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Derivation of Empirical Formulae to Predict Pressure and Impulsive Asymptotes for P-I Diagrams of One-way RC Panels

Azrul A. Mutalib, Masoud Abedini, Shahrizan Baharom, and Hong Hao

***Abstract*—**There are only limited studies that directly correlate the increase in reinforced concrete (RC) panel structural capacities in resisting the blast loads with different RC panel structural properties in terms of blast loading characteristics, RC panel dimensions, steel reinforcement ratio and concrete material strength. In this paper, numerical analyses of dynamic response and damage of the one-way RC panel to blast loads are carried out using the commercial software LS-DYNA. A series of simulations are performed to predict the blast response and damage of columns with different level and magnitude of blast loads. The numerical results are used to develop pressure-impulse (P-I) diagrams of one-way RC panels. Based on the numerical results, the empirical formulae are derived to calculate the pressure and impulse asymptotes of the P-I diagrams of RC panels. The results presented in this paper can be used to construct P-I diagrams of RC panels with different concrete and reinforcement properties. The P-I diagrams are very useful to assess panel capacities in resisting different blast loads.

***Keywords*—**One-way reinforced concrete (RC) panels, Explosive loads, LS-DYNA Software, Pressure-Impulse (P-I) diagram, Numerical.

I. Introduction

SOME RC structural wall panels are designed to function as an efficient bracing system and to offer great potential for both lateral load resistance and drift control [1]. However, most RC wall panels commonly used as architectural non-bearing curtain walls in residential, commercial, and industrial buildings for their appearance and insulation qualities are not designed to resist lateral loads. Building components not capable of resisting the blast wave will fracture and be further fragmented and moved by the dynamic pressure that immediately follows the shock front. These high pressures are the primary reason for the occurrence of building damage as they are typically many orders of magnitude larger than the pressures which the structural elements are designed to withstand [2]. The failure of those panels might impose great threats to occupants and structures. Hence, it is important to assess the performance and damage levels of RC panels under various blast loadings. The degree of damage is strongly dependent on the size of the explosion and its distance to structural elements [3]. Therefore, a comprehensive assessment of structural damage to blast loads should consider the effect of both the blast loading amplitude and duration on structural responses. One of the simplest methods to correlate the duration of blast pressure along with its amplitude to reaching a particular level of damage of the structural component is Pressure-Impulse (P-I) diagrams. P-I diagrams which include both blast pressure amplitude and duration are often used in the assessment of RC structure damages.

This paper performs numerical simulations of responses of RC panels to blast loads. The numerical models are developed in LS-DYNA and are verified with results presented by other researchers. The numerical results are used to formulate empirical formulae to predict pressure asymptote, P_O and impulsive asymptote, I_O to generate P-I diagrams for one-way RC panels.

Masoud Abedini is with the Department of Civil & Structural Engineering, Universiti Kebangsaan Malaysia (corresponding author to provide phone: +60176971420; e-mail: masoud.a877@yahoo.com).

Azrul A. Mutalib and Shahrizan Baharom are with the Department of Civil & Structural Engineering, Universiti Kebangsaan Malaysia (e-mail: azruljkas@gmail.com)

Hong Hao is with the Department of Civil & Structural Engineering, University of Western Australia.

II. Method for Develop P-I Diagrams Using Empirical Formula

The explosion test is good to derive the P-I diagrams however it needs a very large amount of data therefore it is very expensive. With the development of computer technology [4], numerical method is determined to be reliable to analyze the RC column damage to blast loads. The P-I diagrams can be developed based on these four proposed methods;

a) Determination of the various magnitude of blast loads in correlation between pressures (P) and Impulses (I)
b) Definition of the damage index criteria
c) Derivation P-I diagram general formulae based on the pressure asymptotes (P_O) and Impulse asymptotes (I_O) empirical formulae
d) Development of P-I diagrams

In the numerical analyses, the magnitude of the blast loads is imposed based on the UFC-3-340-02 [5] scaling laws. These scaling laws provide parametric correlation between the actual effective distance from the explosion (R) and the charge weight as an equivalent mass of TNT (W). The scaled distance is given as a function of the dimensional distance parameter as:

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

As the scaled distance increases, the peak blast load decreases but the duration of the positive phase blast wave increases resulting in lower amplitude, longer-duration shock pulse.

In order to define damage (D), the damage criteria used should be suitable for evaluation of RC structures related to the member global and material damage, easy to use in assessing the element conditions and easily obtained from numerical or experimental test [6]. The damages are defined based on the support rotation of the members and are classified into low, moderate and severe. When support rotation is 2^o, the damage of the wall is termed as low (*LD*). When the support rotation is 4^o, moderate damage (*MD*) occurs. At 12^o support rotation, the damage is defined as the severe damage (*SD*). Shope [7] used the maximum deflection, δ corresponds to the specific support rotation. The respective δ value for each damage level is calculated by

$$\delta = \frac{b}{2}\tan\theta \tag{2}$$

where b is the shortest span of the wall. The critical values of δ are set to be the numerical maximum mid-height deflection of the RC panel. These damage criteria are used in this study to define damage levels of P-I diagrams.

An examination of fitted P-I diagrams in finds that P-I diagram for RC columns can be expressed analytically as

$$(P - P_O)(I - I_O) = A\left(\frac{P_O}{2} + \frac{I_O}{2}\right)^{\beta} \tag{3}$$

where $P_O$and I_O are the pressure and impulse asymptotes respectively. Fig. 1 shows typical P-I diagrams with *PO andIO of* different *D* [8]. In this study, empirical formulae to predict P_O and I_O are derived from a series of numerical results for RC columns with and without FRP strengthening using the least squares-fitting method.

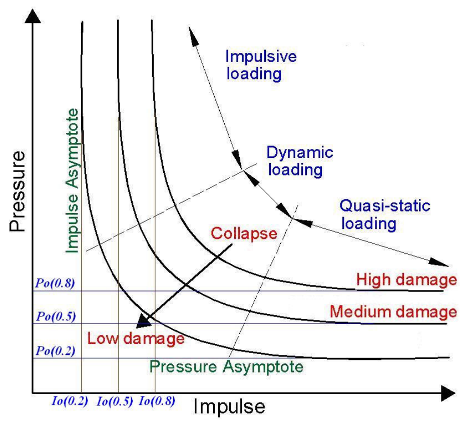
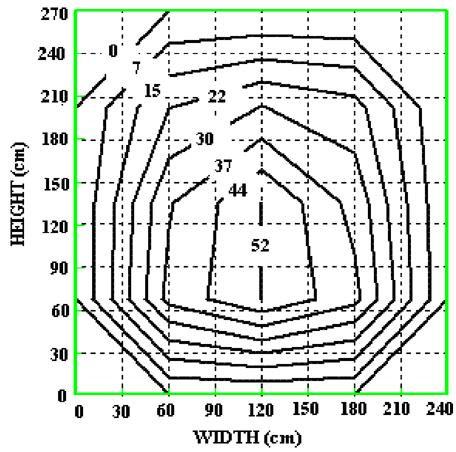


Fig. 1 P-I diagrams with different damage index, *D*

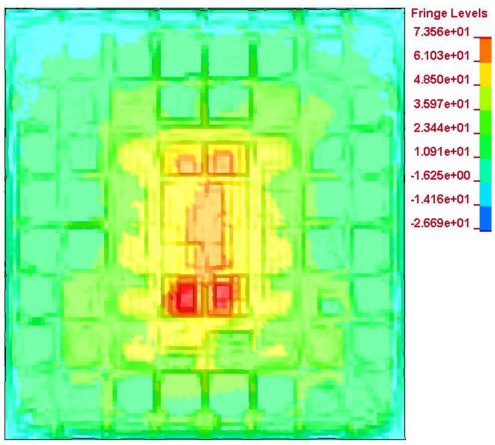
III. Verification of Numerical Model

In order to verify the accuracy and reliability of the numerical model described above, the numerical model is used to simulate the responses of a concrete panel to blast load obtained in a field blasting test. Muszynski & Purcell [9] conducted a field test on the concrete cubicles with a 150mm thick roof and floor. The 2700mm high, 2500mm wide and 200mm thick concrete wall is reinforced with 9mm rebar at 300mm centre to centre spacing. An explosive charge of 830 kg TNT equivalent is detonated at 14.6m standoff distance from the structure.

Fig. 2 shows the comparison of the calculated and field measured residual deflection of the unstrengthened RC wall. As shown, the predicted residual deflections in the present analysis agree well with the measured residual deflection in the field test.



(a)



(b)

Fig. 2 Comparison of unstrengthened RC wall residual displacement contour, (a) Muszynski & Purcell [7] field test result, and (b) present analysis * All contour lines are in mm

IV. Empirical Formula Generation

Empirical formulae are derived to predict P_O and I_O for the P-I diagrams based on the numerical results of parametric studies for each degree of damages. The formulae are developed using the least-squares fitting method as a function of concrete strength f_{cu}, column height H, column width b, column depth d, and the steel reinforcement ratio, ρ. Fig. 3 shows the RC column details.

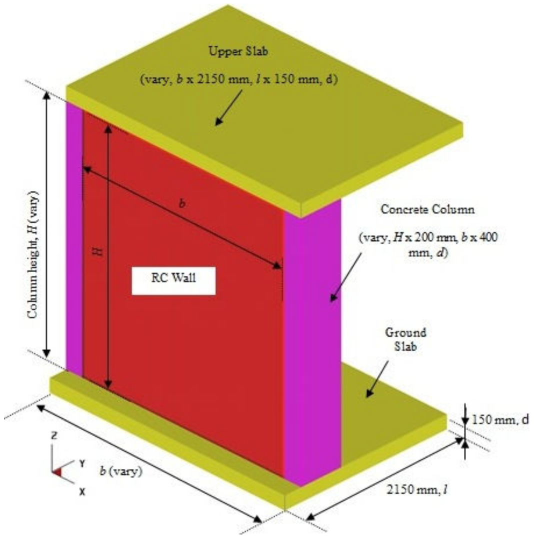


Fig. 3 Dimension details of RC wall

As can be noted in the Table I, and the parametric calculation results of many panels not shown here, the A value is a constant and equal to 0.25. The β value, however, changes for different panels. Based on parametric calculation results, it is found that β value depends on the pressure and impulse asymptotes and can be expressed by an empirical relation as:

$$\beta = 1.37 + 7.4\times10^{-4} P_O + \frac{2.78\times10^3}{I_O} - \frac{4.45\times10^6}{I_O^2} + \frac{2.49\times10^9}{I_O^3} \quad (4)$$

and $\beta \geq 2$ for one-way panel.

Based on numerical results and least-squares fitting, the P_O and I_O at different damage levels can be calculated by

$$P_O(LD) = 4.5 f_{cu} + 3.06d - 0.0026H - 0.042b + 890.06\rho - 326.19 \quad (5)$$

$$I_O(LD) = 96 f_{cu} + 8.54d - 0.053H - 0.055b + 7716.8\rho - 2365.31 \quad (6)$$

$$P_O(MD) = 4.5 f_{cu} + 3.06d - 0.0026H - 0.042b + 890.06\rho - 326.19 \quad (7)$$

$$I_O(MD) = 70 f_{cu} + 12.859d - 0.065H - 0.067b + 1639528\rho - 2041.896 \quad (8)$$

$$P_O(SD) = 4.5 f_{cu} + 3.049d - 0.0032H - 0.042b + 605.32\rho - 318.09 \quad (9)$$

$$I_O(SD) = 100 f_{cu} + 14.187d - 0.174H - 0.188b + 2563167\rho - 241536 \quad (10)$$

In which P_O is in kPa, I_O is in kPa.ms, f_{cu} is in MPa, H, b and d are all in mm.

V. Development of P-I Diagrams

To develop the P-I diagram, initially P_O and I_O of different damage level are calculated using (4)-(10) as derived in the foregoing. Afterward, (3) is employed to plot the P-I diagrams. Fig. 4 show P-I diagrams for one-way RC panel designated as *P1* that is taken as an example. The parameters of the panel are: width b=2500mm, height H=2700mm, depth d=150mm, concrete compressive strength f_{cu}=30MPa and reinforcement ratios ρ=0. 014. The derived P-I diagrams using empirical formulae are nearly the same as the P-I diagrams obtained from LS-DYNA simulations hence the empirical formulae are reasonable and reliable.

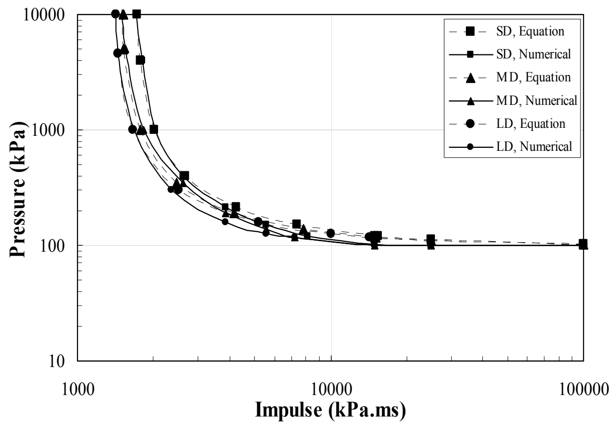


Fig. 4 P-I curves of one-way panel*P1*

TABLE I
VALUE OF PARAMETERS IN (3) FOR *P1*

Level of Damage	P_O (kPa)	I_O (kPa)	A	β
Low, *LD*	100	1400	0.25	2.07
Medium, *MD*	100	1500	0.25	2.06
Severe, *SD*	100	1700	0.25	2.05

As shown in Table II, the proposed empirical formulae give accurate predictions of pressure and impulse asymptotes with an average error of 5.13%. Hence the constructed P-I diagrams are also very close to those obtained from direct numerical simulations. It should be noted that, the equivalent steel area A_{se} should be used when calculating the respective reinforcement ratio. These results demonstrate the accuracy of P-I diagrams constructed using the proposed formulae in this study.

TABLE II
COMPARISON OF IMPULSIVE AND PRESSURE ASYMPTOTES OF ONE-WAY PANEL P1 OBTAINED FROM NUMERICAL SIMULATIONS AND EMPIRICAL FORMULAE

	LD		*MD*		*SD*	
	Po (kPa)	Io (kPa.ms)	Po (kPa)	Io (kPa.ms)	Po (kPa)	Io (kPa.ms)
Numerical results	100	1400	100	1500	100	1700
Formula estimated	93	1409	93	1553	93	1777
Error (%)	-7.35	0.67	-7.35	3.53	-7.35	4.53

*The RC panel *P1*: b=2500mm, H=2700mm, d=125mm, f_{cu}=30MPa, ρ=0.014

VI. CONCLUSION

A numerical model is developed to predict RC panel responses and damage to blast loads. The accuracy of the numerical model is verified by comparing the field test data obtained by other researchers with the numerical simulation results. The verified numerical model is then used to perform intensive numerical simulations of the dynamic responses of one-way RC panels of different material properties and dimensions subjected to blast loads of different peak pressures and impulses. The numerical results are used to con truct P-I diagrams of one-way RC panels. Based on numerical results, empirical formulae are derived to estimate pressure and impulse asymptotes of P-I diagrams as a function of RC panel dimensions, concrete strength and reinforcement ratio. These empirical formulae are verified to give reliable predictions of pressure and impulse asymptotes, which can be used for easy construction of P-I diagrams.

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