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Fire resistance of steel fiber reinforced concrete beams after low-velocity impact loading

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ABSTRACT

Engineering structures in the city environment surrounded with combustible materials are prone to be in the danger of combined effects of blast-induced impact loading and fire. Four steel-fiber reinforced concrete (SFRC) beams were tested after pre-impact loading (impact velocity = 5.4 m/s) to explore their fire-resistance. The beams were first subjected to impact loadings and then exposed to fire with a constant load. The failure patterns of beams were observed, and the time histories of mid-span deflections, temperature field as well as rebar strains were recorded. Moreover, the fire resistance of these beams were discussed. A three-dimensional finite element numerical model considering the effects of strain rate and high temperature were established. In the simulations, a two-step analysis method was utilized. In the first-step, the impact loading process was simulated. While, in the second-step, and the failure behavior of the SFRC beams subjected to both fire and constant mechanical loading was modeled with a sequentially coupled thermal-stress analysis method, in which the simulation results obtained in the first-step were taken as the initial state. Good agreement between the simulation results and the test results illustrates the validation of the simulation method. It is found that the failure patterns of SFRC under the low-velocity impact load is altered from shear type to bending type with the increase of steel fiber dosage. When the impact energy is relative lower, though weakened by the pre-impact, the beam still work in an elastic stage and shows good fire resistance. Moreover, limited to the low-energy impact conditions, the influence of steel fiber content on the thermal and mechanical behaviors of damaged beam can be ignored.

1. Introduction

Reinforced concrete (RC) structures may be subjected to the risks of a variety of loadings during their service life [1], such as normal service loads, earthquake, fire and impact loadings, etc. In the cases that structures are exposed to two or more types of loadings, severe damage may occur. Among these, engineering structures in the city environment surrounded with combustible materials are more prone to be in the danger of combined effects of impact load and fire load for the reason that blast-induced impact and fire always take place concomitantly. In addition, concerns about structure safety under explosion/blast and fire have been further aroused in academia and engineering ever since the World Trade Center terrorist attack in New York city and the explosion accident in Tianjin Binhai New Area of China [2,3].

The effects of mechanical loading, especially the dynamic loading involving earthquake, impact and explosion, however, is almost completely distinct from that of fire. The dynamic loadings are always short-term and transient while the fire is long-term and slow. Accordingly, the failure mechanisms of engineering structures under the aforementioned two kinds of loadings are quite complicated and different from each other. Over the past few decades, mechanical behavior of engineering structures subjected to various loadings has been investigated separately for simplicity [4–8].

In light of that, studies on a single load are far from meeting the requirements of engineering design and analysis, and thus a lot of researchers started to explore the combined effects of two or more types of loadings. Currently, more studies have been focused on the effects of temperature and strain rate on the dynamic properties of concrete material [9–16] while fewer efforts have been devoted to explore the performance of building members. Miao et al. [17] and Miao et al. [18] conducted on a series of experimental and numerical investigations on the fire resistance of RC beams with damages caused by service loadings. It has been found that the fire resistance of RC members is reduced

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significantly by the involved damages. Through a set of full-scale loading tests on an earthquake damaged RC frame subsequently exposed to fire, Kamath et al. [1] have found that the presence of cracking caused by simulated earthquake loading in the RC members does not exacerbate the fire damage while heat transfer in beams and columns would be accelerated by the cracking. Based on the experimental data, Ruan et al. [2] improved the damaged plasticity model to consider the coupling effects of high temperature and high strain rate in concrete. The dynamic responses of RC columns subjected to fire and blast were then investigated numerically. Pan et al. [19] and Zhai et al. [20] conducted a comprehensive study by experimental, numerical and theoretical methods and they all found that after fire exposure, the residual bearing capacity of RC beams is degenerated significantly while the ductility is increased. What's more, the degree of bearing capacity degradation increases with increasing the steel reinforcement ratio. Except for RC members, under combined effects of blast and fire, the mechanical performances of concrete-filled tubular, steel and pre-stressed concrete members have been investigated by Huo et al. [21], Fang et al. [22] and Choi et al. [23], respectively.

It can be concluded from the abovementioned publications that studies on building members exposed to the combined effect of dynamic loadings and fire load are quite rare and scattered. Therefore, further investigations are still in need. Furthermore, it has been realized that the introduction of fibers (e.g., steel fiber and polyvinyl alcohol fiber, etc.) into concrete can increase its tensile strength, ductility and energy dissipation capacity, resulting into a good performance to resist against impact loadings [24]. Similar to those of the ordinary concrete, there are far more studies concentrated on fiber reinforced concrete material and almost all of them separately consider the effects of strain rate and high temperature [25–29].

In Jin et al.'s work [30], the impact resistance of 12 simply-supported steel fiber reinforced concrete (SFRC) beams with different stirrup ratios (0%, 0.253% and 0.502%) and different volume fractions of steel fibers (0%, 1%, 2% and 3%) were tested under a relatively high energy. A corresponding 3-D finite element simulation was also carried out. It has been found that the impact resistant performance of SFRC beams, such as crack pattern, ductility, energy consumption capacity, and deformation recovery capacity can be improved by the addition of steel fibers.

In view of the facts already outlined, the main objective of the present study is to explore the fire resistance of SFRC beams after low-velocity impact. Four SFRC beams were tested with high-performance drop-weight test system firstly and then their fire resistance were examined. During the experiment, the failure patterns of beams were observed as well as the time histories of mid-span deflections and steel rebar strains were recorded. Moreover, a three-dimensional finite element numerical model considering the effects of strain rate and high temperature were established. In the simulations, a two-step analysis method was utilized. In the first-step, the impact loading process was simulated. While, in the second-step, and the failure behavior of the SFRC beams subjected to both fire and constant mechanical loading was modeled with a sequentially coupled thermal-stress analysis method, in which the simulation results obtained from the first-step were taken as the initial state. The simulation results were compared with those observed from the test to further understand the fire resistance performance of SFRC beams with damages caused by impact loading.

2. Experimental programme

2.1. Materials and test specimens

The materials utilized for SFRC include ordinary Portland cement, fine river sand with a fineness modulus of 2.9 and river gravel of 20 mm maximum nominal size. A superplasticizer containing 40% poly carboxylic acid was used in all the concrete mixtures to guarantee the slump of SFRC and water reduction rate can reach up to 30% when the dosage of superplasticizer is 0.5%. The steel fibers employed in SFRC were hook-end corrugated fibers with a length of 30 mm, a diameter of 0.6 mm and an aspect ratio of 50, whose yield strength is 1100 MPa. The volume fractions of steel fibers for beams B-0, B-1, B-2 as well as B-3 were 0%, 1%, 2% and 3%, respectively. The mix proportion was determined according to the procedures defined in "Technical Specification for Fiber Reinforced Concrete Structures" of China [31]. For all the four cases, the water-to-cement ratio and sand-to-aggregate ratio were kept as 0.3 and 0.4, respectively. In particular, it is specified that when the aspect ratio of steel fibers are in the range of 35–55, the amount of water utilized for 1 m^3 concrete should be increased by 7–9 kg for each 0.5% of the increase in steel fiber volume fraction [31]. Thus, the amounts of materials for each case were different and the final mix proportions are tabulated in Table 1.

To make the fibers distribute uniformly, a mortar mixer and the following mix procedures were adopted. The sand and 25%–30% of water were first put in and stirred for 2 min. Next, the cement was added into the mixer and stirred for 2 min. Then the gravel and 1/3–1/2 of fibers were added and mixed for 2 min. Next, the superplasticizer was dissolved in the remaining water, and then added into the mixer and stirred for 2 min. Finally, the remaining fibers were added into the mixer, followed by stirring for 2 min, at which point the whole mixing process was considered complete.

After the mixing process, the cubic samples and beam specimens were casted and cured for a period of 28 days following same procedures. The corresponding compressive strengths of the standard concrete cube samples with a size of 150 mm × 150 mm × 150 mm are also given in Table 1. Each data point in the table is averaged from three samples.

Four SFRC beams were designed according to "Code for design of concrete structures" of China (GB 50010-2010) [32] to test their resistance performance against low-velocity impact and fire. Geometric properties and the detailed reinforcement layout of the beams are illustrated in Fig. 1. It can be seen from Fig. 1 that all the specimens have rectangular sections. The length, width and height of the beams are 2800 mm, 200 mm and 400 mm, respectively. The thickness of concrete cover for longitudinal rebars is 30 mm. Three steel bars with a diameter of 25 mm were employed as main rebars while two rebars of 16-mm diameter were arranged as erective reinforcement. Stirrups were made from rebars of 8-mm diameter, spaced at 150 mm. All stirrups were fixed by welding them to the longitudinal rebars (i.e., the main and erective rebars). The longitudinal reinforcement ratio and stirrup ratio for the beams are 2.01% and 0.337%, respectively. The grades for the longitudinal rebars and stirrups are HRB400 and HPB300. HRB400 and HPB300 are respectively hot-rolled ribbed-steel bar with designed average yield

Table 1
Mix proportions of the steel fiber concrete.

Series code	Steel fiber		Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Super plasticizer (kg/m^3)	Compressive strength (MPa)
	Volume fraction	Mass (kg/m^3)						
B-0	0%	0	154	513	672	1096	3.6	41.90
B-1	1%	78	164	547	696	1044	8.2	42.47
B-2	2%	156	180	600	668	1002	9.0	52.18
B-3	3%	234	196	653	640	960	9.8	60.34