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Temperatures and thermal boundary conditions in reverse channel connections to concrete filled steel sections during standard and natural fire tests

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ABSTRACT

The paper presents fire test and numerical simulation results of temperature distributions in reverse channel connections to concrete-filled tubular columns during standard and natural fire tests. The experiments included a furnace fire test with the composite frame subjected to increasing fire temperature according to the ISO 834 standard time–temperature curve and two natural fire tests in a full-scale structure including a cooling phase. These fire tests examined the effects of fire protection, different connection locations and different connection dimensions. Temperatures at different connection components were recorded. The recorded connection component temperatures were simulated by using the SAFIR fire engineering software to calibrate the thermal boundary conditions in different connection components. From the numerical simulation results, it has been concluded that radiation to the inner surfaces of the reverse channel and the adjacent part of the column tube is only from the gas volume bounded by these surfaces. A lower flame emissivity value than the standard value should be used. For simplicity, a value of $\varepsilon_f = 0.1$ is proposed. Also a lower value of the convective heat transfer coefficient of 10 W/m^{2}K can be used in the connection area.

1. Introduction

Composite steel and concrete columns – with a concrete filled steel tube or partially-encased open cross-section – are becoming more frequently used in load bearing structures because of their high fire resistance and structural efficiency. In particular, concrete filled steel tubes require no formwork and additional steel reinforcement in concrete may be dispensed with in some cases. However, due to the difficulty of access inside the steel tube, making connections to concrete filled tubular columns is generally more complex. As a result, the fin plate connection is commonly used. Although this type of connection is simple and easy to fabricate, its mechanical performance may not be sufficient in many situations. Directly connecting an endplate to the tube requires specialist bolting technologies such as flowdrill or blind bolts. One relatively new connection type [1–4], which combines good mechanical performance, easy accessibility and moderate fabrication cost, is the reverse channel connection, as illustrated in Fig. 1. This type of connection consists of an end plate (welded to the beam and then bolted to the web of a channel) and a channel whose legs are welded to the column tube. The depth of the channel can be varied to accommodate any conventional flexible, flush or extended endplate connection.

When a structure is exposed to a fire attack, connections are key components of the structure, particularly concerning the survivability (robustness) of the structure, as demonstrated by the World Trade Center collapse [5] and the structural fire tests at Cardington [6], Ostrava [7] and Mokrsko [8]. However, contemporary European standards EN 1993-1-2 [9] and EN 1993-1-8 [10] provide very limited information on quantifying the connection thermal and mechanical behavior at elevated temperatures during a fire. In other standards and guidelines around the world, there is no or very simple approach [11,12]: when a structure is fire protected, a thickness of the fire protection applied to connections should be equal or greater.

During a fire, the behavior of the structure changes as a result of material property degradations and changes of the internal forces due to restrained thermal deformations and large structural deformations [13]. During the heating phase of a fire, exposed beams extend. If this extension is constrained by the adjacent structure, a relatively large compressive axial force develops in the

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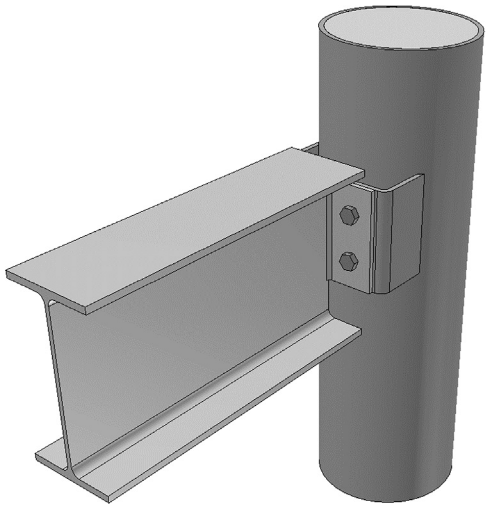

Fig. 1. Schematic of a reverse channel connection of a beam to a concrete-filled tubular column.

beam. Restraint to the thermal bowing of the beam also generates an additional hogging bending moment in the connection. At high temperatures, when vertical structural deformations are very big, axial restraint to the beam results in tension forces in the beam developing catenary action [14]. Connection components may fracture during the catenary action stage. Tension forces may also be generated in the beam and in the connection during the cooling stage. A limited number of fire tests using the reverse channel connection [1] have demonstrated its excellent performance compared to other types of connection to tubular columns.

In order to develop methods to quantify the connection behavior, temperatures in different connection components should be obtained. Against this background, the European RFCS COMPFIRE project was implemented, see [15]. An important work package of the project was to determine connection temperatures. This was achieved by fire tests, detailed numerical simulations to broaden the scope of the fire tests and the development of analytical equations to calculate different component temperatures that may be incorporated into design methods such as EN 1993-1-2 [9]. This paper presents detailed results of the fire tests and a limited number of numerical simulations to determine the thermal boundary conditions to different components of the reverse channel connection. The results of this paper are used to develop a design calculation method.

2. Fire tests

The fire tests included real fire scenarios in a full-scale experimental structure conducted by the Czech Technical University in Prague and a standard furnace fire test on a smaller composite steel and concrete frame structure at the University of Manchester, United Kingdom.

2.1. *Furnace fire test at the University of Manchester*

A small frame was constructed with several connection arrangements. This frame was then placed inside a fire testing furnace with the directional natural gas burners, measuring about 2 m (depth) by 3.5 m (width) and 3.5 m (height). Fig. 2(a) shows the planar arrangement of the test frame inside the furnace and thermocouple locations. Fig. 2(b) shows a sketch of the test frame with connection reference notations. The ISO 834 standard fire temperature-time curve was followed in the fire test.

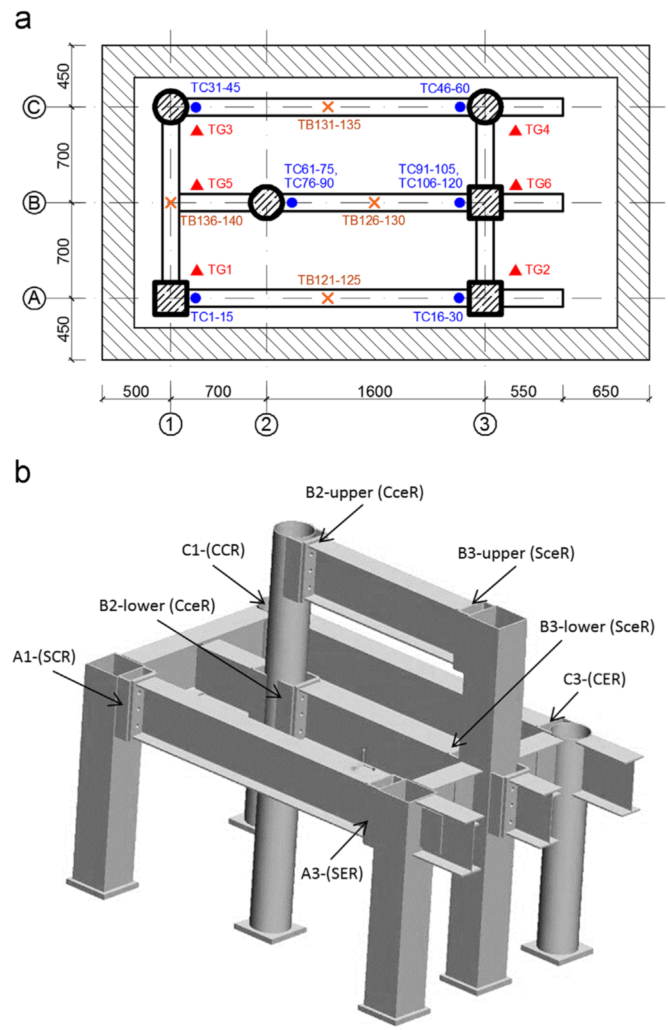

Fig. 2. University of Manchester furnace fire test: (a) furnace ground plan; (b) axonometric view of a test specimen with connection notations.

All steel beams were UB 305x165 × 40 and the steel tubular section filled with C25/30 normal weight concrete was either CHS 244.5 × 8 or SHS 250 × 8. A 100 mm thick C25/30 normal weight concrete slab was placed on top of the steel frame. the steelwork was not fire protected and no additional gravity loading was applied to the frame. table 1 gives an overview of the geometry of the monitored connections on the experimental structure.

140 thermocouples were used to record the temperatures in the reverse channel connection components, the concrete slabs and the beams at mid-span. Each thermocouple was pushed in the drilled hole with the depth that was equal to the half of the plate thickness. In order to achieve deeper hole in plates with the thickness less than 10 mm, the hole was drilled through the short weld made on the surface of the plate. The temperature in the furnace was measured by six standard plate thermometers, see Fig. 3, and the average temperature of these six plate thermometers was used as the reference temperature to follow the standard temperature–time curve. The heating phase took two hours and data recording continued for one more hour to obtain temperature data during cooling. During the cooling phase, electric fans were utilized to faster cool the specimen. The average temperature drop in the furnace was about 10 °C/min. This corresponds to the slope of the parametric temperature curve in the cooling phase for fire compartments of common administrative and residential buildings (the shape parameter $\Gamma = 2.5$).