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Numerical derivation of pressure–impulse diagrams for prediction of RC column damage to blast loads

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Abstract

Pressure–impulse (*P–I*) diagrams are commonly used in the preliminary design or assessment of protective structures to establish safe response limits for given blast-loading scenarios. Current practice in generating the pressure–impulse diagram for structure components is primarily based on the simplified single degree of freedom (SDOF) model. The damage criterion is usually defined in terms of deformation or displacement response. Under blast loads, structures usually respond at their local modes, the equivalent SDOF system derived using the fundamental structure response mode might not be suitable. Moreover, structure is often damaged owing to brittle shear failure. In this case, the deformation-based damage criterion might not be able to give an accurate indication of local damage of a structural component. In this paper, a new damage criterion for RC column is defined based on the residual axial load-carrying capacity. A numerical method to generate pressure–impulse diagram for RC column is proposed. Parametric studies are carried out to investigate the effects of column dimension, concrete strength, longitudinal and transverse reinforcement ratio on the pressure–impulse diagram. Based on the numerical results, analytical formulae to predict the pressure–impulse diagram for RC column are derived. A case study shows that the proposed analytical formulae can be easily used to generate pressure–impulse diagram for RC columns accurately. The results are also compared with those obtained from the SDOF approach. It is shown that the proposed method gives better prediction of pressure–impulse diagram than the SDOF approach.

Keywords: RC Column; Pressure–impulse diagrams; Damage criterion; Numerical derivation; Analytical formulae

1. Introduction

A pressure–impulse diagram is an iso-damage curve (i.e., each combination of pressure and impulse produces the same damage in a structure component) for a particular structural component loaded with a particular loading history (e.g., blast load). It was first developed in the study of houses damaged by bombs dropped on UK in the Second World War [1,2], and then was derived usually from the analysis of an elastic single degree of freedom (SDOF) model [2,3]. These iso-damage pressure–impulse diagrams have also been applied to predict structural damage [4,5], as well as blast-induced human injuries [2,4–6].

Fig. 1 shows the primary features that define a pressure–impulse diagram. The two asymptotes, one for pressure and one for impulse, define limiting values for each parameter. Thus, loads with very short duration (relative to the structure's natural frequency) are called impulsive loading and the structure response is sensitive only to the associated impulse and not to the peak pressure. This forms a vertical line that defines the minimum impulse required to reach a particular level of damage, which the curve approaches asymptotically at high pressures. Conversely, as the load duration becomes longer than the natural frequency, the load is termed quasi-static loading and the response becomes insensitive to impulse but very sensitive to peak pressure. The horizontal asymptote thus represents the minimum level of peak pressure required to reach that particular damage.

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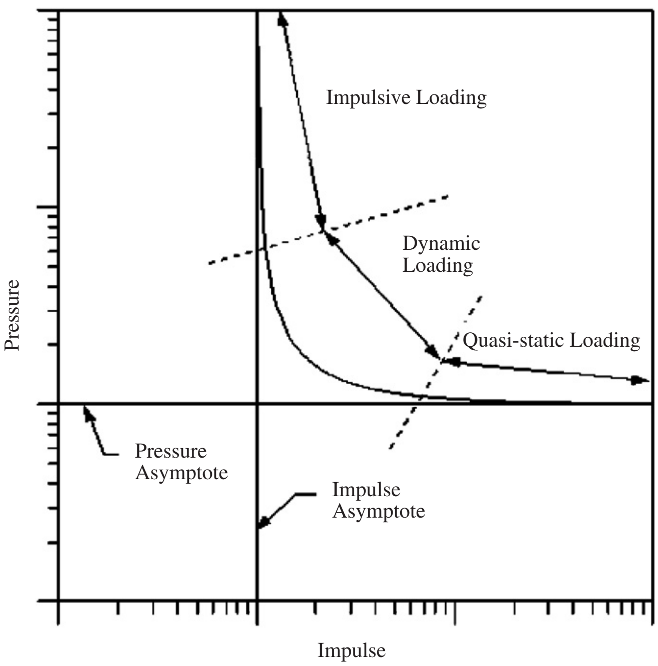

Fig. 1. Sketch of a typical pressure–impulse curve.

As seen, the pressure–impulse curve itself divides the pressure–impulse space into two regions: that above and to the right of the curve where the damage level of the structure component is exceeded, and that below and to the left where the level is lower. The pressure–impulse diagrams usually contain a group of pressure–impulse curves with different degrees of damage. These curves divide the pressure–impulse space into several regions, each corresponding to a particular level of damage, and the curves themselves represent the boundaries between different damage levels, such as low damage, medium damage and high damage.

Great progress on developing *P–I* diagrams of structure components has been made in the recent years. Li and Meng [7,8] have studied the pulse loading shape effects on the pressure–impulse diagram based on the maximum deflection damage criterion and elastic SDOF model. It was found that there is a noticeable loading shape influence on the pressure–impulse diagram when both peak pressure and impulse are important for dynamic structural response. Fallah and Louca [9] have derived pressure–impulse diagram from analyzing SDOF systems with elastic–plastic hardening and elastic–plastic softening under blast loads. Recently, a few researchers have also reported their attempt to use pressure–impulse diagram to evaluate the damage levels of various structural members [10–13]. However, the pressure–impulse diagram generated by the current approaches may not give reliable prediction of structure component damage because of the following reasons:

(1) Most of the previous studies are based on the SDOF model. As is well known, a structure responds to blast load primarily at their local modes. The local modes of the structure may govern the structure damage, especially when the blast load is of short duration [14]. The use of SDOF model may not be suitable for structure damage analysis to blast loads. Moreover, the SDOF model is not suitable to model multi-failure modes of a structural component either. For example, a column might be damaged owing to shear failure initially and subsequently by flexural failure to collapse. Therefore, pressure–impulse diagram generated from analysis of an SDOF system may not give accurate prediction of structural component damage.
(2) The deformation-based damage criterion may not be appropriate for the evaluation of local damage of a structural component subjected to blast loads, especially when the damage is caused primarily by shear failure.

On the other hand, using experiment-based methods to generate the pressure–impulse diagram for structural components is expensive. In order to get enough data to form a valid pressure–impulse diagram, a broad spectrum of loading and structural parameters should be considered.

The objective of the present work is to derive formulae for generating the pressure–impulse diagram for RC columns. The numerical models of a series of columns are established using software LS-DYNA. In the model, both the strain rate effect of the materials and the bond slip between steel bar and concrete are considered. A new damage criterion for the RC column under blast loads is proposed to estimate damage levels. Based on the numerical results and the damage criterion, a simplified numerical method to generate the pressure–impulse of RC columns is proposed. Parameters that may affect the pressure–impulse diagram of an RC column are considered in the present study; they are column dimension, concrete strength, longitudinal and transverse reinforcement ratio. Analytical formulae to predict the pressure–impulse diagram for RC columns are also derived based on the numerical results. The results obtained from the proposed analytical formulae are compared with those based on the SDOF model. It is shown that the proposed method gives better prediction of pressure–impulse diagram of RC columns than that obtained from the SDOF approach.

2. Numerical analysis of RC column damage to blast loads

Structure response and/or damage to blast loads are normally obtained using the following three methods: (1) theoretical analysis (2) explosion test and (3) numerical analysis. Most theoretical studies on the dynamic behavior of structures subjected to blast loads have been mainly dealt with the large plastic deformation of simple structures such as beams and unstiffened plates. Due to the rigid plastic material idealization and the negligence of strain hardening and strain rate effects in the analysis, the theoretical prediction of structure response and damage