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Flexural behavior of ultra-high-performance fiber-reinforced concrete beams reinforced with GFRP and steel rebars

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ABSTRACT

This study describes the flexural behavior of ultra-high-performance fiber-reinforced concrete (UHPFRC) beams reinforced with glass fiber-reinforced polymer (GFRP) rebars and hybrid reinforcements (steel + GFRP rebars). Three GFRP bar-reinforced beams and four hybrid reinforced beams with different reinforcement ratios were fabricated and tested. Owing to the strain-hardening characteristics of UHPFRC, all test beams exhibited very stiff load–deflection behavior after the formation of cracks and satisfied the service crack width criteria of CAN/CSA S806. In addition, deformability factors higher than the lower limit of CAN/CSA-S6 were obtained for all test beams. The increase in the reinforcement ratio of GFRP rebars resulted in the improvement of their flexural performances, including post-cracking stiffness, load carrying capacity, and ductility (or deformability). The use of hybrid reinforcements by replacing a part of a GFRP rebar with a steel rebar contributed to a higher post-cracking stiffness before steel yielding, but led to lower deformability. Based on a sectional analysis, both AFGC/SETRA and JSCE recommendations were appropriate for predicting the moment–curvature response of UHPFRC beams with GFRP rebars and hybrid reinforcements: the average ratios of the maximum moments obtained from experiments and numerical analyses were found to be 1.12 and 0.94, respectively.

1. Introduction

In recent years, ultra-high-performance fiber-reinforced concrete (UHPFRC) has been developed in many countries [1–4]. Compared with conventional concrete, this material exhibits much higher strength, ductility, and fracture toughness in terms of a low water-to-binder ratio (W/B), optimized granular mixture, and incorporation of high volume contents of short steel fibers. In particular, the unique strain-hardening characteristics make it advantageous for use in civil infrastructures. According to the discussion following the 2003 Fourth International Workshop on High Performance Fiber Reinforced Cement Composites [5], fiber-reinforced concrete (FRC), exhibiting strain-hardening response, such as high-performance fiber-reinforced cementitious composite (HPFRCC), engineered cementitious composite (ECC), and UHPFRC, is considered mechanically more performant than the strain-softening FRC, and thus, such composites are favorable to structures subjected to bending. Numerous studies have investigated the material properties of UHPFRC, including mechanical strength, fiber distribution characteristics, shrinkage behavior, bond performance, and durability [6–12], and structural performance with various reinforcements [13–27].

To enhance corrosion resistance of conventional steel bar-reinforced concrete structures in aggressive environments, the use of fiber-reinforced polymer (FRP) rebars has gained the attention of engineers and researchers. The high strength and lightweight characteristics of FRP rebars enables reducing structural weight, and their low elastic modulus contributes to improving the restrained shrinkage performance of concrete with high autogenous shrinkage, such as UHPFRC [9]. However, at serviceability state, the FRP bar-reinforced concrete beams normally exhibit higher deflection and larger crack width than those observed in the case of steel bar-reinforced concrete beams, because of the low elastic modulus of FRP [28]. In order to overcome these drawbacks, several researchers [15,29,30] attempted to use hybrid reinforcements of FRP and steel rebars and strain-hardening UHPFRC. Lau and Pam [29] and Yoon et al. [30] experimentally verified that the low ductility and large deflection of FRP bar-reinforced concrete members are improved when hybrid reinforcements with steel rebars are used. In addition, Ferrier et al. [15] noted that the use of FRP rebars with UHPFRC had the advantage to increase the tensile capacity of the beam, leading to a higher ultimate capacity, and exhibited typical reinforced concrete (RC) beam

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behavior in terms of concrete cracking and failure under tension or compression. However, to the best of the authors' knowledge, no study has reported the flexural behavior of beams made by strain-hardening materials such as UHPFRC with hybrid reinforcements of FRP and steel rebars.

In this study, the authors investigated the flexural response of UHPFRC beams with glass fiber-reinforced polymer (GFRP) rebars and hybrid reinforcements (steel + GFRP rebars). For this purpose, three beam specimens reinforced with one type of GFRP rebars and four other specimens reinforced with a combination of steel and GFRP rebars were fabricated and tested. In addition, the flexural responses of UHPFRC beams reinforced with GFRP rebars and hybrid reinforcements were predicted through a sectional analysis based on AFGC/SETRA and JSCE recommendations [2,31].

2. A state-of-the-art review on reinforced UHPFRC elements

In previous studies, numerous tests were performed to investigate the structural behavior of reinforced UHPFRC under various loading conditions (flexure, shear, torsion, impact, etc.). Yang et al. [14] fundamentally examined the flexural behavior of UHPFRC beams with reinforcement ratios less than 0.02. They reported that all the tested beams exhibited ductile behaviors with the ductility index ranging from 1.60 to 3.75, and that placing concrete at the end of a beam yielded better performance than when concrete was placed at mid-span. Ferrier et al. [17] investigated a new type of hybrid beams made of glued-laminated wood and UHPFRC planks, including steel and FRP rebars, and mentioned that the bending stiffness and ultimate load capacity increased significantly when the wood was hybridized with UHPFRC planks, as compared with when only pure wood elements were used. Yoo and Yoon [27] carried out experimental and numerical studies on the flexural behavior of steel bar-reinforced UHPFRC beams with different steel fibers. They noted that the addition of 2% by volume of steel fibers was effective in improving the post-cracking stiffness and load carrying capacity, and that the use of long straight or twisted steel fibers resulted in higher ductility than that in the case of short straight steel fibers (L_f/d_f = 13/0.2 mm/mm = 65). In contrast to the results obtained by Yang et al. [14], the inclusion of a high volume content (2%) of steel fibers resulted in a decrease in the ductility than that obtained without the fibers, owing to the crack localization properties. Ferrier et al. [15] recently examined the structural response of UHPFRC beams reinforced with carbon and glass FRP rebars and concluded that the carbon FRP rebars were effective in increasing the bending stiffness, leading to a lower mid-span deflection, than in the case of the glass FRP rebar owing to the higher Young's modulus of the former.

Voo et al. [19] investigated shear strength of prestressed UHPFRC I-beams without a stirrup. They reported that the shear strength increased with an increase in the fiber volume fraction and a decrease in the shear span-to-depth ratio (a/d), and the theory of concrete plasticity presented a good basis for their shear design. Bertram and Hegger [20] also reported that the shear strength increased with higher fiber volume fraction and lower a/d ratio; the inclusion of 2.5% of steel fibers resulted in a 177% higher failure load than that without fibers and when the a/d ratio was changed from 3.5 to 4.4, the shear capacity decreased by 10%. In addition, they reported that the shear capacity increased by about 12–14% when the effective prestressing force was increased by 20%, and the size effect on shear strength was more significantly influenced by the beam height than by the web thickness. Baby et al. [21] examined the feasibility of applying a Modified Compression Field Theory (MCFT) for the shear capacity of reinforced or prestressed UHPFRC beams. Based on their analytical results, the MCFT was determined to be applicable for predicting the shear behavior with an effective estimation of the reorientation of the compressive struts with an increase in the load.

Fehling and Ismail [22] investigated the torsional behavior of UHPFRC elements with various volume fractions of steel fibers. They reported that the inclusion of steel fibers was effective in improving the torsional performance, i.e., the cracking and ultimate torsional capacities, torsional ductility, post-cracking stiffness, and toughness. In addition, the use of longitudinal and transverse reinforcements significantly improved the torsional performance. Empelmann and Oettel [16] also observed that the addition of steel fibers (1.5% and 2.5%) resulted in better cracking behavior, i.e., smaller crack widths and more cracks, higher cracking torque, and improved torsional stiffness and ultimate torque; further, the inclination angle was observed to be approximately 45° regardless of the volume fractions of steel fibers. Similarly, Yang et al. [18] reported an improvement in the initial cracking and ultimate torque with an increase in the fiber volume fraction and higher ultimate torque with increases in the ratios of stirrups and longitudinal bars. However, in their study, the angle of the diagonal compressive stress ranged 27–53° and was influenced by the amount of stirrups and longitudinal bars.

Fujikake et al. [23] and Yoo et al. [24] experimentally investigated the impact resistance of reinforced or prestressed UHPFRC beams using a drop-weight impact test machine and predicted the mid-span deflection response using sectional analysis and single- (or multi-) degree-of-freedom system. Yoo et al. [24] reported better performance under impact loading, i.e., lower maximum and residual deflections and higher deflection recovery, with an increase in the longitudinal steel rebars. Aoude et al. [25] examined the blast performance of self-consolidating concrete (SCC) and UHPFRC columns subjected to various blast-impulse combinations using a shock-tube. They noted that reinforced UHPFRC columns exhibited substantially higher blast resistance than did the reinforced SCC columns in terms of decreasing the maximum and residual deflections, enhancing damage tolerance, and eliminating secondary blast fragments. Furthermore, Astarlioglu and Krauthammer [26] numerically analyzed the blast resistance of normal-strength concrete and UHPFRC columns and noted that compared with normal-strength concrete columns, the UHPFRC columns presented lower mid-span displacement and sustained more than four times the impulse.

3. Experimental program

3.1. Materials, mix proportions, and mechanical tests

The detailed mixture proportions are summarized in Table 1. Type 1 Portland cement and silica fume were used as the cementitious materials. Silica sand with a grain size smaller than 0.5 mm was adopted as the fine aggregate, and silica flour with 98% SiO_2 at 2-μm diameter was added as filler in the mixture. The W/B used was 0.2, and 2% of polycarboxylate superplasticizer was incorporated to provide proper fluidity and viscosity. Further, 2% by volume (2 vol.%) of straight steel fibers (diameter: 0.2 mm and length: 13 mm) were added, and the properties of the steel fibers are listed in Table 2.

Table 1
Mix proportions.

W/B(%)	Unit weight (kg/m^3)					
	Water	Cement	Silica fume	Silica flour	Silica sand	SP (%)
20	160.3	788.5	197.1	236.6	867.4	2.0

Note: SP = superplasticizer.