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P-I DIAGRAM GENERATION FOR REINFORCED CONCRETE (RC) COLUMNS UNDER HIGH IMPULSIVE LOADS USING ALE METHOD

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ABSTRACT

Reinforced concrete (RC) column systems are widely used in protective structures designed to resist blast events. Development of correlations between explosive load and the resulting damage in concrete elements are significant for incorporation of blast load in design and also for pre and post-damage assessments. The main purpose of this research is to organizing correlations between explosive load and damage. These correlations are being expressed in Pressure-Impulse diagrams. The damage level is calculated based on the residual axial load-carrying capacity of the damaged RC column. Finite element modeling in LS-DYNA is used to analyze the structures and calculate the damage level for each explosive phenomenon. The Arbitrary Lagrangian Eulerian (ALE) method is used to simulate the explosive loads in the reinforced concrete column. The results demonstrated that increase the column size cause to increase in pressure and impulsive asymptotes and lead to enhanced the pressure-impulse (P-I) diagram.

Contribution/ Originality: Current knowledge on quantifying and predicting explosion damage of RC columns subjected to blast effects is incomplete and limited. This research examines the damage analysis of RC columns using P-I diagram. The P-I diagrams are developed to determine levels of damage on a structure and have also been used in the past to evaluate human response to shock wave generated by an explosion.

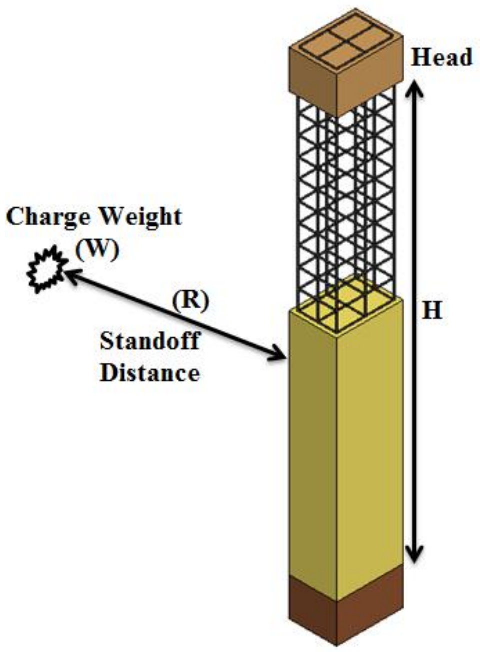
1. INTRODUCTION

One of the simplest methods for describing a structure's response to an applied explosive load is to construct a pressure-impulse (P-I) diagrams [1, 2]. P-I diagrams are commonly used to assess the structural elements under blast loading [3, 4]. At first the P-I diagram applied in World War II to determine the damage extent of structural elements and buildings [2]. Previous researcher [5-9] developed P-I diagram in reinforced concrete structural members subjected to blast loads and reported improved performances over conventionally designed structural components.

In each P-I curve three domains can be identified: impulsive, dynamic and quasi-static loading sensitive regions. The impulsive regime is characterized by short load duration where the maximal structural response is not reached before the load duration is over. The dynamic regime is characterized by the maximum response being reached close to the end of the loading regime. Lastly, the quasi–static regime is characterized by a structure having reached its maximum response before the applied load is removed. The objective of this research is to develop the P-I diagram in RC columns under explosive loads. An advanced finite element modeling tool, LSDYNA is employed for the purpose of the analysis. The Arbitrary Lagrange–Euler (ALE) algorithm is applied in this paper to simulate the blast load in RC columns.

2. DEVELOPMENT OF MODEL AND NUMERICAL SIMULATION

The models consist of two parts namely the rectangular concrete block and the reinforcing steel bars as shown in Figure 1. The rectangular concrete block of dimensions 500×700×4200 mm is modeled using the eight-noded hexahedron elements with constant stress solid element formulation. The steel reinforcement is modeled using the Hughes-Liu beam elements having cross-section integration formulation. In current study 50 mm mesh size is used to simulate solid and beam elements. The numerical model incorporates footing and column head to provide higher fidelity for the column constraints. The interface between concrete and steel is modeled using the *Contact-1D formulation such that the nodes in the steel element are modeled dependent of the nodes in the concrete element. In the numerical model, axial load was applied onto the column head before the application of blast pressures to the column's front face. Materials such as steel and concrete exhibit greater strength when loaded at high rates and standards and manuals for blast-resistant design allow nominal component strengths to be increased by Dynamic Increase Factors (DIF) to account for rate effects. In order to investigate reinforced concrete elements under blast loading conditions, strain rate effect must be considered. Table 1 gives the material properties of the concrete and steel reinforcement.



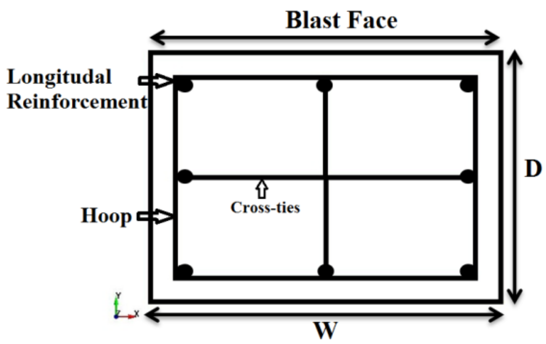


Figure-1. Details of RC column

Table-1. Material properties of concrete and steel reinforcement

Material	Parameters	Value
Concrete	Uniaxial compressive strength	42 MPa
	Mass density	2400 kg/m^3
	Poisson's ratio	0.2
	Tensile stress at failure	6.0 MPa
Steel Reinforcement	Young's Modulus	200 GPa
	longitudinal Steel strength	460 MPa
	transverse Steel strength	250 MPa
	Mass density	7800 kg/m^3
	Poisson's ratio	0.3
	Plastic strain at failure	0.18

3. MATERIAL MODEL

To study the interactive mechanism and dynamic response of reinforced concrete column under blast loads, a proper and reliable dynamic damage model that reflects the characteristics of the concrete material behavior at high strain rate is needed. LS-DYNA has several material models that have been used by researchers to model concrete behaviour, such as Continuous Surface Cap Model for Concrete [10] Winfrith Concrete model [11] and the Karagozian and Case Concrete Damage Model Release 3 [12, 13]. The MAT72 REL3 concrete model was used to characterize concrete properties in the numerical model for this study [14, 15].

The MAT_PIECEWISE_LINEAR_PLASTICITY (MAT_024) material model in LS-DYNA is used to simulate rebar. MAT_024 is an elasto-plastic material model for which arbitrary stress-strain curves can be defined, where up to eight plastic strains and corresponding yield stress points can be set to define realistic non-linear stress-strain behavior of the material [16]. For explosive material, Mat-High-Explosive-Burn (Material Type 8) is used [17]. The Jones–Wilkens–Lee (JWL) equation of state (EOS) is used to model the pressure released by chemical energy during the explosion and it has been widely used in engineering calculations. The JWL EOS can be written in the following form:

$$P = A[1 - \frac{\omega}{R_1 V}]e^{-R_1 V} + B[1 - \frac{\omega}{R_2 V}]e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

Where A, B are linear explosion parameters; ω, R_1 and R_2 are nonlinear explosion parameters; V is relative volume and E is specific internal energy of every unit of mass, P is the pressure of the detonation products of high explosives.

In the model, air is modeled as an ideal gas with material model MAT_NULL and equation of state EOS_LINEAR_ POLYNOMIAL [18]. The pressure related to the energy can be expressed as follows:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E_0 \quad (2)$$

$$\mu = \frac{\rho}{\rho_0} - 1 \quad (3)$$

Where C_0, C_1, C_2, C_3, C_4, C_5 and C_6 are constant, ρ/ρ_0 is the ratio of current density and E_0 is the initial internal energy per volume [19]. A summary description of the material models assigned for the concrete, TNT charge, air, longitudinal reinforcements and stirrups is presented in Table 2.

Table-2. Material properties of concrete, steel reinforcement, explosive and air

Units(g,mm,ms,MPa)								
***MAT_CONCRETE_DAMAGE_REL3(Concrete)**								
RO	f_c	PR						
0.0024	40	0.2						
***MAT_PIECEWISE_LINEAR_PLASTICITY(Reinforcement)**								
RO	E	PR	f_y					
0.0078	2E+005	0.3	460					
***MAT-HIGH-EXPLOSIVE-BURN(Explosive)**								
RO	D	PCJ						
0.00163	6930	2.1E4						
***EOS-JWL(Explosive)**								
A	B	R_1	R_2	w	V_0	E_0		
3.712E5	3231	4.15	0.95	0.3	7000	1		
***Mat-NULL(Air)**								
RO	PC	MU						
1.225E-6	-1E-5	8.5E-10						
***EOS-LINEAR POLYNOMIAL(Air)**								
C_0	C_1	C_2	C_3	C_4	C_5	C_6	E_0	V_0
0	0	0	0	0.4	0.4	0	0.25	1

Source: LS-DYNA [19]

4. NUMERICAL MODELLING OF EXPLOSIVE LOADS

In order to provide an accurate prediction of the dynamic response of RC structures when subjected to blast loads, the first step is to correctly estimate the blast loads likely to be applied on the structure. Information on blast load parameters is available from the standard sources [20-23]. For simulating structures subjected to blast loads different methods of analysis are available in LSDYNA. Multi-Material Arbitary Lagrangian Eulerian(MM-ALE) method is applied in the current study. The ALE algorithm simultaneously describes the motion of fluids and also shows the dynamic response of solids [24-26]. ALE method is a hybrid of the Lagrange part and ALE part and is used in modelling both solids and fluids. In the ALE algorithm, the ALE and Lagrangian meshes must be overlapped to produce better accuracy, but the two meshes do not need to be consistent [27, 28].

A region of air was modelled around the concrete column which provided the space needed for the blast waves to propagate and interact with the column. Fluid-structure interaction (FSI) between ALE (fluid) and lagrangian (structure) materials is defined by CONSTRAINED_LAGRANGE_IN_SOLID. The multi material ALE solver (ELFORM= 11) is used for the TNT and air to eliminate the distortion of the mesh under high deformation and specified as multi material using LS-DYNA multi material capabilities (ALE_MULTI_MATERIAL_GROUP). High explosives were modeled using ALE mesh, specifically the INITIAL_VOLUME_FRACTION_GEOMETRY card with the appropriate distances of the different experimental configurations [29]. The field of the air needs the BOUNDARY NON REFLECTING conditions, in order not to have the reflection of the wave at the boundary of the domain. The finite element model of the RC column is depicted in Figure 2.

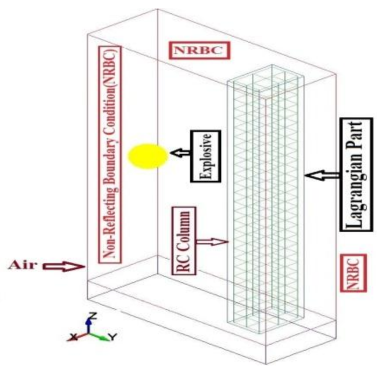


Figure-2. Numerical modelling of blast load

5. VALIDATION OF NUMERICAL MODELING

Validating the numerical models developed in FE codes verifies the accuracy of the modeling approach and corresponding results. This section is illustrated the verification of numerical model with blast field test performed by Baylot and Bevins [30]. The peak pressure on the front face of the column using ALE method is shown in Figure 3 and compared with Baylot and Bevins [30] study. The comparison of the peak pressure of the column measured at explosive elevation and at top of the column. The left two histories are for near explosive height and the right two histories are for top of the column. The peak pressure measured by the experiment study is approximately 7.5 MPa at the explosive level and 2.52 MPa at the top of the column. It is 7.8 MPa at the explosive elevation and 2.54 MPa at the top of the column in the present study. As a result, the difference between peak pressure at explosive elevation and at top of the column in the present study and experimental study are around 3.84% and 0.78 % respectively. Therefore, the peak pressure measured in the present study agrees well with that from the experiment [30].

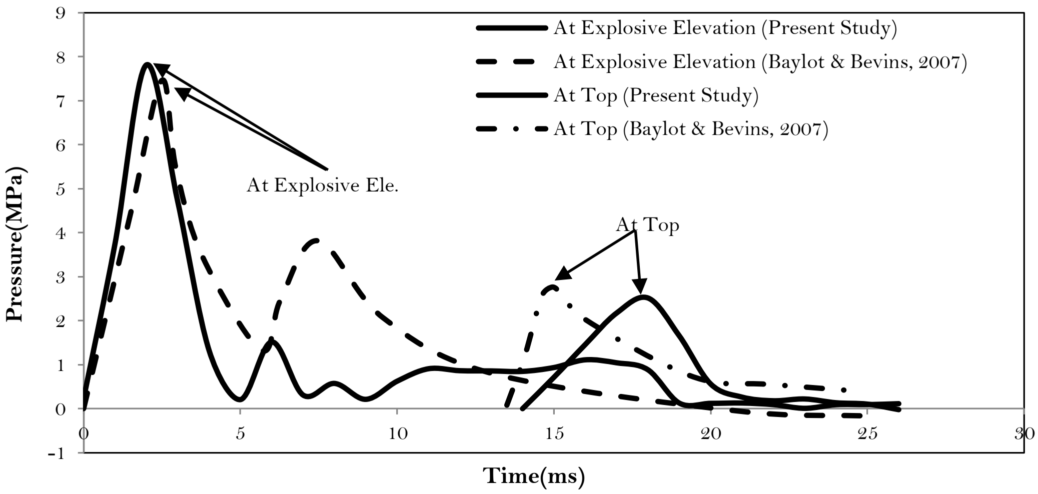


Figure-3. Pressure time histories for column in test No. 2 using ALE method

Source: Baylot and Bevins [30]

6. DERIVATION OF P-I DIAGRAM

In order to generate P-I diagram for RC columns, a series of numerical simulations are carried out to obtain RC column damages at various degrees. Column size is an important factor to increase the column capacity. In this study, three example of RC column are considered. The properties of RC columns are given in Table 3.

Table-3. The properties of RC columns

Column no.	Column depth (mm)	Column width (mm)	Column height (mm)	Cross tie/hoop	Longitudinal reinforcement
C1	500	700	4400	D12@200	8D25
C2	700	700	4400	D12@200	8D25
C3	900	700	4400	D12@200	8D25

The blast loads, i.e., peak pressure and impulse, corresponding to the RC column damages, will be plotted in the P-I space together with the damage level. Figure 4-6 shows the P-I curves for column C1, C2 and C3 respectively generated using numerical simulation. Table 3 summarized pressure asymptote and impulsive asymptote for all columns.

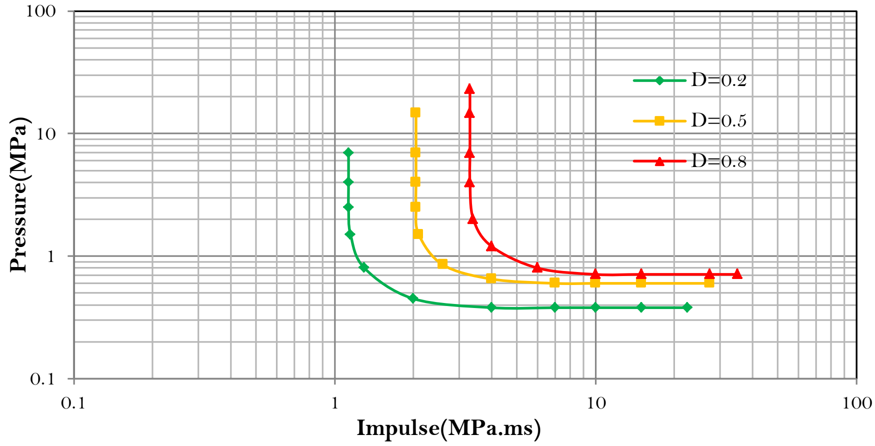


Figure-4. P-I diagram for RC column C1

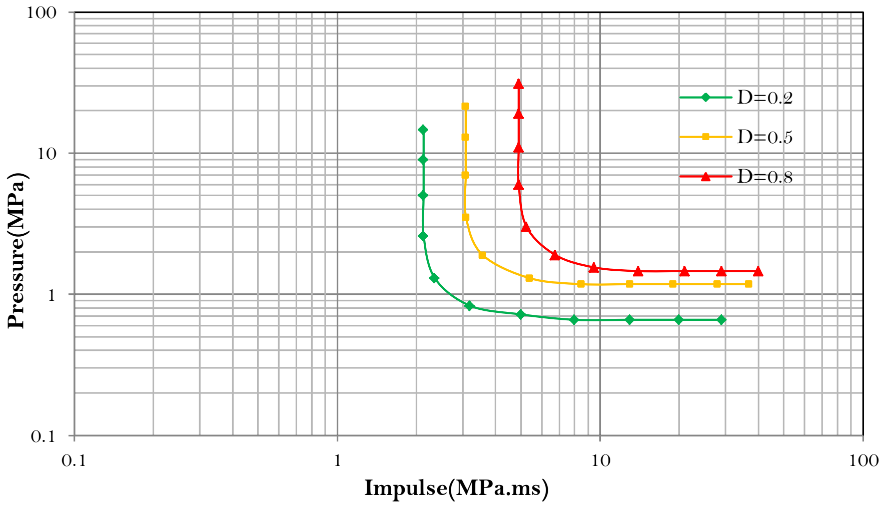


Figure-5. P-I diagram for RC column C2

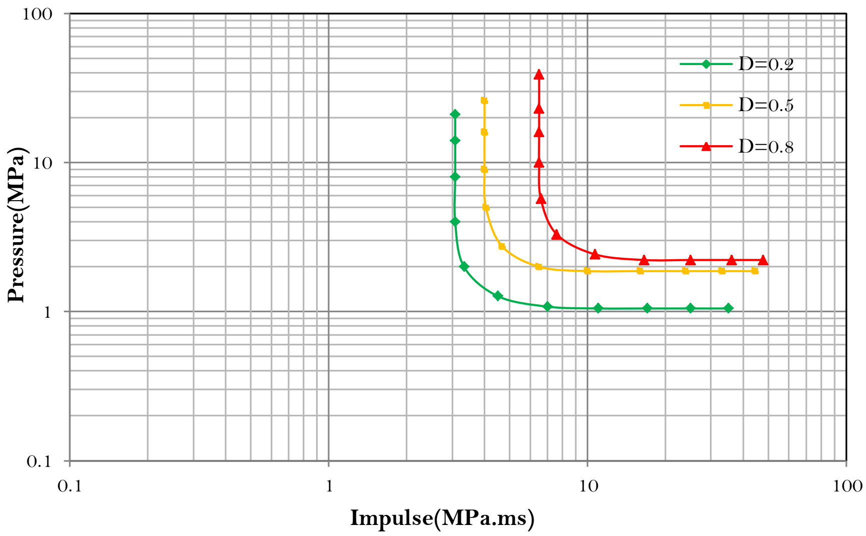


Figure-6. P-I diagram for RC column C3

Table-4. Pressure and impulse asymptotes of the columns

Column	D=0.2		D=0.5		D=0.8	
	Po (MPa)	Io (MPa.ms)	Po (MPa)	Io (MPa.ms)	Po (MPa)	Io (MPa.ms)
C1	0.363	1.2	0.58	3	1.05	4.3
C2	0.715	2	1.22	3.5	2.38	5
C3	0.994	2.6	1.85	3.9	4.03	5.5

The findings show that column C3 has asymptotic values higher than column C1 and column C2. According to Figures 4-6 and Table 4, one can see that increase the column size cause to increase in pressure and impulsive asymptotes and lead to enhanced the P-I diagram. This indicates that a column with larger size can resist a bigger quasi-static loads, dynamic loads and impulsive loads. This is expected because increasing the column size means more concrete area and larger cross-section modulus, which will increase both the shear strength and bending strength of the column.

7. ANALYTICAL FORMULAE TO GENERATE P–I DIAGRAM

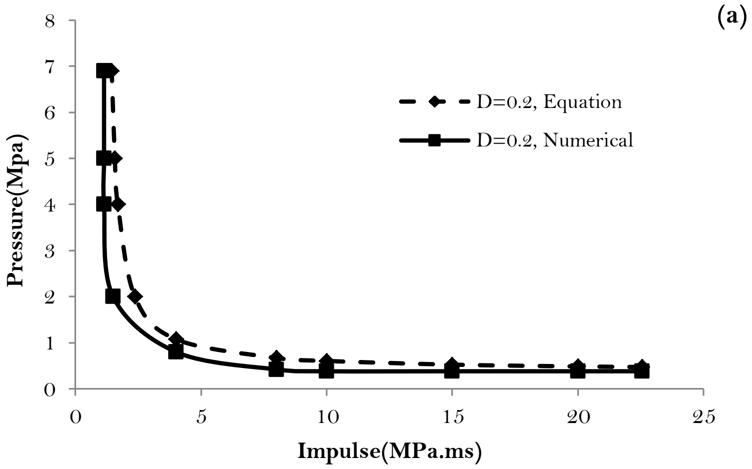
A careful examination of the fitted P-I curves find that they can be expressed analytically as the hyperbolic equation [31-34].

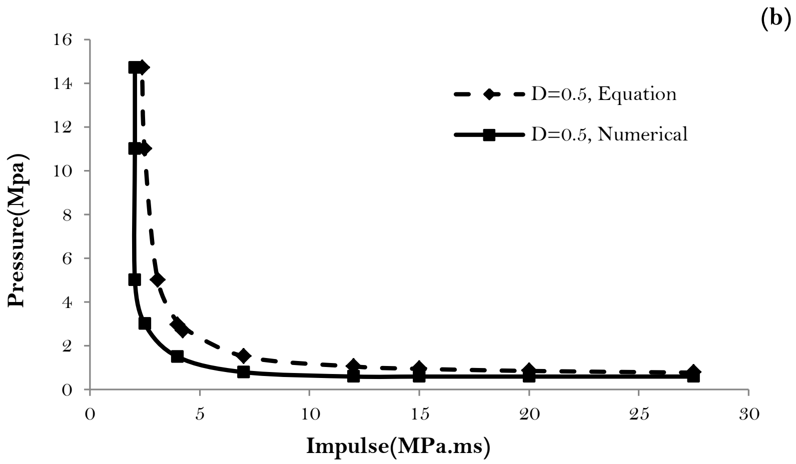
$$(P - P_0)(I - I_0) = 3(\frac{P_0}{2} + \frac{I_0}{2})^{1.5} \qquad (4)$$

Where

- P_0 = The pressure asymptote
- I_0 = The impulsive asymptote

Figure 7 shows the comparison of P-I curves derived according to Eq. (4) and the numerical data for 0.2, 0.5 and 0.8 damage degrees. As shown, Eq. (4) well represents the P-I curve of a RC column. Since using Eq. (4) to model a P-I curve substantially reduces the number of data points required to fit a reliable P-I curve, Eq. (4) is used in this paper to model the variations of P-I curves.





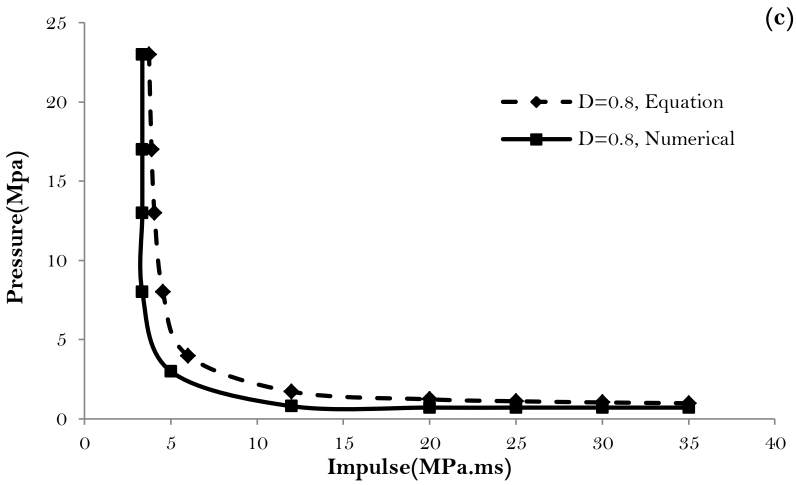


Figure-7. Comparison of P-I diagram for column C_1 generated from Eq. (4) and fitted numerical data.

8. CONCLUSION

This paper performed the numerical analysis of the dynamic response of a RC column that was subjected to explosive loads. The numerical analysis of the column under blast effects was carry out using LS DYNA explicit dynamics finite element package. The results of the current study consist of P-I diagrams can be used for generating damage level due to explosive load for reinforced concrete column. The damage level is calculated based on the residual axial load-carrying capacity of the damaged RC column. These damage criteria can be used for quick assessment of structural damage under explosive loads. This research work and the conclusions drawn has been increased awareness about safety and behavior of RC columns from explosive loads.

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Contributors/Acknowledgement: All authors contributed equally to the conception and design of the study.

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