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Behaviour of restrained steel beam with reduced beam section exposed to fire

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ABSTRACT

Reduced beam section (RBS) is one of the connection types, which is economical and popular for use in steel moment frames in seismic regions. By cutting some portions of the beam flanges near the column face, the RBS connections are designed to form plastic hinge within the RBS zone so that it could enhance the structural seismic performance. However, the steel beams with RBS connections have to provide robustness when exposed to fire. Although the responses of ordinary steel beams to elevated temperatures have been investigated over the last few decades, there has been very limited research on the behaviour of steel beams, with RBS connections in fire. This study includes a series of numerical analysis, to investigate the high-temperature performance of steel beams with RBS connections, compared to the responses of ordinary steel beams to fire. Various parameters have been considered, including the types of fire curves, the levels of beam-end restraints and the cutting profiles of the RBS connections. Overall, the deformation shape of RBS beams at high temperature is similar to that of ordinary steel beams, whereas the RBS beams could have longer period of fire resistance. The cut section actually provides both rotational and axial ductility/deformability to the connection, enhancing its fire resistance. Moreover, the cutting length, proposed by EC8, is also adequate for fire design. The minimum distance, between the RBS zone and the beam-end, proposed by FEMA-350 has been shown sufficient.

1. Introduction

After the 1994 Northridge [1] and 1995 Kobe earthquakes [2], the reduced beam section (RBS) joints have been extensively used in steel moment resisting frames (MRFs) to avoid brittle fractures of beam-to-column connections as observed in these two hazards [3]. The RBS joints, with portion of beam flanges near beam-to-column connections being cut [4], are designed to form a plastic hinge away from a connection so that beams (rather than the beam-to-column interface) could develop ductility, as shown in Fig. 1. In this figure, M_{sd} is the design bending moment; M_{pl} is the cross- sectional bending resistance; and $M_{pl\text{-}RBS}$ is the sectional plastic moment resistance at RBS zone. As indicated by several quasi-static tests [5,6], RBS has excellent energy dissipation capacities under cyclic loads, in terms of forming plastic hinge in the RBS zone and protecting the connection and the connected elements.

The design requirements of connection for fire [7] and that for earthquake [8–10] are very different. In seismic design, it is required that a plastic hinge is formed at the RBS zone to provide sufficient rotational ductility. However, for fire design, connections need to be able to resist very high forces along the axis of the beam; either large compression due to restrained thermal expansion during initial heating or large tension due to the very large beam deflection in the catenary tension phase [11]. The RBS beams, with the flanges cut to provide ductility required by seismic design, may have lower flexural and tensile capacities and poorer fire performance than those of ordinary beams. However, there has been very limited research on the fire resistance of RBS beams, which is worth investigating.

The RBS zone is vulnerable to tensile fracture at high temperature, as indicated in existing fire tests [12–14] on isolated RBS joints. Moreover, the location of the cut section and the depth of circular cutting will affect the behaviour of a beam in fire. Using numerical analysis, Lee et al. [15] found that, unlike ordinary beam-to-column connections, RBS joints subject to fire, mainly failed by local buckling at the top flange and web of the RBS region. However, the effects of the geometrical size of the RBS zone and the beam-end restraints on the fire resistance of RBS joint have not been investigated. The beam-end restraints (both rotational and axial) will affect the internal force distribution and hence affect the behaviour of connection, whereas this effect needs to be quantified.

This paper presents an investigation on RBS beams, considering the effects of geometrical size of RBS, beam-end restraint and fire temperature-time relationship, on the high-temperature performance of RBS beam at elevated temperatures. The robustness of RBS connections in fire is the main concern of this research, and so more attention

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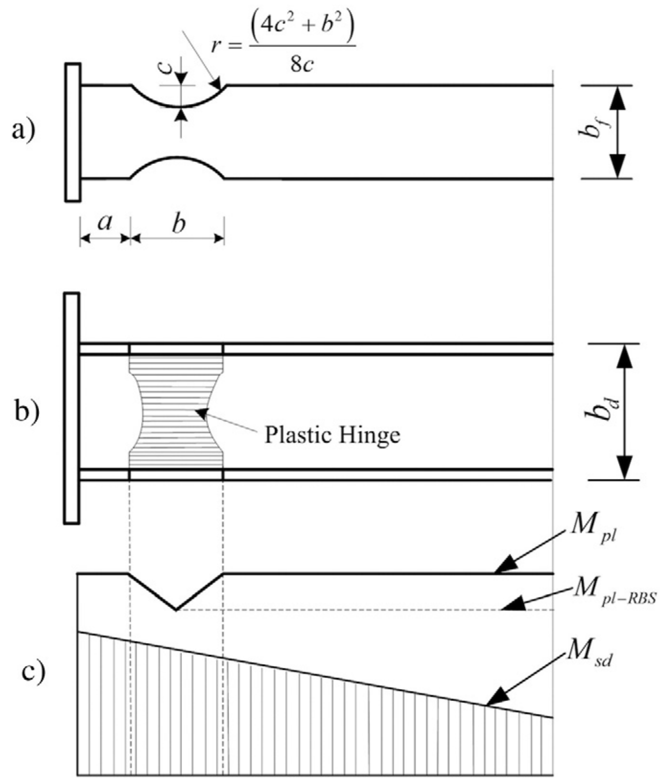

Fig. 1. RBS joints with circular-cut type (a) geometry of RBS joints; (b) location of plastic hinge in RBS zone; (c) bending moment capacity and design bending moment.

has been put on to the fracture time/temperature rather than on the ultimate load/moment capacities. The effects of the supported concrete slab on the temperature distribution in the connection and beam, have also been taken into account.

2. High-temperature performance of ordinary steel beam in fire

The high-temperature performance of ordinary steel beams has been studied widely in the world over the last few decades [16,17]. This section summarizes typical behaviour of ordinary (non-RBS) steel beams in fire.

2.1. Structural damage of steel beams in fire tests

The local buckling in the beam web or flange is a common failure mode, when steel beams are exposed to fire without any fire protection. Fig. 2(a) shows the local buckling of the steel beams after the Cardington office demonstration test (Test 6) [18]. In this test, the maximum deflections of unprotected steel beams reached 640 mm and the beam temperatures reached 1150 °C under a total fire load density of 46 kg/m^2. As can be observed from the figure, the web and bottom flange of the beam experienced severe local buckling near the beam-end due to the deterioration of steel material under high temperature and the increase of fire-induced internal forces. Additionally, the local buckling is also induced by the beam-end restraint to thermal expansion, which causes large compressive stresses at the beam-ends. Furthermore, the demand of beam-to-column connections is still important to the structural fire safety. Fig. 2 (b) shows the connection failure in Cardington fire test (British Steel Test 2: Plane frame test) [18]. The connected plate or the bolt fracture is usually the major failure mode for beams in fire [19]. It means that the beam-end of the ordinary beam is the key zone of bearing higher combination of fire-induced fires and is the weakened section during the structures exposed to fire.

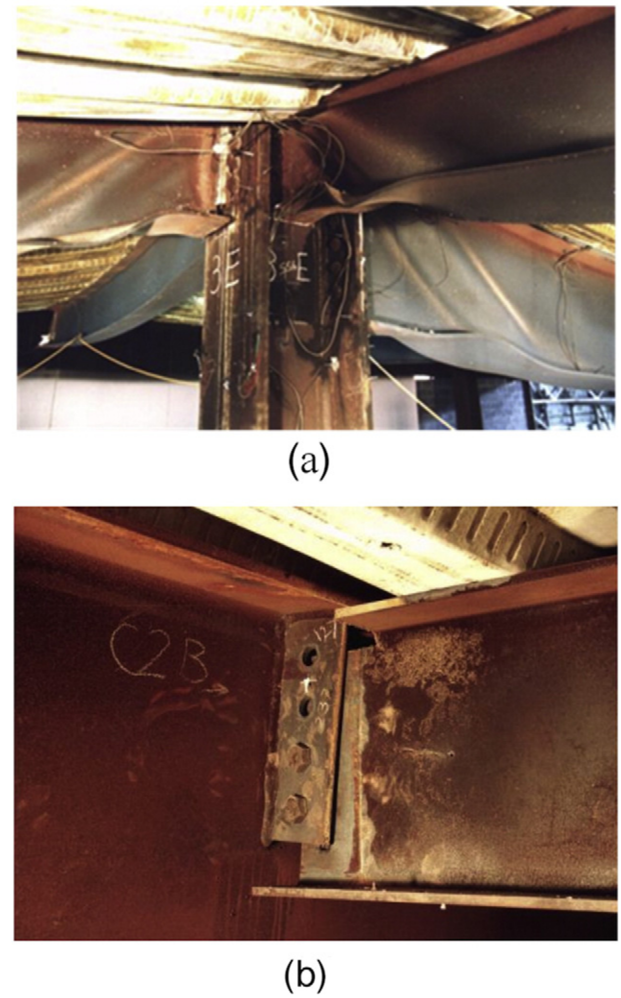

Fig. 2. The local buckling and the fracture of beams in Cardington fire test [18]. (a) Cardington office demonstration test (Test 6); (b) Cardington British Steel Test 2: Plane frame test.

2.2. Fire-induced internal forces

In ambient-temperature design, steel beams are designed to resist bending moment and shear. In fire, a steel beam experiences completely different loading (large axial forces and bending moments), as well as

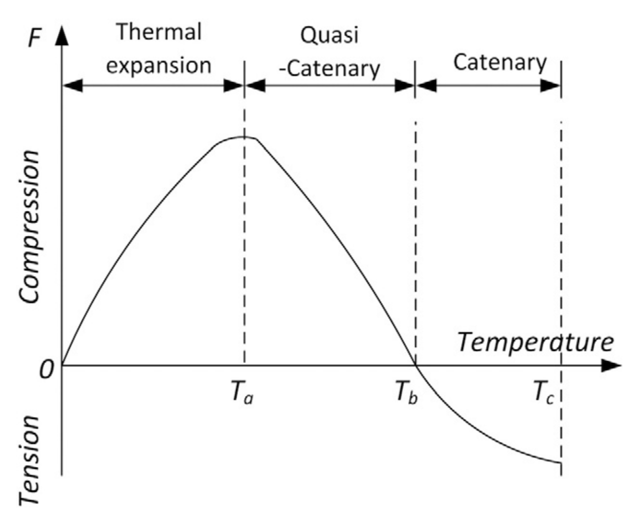

Fig. 3. Axial force in a restrained steel beam exposed to fire.