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Fiber Orientation Effect on Flexural Response of UHPFRC

Doo-Yeol Yoo[1], *Min Jae* Kim[1], *Soonho* Kim[1], and *Young-Soo* Yoon[2,*]

[1]Department of Architectural Engineering, Hanyang University, Seoul, South Korea
[2]School of Civil, Environmental and Architectural Engineering, Korea University, Seoul, South Korea

Abstract. This study aims to examine the fiber orientation effect on flexural behavior of ultra-high-performance fiber-reinforced concrete (UHPFRC) with various casting methods and loading rates. For this, two different placement methods were adopted for making UHPFRC beams along with two different loading rates (i.e., quasi-static and impact). Test results indicated that the flexural performance of UHPFRC beams at both quasi-static and impact loads was significantly influenced by the placement method, leading to dissimilar fiber orientation. Better fiber orientation, denoting that more fibers are aligned in the direction of tensile load, exhibited better post-cracking flexural behaviors in terms of flexural strength, deflection capacity, and toughness, compared to poor fiber orientation. Strength enhancement in UHPFRC beams was obtained by increasing the loading rates, and their deflection-hardening behaviors were successfully observed.

1 Introduction

Concrete has been considered as one of the most effective and economical construction materials for a long time. However, terrorist attacks against civilians frequently occur in recent years, and particularly, the normal concrete, which is widely used as a construction material worldwide, is known to be vulnerable under extreme loading conditions, such as impacts and blasts, owing to its brittle nature under tension. To overcome this drawback, an ultra-high-performance fiber-reinforced concrete (UHPFRC), which was developed by French engineers in the mid-1990's, is currently considered as the material applicable for structures subjected to those extreme loads, due to its excellent mechanical strength, energy absorption capacity, durability, and fatigue resistance [1].

Accordingly, in this study, to verify the effectiveness of using UHPFRC under extreme loading conditions, the impact resistance of UHPFRC beams was investigated using a drop weight impact test machine. In addition, in order to compare the impact and static behaviors, quasi-static flexural tests were carried out according to the ASTM standard. For evaluating the fiber orientation effect on the quasi-static and impact behaviors of UHPFRC beams, two different casting methods were considered, and an image analysis was carried out to quantitatively estimate the effects of fiber orientation and number of fibers in unit area on the flexural behaviors.

2 Experimental Program

In this study, Type 1 Portland cement, silica fume, silica flour, and silica sand were used as dry components. Coarse aggregate was excluded from the mixture to achive excellent tensile or flexural behaviors. The chemical compositions and physical properties of the used cementitious materials are given in a previous study [1], and the detailed mix proportions are given in Table 1. High-strength short straight steel fibers with a diameter of 0.2 mm and a length of 13 mm were incoporated into the mixture by 2 vol%, similar to the UHPFRC mixture commercially available in North America. A water-to-binder (W/B) ratio of 0.2 was applied, and 2% superplasticizer was added to improve the flowability.

Table 1. Mixture 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] W/B = water-to-binder ratio and SP = superplasticizer

To investigate the flexural behaviors of UHPFRC beams with various fiber orientations and loading rates, prismatic beams with a cross section of 100 × 100 mm^2 and a length of 400 mm were fabricated. This satisfied the requirements of ASTM C1609 [2] for width and depth sizes of prismatic beams according to the size of fibers. Two different placement methods were adopted. First, concrete was cast at the end of the mold and allowing it to flow, which is called Case_1, and a large amount of concrete was cast at both ends and the center of the mold, which is called Case_2. The detailed casting methods can be found in a previous paper [3]. In order to accelerate strength development of UHPFRC, steam curing with heat (90 °C) was applied for 2 days after initial 24-hour curing at room temperature.

For the quasi-static loading tests, a four-point load was applied according to the ASTM C1609 [2]. A universal testing machine with a maximum capacity of 25 ton was used, and a loading rate of 0.4 mm/min was applied. The clear span length used was 300 mm. For measuring pure mid-span deflection of the beams, a steel plate with two linear variable differential transformers (LVDTs) was installed at the middle height of the beams. The flexural load was measured from the load cell affixed to the cross head.

A drop-weight impact test machine was also used for evaluating impact resistance of UHPFRC beams. The beam size and clear span length were identical to those used in static flexural tests. An 82-kg hammer was dropped from a height of 600 mm, and thus, a potential energy of 480 Jules was provided. A center point load was applied using a blade load with a striking knife-edge end. The impact load was measured from the strain gauges mounted on the hammer. Since the impact load has an inertial load of the beams, two load cells were installed at supports in order to measure the actual flexural stress applied to the beams. The beams reacted in a very short time under impact loads, so that an accelerometer with a capacity of ± 5000 g was applied to measure the mid-span deflection, which was calculated by double integration of the acceleration measured with time. The data were collected by using a dynamic data logger with a rate of 100 kHz.

3 Experimental Results and Discussion

3.1 Fiber orientation

Fig, 1 shows the pictures of cross section and comparative probability density functions (PDFs) of fiber orientation distribution for the Case_1 and Case_2 beams. The Case_1 beams obviously showed a more left-skewed distribution than the Case_2 beams. The more left-skewed distribution denotes better fiber alignment along the beam length. This is consistent with the findings from the pictures of cross section in the beams that better fiber alignment was observed in the Case_1 beams, compared to their counterpart (Case_2). Based on the image analysis, the number of fibers and coefficient of fiber orientation were calculated. The Case_1 beams exhibited higher number of fibers per unit area (47 ea/cm^2) and higher coefficient of fiber orientation (0.660), as compared to those (37 ea/cm^2 and 0.643) of the Case_2 beams.

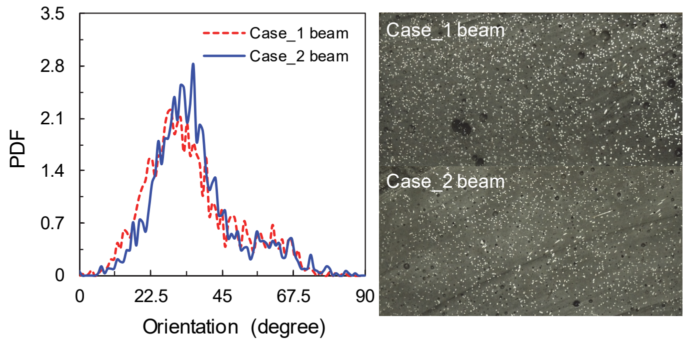

Fig. 1. Fiber orientation distribution

3.2 Flexural behaviors of UHPFRC beams under static and impact loads

The average static flexural stress and deflection curves are shown in Fig. 2. Three prismatic beams were used to obtain the average curve. The flexural stress was calculated by $f = PL/bh^2$, where, P is the applied load, L is the clear span length, b is the width of beam, and h is the height of beam. All of the beams showed a deflection-hardening behavior providing a higher load carrying capacity after the first crack formation. The Case_1 beams provided higher flexural strength and deflection capacity compared to that of Case_2. For instance, the flexural strength of the Case_1 beams was obtained as 36.5 MPa, which is about 37% higher than that of the Case_2 beams. This is caused by the fact that the Case_1 beams had higher numbers of fibers at crack surfaces, due to the better fiber alignment along the beam length, compared to their counterparts. However, the first cracking flexural strength was insignificantly affected by the casting method, because it is more strongly related to the matrix cracking strength rather than the fiber bridging. Due to the better fiber bridging capacity of the Case_1 beams, the higher energy absorption capacity (toughness) was obtained. For example, the toughness of the Case_1 beams at the deflection point of 2 mm, which is $L/150$, was found to be 209 kNmm, approximately 36% higher than that of the Case_2 beams.

The average flexural stress and deflection curves under impact loads are shown in Fig. 3. In this case, three prismatic specimens were also adopted to draw the average curves. Based on a concept of impact behavior of fiber-reinforced concrete (FRC) under flexure [4], the initial peak is related to the first-cracking point in the cement matrix, and the second peak is related to the fiber bridging. It was obvious that the Case_1 beams with the better fiber orientation provided higher first- and post-cracking flexural strengths, compared to those of the Case_2 beams (Fig. 3). In particular, the increased post-cracking flexural strength of the Case_1 beams under impact loading was attributed to the fact that the higher number of fibers more effectively limited the propagation and widening of cracks as compared to their

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counterparts. This is similar results with the case of quasi-static loading conditions. The first-cracking strength was also improved with the better fiber orientation. This is consistent with the findings from a previous study [5]. In their study, the first-cracking strength of UHPFRC under impact loads increased with the reinforcing index, $V_f(L_f/d_f)$, where V_f is the fiber volume fraction, L_f is the fiber length, and d_f is the fiber diameter. The increased number of fibers in unit area for the Case_1 beams led to an increase in the fiber volume fraction in the reinforcing index. Therefore, a higher first-cracking flexural strength was obtained in the Case_1 beams, as compared with the Case_2 beams.

Due to the better impact resistance of the Case_1 beams, a rebound with decreases in both of the flexural stress and deflection was observed. This means that the Case_1 beams were not completely broken under the impact loads with a potential energy of 480 J. On the contrary, the Case_2 beams were completely failed under the impacts with the identical potential energy of 480 J. Therefore, no rebound was observed.

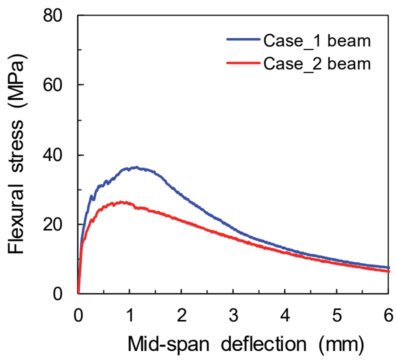

Fig. 2. Quasi-static flexural behaviors

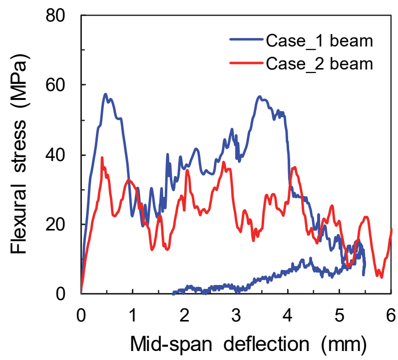

Fig. 3. Impact flexural behaviors

Conclusions

The flexural behaviors of UHPFRC beams under both static and impact loads were investigated with various casting methods. The implications of fiber orientation on the flexural behaviors were also examined based on the image analysis. From the discussions above, the following conclusions were drawn. Better fiber orientation in the longitudinal direction of the beams and a higher number of fibers per unit area were obtained when the concrete was cast at the end of the mold, as compared to pouring a large amount of concrete at both ends and center. Higher static flexural strength, deflection capacity, and toughness were obtained in the beams with better fiber orientation (Case_1). In addition, higher flexural strength and energy absorption capacity were obtained in the beams with better fiber orientation under impact loads. Therefore, it was concluded that providing good fiber alignment in the tensile load direction is effective to improve the flexural performance of UHPFRC under both static and impact loads.

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