International Journal of Impact Engineering 108 (2017) 89–100

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Direct shear behavior in concrete materials

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ARTICLE INFO

Article History:
Received 17 January 2017
Revised 30 March 2017
Accepted 30 March 2017
Available online 1 April 2017

Keywords:
Direct shear
NSC
UHPC
UHPFRC
Static
Impact

ABSTRACT

Direct shear is a sudden and catastrophic failure mechanism in structural concrete structures under highly impulsive loads. This behavior has been studied by various investigators for more than four decades on normal strength concrete (NSC) specimens. Nevertheless, this structural behavior has not been well understood for either static nor dynamic loading domains. Moreover, this behavioral mechanism has only recently been investigated on test articles made of ultra-high performance concrete (UHPC) and ultra-high performance fiber reinforced concrete (UHPFRC) materials whose responses were very significantly different from those observed on NSC specimens. The purpose of this paper is to describe the evolution in understanding direct shear behavior in NSC, UHPC, and UHPFRC for static and dynamic loading regimes, based on data in both the time and frequency domains. The results are compared with the original and modified empirical direct shear models to highlight both the evolution in understanding direct shear behavior and to propose direct shear models for NSC, UHPC, and UHPFRC specimens under both static and impact loads.

1. Introduction

Structural engineers are familiar with shear effects in slender beams, where diagonal cracks develop below the neutral axis 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. However, there is another type of shear failure that was 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 was present [2–5]. This type of shear behavior is termed 'direct shear', it is related to a shearing action along a plane, where the loaded member slides along the stationary support system, as illustrated in Fig. 1.

This behavior has been studied for more than four decades only on normal strength concrete (NSC) push off specimens, and mostly under static loads. Researchers and engineers relied primarily on empirical models for direct shear that were introduced long ago, and it was not clear if those models represented accurately the observed structural behaviors. Furthermore, until recently, the effect of ultra-high performance concrete (UHPC) and ultra-high performance fiber reinforced concrete (UHPFRC) materials, and impact loads on direct shear were unknown.

The objective of this paper is to describe the evolution in understanding direct shear behavior in NSC, UHPC, and UHPFRC for static and dynamic loading regimes, based on data in both the time and frequency domains. The results are compared with the original and modified empirical direct shear models to highlight both the evolution in understanding direct shear behavior and to propose direct shear models for NSC, UHPC, and UHPFRC specimens under both static and impact loads.

2. Background

2.1. Direct shear behavior

The studies reported in [2–4] focused primarily on NSC direct shear specimens with reinforcement across the shear plane (Fig. 2) to develop a better understanding of the direct 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].

Those studies found that the shear slip required to diminish shear strength in NSC did not exceed the reinforcing bar diameter across the shear plane, and that the existence of cracks reduced the

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http://dx.doi.org/10.1016/j.ijimpeng.2017.03.027
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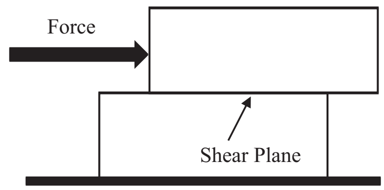

Fig. 1. Direct shear response.

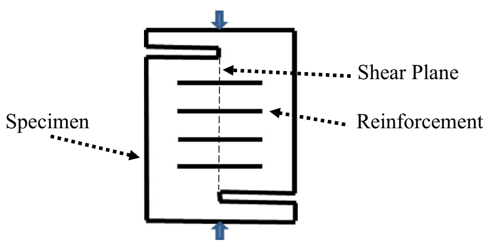

Fig. 2. Direct shear test specimen.

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 that 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 mechanism that consisted of diagonal concrete struts in compression between diagonal cracks along the shear plane, and tension and dowel action in the transverse reinforcement [6,7], as illustrated in Fig. 3. The small diagonal cracks coalesced to form the direct shear crack.

Based on those early studies, Hawkins proposed an empirical model for direct shear [8] that was incorporated into several reports on how to treat direct shear in protective structures [9–11], as described later, herein. Additional efforts to study direct shear were described in [12–13], they 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. However, 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.

The effects of direct shear on structures subjected to blast effects was shown in [14] with field tests on shallow-buried box-type structures, and the finding that two test cases involved direct shear failures. A further study of the direct shear response in [15] noted that reinforced concrete roof slabs exhibited direct shear responses under severe airblast-induced ground shock loading. The direct shear effect produced a vertical failure plane in the roof slab at the face of the supporting walls, and both the top and bottom steel exhibited necking prior to failure. The study in [12] included both static and dynamic tests. However, the dynamic loads were applied by a servo-controlled actuator had a triangular shape, with a peak at 35 to 55 milliseconds. As will be shown later, herein, this loading rate was too slow to represent the direct shear phenomenon observed in either blast, or more recent impact tests.

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 analyze 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 [8–11]. The original model from [8–11] (the dashed segmental curve in Fig. 4) was a piecewise linear fit to the data. That model was later modified in [17] for application to the dynamic domain 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. 4.

The original Hawkins model [8–11] 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 defined 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}. Δ_4 (not shown in Fig. 4) is at the intersection between the segments CD and DE. 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 will be defined later, herein.

Although those theoretical and numerical studies showed 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. Nevertheless, until recently, direct shear has not been fully understood, due

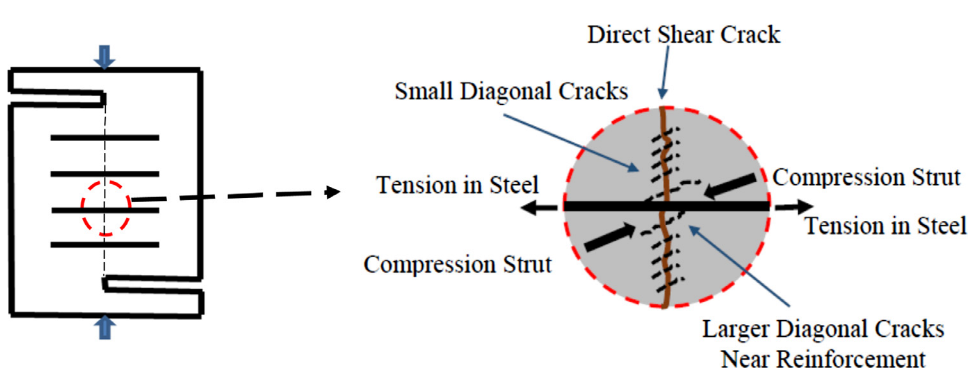

Fig. 3. Structural resisting mechanisms in direct shear.