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Direct tensile responses of aramid fiber reinforced cementitious composites and textile reinforced cementitious composites with 3D spacer fabric at high strain rates

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HIGHLIGHTS

- The tensile responses of AR-FRCCs and 3D-TRCC at high strain rates were investigated.
- The tensile strength of AR-FRCCs increased to 15.8 MPa at high strain rates (194 s^{-1}).
- The 3D-TRCCs produced higher energy absoprtion capacity than the AR-FRCCs.

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ABSTRACT

The direct tensile responses of macro aramid fibers reinforced cementitious composites (AR-FRCCs) as well as textile reinforced cementitious composites with 3D spacer fabric (3D-TRCCs) were investigated at high strain rates. As strain rate increased from static (0.000333 s^{-1}) to high strain rates (up to 194 s^{-1}), the tensile strength of AR-FRCCs considerably increased from 3.49 to 15.82 MPa. However, their rate sensitivities were different corresponding to fiber contents and matrix strength. The AR-FRCCs with higher fiber content clearly produced lower rate sensitivity while the AR-FRCCs with high strength (63.6 or 99.6 MPa) matrices generally produced higher rate sensitivities on their tensile resistance than those with a lower strength (43.7 MPa) matrix. Even though the 3D-TRCCs produced higher energy absorption capacity than the AR-FRCCs, the energy absorption capacity of 3D-TRCCs clearly decreased at strain rates greater than 100 s^{-1}.

1. Introduction

The increasing number of man-made (e.g., missile attacks and bombing in wars) and natural disasters (e.g., earthquakes, hurricanes) has significantly augmented the necessity of high performance construction materials with high resistance especially under high rate loads including impacts and blasts [1–3]. To date, several different high performance construction materials have been developed, e.g., high performance concrete (HPC), fiber reinforced concrete (FRC), high performance fiber reinforced cementitious composites (HPFRCCs), ultra-high performance concrete (UHPC), high performance steel materials, strain hardening cementitious composites (SHCC), and textile reinforced concrete (TRC) [4–7]. Among the above mentioned materials, HPFRCCs have particularly demonstrated higher tensile strength and energy absorption capacity even at high strain rates, as shown in Fig. 1, based on their tensile strain-hardening behavior [7–11].

Current HPFRCCs mostly contain high strength steel fibers or polyvinyl alcohol (PVA) fibers. The HPFRCCs with high strength steel fibers generally demonstrate a very high tensile strength (7–12 MPa) while those with PVA fibers exhibit an extremely ductile material response (3–5% strain capacity) even though their tensile strength is relatively low (3–5 MPa) [11–15]. However, the high strength steel fibers in the HPFRCCs, although they are brass-coated, are still highly susceptible to corrosion. Moreover, PVA fibers generated a significant reduction in the tensile resistance of the PVA fiber reinforced cement composites at elevated temperatures, owing to the changes in the mechanical properties of PVA fibers at high temperatures [16]. Curosu et al. [4] have conducted extensive experiments to overcome the above mentioned limitations from the temperature dependent bond characteristics of micro polymer (polyethylene, aramid and PBO) fibers. Despite

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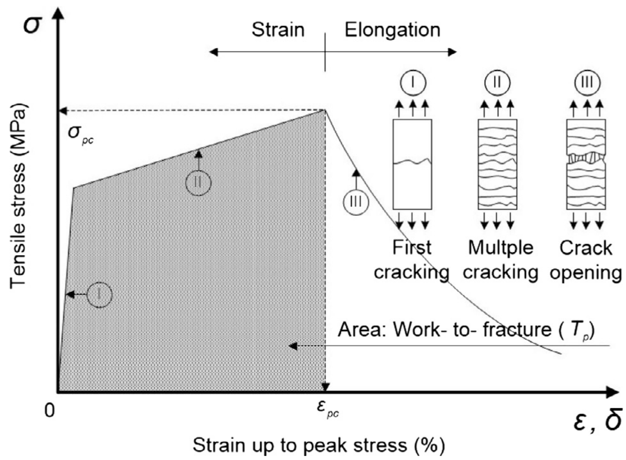

Fig. 1. Tensile strain-hardening behavior at both static and high strain rates [10].

these efforts, HPFRCCs with synthetic fibers still have shown a relatively low tensile strength (3–10 MPa).

In this study, aramid fibers or textile reinforcements with 3D spacer fabrics (containing alkali resistive glass fibers) have been investigated, to overcome the limitations of current HPFRCCs, because they have higher tensile strength and high corrosion resistance. The synthetic fibers generally have higher corrosion resistance than steel fibers; and, the aramid fiber with higher tensile strength and elastic modulus than other synthetic fibers is much favorable for obtaining a hardening response accompanied with multiple cracks under flexural or tensile loads [4,17]. Moreover, aramid fiber reinforced cementitious composites (AR-FRCCs) have improved the fracture energy (4.36 kJ m^{-2}) at static strain rates [18]. However, their responses at high strain rates are not clearly understood yet.

On the other hand, the direct tensile stress versus strain responses of textile reinforced cementitious composites with 3D spacer fabrics (3D-TRCCs) at high strain rates were investigated in this study. Several studies have been performed on the mechanical resistance of textile reinforced cementitious composites (TRCCs) [19–23]. 3D spacer fabrics with high tensile strength and chemical resistant fabrics have been recently developed [24,25]. The 3D spacers would possibly increase adhesion between the textile reinforcements and cementitious composites and improve the performance of composites when the spacer along the Z direction [26,27]. Even though several studies have been carried out on the effects of 3D spacers, including epoxy treatment, geometric patterns, and fabric orientation, on the behavior of 3D-TRCCs, most of them were tested at static rate [28–30]. Yoo et al. [31] have recently performed low-velocity impact tests on the 3D-TRCCs by using an instrumented drop-weight impact machine and found that the 3D-TRCCs exhibit better impact resistance compared to the typical 2D-TRCCs. However, there is still little information about the direct tensile stress versus strain responses of 3D-TRCCs at high strain rates.

Thus, this research aims to understand the direct tensile responses of both AR-FRCCs and 3D-TRCCs at high strain rates, by using an improved strain energy frame impact machine (I-SEFIM), to develop construction materials with higher impact and blast resistance [10,11]. Specific objectives in this study are (1) to investigate the effect of matrix strength and fiber contents on the tensile behavior of the AR-FRCCs; and, (2) to evaluate the high rate effects on the tensile behavior of 3D-TRCCs.

2. AR-FRCCs and 3D-TRCCs

AR-FRCCs typically have demonstrated a deflection hardening response under flexural loads whereas other fiber reinforced cementitious composites (FRCCs) with polyamide or polyethylene terephthalate (PET) fibers generally produced a deflection softening response [32]. The higher tensile strength and elastic modulus of aramid fibers, in comparison to other synthetic fibers, were clearly favorable for generating the higher flexural strength of FRCCs [17]. Curosu et al. [4] also reported the high tensile cracking strength (6.3 MPa) of AR-FRCCs accompanied with multiple micro-cracks. Furthermore, the addition of aramid fibers to mortar clearly increased the fracture energy of cementitious composites at static loads [18,33]. However, there is still little information about the direct tensile stress versus strain responses of AR-FRCCs especially at high strain rates.

On the other hand, TRCCs have demonstrated their advantages in the space efficiency of complex structures owing to the superior tensile resistances [19–23]. Fig. 2, inspired by [19–23], shows the typical tensile stress versus strain response of TRCCs under direct tension. There is a clearly linear elastic region prior to the first cracking point in Fig. 2. Even after the first matrix cracking, the TRCCs still maintained their tensile resistance accompanied with multiple cracks and then they eventually reached maximum tensile strength as the tensile stress increased again. Zhu et al. [34] investigated the effect of different fabric pullout mode on the overall ductility of TRCC at high strain rates by using three different types of fabrics (carbon, polyethylene (PE), and alkali resistant (AR) glass). Vogel et al. [35] discovered that the TRCCs show greater impact resistance compared to FRCCs by using a horizontal impact machine based on the pendulum principle. 3D-TRCCs, among the various TRCCs, have shown very high resistance to delamination and notably high flexural resistance in comparison to typical 2D-TRCCs owing to strong bond between 3D spacer fabric and cement matrix [29]. Although the 3D-TRCCs produced high resistance even at high strain rates [31,36,37], there is still little information about the direct tensile stress versus strain responses of 3D-TRCCs at high strain rates.

3. Experiments

Twenty series of specimens were prepared corresponding to a different matrix, fiber content, and the type of reinforcement to investigate the direct tensile responses of both AR-FRCCs and 3D-

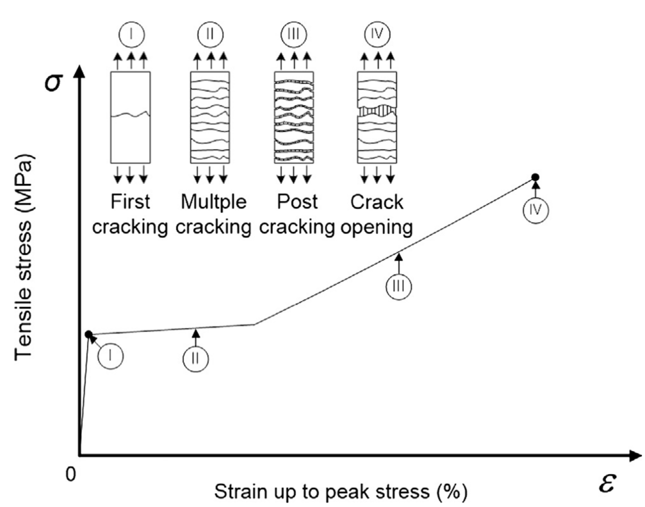

Fig. 2. Typical tensile behavior of TRCCs under direct tensile loading [19–23].