Engineering Structures 102 (2015) 409–423

Contents lists available at ScienceDirect

Engineering Structures

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

Structural performance of ultra-high-performance concrete beams with different steel fibers

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ARTICLE INFO

Article history:
Received 13 June 2015
Revised 22 August 2015
Accepted 25 August 2015

Keywords:
Ultra-high-performance concrete
Flexure
Steel fiber
Ductility
Sectional analysis
Fiber orientation

ABSTRACT

In this study, ten large ultra-high-performance concrete (UHPC) beams reinforced with steel rebars were fabricated and tested. The experimental parameters included reinforcement ratio and steel fiber type. Two different reinforcement ratios (ρ = 0.94% and 1.50%) and steel fiber types (smooth and twisted steel fibers) were adopted. In addition, three different fiber lengths (L_f = 13, 19.5, and 30 mm) for the smooth steel fibers and one fiber length (L_f = 30 mm) for the twisted steel fiber were considered. For a control specimen, a UHPC matrix without fiber was also considered. Test results indicated that the addition of steel fibers significantly improved the load carrying capacity, post-cracking stiffness, and cracking response, but it decreased the ductility. Specifically, with the inclusion of 2% by volume of steel fibers, approximately 27–54% higher load carrying capacity and 13–73% lower ductility were obtained. In addition, an increase in the length of smooth steel fibers and the use of twisted steel fibers led to the improvements of post-peak response and ductility, whereas no noticeable difference in the load carrying capacity, post-cracking stiffness, and cracking response were obtained according to the fiber length and type. Sectional analysis incorporating the suggested material models was also performed based on AFGC/SETRA recommendations, and the ratios of flexural capacities obtained from experiments and numerical analyses ranged from 0.91 to 1.19.

1. Introduction

Ultra-high-performance concrete (UHPC) has been developed in many countries [1–4], and many new studies have been performed in recent years. Because UHPC has a very low water-to-binder ratio (W/B), high-fineness admixtures, and high volume contents of steel fibers (mostly 2% by volume), it exhibits excellent performance in terms of mechanical properties (compressive strength >150 MPa and tensile strength >8 MPa), energy absorption capacity, fatigue performance, and durability [5,6]. In particular, owing to its unique strain-hardening and multiple cracking behaviors, UHPC has been attractive for use in civil infrastructures subjected to tensile and bending loads.

Graybeal [7] and Chen and Graybeal [8] studied the structural behaviors of full-scale prestressed UHPC I- and Pi-girders under flexure based on experiments and numerical simulations. Yuguang et al. [9] also performed a feasible study for applying UHPC in bridge decks, and Yang et al. [10,11] carried out several structural tests of reinforced UHPC beams under flexure for attaining a fundamental understanding. Fujikake et al. [12] and Yoo et al. [13] performed a drop-weight impact test for UHPC beams reinforced with prestressing tendons and steel rebars and suggested analytical models for predicting their deflection responses. In addition, Astarlioglu and Krauthammer [14] numerically analyzed the blast resistance of normal-strength concrete and UHPC columns, and they reported that the UHPC columns exhibited a lower mid-span deflection and sustained more than four times the impulse than those of the normal-strength concrete columns. Likewise, many researchers [7–16] have performed structural tests for various elements made of UHPC containing short smooth steel fibers.

For the material level, numerous studies [5,17–22] have been performed to investigate the effect of fiber properties (i.e., fiber type, geometry, dosage, orientation, etc.) on the mechanical performance of UHPC. Kim et al. [20] investigated the effects of different macro steel fibers on the flexural behaviors of hybrid UHPC. Based on the test results, they noted that the uses of longer hooked-end steel fibers and twisted steel fibers provide better flexural performance including flexural strength, deflection capacity, and energy absorption capacity than that of straight steel fibers. Yoo et al. [21] experimentally and numerically estimated the mechanical and

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http://dx.doi.org/10.1016/j.engstruct.2015.08.029
0141-0296/

fracture properties of UHPC according to the steel fiber content and reported that the flexural performance and fracture energy of UHPC were almost linearly increased with the fiber content even though an insignificant difference in the first cracking properties was observed. In addition, Barnett et al. [22] investigated the effect of placement method on the biaxial flexural performance of UHPC. From their test results, the panels poured from the center were significantly stronger than the panels poured from the edge and randomly, since the alignment of fibers led to more fiber bridging against the radial cracks formed.

The application of UHPC to real structures has been limited thus far because of its high cost. One of the methods reducing the production cost is to use coarse aggregate, since by using the coarse aggregate, the amount of powder can be reduced [23]. Thus, some researchers have recently developed the UHPC with coarse aggregate and investigated its properties. Ma and Orgass [23] performed comparative investigations on the mixing process and mechanical and shrinkage properties of UHPC with and without coarse aggregate. In their study, several findings were obtained; (1) the UHPC with coarse aggregate was easier to be fluidized and reduced the mixing time, (2) there was no distinct difference in the compressive strength according to the existence of coarse aggregates, whereas higher elastic modulus and lower strain capacity were obtained for the UHPC with coarse aggregate, and (3) autogenous shrinkage of UHPC with coarse aggregate was approximately 60% of its counterpart. Wille et al. [24] also investigated the effect of coarse aggregate on the compressive strength of UHPC based on the database from the International Symposium on Ultra High Performance Concrete. They reported that the UHPC containing coarse aggregate with the maximum size ranged from 7 to 16 mm reached a slightly higher strength of 178 MPa on average than its counterpart without coarse aggregate, which reached a strength of 162 MPa on average. On the contrary, the information with regard to the tensile performance of UHPC containing coarse aggregate, which is one of the most important parameters for designing the structures, is very limited, and even though various properties of UHPC might be changed according to the type of coarse aggregate [23], no specific recommendation for the type or performance of coarse aggregate exists. Therefore, further extensive research is required to be done for using UHPC containing coarse aggregate.

Another method is to reduce the steel fiber content, since the price of high strength steel fibers is considerably expansive compared to other drying components for making the matrix material. For instance, 2% by volume of smooth steel fibers occupies approximately 33% of total cost of UHPC used in this study. Therefore, to reduce the steel fiber content without deteriorating its tensile performance or to improve its tensile performance without changing the steel fiber content at the material level is one of the key challenges for UHPC technology. Yoo et al. [5] and Aydın and Baradan [25] very recently reported that the flexural performance and fracture energy are noticeably improved with an increase in the length of smooth steel fibers (or the aspect ratio), which is attributed to an increase in the effective bonding area between the fiber and matrix. Furthermore, Wille et al. [17] noted that the use of twisted steel fibers (L_f/d_f = 30/0.3 mm/mm) improves the tensile strength and strain capacity, although lower fiber contents are adopted compared to that of the short smooth steel fibers (L_f/d_f = 13/0.2 mm/mm) (herein, L_f is the fiber length and d_f is the fiber diameter). These results indicate that the fiber content required to satisfy a certain tensile or flexural performance at the material level can be decreased by increasing the length of smooth steel fibers and by using the twisted steel fibers. However, to the best of authors' knowledge, no published study exists that is related to structural applications of these findings to verify the possibility of improving the performance by increasing the length of smooth fibers and by using the twisted fibers. Thus, investigations on the structural performance of UHPC elements subjected to tension or flexure are required for different fiber types and lengths.

Accordingly, this study investigated the flexural behavior of steel bar-reinforced beams made of UHPC containing no coarse aggregate with two different reinforcement ratios. To evaluate the effects of the type and length of steel fiber on the flexural behaviors of UHPC beams, two different fiber types (smooth and twisted steel fibers) and three different lengths of smooth steel fibers (L_f = 13, 19.5, and 30 mm) were considered. As control specimens, the beams made of UHPC matrix without fiber were also fabricated and tested. Lastly, to predict their flexural behaviors, sectional analysis incorporating suggested material models from experiments and inverse analyses was performed and verified through comparison with the test data.

2. Experimental program

2.1. Materials and mixture proportions

The mixture proportions used in this study are summarized in Table 1. Type 1 Portland cement and silica fume were included as cementitious materials. The chemical and physical properties of used cementitious materials used can be found in a previous study [26]. Silica flour including 98% SiO_2 with a diameter of 2 μm was added as a filler, and silica sand with a grain size less than 0.5 mm was used as a fine aggregate. In order to improve the homogeneity, a coarse aggregate was excluded in the mixture, similar to the classic UHPC from previous studies [6,12,17]. To investigate the effects of the length and type of steel fibers on the mechanical and structural performances, three different fiber lengths of 13, 19.5, and 30 mm [5] for smooth steel fibers (S) and one 30-mm-long twisted steel fiber (T) having a triangular section and three ribs within the fiber length were considered at 2% (by volume), which led to four series of test specimens. The shape of the twisted steel fiber is shown in Fig. 1 [18]. Since several design guidelines of UHPC [4,27] proposed the tension-softening model based on the UHPC mixture including 2 vol.% of steel fibers, most of previous studies [7,10–13] on the structural response of UHPC used 2 vol.% of steel fibers. Therefore, the fiber volume fraction of 2% was also adopted in this study for data consistency. Based on our preliminary mixing [28], the UHPC mixture containing 2 vol.% of smooth steel fibers exhibited no significant difference of fluidity according to the fiber aspect ratio ranging from 65 to 100, whereas the mixture with a fiber aspect ratio higher than 100

Table 1
Mix proportions.

	Unit weight (kg/m^3)							
	Water	Cement	Silica fume	Silica flour	Silica sand	EA	SRA	SP (%)
UHPC w/o fiber	165.5	786.6	196.7	236.0	865.3	59.0	7.9	1.7
UHPC w/fiber	160.3	788.5	197.1	236.6	867.4	–	–	2.0

Note: EA = expansive admixture, SRA = shrinkage reducing admixture, and SP = superplasticizer.