International Journal of Impact Engineering 111 (2018) 187–198

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

# Shear stress versus strain responses of ultra-high-performance fiber-reinforced concretes at high strain rates

Tri Thuong NGO, Dong Joo KIM*

*Department of Civil and Environmental Engineering, Sejong University, 98 Gunja-Dong, Gwangjin-Gu, Seoul 05006, South Korea*

ARTICLE INFO

*Keywords:*
UHPFRCS
Impact shear test
High strain rate
Rate sensitivity
Dynamic increase factor (DIF)

ABSTRACT

Shear stress versus strain response of ultra-high-performance fiber-reinforced concretes (UHPFRCs) at high strain rates up to 248 $s^{-1}$ was investigated by installing the shear test set-up in an improved strain energy frame impact machine (I-SEFIM). The tensile strain-hardening UHPFRCs also produced shear-related hardening response, even at high strain rates, accompanied with multiple cracks. The shear resistance was obviously sensitive to the applied strain rates even though the shear strain rate sensitivity was not as high as the tensile strain rate sensitivity: the dynamic increase factor (DIF)-1.5 for the shear strength of UHPFRCs with 1.5 vol.-% fibers was significantly lower than the DIF (3.2) for the tensile strength at the strain rate of 248 $s^{-1}$ owing to the different distribution of inertial force of mortar matrix surrounding fiber, resulting from difference of loading direction. A DIF predicting equation was finally proposed for the shear strength of UHPFRCs at high strain rates.

## 1. Introduction

The superior strength and energy absorption capacity of ultra-high-performance fiber-reinforced concretes (UHPFRCs), in comparison with normal concrete, is expected to greatly improve the resistance of civil infrastructure under impacts or blasts [1,2]. However, the practical application of UHPFRCs for the purpose of preventing the catastrophic failure of civil infrastructure under such extreme loads still requires deeper understanding about the response of UHPFRCs at the high strain rates under impacts or blasts. Complex failure modes, including compressive, tensile, shear failure as well as local spalling on the surface of structure have frequently been reported when infrastructure was subjected to high rate loads [3–6]. For instance, the concrete wall in military structure in Fig. 1 showed the penetration failure under single missile attack [7]. The response of structures made by UHPFRCs under such high rate impacts and/or blasts would be different with that at static rate owing to rate sensitive material characteristics [8], shown in Fig. 2, as well as inertial effects.

The material properies of UHPFRCs at high strain rates have been intensively investigated during the last ten years [9–17]. Habel and Gauvreau [12] investigated the flexural resistance of UHPFRCs at high strain rates by using a drop-weight impact test method, whereas Parant et al. [13] used a block-bar device for the investigation of the flexural strength of UHPFRCs at high strain rates. The flexural strength of UHPFRCs at the strain rate of 2 $s^{-1}$ was reported as 25% higher than that at static rate [12] while the flexural strength of UHPFRCs was quadrupled at the loading rate of 500 GPa/s [13]. On the other hands, Millon et al. [17] and Noldgen et al. [15] reported, based on their experimental results using a Hopkinson pressure bar test method, that the tensile strength of UHPFRCs was sensitive to the high strain rate between 100 and 160 $s^{-1}$, whereas their fracture energy was not.

Tran and Kim [18] firstly built a strain energy frame impact machine (SEFIM) in 2012 to investigate the direct tensile stress versus strain response of high performance fiber reinforced cementitious composites (HPFRCCs) at high strain rates between 20 and 80 $s^{-1}$. Later, Pyo and El-Tawil [10] in 2015 built a modified SEFIM (M-SEFIM) while Park et al. [9] in 2016 made an improved SEFIM (I-SEFIM) to investigate the tensile response of UHPFRCs at high strain rates (90 to 200 $s^{-1}$). The tensile strength and energy dissipation capacity of UHPFRCs greatly enhanced at the high strain rates, whereas the strain capacity was not sensitive to the applied strain rates [10]. The post-cracking tensile strength of UHPFRCs at high strain rates was approximately 2.8 to 2.9 times higher than that at static strain rate [9]. Park et al. [9] eventually proposed equations for predicting the DIFs for the tensile parameters, including post-cracking tensile strength, strain capacity, and peak toughness of UHPFRCs at high strain rates.

Unlike the tensile resistance of UHPFRCs at high strain rates, there is still very limited information about the shear resistance of UHPFRCs, especially at high strain rates. Millard et al. [6] reported that there was no noticeable enhancement in the shear strength of UHPFRCs, whereas Lukíc and Forquin [16] reported higher shear strength at high strain rates than at quasi-static rate. Lukíc and Forquin [16] insisted that the

* Corresponding author.
*E-mail address:* djkim75@sejong.ac.kr (D.J. KIM).

http://dx.doi.org/10.1016/j.ijimpeng.2017.09.010
Received 10 March 2017; Received in revised form 26 May 2017; Accepted 17 September 2017
Available online 19 September 2017

**Fig. 1.** Punching shear failure of concrete structures under high strain rates [7].

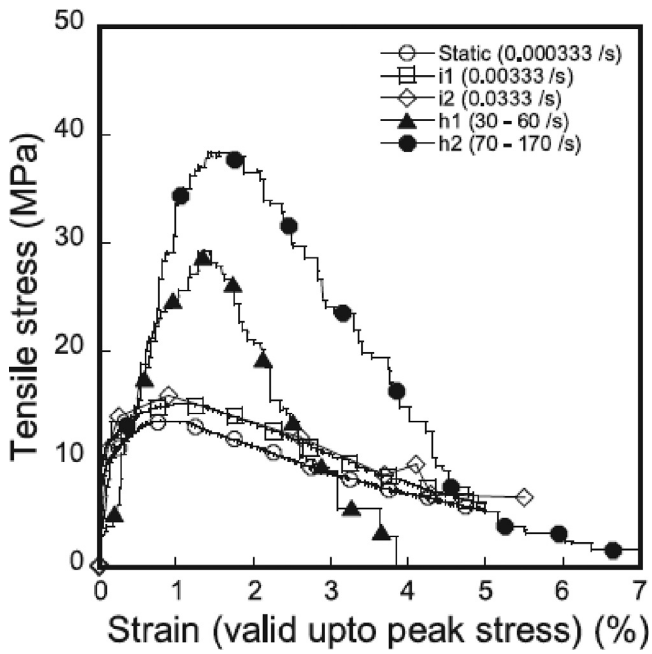


**Fig. 2.** Direct tensile stress versus strain response of UHPFRCs under both static and high strain rates (Park et al. [8]).

apparently higher shear strength at high strain rates was mostly originated from enhanced radial confinement stress at high strain rates.

Although several researchers have reported the shear strength of UHPFRCs [6,16], there is no direct information about their shear stress versus strain responses. In addition, there is no standard shear test method for UHPFRCs yet, event at static strain rates. The current shear test methods (including the Punch-Through Shear (PTS) method [19–23], the Z-shape [6,24–29] or Iosipescu [30,31] methods) for normal concrete are not suitable to reflect the multiple micro-cracking behaviors of UHPFRCs. Authors recently proposed a new shear test method for strain hardening UHPFRCs generating multiple micro-cracking: UHPFRCs exhibited shear - related hardening response accompanied with multiple cracks as shown in Fig. 3 [32].

In this study the shear stress versus strain responses of UHPFRCs at high strain rates was investigated by using a new high rate shear test method. An extensive experimental program was carried out to investigate the rate dependent shear resistance of UHPFRCs using the setup.

## 2. Experiments

Fig. 4 shows an experimental program designed for investigating the strain rate effects on the shear resistance of UHPFRCs: six series of specimens were cast and tested. In the notation of the series, the first letter designates the smooth fiber while the next two characters represent the fiber volume content (“05″ for 0.5 vol.-% fibers content). The fourth character in the notation of the series designates the type of shear test (“S” or “I” indicates static or impact shear test, respectively) while the last two characters indicate the different range of high strain rates 1 (*h1*) and 2 (*h2*).

### 2.1. Material and specimen preparation

The composition of ultra-high-performance concrete (UHPC) matrix and the compressive strength are provided in Table 1 while the properties of smooth steel fibers are listed in Table 2. The detailed procedure of mixing and curing can be found in [9,11,33]. In their experiment, the average compressive strength of 50 mm cubic UHPC specimens was 180 MPa [33]. Cement (Type I), silica fume, silica sand, and silica powder were first dry-mixed for 10 min before water was added. Then, superplasticizer was gradually added and smooth steel fibers were then distributed by hand when the mortar showed suitable workability and viscosity for uniform fiber distribution. Finally, the mixture with fibers was poured into molds by using a wipe scoop with no vibration: the

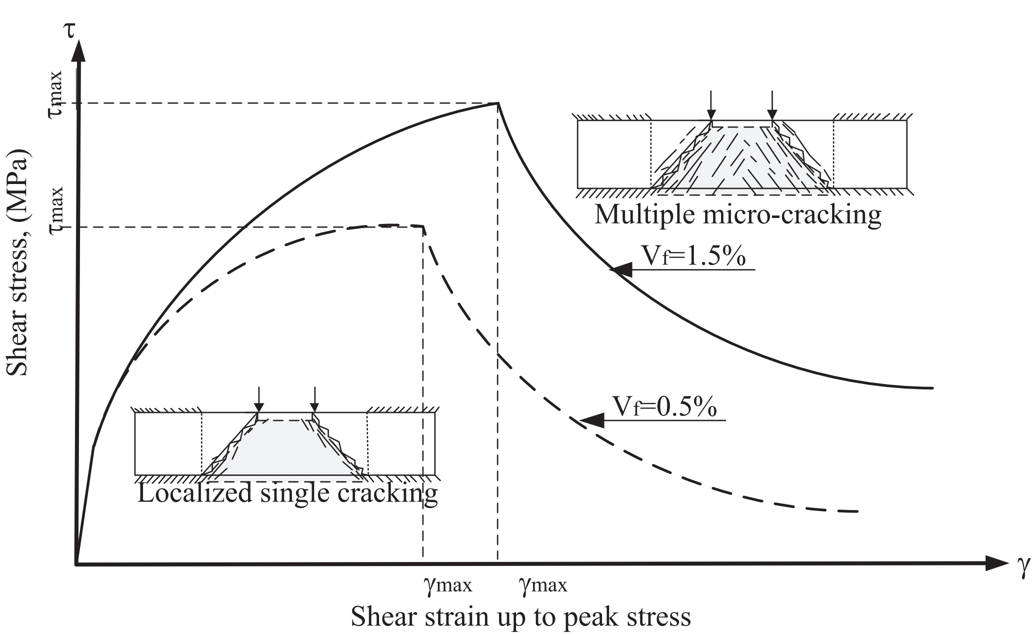


**Fig. 3.** Shear stress versus strain response of UHPFRCs at static rate (Ngo et al. [32]).