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Analytical Study of Reinforced Concrete Columns under Blast Loading

[Ha Eun Park, Eun Sun Jo, Min Sook Kim, Dae-Jin Kim, Young Hak Lee*]

***Abstract*—Columns are the key load bearing elements in concrete frame structures. In this study, the effect of blast loadings occurred within the short distance was analytically examined. Aspect ratio of the column section, longitudinal reinforcement ratio and arrangement of longitudinal reinforcement were considered as variables. And AUTODYN was used to evaluate damage levels and define the relations among these variables with respect to behavior after blast.**

***Keywords*—columns, concrete structures, blast**

I. Introduction

In the past decades, terrorist attacks have drawn attention to deficiencies in current structural design practices. Civilian populations should be protected against terrorism and social/subversive unrest. Critical infrastructures, of which damage could induce a large scale of disaster, should be designed to resist blast loading within an acceptable range. For and economic and safe design of structures against progressive collapse to blast loads, a reliable analysis is essential. In this paper, the effects of three key parameters(including aspect ratio, longitudinal reinforcement ratio, arrangement of longitudinal reinforcement) on residual load carrying capacity of reinforced column under explosive loading is studied. Numerical model was prepared using AUTODYN to predict blast loading and corresponding structural damage.

II. Blast Loadings

Fig. 1 is showing the shock wave produced by detonation of explosive. Loading environments produced by explosive devices include fragments and the blast wave. The combination of pressure and fragment impulse affecting structural damage is not clearly understood yet. Thus, structural damage only from blast in considered in this study. P_{so} is peak incident pressure, P_o is ambient pressure, t_o is duration of positive overpressure, t_o^- is duration of negative overpressure, and is positive specific impulse. In this study, AUTODYN is used to simulate blast loading and structural damage based on Eulerian-Lagrangian coupling.

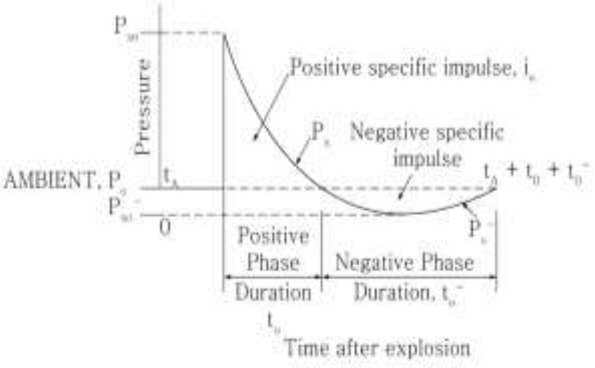

Figure 1. Free-field pressure-time variation

III. Analytical Model

A. Material Models

The RHT model has three limit surfaces; the initial elastic yield surface, the failure surface and the residual friction surface. While the surfaces account for reduction in strength along not only strain rate effects but also different meridians, the static compressive meridian surfaces are depicted in Fig. 2. A piecewise linear Johnson-Cook material model was used to describe the behavior of the reinforcing steel, including strain hardening but not strain-rate and thermal effects. This model is a modification of the Johnson-Cook model, where the dependence on effective plastic strain is replaced by a piecewise linear function of yield stress Y versus effective plastic strain. Fig. 3 shows yield stress versus effective plastic strain of Piecewise linear Johnson-Cook material model.

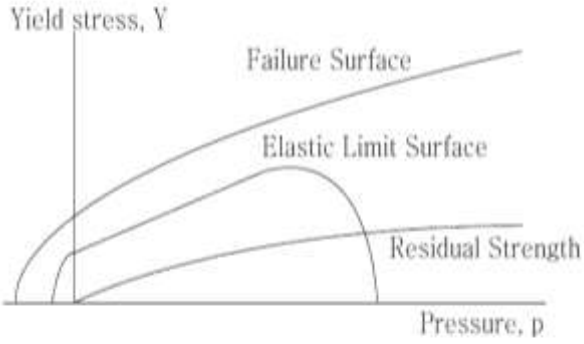

Figure 2. The RHT model used for concrete

Ha Eun Park/ Eun Sun Jo/ Min Sook Kim/ Dae-Jin Kim/ Young Hak Lee
Kyung Hee University
Korea

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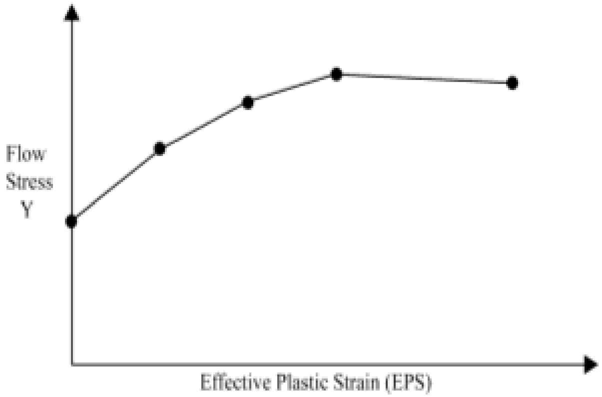
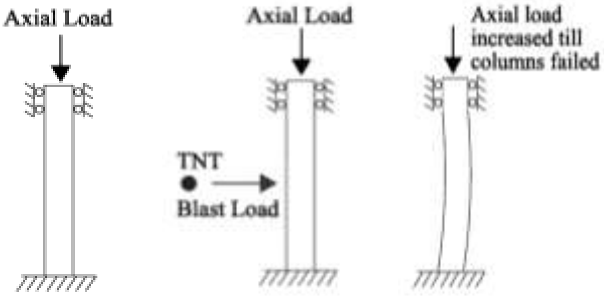


Figure 3. Yield stress versus effective plastic strain

B. *Geometry and Variables*

This study has been analyzed in three stages, pre blast loading stage, blast loading stage and post blast loading stage, as shown in Fig. 4. In pre blast loading stage, numerical model for reinforced concrete column and blast loading is prepared with Lagrangian and Euler, respectively. Constant axial load is applied to the column, which is 20% of the static load carrying capacity. In blast loading stage, damage and structural response of column under blast loading is simulated. Axial loading remains constant as 0.2 P_n throughout this stage. Simulation continues until blast loading disappears and column does not move due to material damping. In post blast loading stage, axial force applied on the damaged column increases statically from 0.2 P_n until the column fails. Column has fixed-fixed supports, except that top of column is free to move in axial direction. 40mm * 40mm * 50mm hexahedral solid mesh was used for the column.



(a) Pre blast loading (b) Blast loading stage (c) Post blast loading stage

Figure 4. Analysis procedure

Failure modes of concrete structure due to blast load vary according to the point of detonation, stand-off distance and TNT charge weight. Especially columns are the key load bearing elements in concrete frame structures. They are typically weak not to long distance explosive loadings but to short distance loadings. In this study, the effect of blast loadings occurred within the short distance was analytically examined. Aspect ratio, longitudinal reinforcement ratio, arrangement of longitudinal reinforcement were selected as key parameters affecting residual load carrying capacity, as shown in Table 1. The TNT amount was set to 500kg and the stand-off distance was 5m.

IV. Effect of Variables

A. *Effect of Aspect Ratio*

Fig. 5 shows mid-span deflections by column length induced by impulse at various aspect ratios. When the impulse is fixed, the deflection ratio decreases as aspect ratio increases, because of larger lateral stiffness and smaller later force proportional to the width of column. Thus, the damage of column increases as the aspect ratio decreases. Fig. 6 indicates that the initial strain energy is similar, but the strain energy changes gradually as time passes. The strain energy absorption increases as the aspect ratio increases.

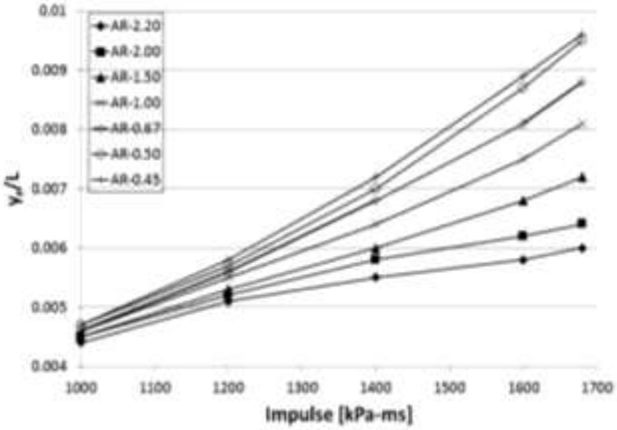


Figure 5. Effect of aspect ratio on the mid-span displacement of columns

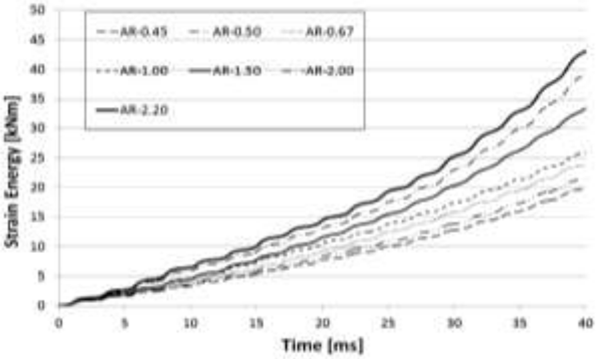


Figure 6. Effect of aspect ratios on strain energy

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TABLE 1. PARAMETER TABLE

No.	**Type**	**Variable**	**Concrete**		**Reinforcement**		**Aspect Ratio**	**Longitudinal Reinforcement Ratio**
			b x h [mm x mm]	***H [mm]***	***Longitudinal***	***Transverse***		
1	AR-2.20	Aspect Ratio	265 x 583	2400	8-D22	D10@200	2.20	1.94
2	AR-2.00		278 x 556	2400	8-D22	D10@200	2.00	1.94
3	AR-1.50		320 x 480	2400	8-D22	D10@200	1.50	1.94
4	AR-1.00		392 x 392	2400	8-D22	D10@200	1.00	1.94
5	AR-0.67		480 x 320	2400	8-D22	D10@200	0.67	1.94
6	AR-0.50		556 x 278	2400	8-D22	D10@200	0.50	1.94
7	AR-0.45		583 x 265	2400	8-D22	D10@200	0.45	1.94
8	LRR-1.94	Longitudinal Reinforcement Ratio	400 x 400	2400	8-D19	D10@200	1.00	1.43
9	LRR-2.53		400 x 400	2400	8-D22	D10@200	1.00	1.94
10	LRR-3.21		400 x 400	2400	8-D25	D10@200	1.00	2.53
11	LRR-3.97		400 x 400	2400	8-D29	D10@200	1.00	3.21
12	LRR-4.78		400 x 400	2400	8-D32	D10@200	1.00	3.97
13	LRR-5.70		400 x 400	2400	8-D35	D10@200	1.00	4.78
14	LRR-1.90		400 x 400	2400	8-D38	D10@200	1.00	5.70
15	ALR-24	Arrangement of Longitudinal Reinforcement	400 x 400	2400	24-D13	D10@200	1.00	1.90
16	ALR-16		400 x 400	2400	16-D16	D10@200	1.00	1.99
17	ALR-8		400 x 400	2400	8-D22	D10@200	1.00	1.94
18	ALR-6		400 x 400	2400	6-D25	D10@200	1.00	1.90
19	ALR-4		400 x 400	2400	4-D32	D10@200	1.00	1.99

B. *Effect of Longitudinal Reinforcement Ratio*

Residual load carrying capacities were analyzed with different longitudinal reinforcement ratios with same cross section area. Fig. 7 shows mid-span deflections normalized at various longitudinal reinforcement ratios. The deflection ratio decreases as longitudinal reinforcement ratios increases. Higher longitudinal reinforcement ratio induced higher lateral stiffness of column, because steel has higher value of Young's modulus comparing to the one of concrete.

Moreover, since reinforcement is more ductile than concrete, more energy can be absorbed in columns with higher longitudinal reinforcement ratio, as shown in Fig. 8. Thus residual load carrying capacity increases as the longitudinal reinforcement ratio increases. Figure 8 shows the strain energy as time passes. It indicates that the strain energy absorption of the column increases as the longitudinal reinforcement ratio increases.

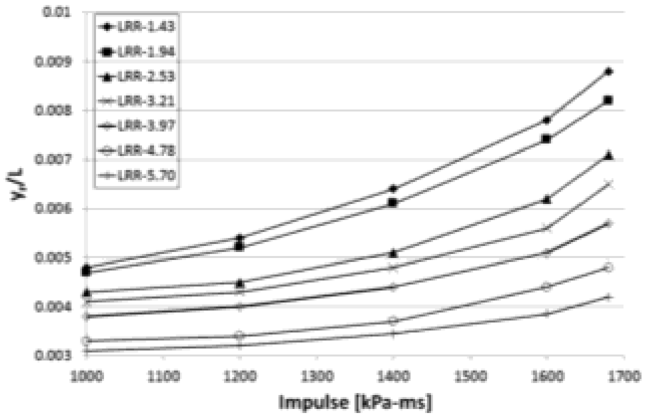

Figure 7. Effect of longitudinal reinforcement ratio on the mid-span displacement of columns

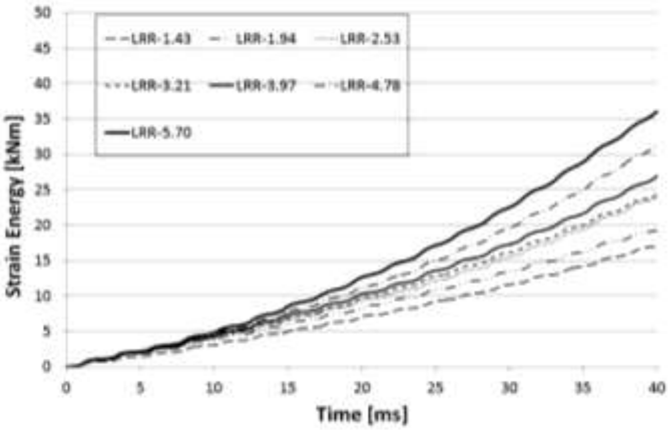

Figure 8. Effect of longitudinal reinforcement on strain energy

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C. *Effect of Arrangement of Longitudinal Reinforcement*

With the same cross section area and reinforcement ratio, effect of arrangement of longitudinal reinforcement on residual load carrying capacities were analyzed. Fig. 9 shows mid-span deflections by column length induced by impulse at various arrangement of longitudinal reinforcement. It indicates that the deflection ratio decreases as the amount of reinforcement increases. This means using large number of small size reinforcement is more effective to improve the stiffness than using small number of large size reinforcement. And Fig. 10 shows the effect of arrangement of longitudinal reinforcement on strain energy. Ductility can be improved throughout the cross section of column as number of longitudinal reinforcement increases, thus the increased number is beneficial to resist the blast loading.

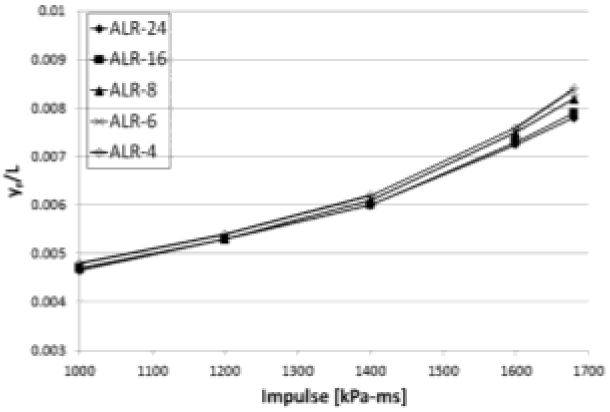

Figure 9. Effect of arrangement of longitudinal reinforcement on the mid-span displacement of columns

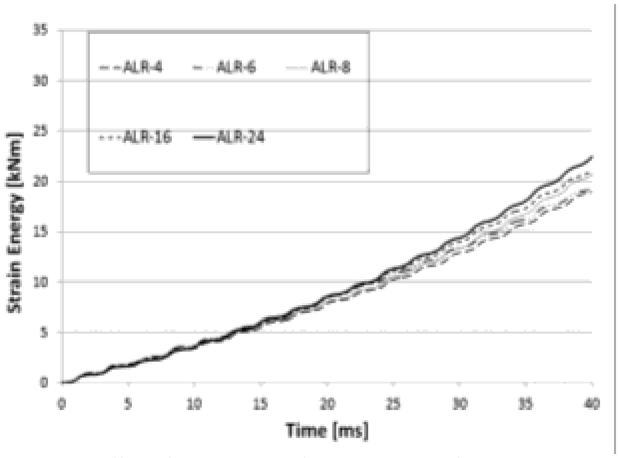

Figure 10. Effect of arrangement of longitudinal reinforcement on strain energy

V. Conclusions

In this study, AUTODYN was used to predict blast loading and corresponding structural damage. Various aspect ratio of column sections with the same sectional area and reinforcement ratio, reinforcement ratio, and various arrangement of longitudinal reinforcements with the same sectional area were considered as variables in order to analyze the behavior of the columns after blast.

- When the impulse is fixed, the deflection ratio decreases as aspect ratio increases, because of larger lateral stiffness and smaller later force proportional to the width of column.
- The deflection ratio decreases as longitudinal reinforcement ratios increases. Higher longitudinal reinforcement ratio induces higher lateral stiffness of column, because steel has higher value of Young's modulus comparing to the one of concrete.
- Ductility can be improved throughout the same cross section area and reinforcement ratio of column as number of longitudinal reinforcement increases, thus the increased number is beneficial to resist the blast loading.
- Failure modes of concrete structure due to blast load vary according to the point of detonation, stand-off distance and TNT charge weight. Therefore, more study is required to provide accurate prediction of the column behavior under blast loading.

Acknowledgment

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About Author (s):

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