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High rate response of ultra-high-performance fiber-reinforced concretes under direct tension

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ABSTRACT

The tensile response of ultra-high-performance fiber-reinforced concretes (UHPFRCs) at high strain rates (5–24 s^{-1}) was investigated. Three types of steel fibers, including twisted, long and short smooth steel fibers, were added by 1.5% volume content in an ultra high performance concrete (UHPC) with a compressive strength of 180 MPa. Two different cross sections, 25 × 25 and 25 × 50 mm^2, of tensile specimens were used to investigate the effect of the cross section area on the measured tensile response of UHPFRCs. Although all the three fibers generated strain hardening behavior even at high strain rates, long smooth fibers produced the highest tensile resistance at high rates whereas twisted fiber did at static rate. The breakages of twisted fibers were observed from the specimens tested at high strain rates unlike smooth steel fibers. The tensile behavior of UHPFRCs at high strain rates was clearly influenced by the specimen size, especially in post-cracking strength.

1. Introduction

Since the September 11 attacks in 2001, to protect and to enhance the resistance of building and civil infrastructure under extreme loading conditions such as airplane impacts and blasts, numerous researches have been intensively carried out to prevent catastrophes [1–4]. The September 11 attacks killed almost 3000 people, caused serious damage to the economy of Lower Manhattan and further generated a significant effect on global security system [5,6].

There have been various approaches in different levels for preventing those catastrophes. One of the approaches is to strengthen the national security systems [1]. The other approach is to develop and apply structural systems with high impact and blast resistance under such extreme loads [2–4]. However, the national security system might not eliminate all potential causes for the collapses or damages of building and civil infrastructure generated by manmade and especially by natural disaster. In addition, the structural systems of existing buildings and infrastructure cannot be easily modified for improving their impact and blast resistance.

Thus, in this study, it is proposed to improve the resistance of infrastructure under natural and manmade extreme events, e.g., airplane impacts, earthquake, blast, and typhoon, by simply attaching ultra-high-performance fiber-reinforced concrete (UHPFRC) panels with high ductility and energy absorption capacity or by overlaying them with UHPFRCs. Strain hardening UHPFRCs, with high tensile strength (over 10 MPa), high ductility (strain capacity over 0.5%) and high energy absorption capacity, could be recently obtained, with small amount of steel fibers (<2.5% by volume), by combining dense ultra high performance concrete (UHPC) matrix containing very fine particles and tailored interfacial bond strength between fiber and matrix [7,8]; and, further enhanced by blending long deformed and short smooth steel fibers [9]. In comparison with other cement based construction materials, strain hardening UHPFRCs showed much higher tensile resistance, as shown in Fig. 1.

The superior direct tensile behavior of UHPFRCs is mostly based on their responses measured at static rate. Owing to the static tensile behavior of UHPFRCs, it has been expected that UHPFRCs would produce higher tensile resistance even at higher strain rates. Although several papers reported about the behavior of UHPFRCs under high strain rates, most of them reported about the flexural behavior of UHPFRCs [10–14]. The flexural resistance of UHPFRCs under impact was found to be much higher than that of steel fiber reinforced concrete (SFRC) and normal concrete [10]. And, the flexural strength and toughness of UHPFRCs under impact significantly increased as the strain rate (or stress rate) increased. The enhancement of flexural strength at high strain rates was reported to be much correlated to the matrix–fiber interface bond characteristics between fiber and matrix [11].

On the other hand, there are a few researches reporting the dynamic tensile strength and fracture energy of UHPFRCs by performing spalling test (indirect tensile test) [15–17]. Millon et al. [15] and Noldgen et al. [16] reported that the spalling tensile strength of UHPFRCs was sensitive to the strain rate, whereas their fracture energy was not. Rong and Sun [17] indicated that the spalling tensile strength of UHPFRCs increased as the strain rate increased from 21 to 66 s^{-1}.

Very few studies have investigated the direct tensile stress versus strain responses of UHPFRCs at seismic rates [12,18]. Habel and

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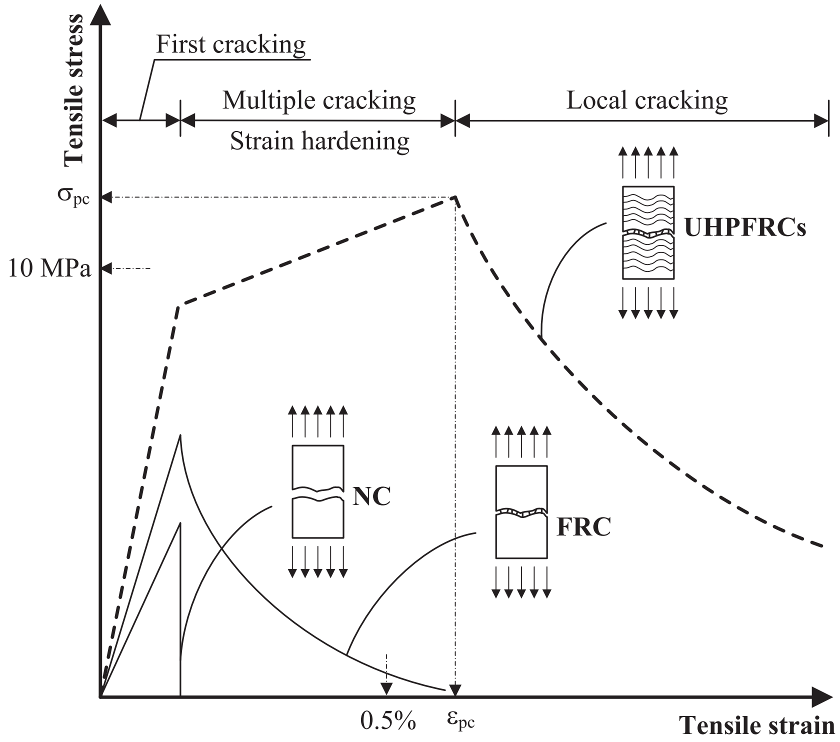

Fig. 1. Tensile response of UHPFRCs in comparison to normal concrete (NC) and fiber reinforced concrete (FRC).

Gauvreau [12] and Wille et al. [18] investigated the direct tensile response of UHPFRCs at the strain rates ranging from static (0.0001 s^{-1}) to seismic (0.1 s^{-1}) rate. They reported that as the strain rate increased from static to seismic rate, the post-cracking tensile strength and the energy absorption capacity of UHPFRCs increased while UHPFRCs still maintained strain hardening tensile behavior accompanied with multiple micro-cracks at seismic rates. According to the best knowledge of the authors, only Cadoni et al. [19] investigated direct tensile response of notched cylindrical tensile specimens of UHPFRCs at high strain rates (50, 100 and 200 s^{-1}) using modified split Hopkinson pressure bar test system (direct tensile test). However, the notched specimen used in their experimental tests might not be appropriate for capturing the stress versus strain response because the stress state around the notch is not uniform and the measured elongation is localized at the notched area. Thus, there is still not enough information about the direct tensile stress versus strain response of UHPFRCs at high strain rates. Specifically, it is questioned whether the tensile strain hardening behavior of UHPFRCs can maintain even at higher strain rates (more than 5 s^{-1}) under impact loads.

Table 1
Test series of tensile specimens.

Type of fiber and volume contents	Strain rate	Cross section (mm^2)	Notation
Twisted 1.5% (T15)	Static rate (S)	25 × 50 (A)	T15SA
		25 × 25 (B)	T15SB
	High rate (I)	25 × 50 (A)	T15IA
		25 × 25 (B)	T15IB
Long smooth 1.5% (LS15)	Static rate (S)	25 × 50 (A)	LS15SA
		25 × 25 (B)	LS15SB
	High rate (I)	25 × 50 (A)	LS15IA
		25 × 25 (B)	LS15IB
Short smooth 1.5% (SS15)	Static rate (S)	25 × 50 (A)	SS15SA
		25 × 25 (B)	SS15SB
	High rate (I)	25 × 50 (A)	SS15IA
		25 × 25 (B)	SS15IB

Recently, Tran and Kim [20–22] published several papers regarding the direct tensile behavior of high performance fiber reinforced cementitious composites (HPFRCCs), reinforced with deformed high strength steel fibers, at high strain rates (10–40 s^{-1}): they applied an innovative strain energy frame impact machine (SEFIM) to perform direct tensile tests, with a small test machine, for HPFRCCs requiring large size specimen [20]. Tran and Kim [21] reported that the HPFRCCs with deformed steel fibers maintained their tensile strain hardening behavior even at higher strain rates and the interfacial bond strength is main source of the rate sensitivity of fiber reinforced cementitious composites. They also found that the strength of matrix had more significant influence on the strain rate sensitivity on the tensile strength of HPFRCCs rather than the fiber volume contents [22]. The application of high strength steel fibers in higher strength matrix is more effective and economical for enhancing the tensile strength of HPFRCCs at both static and high strain rates rather than simply adding more fibers in lower strength matrix [22,23].

In this study, we would investigate the direct tensile stress versus strain response of UHPFRCs which combine very high strength matrix and high strength steel fibers. UHPFRCs are expected to demonstrate very high tensile strength and energy absorption capacity at high strain rates. However, it is questioned whether the combination of high strength matrix and steel fibers can generate superior tensile resistance at high strain rates by maintaining the tensile strain hardening behavior. In addition, which type of steel fiber would be suitable for UHPFRCs at high strain rates? What is the reasonable size of the specimen for tensile testing UHPFRCs to obtain pure material response at high strain rates without any size effects? Those questions motivated us to carry out the experimental research reported in this paper.

The aim of this research is to develop the fundamental understanding about direct tensile response of UHPFRCs at high strain rates. The specific objectives are: (1) to investigate the direct tensile stress versus strain responses of UHPFRCs at high strain rates (5 to 24 s^{-1}); (2) to