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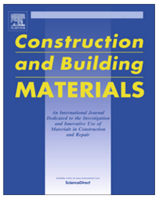

Size-dependent impact resistance of ultra-high-performance fiber-reinforced concrete beams

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HIGHLIGHTS

- Flexural strength of UHPFRC decreases with increasing specimen size.
- Using twisted or long straight fibers improves static flexural performance of UHPFRC with short straight fibers.
- Deflection-hardening response of UHPFRC under impact is successfully captured.
- Long straight steel fiber is most effective in improving impact resistance of UHPFRC.
- Strain-rate is proper to analyze DIF on f_{LOP} of UHPFRC excluding size effect.

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ABSTRACT

This study examines the rate dependent flexural behavior of ultra-high-performance fiber-reinforced concrete (UHPFRC) beams with three different sizes. Two different loading rates (static and impact), fiber aspect ratios (l_f/d_f of 65 and 100), and fiber types (straight and twisted) were considered. Test results indicated that the static flexural performance, including the flexural strength and toughness, were improved by increasing the fiber aspect ratio or through the use of twisted steel fibers. The static flexural strength clearly decreased with an increase in specimen size due to a decrease in the number of fibers at the crack surface. The use of straight steel fibers with a higher aspect ratio of 100 provided the best impact resistance in terms of the highest post-cracking flexural strengths and the largest normalized energy dissipation rates, compared to those of twisted steel fibers and straight steel fibers with a reduced aspect ratio of 65. Thus, the use the straight steel fibers with high aspect ratios was recommended to improve the impact resistance of UHPFRC. Dynamic increase factor (DIF) on the flexural strength of UHPFRC beams was properly investigated with strain-rate, regardless of specimen size. In addition, there were no effects with regard to the fiber aspect ratio and type on the relationship between the DIF of the first-cracking flexural strength and the stress- (or strain-) rate.

1. Introduction

Ultra-high-performance fiber-reinforced concrete (UHPFRC), which was developed in the mid-1990s, has been considered as one of the most promising construction materials for architectural or civil structures subject to extreme loads, such as earthquakes, impacts, and blasts. Such interest is primarily due to the results of its excellent mechanical properties, i.e., strength and energy absorption capacity, under both static and dynamic loads. To achieve such superb mechanical properties, a densified microstructure was applied through the uses of a low water-to-binder ratio (W/B), a high-range water reducing agent, and very fine admixtures, and a high volume content of micro steel fibers was incorporated [1].

Enhancing static tensile and flexural performance of UHPFRC was successfully achieved by using deformed (hooked or twisted) steel fibers or by increasing aspect ratio of straight steel fibers without increasing the fiber volume content [2,3]. Wille et al. [2] reported that high tensile strengths (up to 15 MPa) and strain capacities (approximately 0.6%) are obtained at a fiber volume fraction of 2% by improving the fiber bond performance, resulting from an increase in the matrix density, fiber strength, and mechanical bond performance through fiber deformation. Yoo et al. [3] noted that improvements in the biaxial flexural behavior of

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UHPFRC, including strength, deflection capacity, and toughness, were obtained by increasing the aspect ratio of straight steel fibers from 65 to 97.5, and its flexural behavior was substantially influenced by the fiber orientation, which varied depending on the placement method.

Several researchers [4–7] have additionally investigated the mechanical properties of UHPFRC at high-rate loadings with a variety of parameters and reported some inconsistent results with the static tests. Rong et al. [4] examined the effect of fiber content on the dynamic compressive behavior of UHPFRC using a split-Hopkinson pressure bar (SHPB) test machine with cylindrical specimens that were 70 mm in diameter and 35 mm long. They [4] reported that the dynamic compressive toughness was improved with an increase in the fiber content and strain-rate, and the compressive strength also increased with an increase in strain-rate. Tran et al. [5] investigated the tensile behavior of UHPFRC at high-rate loadings using a strain energy frame impact machine (SEFIM). In their study [5], although the best static tensile performance was obtained when using twisted steel fibers, the highest impact resistance was achieved when using long straight steel fibers because the twisted steel fibers fractured under impact loading prior to being completely pulled out. Wille et al. [6] similarly reported that lower tensile strength values for UHPFRC were obtained with twisted steel fibers at high-rate loadings as opposed to straight steel fibers, due to its limited strain-rate sensitivity. Yoo et al. [7] investigated the impact and residual performance of UHPFRC beams with various potential energies and fiber types, using a drop-weight impact test machine. Similar to the dynamic tensile test results [5,6], improved impact resistance under flexure, including strength and energy absorption capacity, were obtained in UHPFRC beams with long straight steel fibers, compared to those with short straight or twisted steel fibers.

Prior to designing UHPFRC structures at high-rate loadings, it is very important to examine size effects on the relationship between the dynamic increase factor (DIF) and the strain-rate. This is because structures subject to high-rate loadings have various sizes, and these are designed based on enhanced material models, obtained by the DIF versus strain-rate relationship. Prior researchers [8,9] have investigated size effects in normal- and high-strength concrete cylinders and beams under impact loading. Bindiganavile and Banthia [8] reported that plain concrete exhibited size effect under impact loads, and that the flexural strength was more sensitive to specimen size than the compressive strength under both static and impact loads. Krauthammer et al. [9] also examined size-dependent impact behavior under compressive loads and reported that size effect exists in high-strength concrete under both static and dynamic compressive loads, and if the energies associated with the impact are extremely higher than the specimen's resistance, the specimens may shatter at lower stress values than their real strength. To the best of the authors' knowledge, Tran et al. [5] only investigated the size-dependent impact resistance of UHPFRC up to date. However, inconsistent with conventional size effect laws [10,11], the enhanced dynamic tensile strength of UHPFRC was obtained in larger specimens (cross-section of 25 × 50 mm^2), compared to that in smaller specimens (cross-section of 25 × 25 mm^2) [5]. This disjointed observation may have been caused by the inertial effect of the specimen used. Thus, there exists a pressing need to investigate the actual size-dependent mechanical properties of UHPFRC under high-rate loadings without inertial effect.

Accordingly, this study examined the effects of steel fiber types, aspect ratios, and specimen sizes on the rate dependent flexural behavior of UHPFRC. In doing so, two different steel fiber types (straight and twisted) and aspect ratios (l_f/d_f of 65 and 100), in addition to three different specimen sizes (50 × 50 × 250 mm^3, 100 × 100 × 400 mm^3, and 150 × 150 × 550 mm^3) were adopted, where l_f is the fiber length and d_f is the fiber diameter. The detailed objectives were: 1) to examine the effect of steel fiber types and aspect ratios on the rate dependent flexural behavior of UHPFRC, 2) to estimate the size effects on the static flexural behavior and the relationship between the DIF and the strain- (or stress-) rate, and 3) to evaluate the number of fibers per unit area one of the most important parameters dominating the post-cracking flexural behavior based on an image analyses.

2. Experimental program

2.1. Materials and mixture proportions

Type 1 Portland cement and silica fume were used as cementitious materials. The Type 1 Portland cement primarily consisted of CaO (61.3%) and SiO_2 (21.0%) and possessed a specific surface area of 3413 cm^2/g. Silica fume was mainly composed of very fine particles with SiO_2 (96.0%) and a specific surface area of 200,000 cm^2/g. The properties of cementitious materials, i.e., cement and silica fume, are summarized in Table 1. Silica sand was also incorporated as a fine aggregate, while silica flour was included as a filler. In order to prevent degradation of the tensile or flexural performance of UHPFRC, coarse aggregates were excluded from the mixture [12]. A W/B ratio of 0.2 was used. 2% (by cement weight) superplasticizer (high-range water reducing agent) with a density of 1.06 g/cm^3 were incorporated to achieve a material with adequate fluidity, which is one of the very important parameters to control fiber dispersion and orientation. In addition, enough viscosity of cement mortar was assumed to be obtained because it included a high amount of powders. The detailed mixture proportions adopted in this study are summarized in Table 2.

Commercially available UHPFRC in North America includes 2% by volume of steel fibers [13]. Thus, a large number of earlier studies with regard to UHPFRC were carried out with the use of that quantity of steel fibers. For data consistency, 2% by volume of steel fibers were also adopted in the current study for all tested series. To investigate the effects of the steel fiber aspect ratio and type on the flexural performance of UHPFRC under both static and impact loadings, two straight steel fibers with aspect ratios (l_f/d_f) of 65 and 100 and one twisted steel fiber with an aspect ratio (l_f/d_f) of 100 were used. The twisted steel fibers possessed a triangular shape with three ribs within the length of the fiber [14].

2.2. Specimen size and preparation

Three different beam sizes were considered in order to investigate size effects on the rate dependent flexural behavior of UHPFRC: small-size beam (S), 50 × 50 × 250 mm^3, medium-size beam (M), 100 × 100 × 400 mm^3, and large-size beam (L), 150 × 150 × 550 mm^3, as shown in Fig. 1. All specimens were mixed using a 120 L capacity pan mixer. A detailed mixing sequence is provided in an earlier paper [3]. To provide identical

Table 1
Compositions and physical properties of cement and silica fume.

Composition% (mass)	Cement*	Silica fume
CaO	61.33	0.38
Al_2O_3	6.40	0.25
SiO_2	21.01	96.00
Fe_2O_3	3.12	0.12
MgO	3.02	0.10
SO_3	2.30	–
Specific surface area (cm^2/g)	3413	200,000
Density (g/cm^3)	3.15	2.10

* Type 1 Portland cement.