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Analysis of direct shear failure mode for RC slabs under external explosive loading

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ABSTRACT

The single degree of freedom system (SDOF) is used to predict the shear responses of RC (reinforced concrete) members under external blast loading in the present study. An RC member suffering a blast may experience both flexural and shear failure modes. Under very high amplitude short duration shock, structural failure is usually governed by direct shear loading, whereas under low amplitude long duration shock, the structural failure is most likely governed by flexural damage. However, most previous studies are based on the assumption that flexural response dominates the failure mode without taking shear failure into consideration. In the present study, dynamic response equations of a structural member experiencing direct shear failure are derived for elastic, plastic and elasto-plastic shear resistance–slip models. With these equations the P–I curves of both flexural and direct shear failure modes are generated for an RC slab. Furthermore, a parametric study is conducted to investigate the effect of different parameters of RC slabs on the pressure–impulse (P–I) diagrams based on the elasto-plastic model. Finally, based on the results from the parametric studies, curve fitting technique is used to generate the P–I curves for RC slabs in a simplified way.

1. Introduction

Due to an increase in terrorist attacks and various accidental explosions in recent years, structural responses to blast loading have become increasingly important issues for governments and engineers who seek to minimize harm to both public and private structures. More and more investigation, therefore, has been conducted on the response of structures subjected to blasts.

It is known that when an RC member is subjected to high amplitude blast loads, its failure is dominated by the crushing and spalling of concrete and by direct shear damage; whereas under low amplitude overpressure, its failure is most likely governed by flexural damage. Flexural responses have, in fact, been the subject of considerable research, while direct shear failure is seldom taken into account during blast response analysis [1], as it is very difficult to analyze RC members under high amplitude shock loading of an extremely short duration.

Experimentally, however, it has been observed that when an RC member is subjected to a distributed load of extremely short duration, some of the structural members may fail at the positions near the support instead of the flexural failure occurring at mid-span [2], it is because the maximum shear force may cause a failure plane parallel to the loading direction [3]. As noted by Ma et al. [4], compared with bending failure, shear failure is sometimes a kind of brittle failure that may cause the collapse of structural members. Therefore, direct shear failure may dominate the damage caused by an explosion, especially when the detonation is very close to the structural member [5].

As it is not straightforward to derive the closed form solutions for the responses of an RC member subjected to blast loading, approximation techniques such as single-degree-of-freedom (SDOF) models provide quick evaluation for assessment of structural members and offer relatively good results [6]. The SDOF system is therefore used to model direct shear failure of a support under external blast loading.

Pressure–Impulse (P–I) diagrams are commonly used to assess the structural damage of a member subjected to a blast load. Based on the assumption that a structure is often damaged owing to the flexure response; several momentous developments on using different methods for generated the P–I curved can be summarized as following: The earliest works on P–I diagrams are included in the work of Abrahamson and Lindberg [7] for concerning the linear elastic to rigid–plastic beams and plates against blasts. Afterwards,

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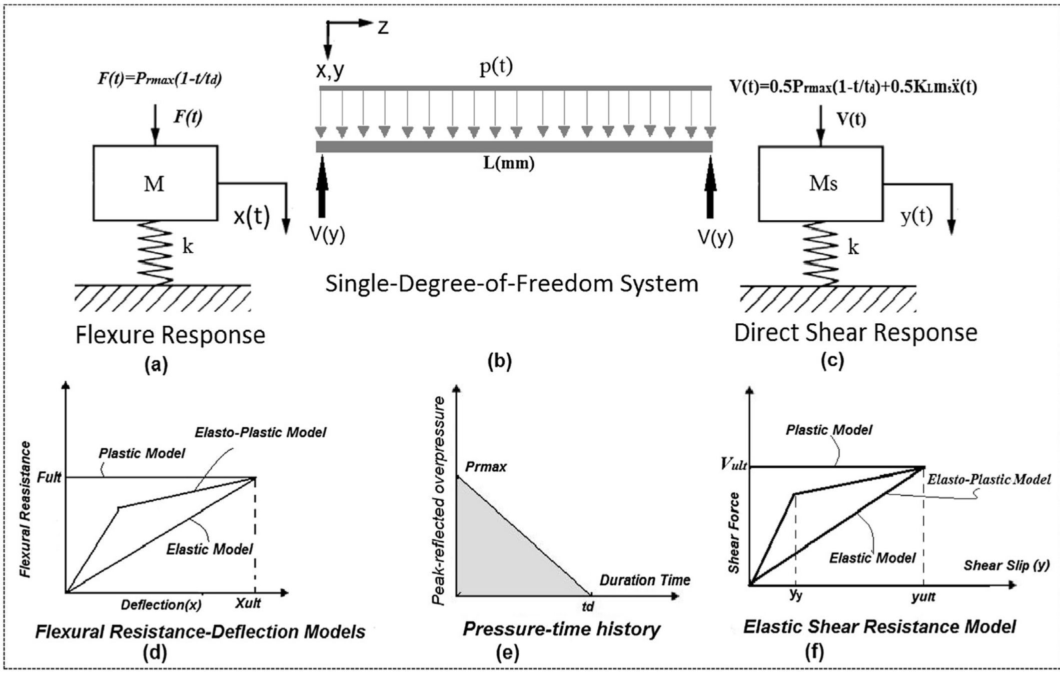

Fig. 1. SDOF systems of flexure and direct shear response.

many researchers have worked extensively on the subject of pressure–impulse diagrams, for example, Fallah and Louca [8], the flexural response resistance functions in their research have been categorized into elastic, elastic–plastic hardening, elastic–plastic–softening, rigid–plastic–hardening and rigid–plastic–softening. Furthermore, both bilinear and nonlinear flexural resistance functions have been considered to obtain the P–I diagrams of concrete structures [9]. After comparing the suitability, applicability and reliability of various methods in constructing P–I diagrams for structural components, Shi et al. [10,11] have used numerical method and analytical formulae for predicting the P–I curves of RC column. Recently, a great deal of progress has been made on the development of P–I diagrams for different structures under blast loads such as RC and FRC (fiber reinforced concrete) circular plates [12], continuous beams [13] and simply supported ultra high performance reinforced concrete (UHPRC) slabs [14]. However, the shortcoming of the discussed existing works on P–I diagrams is mainly regarding to the flexural response, the need for considering the different failure modes such as direct shear response hasn't been conducted. Beside failure in flexural mode, many experiments prove that some structures can be failed in a combined shear and flexural response under explosion [15,16]. In addition, a unique form of shear failure at the supports of RC beams and slabs is also observed in some experiments [17]. In order to determine the overall survivability of an RC member, both the flexural and direct shear failure modes need to be considered. Thus a P–I interaction diagram exhibiting two curves is required to indicate the combination of load and impulse.

Normally, the current dynamic systems for modeling the P–I diagrams of the shear and flexural response for structural members against blasts consist of two major approaches. The first approach is based on an approximate yield curve relating limiting values of shear force and bending moment and various deformations are found to occur with combination of bending and shear sliding depending upon the velocity profile [18]. By taken the transverse shear effects, boundary conditions, pulse shape effects into considerations, considerable research has been conducted for using theoretical analysis to evaluate the dynamic plastic responses of various metallic structural members, such as, beams, plates, and shells [18–28]. Although Jones and Li have shown in numerous studies moving plastic hinges of purely flexural nature where a plastic hinge is formed near the support and moves inward as a consequence of the minimum upper bound theorem of plasticity, the closed form solutions can only be derived for beams with a rigid–plastic shear–slip and moment rotation relationship which

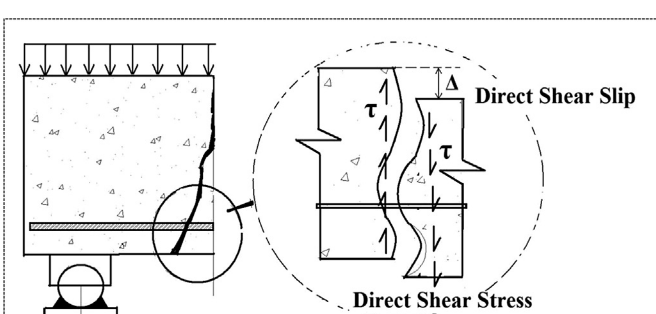

Fig. 2. Direct shear resistance–slip models.

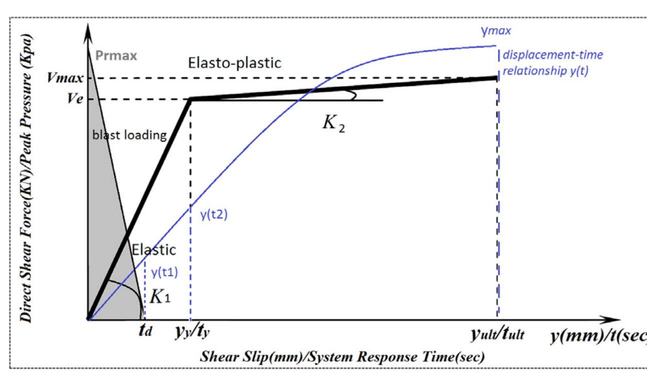

Fig. 3. Response in elastic phase of the elasto-plastic model of direct shear mode.