4,000℃. The main blast effect is impulsive pressure loading from the blast wave (ASCE, 1997; Baker, 1973; Mays and Smith, 1995).
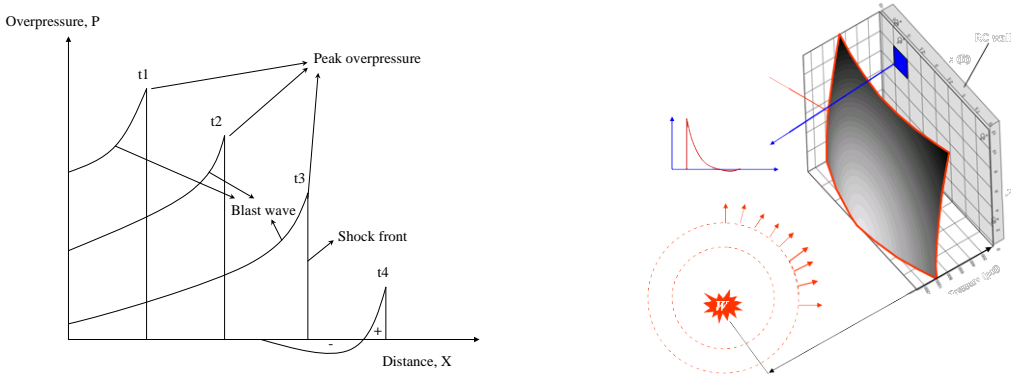
(a) Overpressure with explosion distance　　　(b) Pressure variation with structural geometry
Figure 1. Overpressure with distance at various times (ASCE, 1985; Yi *et al.* 2008)

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(a). 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 (Hopkinson, 1915). The scaled distance, Z, is defined using the Hopkinson-Cranz's cube root law as (ASCE, 1999):

$$Z = R / E^{1/3} \ or \ Z = R / W^{1/3} \tag{1}$$

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.

TEST PROCEDURE

Test specimens

As shown in Figure 2, nine 1000 × 1000 × 150 mm reinforced concrete slab specimens with double lattice reinforcements with 12-D10 steel bars with 82mm regular spacing in each direction were made for the experiment. The bar yield strength and ultimate strength are 400 MPa and 600 MPa, respectively. The average 28day concrete compressive strength is 24 MPa and the average compressive strength at the age of testing is 25.6

MPa. The mix proportion of concrete slab specimens is shown in Table 1. The specimens include NSC(normal strength concrete; the control specimen), CFRP(carbon fiber reinforced polymer), polyurea(same thickness as CFRP specimen), BFRP(basalt fiber reinforced polymer), and CFRP with polyurea specimen. CFRP and BFRP specimens were retrofitted to concrete on one side with 2 layers. And polyurea are sprayed to concrete with same thickness as CFRP. Also, total retrofitted thickness of CFRP with polyurea specimens is same as the other retrofitted specimens with sprayed on the specimen with one layer of CFRP sheet. Two specimens are made for each case except for the BFRP specimen.
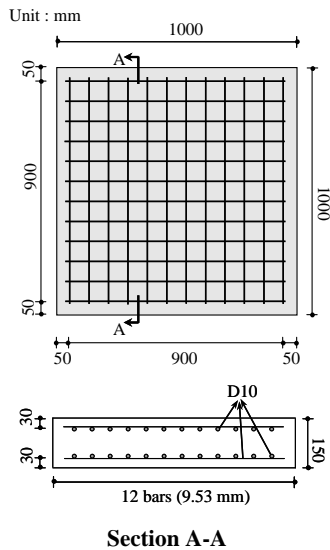
Figure 2. Test specimen geometry

Table 1. Mixed proportion of concrete slab specimen

Target Strength (MPa)	Slump (mm)	W/B (%)	S/a (%)	Unit Water (kg)	Unit Binder (kg)		Unit Fine Aggregate (kg)	Unit Coarse Aggregate (kg)	AE (%)
					C	FA			
24	100	49.8	47.7	163	294	33	880	957	2.45

Table 2. Material properties of retrofitted materials

Property	CFRP	PolyUrea	Basalt FRP
Tensile Strength (MPa)	876	20	2500~4800
Tensile Modulus (GPa)	72.4	Bond strength 2.1 MPa	89
Elongation (%)	1.2	310	3.1

Test setting

As shown in Figure 3, the test specimen is placed on a buried steel frame box in the ground. This setting system can eliminate the clearing effect by the ground surface acting as a target of infinite dimensions with the test specimen being part of this unlimited surface (Razaqpur *et al.* 2007). The specimen placed on the buried steel box is fixed by clamps used to prevent uplift and keep the consistent boundary condition. 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 wood horizontal bar. Figure 4 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.
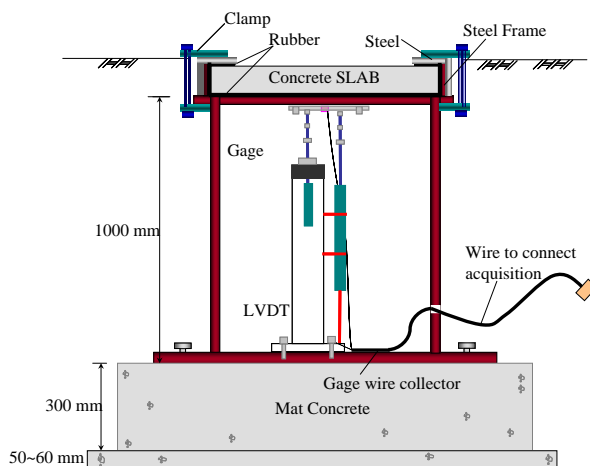

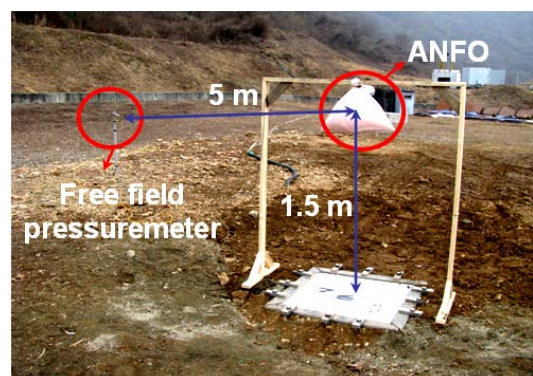Figure 3. Overview of supporting steel box

Figure 4. Test setup

Measurement outline

The free field incident pressure was measured at 5m from the center of the test slab specimens as shown in Figure 3 where reflected pressure on concrete specimen was measure at the center of the top surface of the specimen and 230mm from the center between the center and 1/3 point of specimen diagonal length. To measure strain, 6mm strain gauges are attached on tensile part of steel and 30mm strain gauges are attached on concrete upper and lower surfaces as shown Figure 5. 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. The data acquisition systems used are Dewe 2010 and Dewe 5000.
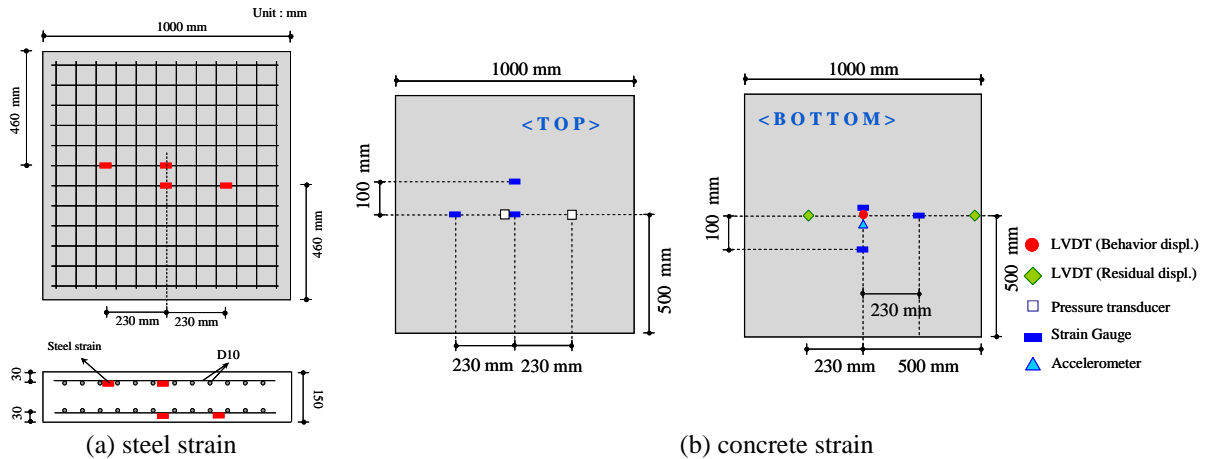

(a) steel strain   (b) concrete strain
Figure 5. Sensor location of the concrete specimen

TEST RESULTS

The measured free field pressure for the test of CFRP specimen is similar with the analysis blast pressure results obtained using ConWEP as shown in Figure 6(a). In case of reflected pressure on concrete surface, specimen (Figure 6(b)) was applied with a secondary pressure due to sequential detonation of ANFO charge. But, this type of sequential pressure load was observed in the simulation using ConWEP. The duration of reflected pressure is less than 0.5msec, which shows that the high pressure was applied to the specimen for a very short duration. The applied impulse which is constituted by pressure and duration is shown in Table 1 and the reflected impulse is generally 10 times greater than the free field pressure in this test.

(a) Free field pressure on CFRP   (b) Reflect pressure on CFRP
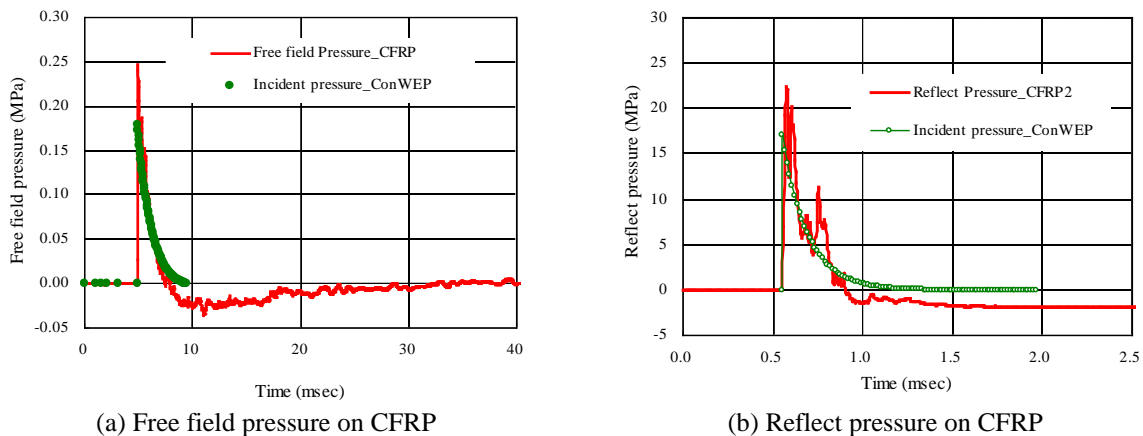Figure 6. Blast pressure on concrete specimen

Although NSC 1 was charged with TNT 35 lbs for preliminary test, the reflected pressure on specimen did not recognize the signal. Therefore, based on the preliminary test, ANFO 35lbs was selected as an appropriate charge.

In Table 1, the maximum strains of steel rebar and concrete/FRP obtained at the center of the specimens are tabulated. The results showed that all of bottom steels have yielded where as some have and have not yielded in top steels. The strain gauges for concrete and FRP attached at the top and bottom surfaces showed large strains, which means the specimens have gone through significant damages and plastic deformations, generally exceeding 10,000 $\mu\varepsilon$. Even though the concrete strain has exceeded allowable strain, the residual strain was

nearly 1,000 ~5,000 *με,* showing great recovery. From the test results, it can be concluded that the retrofitted FRP concrete specimen has a great ability to recover strain and a sufficient ductility.

Table. 1 Blast test results

SPECIMEN		NSC1	NSC2	CFRP1	CFRP2	UREA1	UREA2	CPU1	CPU2	BFRP
Charge		TNT 35lb	ANFO 35lb	ANFO 35lb	ANFO 35lb	ANFO 35lb	ANFO 35lb	ANFO 35lb	ANFO 35lb	ANFO 35lb
Reflect Pressure	Center (MPa)	NR	21.23	NR	22.66	22.66	24.07	31.95	24.26	33.17
	Impulse (MPa-msec)	NR	NR	NR	2.54	4.03	2.91	3.56	3.87	3.9
	230mm(MPa)	NR	26.58	NR	21.08	20.62	21.74	20.19	19.6	30.01
	Impulse (MPa-msec)	NR	3.26	NR	3.8	2.8	2.91	1.29	484.69	4.64
Free field pressure	Peak overpressure	30.06	23.39	NR	22.09	25.51	24.68	23.02	18.68	15.53
	Impulse (MPa-msec)	0.34	0.23	NR	0.22	0.22	0.2	0.22	0.21	0.21
Max. displacement (mm)		over 25	18.565	17.000	12.288	19.265	12.033	NR	11.630	14.889
Average Max. displ(mm)		18.565		14.644		15.649		11.630		14.889
Residual displacement (mm)		12.260	5.790	4.152	1.738	5.285	5.000	NR	3.280	10.048
Average resi. displ.(mm)		9.025		2.945		5.143		3.280		10.048
Maximum Strain (center)	Steel up	16012	5964	5035	3603	9553	6014	8224	4601	11096.5
	Steel bot	15998	over 28113	9683	7434	30803	28230	28324	28783	33638
	Conc up	-	11848	16005	25568	10338	10654	22042	9235.9	16919
	Conc/FRP bot	over 16007	-	over 16012	13119	28304	28255	16514	21377	28272

* NR : Not Record   * resi. : residual   * NSC : Normal strength concrete(reference)
* Urea : retrofitted by PolyUrea specimen   * CPU : retrofitted CFRP with PolyUrea specimen   * BFRP : retrofitted by Basalt FRP specimen
- : died gauge

The maximum and residual displacements of each specimen were measured at the center of the specimen. To measure specimen behaviour under blast loading as shown in Figure 3, LVDT is connected to the specimen. From this time-displacement relationship, frequency of the specimens under blast load is measured and compared to the analytical results. As shown in Figure 4, the results vary significantly from a specimen to a specimen due to variabilities in environmental conditions and explosive charge shape. Therefore, the average displacements are compared. In case of maximum displacement, CFRP with polyurea(CPU) specimen shows smallest displacement due to combination highly ductile material of polyurea and highly stiff and strong material of CFRP. Polyurea specimen does not have sufficient stiffness compared to CFRP specimen. The maximum displacement of BFRP specimen is similar to CFRP specimen, but its residual displacement is nearly large as the NSC specimen. It seems that the BFRP is an inappropriate blast strengthening material if residual displacement is an important parameter. In case of maximum displacement, CFRP, polyurea, CPU and BFRP have retrofitted effect of 21.4%, 15.7%, 37.4% and 19.8%, respectively. And for residual displacement, CFRP, polyurea, CPU and BFRP with respect to NSC have retrofitted effects of 67.4%, 43.0%, 63.7% and -11.3%, respectively.
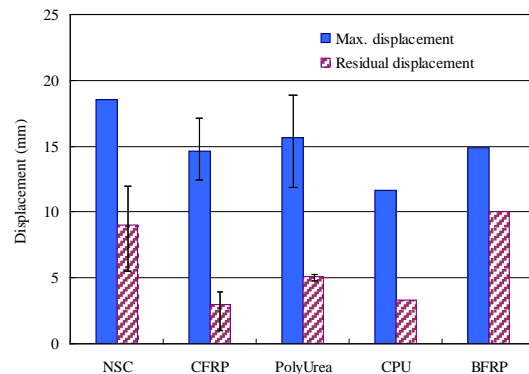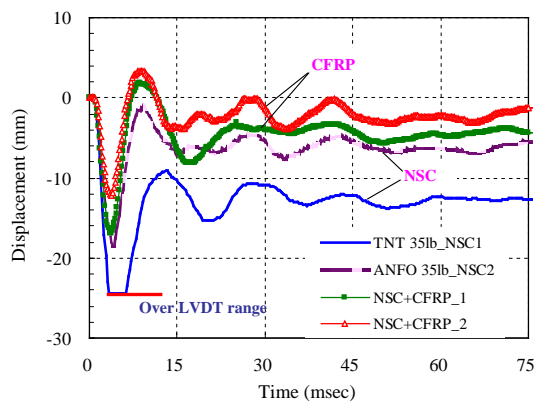

Figure 3. Behavior of concrete specimen (NSC,CFRP)   Figure 4. Error bar of displacement under blast loading

Even though the displacement is one of the estimating parameter for retrofit effect, significant variations and uncertainties can exist. To assess the effectiveness of each strengthening method, the specimens were inspected for cracking, spalling, and delamination. The crack pattern of NSC specimen of bottom surface is shown in Figure 5(a). The damages are concentrated at the center and the overall crack pattern follow concrete yield line. Also, the NSC specimens show a shear failure compared to retrofitted specimens, which show a bending failure. The retrofitted specimens show debonding failure in interface of FRP and concrete surface.
Also, local concrete crushing has been observed around supported edges in FRP strengthened specimen due to more rigidity.

(a) Normal strength concrete specimen   (b) Failure of each FRP specimen
Figure 5. Failure mode each specimen under blast loading

However, the retrofitted specimens generally suffered less damage than the control specimens from the perspective of cracking and overall concrete failure. It can be safely concluded that retrofitted FRP can sufficiently absorb the energy due to blast load.

CONCLUSIONS

From this study, various externally bonded strengthened RC slabs' response induced by explosive blast wave pressure are evaluated to understand the retrofit effect. The reflected blast pressure and impulse values calculated using the ConWEP were in reasonable agreement with the experimental data. The performance of retrofitted specimens compared to control specimens when subjected to blast loads of ANFO 35 lbs has shown the retrofitted effect about 15~38% for maximum displacement. An average of retrofitted residual displacements was higher than normal strength concrete specimen's residual displacement, even though there was no consistent trend due to various environmental conditions. Therefore, to evaluate the damage under blast load, failure mode must be considered. From the test results, the retrofitted FRP specimen has shown bending failure proving that retrofitted FRPs can be used for structural blast strengthening.

ACKNOWLEDGMENTS

REFERENCES

ASCE Committee on Dynamic effect of the Structural Division (1985), *Design of Structures to Resist Nuclear Weapons effect*, American Society of Civil Engineers, Manuals and Reports on Engineering Practice-No.42.

ASCE Task Committee on Blast Resistant Design on the Petrochemical Committee (1997), *Design of Blast Resistant Buildings in Petrochemical Facilities*, Reston, VA, 5.19-5.22.

ASCE Physical Security (1999), *Structural Design for Physical Security*: State of the Practice Report, Task Committee on Physical Security, American Society of Civil Engineers, New York, 4.1-4.48.

Baker, W. E. (1973), *Explosions in Air, Wilfred Baker Engineering*, San Antonio.

DTRA/TSWG Program (1999), *Blast Mitigation for Structure, Status Report*, Commission on Engineering and Technical Systems, National Research Council, National Academy Press, Washington, DC, USA.

Hopkinson, B. (1915), *British Ordnance Board Minutes*, 13565, 1915.

Kim, H. J., Nam, J. W., Kim, S. B., Kim, J. H., and Byun, K. J. (2007). "Analytical Evaluations of the Retrofit Performances of Concrete Wall Structures Subjected to Blast Load*", Journal of the Korea Concrete Institute*, 19(2), 241-250.

Mays, G. C. and Smith, P. D. (1995), *Blast effect on Buildings: Design of Buildings to Optimize Resistance to Blast Loading*, Thomas Telford.

Mosalam, K. M. and Mosallam, A. S. (2001). "Nonlinear Transient Analysis of Reinforced Concrete Slabs Subjected to Blast Loading and Retrofitted with CFRP Composites*", Composite Part B : engineering* , 32, 623-636.

Razaqpur, A.G., Tolba, A., Contestabile, E. (2007) "Blast loading response of reinforced concrete panels reinforced with externally bonded GFRP laminates", *Composite Part B : engineering*, 38, 535-546.

Yi, N.H., Nam, J.W., Kim, S.B., Kim, J.J.H., Byun, K.J.(2008) " HFPB analysis of RC structures under blast loads considering concrete damage model", *The 3rd ACF International Conference-ACF/VCA 2008.*