Composite Structures 126 (2015) 233–245

Contents lists available at ScienceDirect

Composite Structures

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

Response of ultra-high-performance fiber-reinforced concrete beams with continuous steel reinforcement subjected to low-velocity impact loading

Doo-Yeol Yoo [a], Nemkumar Banthia [a], Sung-Wook Kim [b], Young-Soo Yoon [c,*]

[a] Department of Civil Engineering, The University of British Columbia, 2024–6250 Applied Science Lane, Vancouver, BC V6T 1Z4, Canada
[b] Structural Engineering Research Division, Korea Institute of Construction Technology, Daehwa-dong, 283, Goyangdae-ro, Ilsanseo-gu, Goyang-si, Gyeonggi-do 411-712, Republic of Korea
[c] School of Civil, Environmental and Architectural Engineering, Korea University, 5-ga, Anam-dong, Seongbuk-gu, Seoul 136-713, Republic of Korea

ARTICLE INFO

Article history:
Available online 26 February 2015

Keywords:
Ultra-high-performance fiber-reinforced concrete
Impact
Strain rate
Reinforcement ratio
Sectional analysis
Single-degree-of-freedom

ABSTRACT

To investigate the effect of the reinforcement ratio on the flexural behavior of ultra-high-performance fiber-reinforced concrete (UHPFRC) beams under impact loading, a total of four large-sized (200 × 270 × 2900 mm) beams were fabricated and tested using a drop-weight impact test machine. The incident kinetic energy and impact velocity were 4.2 kJ and 5.6 m/s, respectively. A higher reinforcement ratio exhibited lower maximum and residual deflections and better deflection recovery. The test results also indicate that the maximum crack width at a certain drop stage decreased with the reinforcement ratio. A nonlinear analytical model for predicting the impact behavior of a UHPFRC beam was developed using multi-layer sectional analysis and single-degree-of-freedom analysis, and the model was verified through comparison with the experimental results.

1. Introduction

Recently developed ultra-high-performance fiber-reinforced concrete (UHPFRC) is a special type of ultra-high-strength concrete that includes a high volume of steel fibers. Because it uses a very low water-to-binder ratio (W/B) of 0.2 and includes high fineness additives along with discontinuous steel fibers, UHPFRC exhibits superior strength (compressive strength >150 MPa and tensile strength >8 MPa), ductility and fracture toughness and is also characterized by a strain-hardening response under tension [1]. Therefore, some researchers currently regard it as a promising material for innovative structures subjected to severe loading conditions such as impact, shock, and explosive loadings [2].

Several studies [2–5] have reported that the material and structural behaviors of UHPFRC under a high strain rate are very different from those under a quasi-static loading condition. Unfortunately, however, current understanding of the impact and blast resistances of structural UHPFRC beams under high strain rates is very limited [2,4], compared to that under quasi-static loading conditions [6–8]. Thus, the response of UHPFRC beams under a high strain rate needs to be investigated, and a useful analytical model needs to be developed for the application to the structural elements subjected to various severe loadings.

Accordingly, in this study, the impact response of UHPFRC beams reinforced with steel rebars was investigated. To do this, four large-sized UHPFRC beams with various reinforcement ratios were fabricated and tested using a drop-weight impact test machine. In addition, to predict impact behavior, a nonlinear analytical method, which includes (1) the determination of resistance–deflection models considering the strain rate effect based on multi-layer sectional analysis and (2) the prediction of the deflection–time response using a single-degree-of-freedom (SDOF) system, was developed and verified through comparison with the experimental results.

2. Experimental program

2.1. Materials and mix proportions

The mix proportions used in this study are summarized in Table 1. Type I Portland cement and silica fume were used as cementitious materials. The details of chemical compositions and physical properties of the cementitious materials are listed in Table 2 and also can be found in a previous study [9]. For all test specimens, a W/B of 0.2 was used. Sand with a grain size smaller than 0.5 mm and 2-μm-diameter silica flour with 98% SiO_2 were

* Corresponding author. Tel.: +82 2 3290 3320; fax: +82 2 928 7656.
E-mail address: ysyoon@korea.ac.kr (Y.-S. Yoon).

http://dx.doi.org/10.1016/j.compstruct.2015.02.058
0263-8223/

Table 1
Mix proportions.

Relative weight ratios to cement						Steel fiber (V_f, %)	Flow (mm)
Cement	Water	Silica fume	Sand	Silica flour	Superplasticizer		
1.00	0.25	0.25	1.10	0.30	0.016	2%	230

Where, V_f = volume fraction of fiber.

also incorporated in the mixture (without coarse aggregate). To improve the workability, 1.6% (by cement mass) of polycarboxylate superplasticizer was used, and to improve tensile performance, 2% by volume of micro steel fibers were added. The properties and geometry of the steel fibers are listed in Table 3.

2.2. Mechanical tests

To estimate the compressive behaviors including compressive strength, elastic modulus, and stress–strain response, a total of three cylindrical specimens with a dimension of φ100 × 200 mm were fabricated and tested according to ASTM C 39 [10]. This test was performed using a universal testing machine (UTM) with a maximum load capacity of 3000 kN. To measure the average compressive strain, a compressometer with three linear voltage differential transducers (LVDTs) was installed.

In addition, a total of three prismatic beam specimens with a dimension of 100 × 100 × 400 mm and a 10-mm notch (0.1 × height of beam) at mid-length were fabricated and tested similarly to the test method used by Kang and Kim [11]. A load was applied using a UTM with a maximum load capacity of 250 kN through displacement control. To measure the center deflection, two LVDTs were installed on both sides of the specimen, and to obtain crack mouth opening displacement (CMOD), a clip gage with a capacity of 10 mm was located at the notch. The detailed test setups for both the compression and flexure tests can be found in a previous study [9].

2.3. Details of specimens and test setup for impact loading test

Four large-sized UHPFRC beams reinforced with internal steel rebars were fabricated to investigate the impact behavior. The detailed geometry and arrangement of reinforcements are shown in Fig. 1. Due to the high ductility of UHPFRC resulting from a high volume content of steel fibers, a part of the longitudinal reinforcement can be substituted [6]. Thus, all tested beams used in this study were designed to have a low reinforcement ratio of less than 2%. The test specimens were 2900 mm long with a rectangular cross section of 200 × 270 mm. To provide uniform fiber orientation and dispersion, UHPFRC was placed at the end of specimen and allowed to flow. The specimens were reinforced with one or two layers of reinforcement, and the main variable was the reinforcement ratio. The specimens were divided into two series: a beam series without

Table 2
Chemical compositions and physical properties of cementitious materials.

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 (cm^2/g)	3413	200,000
Density (g/cm^3)	3.15	2.10

Table 3
Properties of steel fiber.

Fiber type	Diameter (mm)	Length (mm)	Aspect ratio (L_f/d_f)	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)
Smooth fiber	0.2	13.0	65.0	7.8	2500	200

Where, L_f = length of fiber, d_f = diameter of fiber.

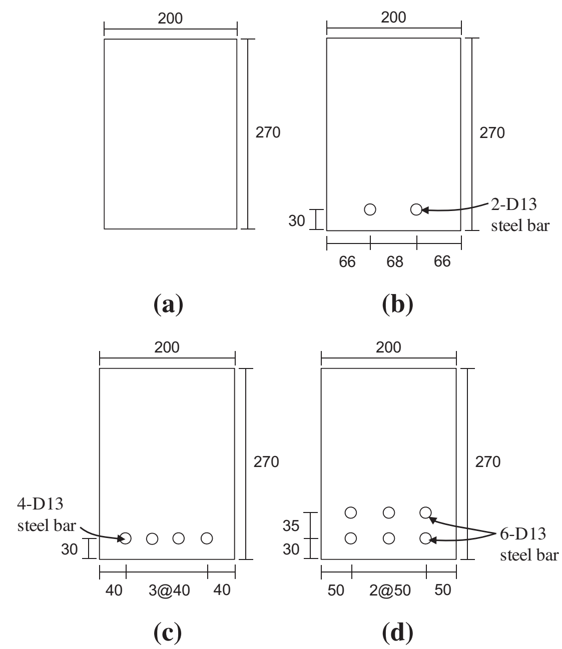

Fig. 1. Section details of impact test program (unit: mm); (a) UH-N, (b) UH-S-0.53%, (c) UH-S-1.06%, (d) UH-S-1.71%.

steel rebar (UH-N) and a beam series reinforced with steel rebars (UH-S-ρ). The letters ρ indicates the reinforcement ratio. A diameter of 12.7 mm was used for steel rebars as longitudinal reinforcements, and the detailed properties of the steel rebar are summarized in Table 4.

For the impact loading test, a drop-weight impact test machine with a drop weight of 270 kg was used, as shown in Fig. 2. A single impact load was applied to the mid-span of the beam by dropping a free-falling drop weight from a constant drop height of 1600 mm, and the striking face consisted of a 20 mm thick and 40 × 210 mm sized rectangular steel plate with a flat contact surface. The clear span length was 2500 mm. The kinetic energy and impact velocity were found to be 4233.6 J (kg · m^2/s^2) and 5.6 m/s, respectively. To obtain the impact load (*force* = *mass* × *acceleration*) and time response for SDOF analysis, an accelerometer with a capacity of ±500 g was affixed to the drop weight. Saatcı [12] has experimentally verified that the calculated impact load from acceleration was almost identical to the measured impact load. Habel and Gauvreau [5] have also used the impact load calculated from acceleration to

Table 4
Properties of steel reinforcing bar.

Rebar type	d_r (mm)	A_r (mm^2)	E_r (GPa)	f_y (MPa)	f_u (MPa)
D13 steel bar	12.7	126.7	200.0	522.7	627.6

Where, d_r = nominal diameter of rebar, A_r = area of rebar.
E_r = elastic modulus of rebar, f_y = yield strength of rebar.
f_u = ultimate strength of rebar.