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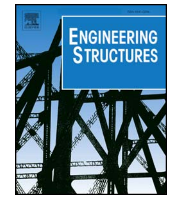

Structural response of steel-fiber-reinforced concrete beams under various loading rates

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ABSTRACT

This study presents the rate-dependent structural behavior of reinforced concrete (RC) beams with and without steel fibers and stirrups. Three different loading rates, i.e., quasi-static, impact, and blast loading, were adopted, and three different volume fractions (v_f) of hooked steel fibers, i.e., 0, 0.5, and 1%, were considered. The test results indicate that the addition of steel fibers enhanced the static, impact, and blast resistances of the RC beams in terms of higher load carrying capacity, higher energy absorption capacity, and lower maximum and residual displacements. However, the inclusion of 0.5 and 1 vol% steel fibers was insufficient to prevent brittle shear failure of the RC beams without stirrups. On the other hand, brittle shear failure was effectively prevented by incorporating stirrups. The beams including both 0.5 vol% steel fibers and stirrups demonstrated the highest performance, regardless of the strain rate in all the three loading conditions. Lastly, the static shear strengths of reinforced steel-fiber-reinforced concrete beams were effectively predicted based on Aoude's model, and the effectiveness of using steel fibers was greatest under the static loading condition, as compared with impact and blast loading conditions.

1. Introduction

Concrete has been widely used for the construction of buildings and civil infrastructure. However, owing to its brittleness and low energy absorption capacity, its application to structures subjected to extreme loadings such as earthquakes, impacts, and blasts has been limited thus far. In order to overcome this drawback, numerous researchers [1–11] have added discontinuous fibers into the mixture because the addition of steel fibers generally increases the ductility of concrete. Yoo et al. [1] experimentally analyzed the impact response of ultra-high-performance concrete (UHPC) beams with various steel fibers by using a drop-weight impact machine, and reported that the addition of steel fibers was effective in decreasing residual displacement, enhancing residual capacity after impact damage, and preventing local failure at the contact surface between the drop hammer and concrete beams. Zhang et al. [2] and Kantar et al. [3] also reported that steel fibers enhance ductility and impact resistance of concrete. However, adding fibers beyond the critical content does not significantly increase structural capacity [12,13]. Therefore, selecting the optimal fiber content is critical for engineers to provide safe and economical design.

For these purposes, numerous studies of steel fiber reinforced concrete (SFRC) have been conducted. These studies verified the advantages of using steel fibers in structural members and provided prediction models to estimate the contribution to structural capacity. As a result of these efforts, design guidelines and provisions for the use of SFRC in beams have been proposed in several countries by researchers and standards [12,14–19]. Choi et al. [14] theoretically predicted the shear strength of slender SFRC beams (beam span–depth ratio, $a/d > 2.5$) and demonstrated that the proposed strength model predicted the test results of SFRC beams more accurately than existing shear strength models. Majdzadeh et al. [20] also proposed a shear strength model of SFRC and determined that 1% fiber volume fraction was optimal; no benefits were noted when the fiber volume fraction was increased beyond 1%. However, despite numerous studies, practical applications of SFRC for protective structures still have limitations because the most of the studies on SFRC have been performed under static loading condition. Banthia [21] performed high strain rate tests on FRCC (fiber reinforced cementitious composite) beams using modified Charpy pendulum machine and reported that the results of the high strain test varied from those of static tests in terms of effectiveness of fiber reinforcement. Saatci et al. [22] experimentally investigated the shear mechanisms of impact behavior of RC beams and concluded that

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the prediction model is to consider shear mechanisms notwithstanding whether the member is flexure-critical under static load because the failure mode can be altered by strain rate. Therefore, to gain wider acceptance for the structural use of SFRC, further research is required to accumulate test data and study the effect of steel fiber in SFRC beams considering various strain rates.

Accordingly, in this study, static, impact, and simulated blast tests were carried out on reinforced concrete and SFRC beams, to investigate the effect of hooked steel fibers on their static and dynamic behavior. In addition, the structural responses of RC beams with and without stirrups, under various loading conditions, were examined to evaluate the effectiveness of incorporating stirrups.

2. Research significance

The significance of this research is that three loading rates (i.e., static, impact, and blast) were applied to RC beams to evaluate the shear contribution of steel fibers and stirrups. In a majority of the previous studies [1–11], impact and blast tests were performed on RC beams or slabs made from various materials, to examine the influence of the material type. Furthermore, as the structural behavior of SFRC beams is substantially affected by the beams' span–depth ratio (a/d) [12,15], structural tests are to be conducted on test specimens with similar beam span–depth ratios (a/d). However, studies on identical specimens under various loading rates are few.

Accordingly, in this study, fifteen reinforced SFRC beams with identical beam span–depth ratio (a/d) were fabricated and tested under static, impact, and blast loads, in order to investigate the implication of steel fibers and stirrups on the structural behavior of RC beams under various loading rates.

3. Experimental program

3.1. Details of test specimens

The experimental program consisted of three phases: static, impact, and blast tests. Fifteen reinforced SFRC beams, divided into three groups, were fabricated and tested under various loading rates to investigate the effect of steel fibers and shear reinforcement in RC beams. The details of the specimens are listed in Table 1. The fiber volume fraction and details of shear reinforcement were considered as variables. As illustrated in Fig. 1, all specimens were 125 mm in width, 250 mm in height, and 2438 mm in length, and longitudinal reinforcements, which consisted of two deformed steel reinforcing bars of diameter of 19.1 mm (denoted as D19). This amount of flexural reinforcement was selected to ensure the occurrence of shear failure prior to that of flexural-failure (shear-bending capacity ratio $\alpha = 0.42$). The ends of the longitudinal reinforcements had 90° hooks to ensure the full development length. Two specimens of each test series incorporated shear stirrups that were designed according to the minimum shear requirements of CSA A23.3-2014 [18] and were composed of 8 mm non-deformed steel wires ($\alpha = 1.91$). They were conventional U-shaped open stirrups and spaced at 125 mm along the shear span of the specimens.

Table 1
Beam and concrete properties.

Specimen	Fiber content, V_f (%)	Transverse reinforcement spacing, s (mm)	Compressive strength, f_c' (MPa)	Modulus of rupture, f_{rp} (MPa)	Modulus of elasticity, E_c (GPa)
SFRC-0%	0.0	–	42.20	7.58	36.45
SFRC-0%-S		125			
SFRC-0.5%	0.5	–	42.41	7.29	35.81
SFRC-0.5%-S		125			
SFRC-1.0%	1.0	–	44.27	9.73	38.65

3.2. Material properties

The concrete properties and mix proportions are summarized in Tables 1 and 2. All specimens were fabricated with an identical mixture that had a water-to-cement ratio of 0.43, sand-to-aggregate ratio of 0.88, and maximum aggregate size of 15 mm. Moreover, 30 mm hooked-end steel fibers were used in the concrete, and the fiber content varied among 0, 0.5, and 1.0%. The compressive and flexural strengths were measured based on ASTM C39 [23] and C1609 [24], on cylinders with a diameter of 100 mm and height of 200 mm, and beams with a cross-section of 100 × 100 mm and a length of 400 mm. In order to ensure a generality of structural tests, the D19 Grade 400 Korean Standard (KS) deformed reinforcing bars, practically used in construction field, were used as the longitudinal bars for all specimens. 8 mm non-deformed steel wires (N8) were used for transverse reinforcements. Steel coupons for each type of reinforcing bars were tested to evaluate the mechanical properties of reinforcing bars in accordance with ASTM A1035/A1035M [25]. The properties of the fibers and reinforcements are presented in Tables 3 and 4 and Fig. 2.

3.3. Test procedure

3.3.1. Static test

Static four-point flexural tests were carried out on the five specimens with quasi-static loading rate of 0.02 mm/s. As part of the tests, deflections and strains were measured, and crack patterns were also examined. The pure mid-span deflection, excluding the support settlement, was measured by linear variable differential transducers (LVDTs). Electrical resistance strain gauges were glued to the centers of all the longitudinal reinforcements. The clear span was 2222 mm, and the distance from the loading plates to the supports was 743 mm, resulting in a clear shear span–depth ratio (a/d) of 3.7. A universal testing machine (UTM) with maximum load capacity of 2800 kN was used for applying monotonic flexural loads, and 160 × 25 mm steel bearing plates were placed at the location of the loading and supports to prevent local crushing of the concrete.

3.3.2. Drop-weight impact test

The test setup for the drop-weight impact test is illustrated in Fig. 3, and the boundary conditions of the impact tests were similar to those of the static test. The test setup consists of several components: guide beams, drop hammer, and supports. The guide beams were fabricated using two steel H-beams (150 × 150 × 75 mm). The centers of the guide beams were aligned with the center of the specimen. The hammer was composed of three components: mass blocks, guide blocks, and a weight tup. The mass blocks were fabricated by bolting several rectangular steel blocks. The mass of the hammer could be adjusted by varying the number of bolted blocks. The guide blocks were attached to the mass block, and aided the hammer to drop along the guide beams. The guide blocks were covered with Teflon plates to reduce friction between the guide blocks and guide beams. The drop weight tup was hemispherical, with a diameter of 150 mm. The supports were fixed on the strong floor of the laboratory and designed to prevent rebounding of the specimens under impact load. A laser LVDT was located at the center of the specimen to measure the maximum and residual displacement at the center of the specimen. Two load cells of capacity 490 kN were mounted on the supports to measure the reaction forces, and a load cell of capacity 1960 kN was used in the drop-weight to measure the impact force. The laser LVDT and load cells were connected to a dynamic data logger (DEWE-43V, Dewesoft). The sampling rate of the data logger was 200 kHz. Under this sampling rate, two hundred data points can be scanned per millisecond. In the drop weight system, an impact load can be applied by dropping a weight on the specimen, and the magnitude of the applied impact load can be adjusted using various methods: by varying the mass of the weight, adjusting the drop height, or regulating the initial dropping speed. In this