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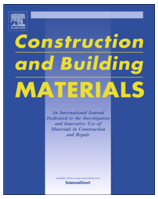

Strain rate-dependent shear failure surfaces of ultra-high-performance fiber-reinforced concretes

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HIGHLIGHTS

- The shear strength of UHPFRCs increased as the strain rate increased beyond 111 s^{-1}.
- The shear strength of UHPFRCs is dependent upon the confining pressure.
- An empirical equation predicting the confined shear strength was proposed.
- Shear failure surfaces at different strain rates were obtained.

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ABSTRACT

Strain rate-dependent shear behavior of ultra-high-performance fiber-reinforced concretes (UHPFRCs) with confining pressure was investigated using a new shear test setup in an improved strain energy impact machine (I-SEFIM). Different confining pressures were applied to the specimens prior to shear testing at both static and high strain rates, and were maintained during testing. The shear strength of UHPFRCs was highly sensitive to the applied strain rate and confining pressure. The effect of confining pressure on the shear strength was more pronounced at a static rate rather than at high strain rates. Strain rate-dependent shear failure surfaces of UHPFRCs were proposed.

1. Introduction

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is a potential material for wide use in protective structures for aeronautics, nuclear industry, and military buildings as a safeguard against impact or blast loading, owing to its superior mechanical characteristics [1–3]. During impact or blast loading, complex damage types such as spalling, scabbing, cratering, and shear failure can occur [4–6]. Under missile attacks to a rigid concrete wall, a triaxial compression and shear stress condition is generated in the core of the target, and the inertia of the surrounding material creates passive confinement in front of the missile [3,7,8]. The resistance capacity of the concrete wall, therefore, is strongly dependent on the mechanical behavior of concrete materials such as UHPFRCs at high strain rates and confining pressures. Consequently, in the design and/or analysis of such UHPFRC structures, the mechanical behavior of UHPFRCs under high strain rates and confining pressure must be understood.

In recent years, the influence of confining pressures and high strain rates on the compressive, tensile, and flexural strength of UHPFRC have been investigated by a considerable number of researchers [9–22]. The compressive strength, strain capacity, and ultimate strain of UHPFRCs noticeably increase as the strain rate increase (Lai and Sun [9] and Rong et al. [10]). Deng and Qu [11] experimentally investigated the behavior of ultra-high performance concrete (UHPC) confined by hybrid fiber-reinforced polymer (HFRP) tubes. They reported that HFRP tubes could effectively increase the compressive strength and ultimate strain of UHPC specimens. The significant enhancement of tensile strength and flexural strength of UHPFRCs at high strain rates was also reported by several authors [12–21]. Park et al. [13] reported the tensile strength of UHPFRC with 1.5% smooth steel fiber at a strain rate of 127 s^{-1} was 2.5 times higher than its static

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tensile strength. Pyo and El-Tawil [21] tested UHPFRC specimens at strain rates of 90–145 s^{-1}, showing that, by increasing the strain rate, the material maintains its strain capacity and has highly-enhanced strain dissipation capacity, making it particularly suitable for structures resistant to blast and impact loading. Yoo et al. [19,20] investigated the effects of fiber geometry and orientation on the flexural-impact behavior of UHPFRCs. They reported that the UHPFRC beams with better fiber orientation produced higher flexural strength and energy absorption capacity under impact loading conditions, and the long straight steel fibers were more favorable than twisted steel fiber in terms of impact resistance and residual performance after impact damage.

In comparison to its tensile and compressive strengths, there is still little information available on the shear strength of UHPFRCs, especially at high strain rates as well as under confining pressures. Lukíc and Forquin [23] experimentally observed the enhancement of shear strength under dynamic loading in comparison with quasi-static response, where the enhancement of confined shear strength was thought to be the consequence of a higher radial confining stress. Ngo and Kim [24] reported that the shear resistance of UHPFRCs was clearly sensitive to the applied strain rates even though the shear strain rate sensitivity was not as high as the tensile strain rate sensitivity, whereas Millard et al. [6] indicated no significant strength enhancement with the shear stress loading rate of UHPFRCs. The limited amount of information on the shear behavior of UHPFRCs may be due to the lack of standard shear test methods for UHPFRCs, even at static strain rates.

Several experimental techniques using different types of shear specimens (such as push-off specimens [6,25–30], punch-through specimens (PTS) [31–35], and Iosipescu specimens [36,37]) have been used to characterize the confined or unconfined shear strength of normal concrete (NC) as well as fiber reinforced concrete (FRC). However, these methods cannot indicate the unique strain-hardening response (accompanied by the formation of multiple microcracks) of UHPFRCs under tension [38]. In addition, most previous studies considered the passive confining rather than active confining, which are significantly important in pre-stressed concrete structures such as pre-stressed walls, beams, slabs, or deck bridges.

This study aims to understand the influence of confining pressure and strain rate on the shear resistance of UHPFRCs. The shear test method, newly developed by Ngo and Kim [38], is capable of measuring the shear-related hardening response of UHPFRCs, accompanied with multiple microcracks. The first objective is to investigate the effect of confining pressure on the shear resistance of UHPFRCs; the second objective is to investigate the strain rate effect on shear resistance of UHPFRCs; the third objective is to propose the strain rate-dependent shear failure surfaces of UHPFRCs for numerical simulation of UHPFRC structures.

2. Experimental

An experimental program was designed to investigate the effect of confining pressure and high strain rate on the shear resistance of UHPFRCs, as shown in Fig. 1: seven series of specimens were cast and tested. In the notation of the series, the first two letters designate the level of confining pressure applied to the specimen, the next character represents the type of shear test ("S" or "h" indicates static or impact shear test, respectively), and the last character indicates the different range of high strain rates 1 (*h1*) and 2 (*h2*).

2.1. Materials and specimen preparation

The composition of the UHPC matrix and main properties of the steel fiber are listed in Tables 1 and 2, respectively. Details of the mixing and curing procedures can be found in [39]. Dry ingredients including cement (Type I), silica fume, silica sand, and silica powder were first mixed for 10 min. Water and superplasticizers were gradually added, and this mortar mixture was further mixed until it showed adequate workability for uniform fiber distribution. The smooth steel fiber was carefully dispersed by hand into the matrix and further mixed for approximately 2 min. The workability of the mixture was checked by a flow test according to ASTM C1437 standard [40]. Finally, the mixture was poured into plastic molds without vibration. All molded specimens were stored in a laboratory at room temperature for 48 h prior to demolding. The specimens were then cured at 90 ± 3 °C for 72 h in a hot water tank before stopping the curing and storing the samples in dry conditions. All specimens were tested after 28 days.

Thirty-four prism shear specimens ($50 \times 50 \times 210$ mm^3) were cast to investigate the shear resistance of UHPFRCs. In addition, six cubic specimens ($50 \times 50 \times 50$ mm^3) were cast and tested to determine the compressive strength of the UHPC matrix.

2.2. Test setup and procedure

The setup of the static shear tests is given in Fig. 2. Details of the original test methods and testing procedures can be found elsewhere [21,35,42]. In this study, a high strength aluminum alloy frame was made to generate and maintain pre-stress along the longitudinal axis of the specimen during testing. As the rotating screw at one end of the aluminum alloy frame was tightened, the specimen and the load cell were pre-stressed along the longitudinal axis. The pre-stressed value was measured by a load cell and indicator system. Three levels of pre-stress (0, 2, and 4 MPa) were applied. The maximum value of pre-stressed stress was selected based on the maximum designed capacity of the frame. The vertical displacement of the middle region of the specimen was measured by two linear variable displacement transducers (LDVTs), while the applied load was measured by a load cell inside a universal testing machine (UTM). The speed of machine displacement was maintained at 1 mm/min during static shear testing.

Fig. 3 shows the shear test setup at high strain rates. A shear test setup with the same specimen size and boundary conditions as the static rate was employed in the improved strain energy frame impact machine (I-SEFIM) to investigate the shear resistance of UHPFRCs at high strain rates. The procedure to generate impact loading on the shear specimen of I-SEFIM was described in [23,40,41]. The transmitter bar was contacted to the middle part of the specimen through the fixed grip, while two ends of the specimen were fixed to the moved grip. The shear stress was obtained from two dynamic strain gauges attached on the surfaces of the transmitter bar while the shear strain of the specimen was measured from the relative displacement of two marked points on the fixed and moved grip by a high-speed camera system, as shown in Fig. 3b. A high-strength aluminum alloy frame was also installed to generate and maintain a confining pressure along the longitudinal axis of the specimen, as can be seen in Fig. 3c. Two pre-stressed levels (0 and 2 MPa) were applied to the specimen and two combinations of coupler and energy frame types of I-SEFIM were used to control the speed of the impact system [24]. It is noted that only the pre-stressed level of 2 MPa was investigated, since the confining frame was not strong enough to generate and maintain a higher confining level at this time. In addition, the fixed ends of the specimen prevented the additional slip of the specimen from the confining frame during the test.

The compressive strength was tested according to ASTM C109/C109M [43] while the flow test was in accordance with ASTM C1437 standard [40]. Notably, there is no still standard for the flowability of UHPC mixture, and so the flowability in Wille et al. [44] was used as a reference.

3. Results

3.1. Spread value and compressive strength of UHPC

The compressive strength of the UHPC matrix and the spread value of mixture are listed in Table 3. The average compressive strength of UHPC is 189 MPa, while the average flowability of UHPC mixture is approximately 220 mm. This flowability matched well with the values reported by Wille et al. [44] and Kang and Kim [45].

3.2. Shear stress versus strain response of UHPFRCs at static rates

The shear stress versus strain relationship of UHPFRCs at static rate is shown in Fig. 4. The shear stress (τ) was calculated using Eq. (1), while shear strain (γ) was calculated using Eq. (2)

$$\tau = \frac{P}{2bd} \qquad (1)$$

$$\gamma = \frac{\delta}{a} \qquad (2)$$

where b is the specimen width (mm), P is the applied load (kN), d is the depth of the specimen (mm), a is shear span (mm), and δ is the