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Fire response of exterior reinforced concrete beam-column subassemblages

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ABSTRACT

Investigating the structural response of reinforced concrete beam-column sub-assemblies at elevated temperatures is the purpose of this paper. This goal was achieved by conducting the ISO-834 standard fire test on two identical one-third scaled reinforced concrete beam-column subassemblage test specimens. The test specimens, which each consisted of one reinforced concrete cantilever beam anchored at the mid-height of a reinforced concrete column, were installed together in a full scale furnace and subjected to downward and upward service loads, respectively. The fire compartment fully engulfed the cantilever beams (except the beams' top face and the loading points), the beam-column connections and the lower columns. The fire test terminated after 74 min as soon as the tensile longitudinal steel bars of the upward-loaded cantilever beam attained the predefined critical temperature 530 °C. The lower columns exhibited partial concrete spalling and typical diagonal cracks appeared at the beam-column connections. Based on the recorded internal temperature distributions at the joint cores it was found that the material strength loss in the fire had insignificant impact on the load bearing mechanism of the joints. On the other hand, the gradual decrease in rotation capacity of the beam ends during the fire course considerably influenced the load-deflection relationship. A detailed numerical work has been carried out to simulate the response of the test specimens and will be published elsewhere.

1. Introduction

Under exposure to extreme building fires, occurrence of destructive forces within reinforced concrete beam-column connections, irrespective of the location of plastic hinges, is very likely. Thus, it is of great importance to ensure that a fire-exposed beam-column connection fulfils its primary design objective, i.e., the safe transfer of shear and moment demands between other structural elements. However, the thermo-mechanical interactions between the individual members (beams and columns) under the internal thrusts as a result of restrained thermal expansions and moment redistribution due to non-uniform heating have been less appreciated in the literature. A detailed review on previous studies in this respect is reported in Ref. [1]. In the previous studies by the authors, the above-mentioned thermal and mechanical interactions were investigated by conducting the ISO-834 standard fire test [2] on two series of moment-resisting reinforced concrete frames, which were designed based on the conventional seismic design codes of Japan [1,3]. The prescriptive cover concrete recommended in the design code were assigned to meet a fire rating of 60 min. The test setup is schematically illustrated in Fig. 1a. As can be seen in the figure, the side columns provided an axial and rotational restraints at the beam ends. It was seen that during the early stage of fire the thermal expansion of the heated middle reinforced concrete beam imposed significant outward drifts on the columns such that the columns accommodated considerable deformations. The beneficial prestressing action of the generated axial thrusts within the beam incredibly increased its fire resistance. However, as the fire continued due to the progressive fire damage the beam ends at the column faces underwent severe rotation capacity loss. Meanwhile, the rapid increase in the beam mid-span deflection overtook the decreasing rotation capacity and consequently resulted in structural collapse approximately 180 min after the start of fire test.

In this study to investigate the fire response of an ideal beam-column connections under no lateral thermally-induced thrust and no moment redistribution influence, the authors reduced the degree of structural indeterminacy of the test specimen in Fig. 1a. This was done by removing the mid-section of the reinforced concrete beam and turning it into two separate reinforced concrete cantilever beams, as shown in Fig. 1b. As it will be discussed in the later sections, the two cantilever beams of the test specimen were equally loaded at their free ends with opposite directions (upward loading and downward loading). The recorded thermo-mechanical responses of the two test specimens in this study revealed important features of such structures when exposed to fire. Moreover, the reported results in this paper are of great importance in developing structural macro-models for predicting the interaction between the beams, joints, and columns in redundant

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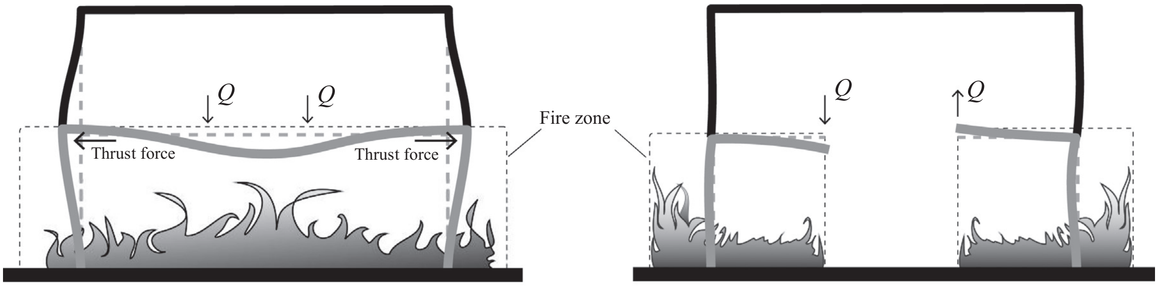


(a) Moment resisting frame in fire (b) Beam-column subassemblage in fire

Fig. 1. Beam-column sub-assemblage fire test approach [1,3].

structures. The authors has been carried out an extensive numerical work in this respect which will be published elsewhere.

2. Linear structural response mechanism

To study the structural performance of an exterior beam-column subassemblage, such as those illustrated in Fig. 1b, the load-deflection relationship of the cantilever beams and the load-bearing mechanism of the joints in the figure at room temperature are defined in the first step. The influence of fire will be then discussed based on the recorded thermal and mechanical responses in this study.

2.1. Cantilever beam

The linear response of a singly reinforced cantilever beam (before yielding either the tension longitudinal reinforcement or the flexural compression zone) comprises three flexibility components, as illustrated in Fig. 2. Flexural deformation δ_f, shear deformation δ_v (ignoring stirrups), and slip deformation δ_s, the sum of which defines the total displacement at the loading point, as expressed by Eq. (1).

$$\delta = \delta_f + \delta_v + \delta_s = \int_0^l x\varphi(x)dx + \frac{Ql}{A_v G_{eff}} + \theta l \tag{1}$$

Where, $\varphi(x)$ is curvature (due to the load Q), A_v is effective shear area, G_{eff} is constant shear modulus of elasticity, and θ is beam end rotation at anchorage face.

By assuming a uniform bond stress $\bar{u}$ and a triangular tensile stress distribution along the anchorage length l_a in Fig. 2c, slip s_a at the face of anchorage can be obtained by integrating the anchorage strain along length l_a. Thus, assuming the rotation θ occurring about the neutral axis, the rotation at the anchorage face is

$$\theta = \frac{s_a}{d-c} = \int_0^{l_a} \varepsilon_s dx \times \frac{1}{d-c} = \frac{f_{s,\max}^2 d_b}{8E_s\bar{u}(d-c)} \tag{2}$$

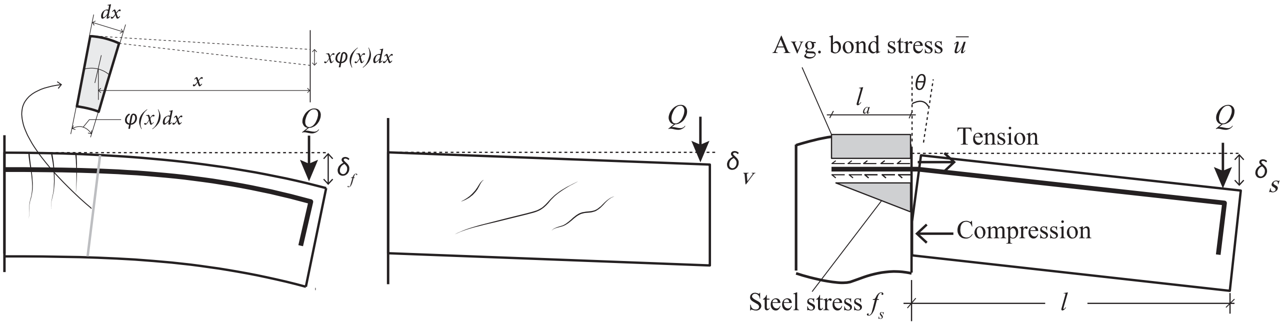
Here, d is the distance from the extreme compression fiber to the centroid of tension bar, c is the compression zone depth, E_s is modulus of elasticity of steel, d_b is the nominal diameter of bar, and $f_{s,max}$ is the tensile stress of bar at anchorage face.

Regarding the influence of elevated temperatures on the flexural component in Eq. (1), very limited fire endurance tests on unrestraint reinforced concrete beams were carried out, of which beam tests conducted by Lin et al. [4], Dotreppe and Franseen [5], and Raouffard et al. [6] are notable. It can be concluded from these tests that the most important factor that affects the flexural behavior of reinforced concrete structural elements is the temperature history in the tensile reinforcement. In contrast, the compressive strength and stiffness of concrete are less sensitive to variations in temperature in the event of a fire and thus accuracy in predicting concrete temperatures is of lesser importance [7]. Experimental studies on the influence of fire on shear strength of reinforced concrete beams are very limited as well [8,9]. The results of such beam tests implied that shear strength of beams at elevated temperatures did not appear to be a problem. To investigate the bond problem in fire, the development of accurate bond stress-slip models is an essential requirement. Numerical studies by Kuang [10] and Raouffard and Nishiyama [11] showed that bond reduction under fire exposure has an important influence on flexural behavior of reinforced concrete structures, especially when the temperature of the reinforcing steel bars exceeds 500 °C.

2.2. Beam-column joint

Under service load shear demands in beam-column joints are expected to generate shear stresses below allowable levels stated in seismic design codes. However, as it was mentioned earlier, under fire-induced axial thrust actions joints could undergo excessive shear forces. The disposition of transmitted forces and moments at room temperature from adjacent members around and within a typical beam-column connection is simplified in Fig. 3. Note that it is assumed that beam member is cantilever, thereby no axial force would emerge due to Poisson effect and/or thermal expansion in fire.

In a linear response and at onset of joint cracking, the horizontal



(a) Flexure (b) Shear (c) Slip

Fig. 2. Linear flexibility of singly reinforced cantilever beam.