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Experimental and numerical investigations of fire resistance of continuous high strength steel reinforced concrete T-beams

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ABSTRACT

This paper presents experimental and numerical results of performance and fire endurance of high strength steel reinforced concrete (RC) continuous T-beams under the standard ISO 834 condition. The fire tests included six specimens using steel reinforcement of 500 MPa yield strength with different load levels and reinforcement ratios. In all cases, the failure mode was flexural failure due to the formation of a plastic hinge mechanism. However the sequence of plastic hinge appearance was different from that at ambient temperature due to the increased support bending moments in fire as a result of restrained thermal bowing. Formation of a plastic hinge mechanism indicates sufficient reinforcement ductility to enable complete redistribution of bending moments and absence of any buckling failure of the T-beam stem in the compression region at very high temperatures. The load ratio was the most critical design parameter, with the fire resistance times of the specimens being146 min, 93 min and 64 min for load ratios of 0.3, 0.5 and 0.7 respectively. For the T-section, the temperature field of the flange plate was similar to that of a one-side fire exposed RC slab, and that of the web similar to that of a three-side fire exposed RC rectangular beam. Further numerical simulation results using steel reinforcement of 690 MPa yield strength confirm that continuous, high strength steel reinforced concrete T-beams can be designed using plastic analysis.

1. Introduction

Reinforced concrete (RC) structural systems are commonly used in high-rise buildings. They are required to achieve sufficient fire resistance because fire represents one of the most severe environmental conditions to which building structures may be subjected in their life time.

Many practical RC beams are designed as continuous beams owing to their structural efficiency compared to simply supported beams. However, continuous RC beams have more complicated fire behaviour than their simply supported counterparts, primarily due to the effects of moment redistribution as a result of restrained thermal bowing. A summary of the previous research studies on continuous RC beams in fire in Table 1 shows that a large number of fire tests have been conducted on such beams. These fire test results, and the analysis results by others, such as Gustaferro et al. [1], Desai [2], Talamona et al. [3], Riva and Franssen [4], El-Fitiany et al. [5], Wang et al. [6], indicate that the final failure mode of continuous RC beams in fire is the formation of a complete plastic hinge mechanism with unlimited moment distribution. This conclusion has formed the basis of a number of design methods for the fire resistance of continuous RC beams.

This was possible because the reinforcement used had relatively low strengths and all the beams achieved flexural bending failure. However, Table 1 shows that the highest yield strength of reinforcement in the fire tests on continuous RC beams was 420 MPa. With steel reinforcement of higher yield strength of 500 MPa being commonly used in RC beams, it is necessary to conduct new fire tests and new analysis to cheque whether the same failure mechanism, hence the same design rules, can be applied to continuous RC beams with higher yield strength reinforcement steel.

Furthermore, the cross-section of many RC beams is T shape. When used in continuous construction, the stem of the T-section in the hogging moment region is in compression. The high temperature and narrow width of the stem may induce different behaviour such as lateral buckling. New research is necessary to establish the T section dimensions under which lateral buckling of the stem does not occur. Against this background, this paper reports the results of new fire resistance tests on two-span

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Table 1
Summary of previous experiments on RC beams exposed to fire or after exposure to fire.

Reference	Nominal yield strength of steel reinforcement (MPa)	Concrete compressive strength (MPa)	Type of beams	Section type	Fire condition	Final failure mechanism
Lin et al. [14], 11 tests	420	–	Interior span plus two cantilever spans	Rectangular	Interior span exposed to fire	Flexural failure
Ellingwood et al. [15], 6 tests	420	27.6	Interior span plus one cantilever span	Rectangular	Interior span exposed to fire	Flexural failure
Shi et al. [16], 6 tests	270	29.5	Two continuous spans	Rectangular	Single span or both spans exposed to fire	Formation of plastic hinge mechanism
Dwaikat and Kodur [17], 6 tests	420	52.2 or 93.3	Simply supported or single span with axial restraint	Rectangular	Exposed to fire	Flexural failure
Wang et al. [6], 5 tests	500	42.7	Simply supported beam	Rectangular	Exposed to fire	Flexural failure
Miao et al. [10], 7 tests	400	31.0	Simply supported beam	Rectangular	Exposed to fire	Flexural failure
Xiang et al. [18], 4 tests	335	38.5	Two continuous spans	T-section	After exposure to fire	Flexural failure or tensile failure of CFRP
Yu et al. [19], 7 tests	235	30.0	Two continuous spans	Rectangular	After exposure to fire	Formation of plastic hinge mechanism

"-" Not provided.

continuous RC T-beams using steel rebars of nominally 500 MPa in yield strength. To extend the scope of the fire tests to investigate the effects of changing other design parameters, the test results are used to validate a finite element simulation model using ABAQUS. The validated numerical simulation model is then used to examine the failure mechanism of continuous RC T-beams with reinforcement steel yield strength of 500 MPa and 690 MPa.

2. Experimental programme

2.1. Test specimens

Six continuous RC T-beams (to be referred to as GB1–GB6) with steel reinforcement bars of 500 MPa in nominal yield strength were prepared and tested at ambient and in fire. All these samples were designed with the same geometry according to the specifications of the Chinese Code for design of concrete structures (GB 50010–2010) [7] as shown in Fig. 1 which gives the detailed geometry and arrangement of reinforcement. Among these specimens, GB1 and GB2 (duplicate) were tested at ambient temperature to obtain the ultimate capacity of the beams at room temperature. GB3, GB4 and GB6 had the same reinforcement ratio of 0.7% but different load ratios (defined as the applied load in the fire test to the ambient temperature capacity), the load ratio being 0.3, 0.5 and 0.7 respectively. Specimen GB5 had a reinforcement ratio of 1.0% and was subjected to the same load value with specimen GB4. The middle support was inside the furnace. To avoid its failure and also to improve accuracy of measurements for the support reactions, the middle support was suspended, as detailed in Fig. 2. Fig. 3 illustrates the test set up.

2.2. Material properties

All samples were cast with commercial concrete. The measured cube compressive strength at ambient temperature at 28 days was 64.5 MPa, and the elastic modulus was 35,800 MPa. Table 2 lists the measured properties of the different grades of steel reinforcement used in different locations of the specimens.

2.3. Instrumentation

The experiments were carried out in the horizontal furnace at Southeast University, Nanjing, China, with the test setup shown in Fig. 3. In the fire test, loads were applied at the middle of each span to pre-defined values and kept constant before starting the fire. An I-shape beam was laid below the loading jack to spread the load evenly to the concrete slab. Load cells were placed at each support and each load point to record the actual applied loads and reactions. Displacement transducers were attached to the supports and the load points to monitor the vertical displacements at these locations and the axial displacements at both ends.

2.4. Temperature measurement arrangement

The furnace temperature followed the ISO-834 standard fire curve. During the experiment, fire exposure was on the bottom side of the continuous T-shape beam flange and three-sides of the T-stem. The top side of the beam was in contact with the ambient temperature air and the beam ends were insulated.

Due to symmetry, temperature measurements were taken in only one span of the test beam. Fig. 4 shows the locations of the thermocouples in the concrete T-beam and in the steel reinforcement. Nickel chromium alloy thermocouples, with a temperature range from −200 °C to 1100 °C, were used. For specimens GB1 and GB2 tested at room temperature, strain gauges, instead of