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Cyclic behavior of UHPFRC flexural members reinforced with high-strength steel rebar

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ABSTRACT

Ultra-high performance fiber reinforced concrete (UHPFRC) is a unique class of fiber reinforced concrete. It features an ultra-high compressive strength and a ductile, tensile strain hardening behavior accompanied by multiple narrow cracking. The cyclic flexural performance of UHPFRC structural beams reinforced with high-strength steel with a specified yielding strength of 680 MPa is experimentally investigated in this study. Six cantilever beams are prepared and tested under displacement reversals. The experimental variables include the reinforcement ratio of the high-strength longitudinal rebar and the amount, location, and length of steel fibers in the beams. The intermediate and ultimate behaviors of these cantilever members are discussed using multiple performance parameters, including strength capacity, flexural ductility, failure pattern, hysteretic response, energy dissipation capacity, and stiffness retention. The results show that UHPFRC beams reinforced with high-strength steel are able to show satisfactory cyclic flexural performance prior to failure. The addition of steel fibers substantially enhances the damage tolerance ability of the high-strength beams, even when the fibers are selectively used only in the top and bottom beam sections. The proposed composite of UHPFRC and high-strength steel rebar not only takes advantage of the ultra-high mechanical properties of both materials, but also resolves the issue of potential premature failure patterns associated with high-strength concrete and high-strength steel rebar.

1. Introduction

High performance fiber reinforced cementitious composites (HPFRCCs) are distinguished from traditional fiber reinforced cementitious composites (FRCC) by their unique tensile strain hardening behavior accompanied by multiple narrow cracks [1–5], as shown in Fig. 1. Depending on the mixing design and the fiber type, the ultimate tensile strain of HPFRCCs ranges between 0.2% and 8%, which can be up to 100 times greater than that of conventional concrete materials. When HPFRCCs are under compression, fibers can provide a confining effect similar to that of stirrups in reinforced concrete, enhancing the compressive strength and ductility. The appealing mechanical performance of HPFRCCs in the material level has motivated researchers and engineers to explore their applications in earthquake-resistant structures [6–12]. Ultra-high performance fiber reinforced concrete (UHPFRC) is a special class of HPFRCCs [13–20]. It is made by an optimized gradation of granular materials with minimal or no coarse aggregate. Its material proportion is characterized by a high cementitious material content with a very low water/binder (w/b) ratio. The tailored mixing design of UHPFRC leads to an ultra-high compressive strength. In contrast to the brittle and explosive failure pattern of conventional high-strength concrete, UHPFRC exhibits a significantly improved ductility and residual strength under compression, and shows ductile strain hardening behavior under tension.

Lampropoulos et al. [21] numerically investigated the feasibility of using UHPFRC for strengthening RC beams, and suggested that superior strengthening performance could be achieved by using UHPFRC jackets. Xu et al. [22] experimentally studied the behavior of UHPFRC columns subjected to blast loading. It was found that UHPFRC columns could effectively resist the overpressures and shock waves, restraining the maximum and residual displacements of columns. Hosinieh et al. [23] experimentally studied the behavior of UHPFRC columns under pure axial loading. It was concluded that using UHPFRC to replace normal concrete in columns could improve the post-peak ductility of columns more significantly when the confinement steel was less. Yoo et al. [24] studied the flexural behavior of UHPFRC beams reinforced with glass fiber-reinforced polymer (GFRP) rebars and hybrid reinforcements (steel + GFRP rebars). The results indicated that all test beams satisfied the code-specified service crack width criteria and showed very stiff load–deflection behavior after the formation of cracks.

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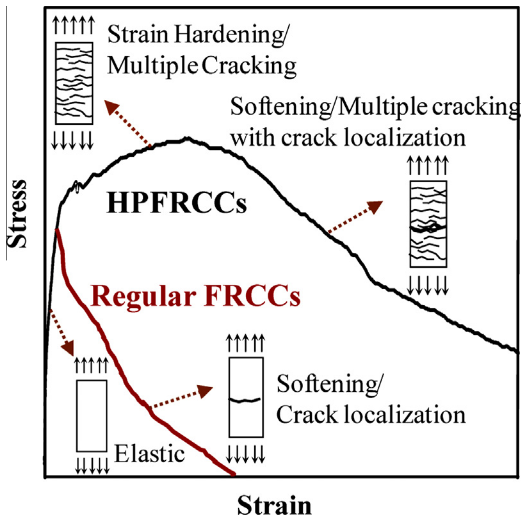

Fig. 1. Comparison between HPFRCCs and regular fiber reinforced cement-based composites (FRCCs).

Astarlioglu and Krauthammer [25] numerically investigated the response of UHPFRC columns under impulsive loads. It was concluded that the peak displacements of UHPFRC columns were about 30% smaller than those of regular concrete columns, and the level of axial loading had a significant influence on the behavior of UHPFRC columns. Han and An [26] suggested the use of bundled longitudinal reinforcing bar as a substitute for steel fibers for enhancing the flexural ductility of UHPFRC beams. Palacios [27] experimentally investigated the behavior of UHPFRC columns under displacement reversals. It was found that the use of UHPFRC changed the typical failure mode of concrete columns. The results also indicated that UHPFRC columns exhibited higher peak strength and greater drift capacity prior to significant strength degradation compared to conventional normal strength RC columns. Ren et al. [28] studied the triaxial compressive behavior of UHPFRC and then applied the results to analyze the behavior of UHPFRC against projectile high-speed impact. Baby et al. [29] applied the modified compression field theory to predict the flexure-shear behavior of prestressed and reinforced UHPFRC beams. The numerical model was able to predict the reorientation of the compressive struts due to increasing force demands. Makita and Brühwiler [30] proposed empirical fatigue damage models for UHPFRC. In their model, the tensile fatigue behavior of UHPFRC was analyzed based on the elementary damage mechanics theory. Bastien-Masse and Brühwiler [31] suggested a composite model for predicting the punching resistance of reinforced UHPFRC–RC composite slabs.

Although many studies have confirmed the superior mechanical and damage tolerance properties of UHPFRC under monotonic or blast loading, limited research has been carried out on the seismic performance of UHPFRC structural members [27]. The study presented herein investigates the cyclic flexural behavior of an innovative UHPFRC structural beam reinforced with high-strength steel rebar. The employment of high-strength steel rebar to replace the one with normal strength allows designers to reduce the amount of required reinforcing steel, which eases the placement of UHPFRC. It also takes advantage of the high strength and ductility of UHPFRC. The use of high-strength steel rebars in conjunction with UHPFRC is a potential method for resolving the unfavorable failure modes that could arise when high-strength steel is used in normal concrete members. These issues include concrete crushing before reinforcing bars yield, buckling of compressive steel rebar, premature crack widening, and splitting bond failure [32–37]. The objective of the study is to characterize the flexural performance of UHPFRC structural beams longitudinally reinforced with high-strength steel rebar under seismic action. Six structural cantilever beam specimens with varying designs are tested under displacement reversals. The design parameters include the flexural reinforcement ratio and the amount, type, and location of steel fibers used in the structural beams. The test results are discussed using multiple performance variables, including strength capacity, flexural ductility, cracking pattern, hysteretic response, energy dissipation capacity, and stiffness retention.

2. Materials

The tested structural elements are composite beams consisting of UHPFRC and high-strength steel rebar. The details of the employed materials are presented in this section. It should be noted that the term UHPC (ultra high performance concrete) generally has a broader definition than UHPFRC, i.e., it can be used to refer to the UHPFRC with or without fiber reinforcement. In order to better differentiate between fiber reinforced and non-fiber reinforced UHPC in this study as well as to prevent excessively long phrases, the term UHPC herein refers to the non-fiber reinforced UHPC, whereas the term UHPFRC is the UHPC material reinforced with fibers.

2.1. UHPFRC

The mixed proportions of the UHPFRC material employed in this study are given in Table 1. The components include Type I ordinary Portland cement, silica fume, silica sand (with particle sizes ranging between 0.1 mm and 0.3 mm), quartz powder, polycarboxylate-based superplasticizer admixture, water, and high-strength hooked steel fibers. In order to study the effect of fibers on the performance of beams, different amounts of steel-hooked fibers are used in the beam specimens, namely 0%, 1%, or 2%. In addition, the performance of two types of high-strength steel fibers with lengths of 30 mm and 60 mm, respectively, is studied. Details of the fibers are listed in Table 2. The UHPFRC mixtures prepared in this study have adequate workability, with the measured diameters in the slump flow test of about 600 mm and 620 mm for the ones with the 30 mm-long fibers and 60 mm-long fibers, respectively. It is worth mentioning that the addition of the steel fibers with a greater aspect ratio (i.e., length over diameter) intends to decrease the workability of UHPFRC mixtures and the dispersion of fibers.

The compressive strength of the UHPFRC material is determined using compressive tests of standard cylinder specimens (100 mm × 200 mm). The tensile properties of UHPFRC are

Table 1
Mix proportions of UHPFRC (proportion by weight).

Type I Portland cement	Silica fume	Silica sand	Quartz powder	Water and superplasticizer	Fiber (by volume)
1	0.23	0.5	0.39	0.31	0%, 1%, 2%

Table 2
Properties of hooked steel fibers.

Type of fibers	Length (mm)	Diameter (mm)	Specified yielding strength (MPa)	Elastic modulus (GPa)
I	30	0.38	3070	210
II	60	0.90	2300	210