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# Application of fire-resistant steel to beam-to-column moment connections at elevated temperatures

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ABSTRACT

This paper presents a new method of using fire-resistant steel to improve the fire-resistance of beam-to-column moment connections in steel structures. Two full-scale beam-to-column moment connection specimens were tested at elevated temperatures according to the standard ISO-834 fire to verify the feasibility of the proposed method. In addition, a detailed 3-D finite element model was developed to simulate the structural behavior of the column-tree moment connection specimens in fire. The fire test results show that the proposed method can effectively extend the fire endurance time, reduce structural deformation, and raise the critical temperature to failure for the beam-to-column moment connections. The numerical results obtained from the 3-D finite element analyses for the two specimens successfully simulated the fire test results.



## 1. Introduction

In fire conditions, beam-to-column connections play an important role in the structural behavior of steel structures. Due to the degradation of the strength and stiffness of steel at elevated temperatures, whether the connections can sustain large forces and rotations in fire directly affects the ability of the connections to redistribute forces from the beams to other structural members, and influences the survival time of steel structures in fire. Evidence from the WTC building collapses [1,2] demonstrated the importance of connections for steel structures in fire. Many fire scene investigations of steel buildings and the results of the Cardington full-scale eight story steel building fire tests in the UK [3] have also shown how the connections help the structural system survive extreme fires without progressive collapse. Therefore, preventing beam-to-column connections from failing is important for steel structures subjected to fires. Traditionally, to protect steel structures from fire damage, fire-protection materials such as thermal insulation components are required by the prescriptive-based fire protection design method. By applying the prescribed thicknesses of fire-protection material on steel members as surface coatings, the temperatures of steel members can be kept below the specified high temperatures for the given fire durations, and steel members can achieve the fire ratings required by code. However, this traditional method can add 30% to the construction cost of bare steelwork [4] and increase the construction time for steel structures.

In addition to the traditional method, the use of fire-resistant steel, which can retain 2/3 or more of its specified ambient-temperature yield strength at 600 °C, provides an alternative way to improve the fire-resistant ability for components of steel structures. The superior high-temperature mechanical properties of fire-resistant steel have been reported by Sakumoto et al. [5] and Kelly and Sha [6]. Using structural members made of fire-resistant steel can effectively reduce the usage of fire-protection coatings. Moreover, in some special fire conditions in which the steel temperature will not reach 600 °C, structural members made of fire-resistant steel may be exposed to fire without any protection [5]. However, experimental investigations of beam-to-column connections made of fire-resistant steel are rarely reported in literature. This may be due to the difficulty of conducting beam-to-column connection tests and the variety of the connection types. In addition, the cost of fire-resistant steel is still higher than that of conventional steel, so it is important to determine how to use fire-resistant steel economically. Instead of applying fire-resistant steel to all of the structural members, fire-resistant steel could be used only in the parts that are most important or susceptible to fire. The particular design of a column-tree moment-resisting frame (MRF) system makes it possible to use fire-resistant steel in the moment connection portion of the system to improve the fire-resistant performances of beam-to-column moment connections. The column-tree MRF is a common steel construction design used in some high seismic risk regions due to its better quality

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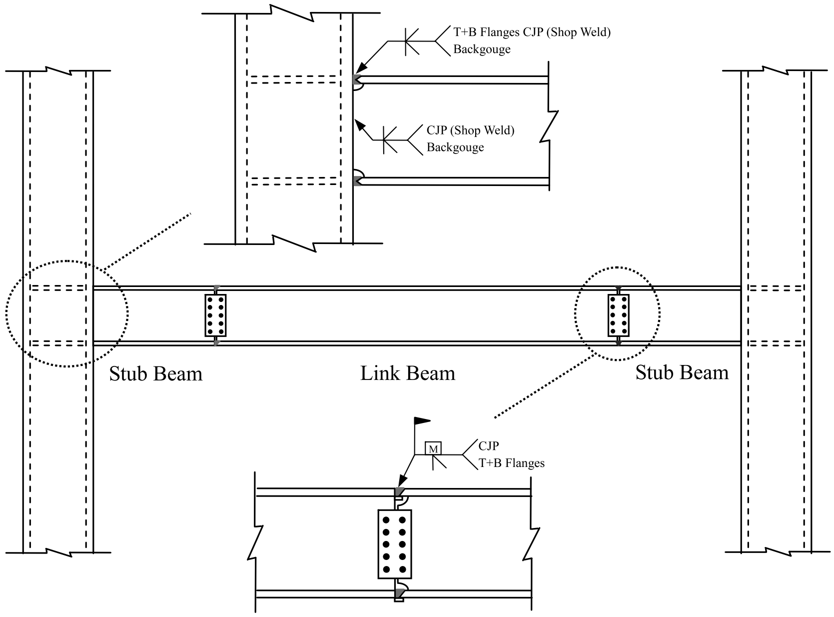


**Fig. 1.** Part of a typical column-tree moment resisting frame.

control in beam-to-column joint welding and its erection efficiency during construction. Fig. 1 shows the part of a typical column-tree moment-resisting frame in Taiwan. To improve the fire-resistance of the moment connections, we proposed that the stub beams in column trees can be made of fire-resistant steel. The feasibility of this proposal is examined by two full-scale beam-to-column moment connection specimens in the experimental portion of this study.

Several beam-to-column connection fire tests have been conducted in the past to understand the structural behavior of beam-to-column connections at elevated temperatures. Most of these studies focused on the bolted connections, and the specimens were isolated beam-to-column subassemblages [7–9]. Unlike the previous experimental studies using isolated specimens, Ding and Wang [10] utilized complete "rugby goalpost" subassemblage frames to conduct steel beam to concrete-filled tubular column connection tests to four types of connections. This "rugby goalpost" type specimen can provide axial restraint to the beam and simulate the realistic forces applied to a connection. Qian et al. [11] tested six bare steel beam-to-column cruciform specimens with extended plate connections at three high temperatures (400 °C, 550 °C and 700 °C). Some of the specimens were tested with the beams subjected to various compressive axial forces to simulate axial restraint effects. Yu et al. [12] developed a unique test setup that could apply both shear and tying forces to beams to test 14 beam-to-column specimens with fin plate connections subjected to catenary action at elevated temperatures.

From the previous literature review of beam-to-column connections in fire, it can be seen that most experimental efforts focused on bolted connections, and useful data and experiences were obtained to understand the structural behaviors of various bolted beam-to-column connections in fire. The behaviors of welded beam-to-column moment connections, such as column-tree moment connections and the popular flange welded and web bolted moment connections, at elevated temperatures are rarely reported. Therefore, the two objectives of this study are as follows:

(1) Conduct fire tests on full-scale column-tree moment connection specimens to verify the feasibility of the proposed method.
(2) Develop a detailed 3-D FE model to accurately simulate the structural behaviors of the H-beam to box–column column-tree moment connection specimens at elevated temperatures.

## 2. Test specimens

### 2.1. Specimen design and fabrication

In order to determine the effect of using fire-resistant steel in the stub beam of a column-tree moment connection, two full-scale column-tree moment connection specimens were fabricated and tested at elevated temperatures for comparison. The two specimens were identical in dimensions, fabrication process, welding procedures, and materials, but different in the steel types used for the stub beams. The stub beam in Specimen #1 was made of fire-resistant steel, while that of Specimen #2 used normal structural steel. Each column-tree moment connection specimen was composed of a column tree (including a stub H-beam and a box–column) and a link H-beam spliced to the stub beam. The design of the column-tree moment connection specimen came from an exterior H-beam to box–column subassemblage of a newly designed and constructed steel building in Taipei, Taiwan. Fig. 2 shows the analogy of a constantly loaded specimen in a heating furnace to simulate an exterior column-tree moment connection of a building in fire. When a steel MRF building is on fire, the beam-to-column moment connections sustain not only moments but also compressive or tensile axial forces due to the responses of the beams to the fire. To resist moments in some high seismic or wind risk areas, a moment connection usually has sufficient strength capacity to resist the tensile axial forces in fire as well. Hence, tensile failures of moment connections are rarely reported in fire scene investigations of steel structures. Instead, local flange buckling or web buckling are the common failure modes for beam-to-column moment connections in fire [3]. In order to simulate the common local buckling failure modes in the fire experiment, a constant vertical load was applied to the H-beam to box–column subassemblage specimen at the cantilevered beam end to approximate a negative moment gradient near the moment connection. It is noted that, in the fire experiment, the two bare specimens were entirely exposed to fire in the furnace without fireproof coatings to simulate the most severe fire condition. Figs. 3 and 4 illustrate the dimensions and welding details of the test specimens, and Table 1 lists the steel types, bolts and weld metals used to fabricate the two specimens. Table 2 lists a summary of the weld metals for all the welding processes (see Fig. 4) utilized