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Experimental and numerical investigation into RC beams subjected to blast after exposure to fire

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ABSTRACT

RC structures may be exposed to fire and blast due to accidents or terrorist attacks during the service life. To investigate the performances of RC structures subjected to blast loadings after fire exposure, a series of model tests on RC beams were carried out. The beams were firstly fired on three surfaces following the temperature time history suggested by ISO384 in a furnace and blast tests were then performed by a developed blast test setup. An FE model was developed to further study the heat transfer process and dynamic response of the RC beams after numerical simulation of exposure to fire by software ABAQUS. The developed numerical method was validated against the test data. Experimental and numerical results showed that more and more cracks emerged at the mid-span zone of the beam under blast loadings as the fire duration increased, and the peak and residual displacements of the RC beam increased nearly linearly with the fire duration. RC beams after fire exposure suffered greater blast-induced damage than those were not exposed to fire.

1. Introduction

Reinforced concrete (RC) structures may be exposed to extreme hazards such as fire, earthquakes and terrorist blast attacks during the service life. The accidental fire usually induces explosion in the city environment surrounded with combustible materials, and vice versa [1]. It leads to the fact that the RC structures are in danger of combined effect of fire and blast. However, safety concern about combined effect of fire and blast that significantly aggravates the damage of RC structures has been greatly aroused by scientists and engineers ever since the 9/11 terrorist attack in New York.

Unfortunately, the dynamic performances of RC structures subjected to blast or fire have been studied individually during the past several decades. The existing investigations into combined effect of blast and fire are very limited, and the available literatures mainly focused on steel structures. An integrated adaptive method for fire and explosion analysis on steel frames was put forward by Song and Izzuddin [2,3]. It took high temperature and high strain rate effects on steel material into consideration. The approach was able to predict the behaviors of steel frames under fire that had been damaged previously by blast loadings. Wang et al. [4] theoretically calculated the responses of simply supported steel beams subjected to blast loadings in the environment of elevated temperature. The related material parameters such as Young's modulus and yield stress varying with the temperature were considered in the analysis. A fiber element approach in ABAQUS to predict the dynamic performances of steel frames under blast loadings and post-explosion fire was firstly proposed by Liew and Chen [5] and then the mixed element approach on fire analysis of steel frame after subjected to explosion was also presented [6]. The vibration frequency and amplitude of steel columns under the coupled action of heat and force were theoretically deduced by Sun and Nuo [7]. A three-step explicit numerical method based on the layered Timoshenko beam element approach was proposed by Fang et al. [8,9] to analyze the fire resistance of steel members after explosion. The calculated results were validated by the existing test data. A fire resistance experiment was conducted by Yu et al. [10] on the steel T joint after damaged by explosion, and a validated numerical model was further developed.

The available literatures, especially the test data, focused on the RC structures under blast and fire are very limited comparing to those on steel structures. The dynamic behaviors of concrete material after exposure to high temperature up to 700 °C were experimentally investigated using a Split Hopkinson Pressure Bar [11]. The results revealed that the DIF (Dynamic Increase Factor) of fire-damaged concrete decreased with the ever-experienced high temperature. The dynamic properties of normal weight concrete at elevated temperature from 20 °C up to 950 °C were systematically studied using a specially manufactured microwave-heating automatic time-controlled Split Hopkinson Pressure Bar (MATSHPB) by Chen et al. [1]. It was reported that the failure phenomena and DIF of normal concrete under both high strain rate and high temperature were significantly different from those of concrete at ambient temperature.

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The empirical relations on dynamic increase factor of compressive strength and secant elastic modulus of normal concrete at elevated temperature were presented. Kakogiannis et al. [12] studied the load bearing capacity of the RC hollow core slabs firstly subjected to fire and then to blast loadings experimentally and numerically. They pointed that the crack patterns and dynamic responses were indeed altered after suffering fire exposure, e.g. the eigen frequency lowered down and the maximum dynamic deformation increased. However, the considered highest temperature is only 450 °C that is too low for a real fire disaster. Fang et al. [13] extended the layered Timoshenko beam element approach [9,10] to predict the deformation and fire resistance of RC beams firstly subjected to explosion after exposure to fire. Ruan et al. [14] proposed a numerical approach in ABAQUS to predict the dynamic behaviors and failure modes of RC columns subjected to gas explosion after exposure to fire, although it still requires numerous experimental validation.

Actually, the in-situ blast tests were difficult to be conducted during a standard fire in the laboratory. The blast loads would inevitably damage the fire furnace. It has been proved that the quasi-static properties of concrete only depend on the ever-experienced highest temperature [1]. Thus, the blast-resistant tests on RC structures after exposure to fire would also shed light on the blast-resistant performances under fire.

In order to investigate the performances of RC beams subjected to blast after exposure to fire, a series of in-situ blast tests on RC beams were conducted in this study. The RC beams were firstly heated in a gas furnace. After cooling to the ambient temperature, the beams were then exposed to explosion in a specially designed test frame. The histories of temperature distribution in the beams, the overpressure time histories on the beam surface, and the displacements time histories of the beams were recorded. A UVARM subroutine was developed in ABAQUS to calculate the peak temperature filed within the RC beam cross-section during the heating and cooling process, and a fine finite element model was developed in ABAQUS to further reveal the blast-resistant performances of the RC beams after exposure to fire. The comparison between the numerical predictions and test results, and some discussions were given.

2. Test program

2.1. Specimen preparation

The tested RC beams are 2500 mm long with square cross section of 200 mm side length. Fig. 1 shows the details of the beams. The longitudinal reinforcing bars are HRB400 grade. The shear stirrups are HRB235 grade. The longitudinal and shear reinforcement ratio is 1.17% and 0.19%, respectively. The concrete cover depth of the longitudinal bars is 20 mm.

The beams were casted with normal strength concrete (NSC) of C30 grade, which was made by PII 42.5R Ordinary Portland Cement and carbonate aggregate. The fineness modulus of fine aggregate (river sand) was 2.6, and the diameter of coarse aggregate (basalt rubble) ranged from 5 mm to 32.5 mm. The detailed mix proportion is given in Table 1.

Table 1
Mix proportion (kg/m^3).

Water	Cement	Silica fume	Mineral fine	Fine aggregate	Coarse aggregate
184	284	44	72	767	1150

The specimens were moistly cured in the moulds for 28 d. Laboratory tests were conducted to get basic material mechanical parameters. The average compressive strength of the 150 mm cubic concrete specimen was 32.40 MPa according to Chinese standard GBJ81-85. The average yield strength of the longitudinal reinforcing bars and stirrups was 540.1 MPa (ϕ10 mm), 451.4 MPa (ϕ16 mm) and 492.2 MPa (ϕ6 mm), respectively, whilst the corresponding ultimate strength was 619.4 MPa (ϕ10 mm), 620.5 MPa (ϕ16 mm) and 716.9 MPa (ϕ6 mm).

2.2. Measuring instrumentation

The 0.91 mm thick type-K Chromel-alumel thermocouples were fixed at the mid-span section in each specimen to record the temperature time histories of concrete and rebar during fire exposure, as shown in Fig. 2. Each beam was instrumented with six thermocouples; the location and numbering of the thermocouples in the cross section are shown in Fig. 2b.

The PCB B102 series pressure transducers were used to record the overpressures on the specimen. The WYJL-300 (LVDT) displacement transducers were used to measure the dynamic displacement. The installation and location of the pressures and displacement transducers are described in Fig. 3a. The transducers were mounted at even space of 380 mm from mid-span to the end of the beam. Fig. 3b and Fig. 3c present the photos of the position of the pressure and displacement transducers. Data acquisition instrument DH-5927 (up to 200 KHz sampling frequency, Fig. 3d) was used to deal with the captured signal.

2.3. Fire and blast test setup

The fire and blast tests were arranged subsequently to fulfill the purpose of the study. The fire tests of the RC beams were carried out using a gas furnace commissioned at Southeast University in Nanjing, China, as shown in Fig. 4a. The furnace fueled with natural gas has the maximum heating power of 2.5MW that is capable of maintaining the standard temperature time history suggested by ISO834. The chamber of the furnace is 3 m wide, 4 m long, and 2 m high, which was constructed with firebricks. Four gas burners located within the furnace provide thermal energy, while the four thermocouples distributed around the chamber to monitor the temperature during heating and cooling process. The monitoring data are used to adjust the fuel supply, and maintain predetermined temperature time history. Small view ports on either side of the furnace wall are feasible for visual observation of phenomena on testing specimens.

The blast tests on the RC beams were carried out in a specially designed setup, as shown in Fig. 5a. It was constructed in a pit and consisted of the supporting bracket and mounting frame, as shown

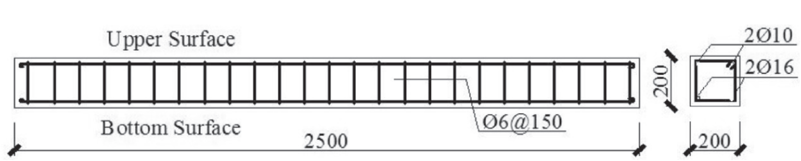

Fig. 1. Details of tested beam/mm.