Engineering Structures 72 (2014) 193–202

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Interaction between direct shear and flexural responses for blast loaded one-way reinforced concrete slabs using a finite element model

Jonathon Dragos [b], Chengqing Wu [a,b,*]

[a] TCU–UA (Tianjin Chengjian University–University of Adelaide) Joint Research Centre on Disaster Prevention and Mitigation, China
[b] School of Civil, Environmental and Mining Engineering, The University of Adelaide, SA, Australia

ARTICLE INFO

Article history:
Received 5 December 2013
Revised 25 April 2014
Accepted 28 April 2014
Available online 16 May 2014

Keywords:
Blast load
Structural response
Numerical analysis
Direct shear

ABSTRACT

In this paper, both the moment–curvature flexural behavior and the direct shear behavior are incorporated into a numerically efficient one dimensional finite element model, utilizing Timoshenko Beam Theory, to determine the member and direct shear response of one-way reinforced concrete slabs subjected to blasts. The model is used to undertake a case study to demonstrate the flexural member response behavior during the direct shear response and is then used to carry out a parametric study to better understand the interaction of the flexural member response and the direct shear response. This is done by comparing pressure impulse curves corresponding to direct shear failure for one-way reinforced concrete slabs with varying depth, span and support conditions. The results aim to provide insight to facilitate the development of more accurate simplified methods for determining the direct shear response of blast loaded reinforced concrete members, such as the single degree of freedom method.

1. Introduction

The single degree of freedom (SDOF) method is a first order method, typically used to determine the response of structural members subjected to blasts. Due to its relative accuracy, despite its simplicity, it is widely referenced in guidelines such as the most recent guidelines of UFC 3-340-02 [1] and ASCE guidelines [2,3] for undertaking simple analyses. It was first introduced as a method to determine the flexural response of steel and reinforced concrete (RC) beams and one-way slabs subjected to blasts [4] but has since been extended to account for additional behaviors, failure mechanisms and types of structural members. For example, Park and Krauthammer [5] and Nassr et al. [6] extended the SDOF method to account for the $P-\Delta$ effects associated with axial loads acting on columns. Krauthammer [7] and Astarlioglu et al. [8] extended the SDOF method to account for both the flexural and the tensile membrane behaviors in a single analysis technique. The SDOF method has also been extended to determine the response of masonry walls [9,10] and even for determining the response of RC beams and slabs retrofitted with foam cladding [11] subjected to blasts.

According to many studies, it has been observed experimentally that a RC structural member can undergo shear failure at the supports, commonly referred to as direct shear failure [7,12]. This failure mechanism occurs due to a high amplitude blast loading caused by the detonation of a charge which is in close proximity to the RC specimen. Therefore, much effort has been invested to extend the SDOF method for determining the direct shear response of RC members subjected to blasts. For example, Krauthammer et al. [12] and Krauthammer et al. [13] developed a SDOF approach which analyses the direct shear and flexural responses separately using two differential equations. Although the equations governing the direct shear and flexural responses are not directly coupled, the shear force which drives the direct shear response is determined based on the loading, total inertial force and the distribution of inertial forces at each time step during the flexural member response. Low and Hao [14] also utilized a similar SDOF approach in which the direct shear response is determined separately from the flexural member response, but is determined based on the loading, inertial force of the member, and the deflection profile of the member which is calculated from the flexural response. Although such SDOF methods have been developed, no research has been undertaken to thoroughly validate these methods. Also, very little research has been conducted to determine how the response of the member itself, being the flexural response, influences the direct shear response.

Furthermore, studies have been conducted on rigid-plastic beams having both rigid-plastic direct shear behavior and rigid-plastic flexural behavior [15,16] in which a fully coupled analytical approach was used to determine both the direct shear and midspan flexural deflection responses. However, as this can only be applied to

* Corresponding author at: School of Civil, Environmental and Mining Engineering, The University of Adelaide, SA 5005, Australia. Tel.: +61 8 83134834.
E-mail address: cwu@civeng.adelaide.edu.au (C. Wu).

http://dx.doi.org/10.1016/j.engstruct.2014.04.043
0141-0296/© 2014 Elsevier Ltd. All rights reserved.

rigid-plastic beams, with rigid-plastic direct shear slip and moment–rotation relationships for shear and rotational hinges, respectively, they cannot be applied directly to RC or steel specimens.

In this paper, the flexural behavior of a RC cross-section and the direct shear slip behavior are both incorporated into a one-dimensional (1D) finite element model (FEM). The 1D FEM simulates a dynamic analysis by discretizing the member into 1D beam elements and applying Timoshenko Beam Theory [17]. Although other more comprehensive models exist [18–23], the 1D FEM is adopted due to its numerical efficiency, making it a suitable model for undertaking large parametric studies. However, despite its numerical efficiency it has advantages over other numerical techniques, such as the finite difference method [24–26], due to its generality, solution accuracy and stability [27]. The flexural behavior is determined using a regular moment–curvature analysis and the direct shear slip behavior is determined using the proposed model by Krauthammer et al. [12], based on the research conducted by Hawkins [28], Mattock [29], and Walraven and Reinhardt [30]. Also, artificial shear springs are implemented into the 1D FEM to account for the direct shear slip response at the support.

The moment–curvature analysis, direct shear model and 1D FEM are first described and a case study is undertaken to investigate the RC flexural member response during the very short time-scale at which the direct shear response occurs. Then, due to the numerical efficiency of the 1D FEM, a parametric study is undertaken to investigate the influence of the depth, span and support conditions on the direct shear response. This investigation is undertaken by comparing pressure impulse (PI) curves corresponding to direct shear failure. Then, a loose comparison between the results of the parametric study and the analytical solutions by Ma et al. [16] on rigid-plastic beams is made. Finally, a small comparison is made between two direct shear models which identifies the effect of the softening region of the direct shear model on the direct shear PI curve. The fast-running 1D FEM being utilized complements the nature of the parametric study being performed, as it does not require the same level of accuracy as that provided by a three dimensional finite element analysis software. However, the parametric study does require that the 1D FEM be capable of correctly accommodating for the interaction between the flexural and direct shear responses of RC structural members, which is true. As a whole, the current study investigates the influence of the flexural behavior and geometric properties on the direct shear response and failure of one-way RC slabs. By doing this, the investigation endeavors to provide some insight into the structural dynamics mechanisms and their effects, which need to be accounted for when modeling the direct shear response of one-way RC slabs using an SDOF approach. As no SDOF approach for simulating the direct shear response of one-way RC slabs has been thoroughly validated in the literature, the current study stands as a starting point for developing and validating such an approach. Furthermore, the results and conclusions obtained from this study could also be used to develop empirical equations allowing PI curves to be quickly determined, such as what was provided by Shi et al. [31] for RC columns and Dragos et al. [32] for one-way ultra high performance concrete slabs.

2. Moment–curvature analysis of a section

A traditional moment–curvature analysis is used to determine the flexural behavior of a cross-section, as seen in Fig. 1. As seen in Fig. 1(b), a linear strain profile over the depth of the section was assumed as by Euler Bernoulli Theory [33], in which the curvature, χ, can be determined as the slope of this function. From the linear strain profile, Popovics' compressive concrete stress strain relationship [34] was used to determine the concrete compressive stress and the stress in the reinforcing bars were determined from a typical steel stress strain relationship, to form the stress profile in Fig. 1(c). From the stress profile, the force profile in Fig. 1(d) can also be determined. For a given compressive strain acting on the extreme compressive fiber, corresponding to point *a* in Fig. 1(b), the curvature was altered until equilibrium was achieved. It should be noted that, adjusting the curvature, while keeping the curvature at point *a* constant, causes a shift in the position of the neutral axis. For this case, equilibrium corresponded to the condition in which the sum of the forces, seen in Fig. 1(d), equated to zero. For a section in equilibrium, the sum of the moment due to each of the forces corresponds to the resisting moment, *M*. To plot a single point on the moment–curvature relationship, for a given value of strain at the extreme compressive fiber, *a*, equilibrium was first determined and then the curvature, χ, and resisting moment, *M*, were plotted. This process was repeated for various values of strain at the extreme compressive fiber, *a*, to produce many points, thus forming the moment–curvature relationship.

3. Direct shear slip function

The support slip, due to a vertical crack forming at the support, is governed by the direct shear force-slip function. The functions being utilized within this model, seen in Fig. 2, are fully outlined by Krauthammer et al. [12]. The entire function provided by Krauthammer et al. [12] consists of a tri-linear ascending region, a linear softening region and a constant shear force region, which remains constant until failure is reached. According to Krauthammer et al. [12], the behavior of the third constant shear force region is based on a model only applicable to large deformations of a well anchored bar embedded in concrete and will therefore be ignored in this study. Fig. 2(a) shows the tri-linear ascending region of the direct shear slip function, whereas Fig. 2(b) shows both the ascending and the softening regions of the direct shear slip functions. The yield shear force, V_y, ultimate shear force, V_u, and slope of the softening region, k_s, in Fig. 2(a) and (b) can all be determined using the equations provided in Krauthammer et al. [12]. In Fig. 2(a), the ultimate support slip at which failure occurs, $y_{v,u}$, is equal to 0.6 mm. In Fig. 2(b), the ultimate support slip at which failure occurs, $y_{v,u}$, can be calculated based on the slope of the softening region, k_s, and the ultimate shear force, V_u.

The parametric study within Section 6 will utilize only the ascending region of the direct shear slip function, seen in Fig. 2(a), whereas the study in Section 7 will utilize both the ascending and softening regions of the direct shear slip function, seen in Fig. 2(b).

4. Finite element model

To determine the dynamic response of a RC beam or one-way slab subjected to blast loading, a 1D finite element method is utilized. The FEM divides the member into several beam elements to which Timoshenko Beam Theory [17] is applied. Timoshenko Beam Theory is adopted as it allows for both flexural and shear deformation, as well as rotational inertia, as seen in Eqs. (1) and (2).

$$\frac{\partial M}{\partial x} - Q = -\rho_m I \frac{\partial^2 \beta}{\partial t^2} \quad (1)$$

$$\frac{\partial Q}{\partial x} + q = \rho_m A \frac{\partial^2 v}{\partial t^2} \quad (2)$$

where *M* is the applied bending moment, *Q* the applied shear force, *q* the distributed load acting transverse to the beam, *A* the cross