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Direct shear resistance models for simulating buried RC roof slabs under airblast-induced ground shock

Theodor Krauthammer [a,*], Serdar Astarlioglu [b]

[a] Center for Infrastructure Protection and Physical Security, University of Florida, PO Box 116580, Gainesville, FL 32611-6580, USA
[b] Hinman Consulting Engineers, Inc., 1800 Diagonal Road, Suite 525, Alexandria, VA 22314, USA

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ABSTRACT

Direct shear is a known response mechanism in Reinforced concrete (RC) slabs subjected to blast loads that may cause their sudden and catastrophic failure. It poses a very serious hazard to facilities subjected to blast. The empirical equations defining the direct shear resistance function for RC elements were developed in the 1970s based on results from a limited number of static tests. These equations have been used for the analyses of structural response under blast and ground shock effects since the 1980s. However, the direct shear mechanism in the short-duration dynamic domain has not been sufficiently studied, and it was not clear if those models are accurate. New static and impact test data from shear specimens with three reinforcement ratios were used to derive modified direct shear resistance functions that were different from the resistance functions proposed in the 1970s. One must determine if the new resistance functions could accurately represent the behavior of RC slabs subjected to blast loads. Furthermore, one had to understand the behavioral differences in the numerical simulations that could be associated with the two types of resistance functions, and provide recommendations on how to most appropriately represent direct shear in such analyses. This paper is focused on the assessment of the new direct shear resistance functions in RC, and the results from the parametric study were compared results obtained with the previous empirical direct shear model and with precision field test data to provide conclusions and recommendations.

1. Introduction

Most structural engineers are familiar with the effects of shear in reinforced concrete (RC) flexural elements, such as beams. That shear problem has been extensively studied, and it was shown that for ductile beams (where failure is governed by rupture of the tensile reinforcement) diagonal cracks develop below the neutral axis of the beam, along directions defined by the principle stress field, as described in [1]. Because of the diagonal cracks and tensile reinforcement failure, this type of shear is termed 'diagonal tension', it is related to changes in the flexural moment along the beam, and various recommendations have been adopted for shear reinforcement along such a beam to resist its effects [1]. However, there is another type of shear failure that has been noticed in structural concrete loaded statically that could appear near locations of geometric discontinuities, where the cracks are perpendicular to the axis of the member, and where no flexural behavior is present [2–5]. This type of shear behavior is termed 'direct shear', it is related to a shearing action along a shear plane, where the loaded member slides along the supporting members, as illustrated in Fig. 1.

2. Objectives and scope

Direct shear is a known structural response mechanism in RC slabs subjected to blast loads that may cause their sudden and catastrophic failure. This response poses a very serious hazard to protected facilities subjected to blast. Empirical resistance functions for direct shear in RC elements were introduced in the 1970s, based on a limited number of static tests, and their empirical adaptation for the analyses of structural response under blast and ground shock effects has been used since the 1980s. However, the direct shear mechanism in the short-duration dynamic domain has not been sufficiently studied, and it is not clear if those models are accurate. New static and impact tests on RC direct shear specimens with three reinforcement ratios provide results that were used to derive modified direct shear resistance functions that were different from the resistance functions proposed in the 1970s. This

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* Corresponding author.
E-mail addresses: tedk@ufl.edu (T. Krauthammer), Serdar@hce.com (S. Astarlioglu).

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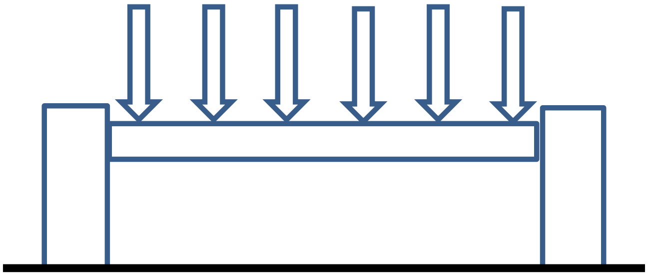

Fig. 1. Direct shear behavior.

enabled one to study the behavioral differences in the numerical simulations that could be associated with the two types of resistance functions, and provide recommendations on how to most appropriately represent direct shear in such analyses. The two direct shear models were used for the analysis of RC roof slabs subjected to airblast-induced ground shock that were tested in the 1980s, and the results were compared to understand the effects of the direct shear models on numerical simulations.

3. Background

The studies reported in [2–4] focused primarily on direct shear specimens with reinforcement across the shear plane (Fig. 2) to develop a better understanding of the shear strength, and its relationship with material and geometric properties of the specimens. The parameters studied included the effects of shear strength on uncracked and pre-cracked specimens, reinforcement ratios and spacing, concrete strength, application of stresses parallel and transverse to the shear plane, and the influence of dowel action in the reinforcement, as summarized in [5].

It was found that the shear slip required to diminish the shear strength did not exceed the reinforcing bar diameter across the shear plane, and that the existence of cracks reduced the ultimate shear capacity and increased relative slip. Changing the reinforcement size and spacing affected the shear strength, while reducing the concrete strength set an upper limit beyond which changes to the reinforcement parameter had a lesser effect on shear resistance. Below this upper limit, the shear strength of pre-cracked specimens primarily depended on friction. Externally applied compressive stresses transverse to the shear plane increased the direct shear resistance of both cracked and uncracked specimens by reducing the crack width and enhanced both friction and aggregate interlock. The accompanying theoretical work showed a relationship between the observed shear strength and the formation of a truss-like mechanisms that consisted of diagonal concrete struts in compression between diagonal cracks along the shear plane, and tension and dowel action in the transverse reinforcement. Consequently, an empirical model for direct shear, based on those early studies was proposed by Hawkins [6], that was incorporated into several reports on addressing direct shear in protective structures [7–9], as will be described later, herein. Additional efforts to study direct shear are described in [10–13] that included both precision tests on the same type of specimens, as shown in Fig. 2, and theoretical studies focused on obtaining shear stress vs. shear slip relationship along the shear plane. Although a study reported in [12] included both static and dynamic tests, the dynamic loads were applied by a servo-controlled actuator and the triangular load pulse reached its peak after 35 to 55 ms. As will be shown later, herein, this loading rate was too slow to represent the direct shear phenomenon observed in either blast impact tests. Therefore, most of those earlier studies addressed only the behavior in the static domain, and they did not enable one to develop an accurate characterization of direct shear behavior under short-duration dynamic loads.

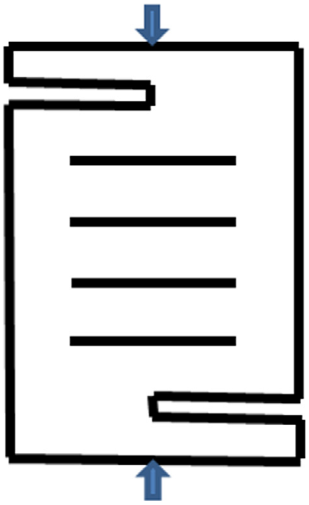

Fig. 2. Direct shear test specimen.

The effects of direct shear on structures subjected to blast effects was shown in [14] with field tests on shallow-buried box-type structures that included two test cases with direct shear failures. The direct shear phenomenon was also studied in [15], and reinforced concrete roof slabs exhibited direct shear responses under severe airblast-induced ground shock loading. Direct shear produced a vertical failure plane at the edge of the roofs, and both the top and bottom steel exhibited necking prior to being severed nearly flush with the failure plane. Several theoretical and numerical studies were carried out previously [16–21] to investigate the behavior of direct shear in structural concrete systems subjected to blast, with a particular attention to the test structures used in [14,15]. The studies in [16,18–20] employed a Timoshenko beam approach with a shear failure criterion to characterize the sequence of flexural and localized shear behaviors that could lead to a better understanding of the observed responses during the tests. The studies in [17,21] employed a single-degree-of-freedom (SDOF) approach that operated on two loosely-coupled systems, one for the flexural response and one for the direct shear response, to study the same structures that were tested in [14,15]. The direct shear resistance function used in those studies was based on the empirical model proposed and described in [6–9]. The original model from [6–9] (the dashed segmental curve in Fig. 3) was modified in [17] by applying an enhancement factor of 1.4 to account for the effects of in-plane compression and rate effects that were not considered in the static model, as shown by the solid segmental curve in Fig. 3.

The original Hawkins model [6–9] utilized a piecewise-linear approach to relate direct shear strength and corresponding shear slip values, as obtained experimentally. The slip values Δ_1, Δ_2, and Δ_3 define the slip at Points A, B, and C that correspond to the shear strengths τ_e and τ_m. τ_e is the shear strength at the end of the elastic range, and τ_m is the maximum shear strength. τ_L is the residual shear strength between Points D and E that terminates at the maximum slip Δ_{max}. K_e is the elastic slope, K_c is the post-cracking slope, and K_u is the slope of the direct shear strength beyond the peak value. The different segments of these models are defined later, herein.

Although those theoretical and numerical studies showed very good agreement with the observed structural behaviors during the field test in [14,15], no test data were recorded that could be used to characterize the direct shear behavior in the dynamic domain. Therefore, direct shear was not been fully understood,