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Behavior of steel pallet rack beam-to-column connections at elevated temperatures

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ABSTRACT

Beam-to-column connections (BCCs) in steel pallet racks (SPRs) govern the stability of the structure in the down-aisle direction and possess a complex behavior as compared with the customary steel connections used in building structures because of the absence of bolts and welds. This behavior becomes increasingly complicated in case of hazardous conditions, such as fire, and needs careful design considerations. Warehouse fires are associated with higher average property losses per fire than most other occupancies. The existing literature completely lacks the studies focusing on the behavior of SPR BCCs under fire. This paper predicts the experimental and numerical behavior of SPR BCCs subjected to elevated temperatures. Eight sets of connection specimens, with three specimens in each set, were selected based on the variation in column thickness, beam depth, and the number of tabs in the beam end connector. A total of twenty-four tests were performed at three different temperature ranges (450 °C, 550 °C, and 700 °C) using the double cantilever test method. The major failure modes and the moment-rotation (M-θ) behavior of the SPR BCCs at elevated temperatures were evaluated and compared with the results of ambient temperature testing of SPR BCCs available in the literature. The findings indicated a noticeable degradation in the strength and stiffness of the connection due to thermal action. A non-linear three-dimensional (3D) Finite element (FE) model was developed to simulate the experimental investigations. The FE model exhibited a close agreement with the experimental results.

1. Introduction

During the last few decades, the growing application of low-to-high-rise pallet racking system has encouraged researchers to develop experimental and theoretical approaches to understand the stability and reliability behavior of these structures precisely. Steel pallet racks (SPRs) are 3D structures made up of cold-formed steel (CFS) members. In SPRs, most commonly two perforated columns are spaced apart by bolting or welding struts to make a truss frame. The struts work as cross-bracing and prevent sway in the "cross-aisle direction." A long direction with different story heights between two pallets is called the "down-aisle direction," which is left unbraced for a quick and unblocked access to the stored goods. The resistance to sway instability in the down-aisle direction is provided collectively by the beam-to-column connections (BCCs) and base connection. The behavior of SPR BCCs plays a significant role in maintaining structural stability, especially when the rack is subjected to fire, because of the lack of bracing in the down-aisle direction and the vulnerability of thin-walled SPR members against premature buckling and instability.

SPR BCCs are boltless semi-rigid connections, and the connecting device, the "beam end connector," is used to join the column and beam. This connector allows the easy unlocking of the joint and the re-assembly of the structure according to storage requirements. A common analytical model for the design of SPR BCCs is yet to be adopted globally mainly because of the aberrant and varying designs of the commercially available beam end connectors. Most recent design codes such as Rack Manufacturing Institute [1], European Committee for Standardization (EN 15512) [2], and Standards Australia (AS 4084) [3] suggest that experimental testing should be used to predict the behavior of SPR BCCs.

Fire is a significant threat for any structure that can extensively damage lives and goods. Modern high-bay supermarkets and warehouses have compact designs, significant height, and densely stored goods in a large number of racks with heights up to 40 m, creating ideal conditions for rapid fire propagation. Compared with other materials, CFS members have high slenderness, less resistance to buckling, and high value of thermal conductivity.

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When CFS members become exposed to fire, the temperature increases rapidly which decreases the properties of the material constituting the structural members. This event results in the rapid loss of strength and stiffness of the entire structure, leading to its early and unwanted collapse. In this case, the thermal forces induced on beams and columns are strongly affected by the detail of the BCC, such as the connection type (flexible, semi-rigid, and rigid), and the connection becomes significantly responsible to maintain the global stability.

The fire safety design of CFS has received increasing attention in recent years owing to the continuous loss of properties and lives during fires. Diverse studies have extensively investigated the fire behavior and design of semi-rigid connections between CFS members [4–11] as well as the behavior of SPR BCCs at ambient temperature [12–21], but the behavior of SPR BCCs subjected to fire is yet to be looked into. The recent design codes do not offer any specific guidelines to predict the moment-rotation-temperature (M-θ-T) relationships of SPR BCCs. This study investigates the behavior of SPR BCCs subjected to elevated temperatures. Eight sets of specimens, with three specimens in each set, are identified based on the variations in column thickness, beam depth, and number of tabs in the beam end connector. The specimens are then tested at three different temperature ranges using the double cantilever test method to investigate the flexibility of SPR BCCs at elevated temperatures. The results of the elevated temperature testing are compared with those of the ambient testing of SPR BCCs available in the literature [18]. A nonlinear three-dimensional 3D finite element (FE) model is developed to simulate the elevated temperature based experimental investigations on a commercially available software Abaqus [22] and the results are compared with FE modeling performed at ambient temperature by Shah et al. [20].

2. Experimental investigations

2.1. Material properties

CFS sections are used for columns and beams, and the beam end connectors are manufactured from hot rolled steel. The material properties of members and beam end connectors are obtained using the tensile test performed at ambient temperature and are given in Table 1.

2.2. Specimen details

Eight sets of specimens are identified. Each set is composed of three specimens and distinguished by two different column thicknesses, four different beam depths, and the number of tabs in the beam end connector that can either be four or five. Fig. 1(a) illustrates the cross-section of the column. Box beams with four different depth values (i.e., B1, B2, B3, and B4) are used for experimental testing. B1 and B2 have a four-tab beam end connector, whereas B3 and B4 have five tabs. Fig. 1(b) presents the cross section of the box beam, and Table 2 lists the dimensions of the columns and beam sections. The geometry of the beam end connectors is distinguished by the number of tabs in the beam end connector. Connectors “A” with a depth of 200 mm and “B” with a depth of 250 mm have four and five tabs, respectively. Fig. 1(c) shows the cross-section of the beam end connector. All dimensions of the specimens are the measured values.

Table 1.
Material properties of specimens.

Member	Young's modulus (E) (GPa)	Poisson's ratio (ν)	Yield strength (fy) (MPa)	Ultimate strength (fu) (MPa)
Column	210	0.3	459	575
Beam			353	497
Beam-end-connector			263	365

A total of twenty-four tests are conducted. Each specimen in a specified set is tested at three different temperature ranges listed in Table 3. To clearly represent the groups of specimens under investigation, each set of experiment is given a certain specimen ID, all of which are listed in Table 3 along with the number of tests performed. For example, for specimen ID “2.0UT-92BD-4T,” 2.0UT represents a column thickness of 2.0 mm, 92 BD depicts a beam depth of 92 mm, and 4 T denotes that the number of tabs in the beam end connector is four.

2.3. Selection of test set-up and temperature ranges

To investigate the behavior of the beam end connector, the design standards for storage rack design [1–3] recommend alternative testing methods. One of these approaches is the ‘cantilever test method’. This method can be extended further by attaching additional beam to the other side of the column; hence called the double cantilever test method. Although the cantilever test method is well recognized by the design codes and researchers, the double cantilever testing has also proven to give valid connection response based on the previous work and yields better results from the overall rack design point of view [14,16]. Bajoria and Talikoti [14] compared the results of tests based on cantilever and double cantilever methods with full-frame experimental set-ups and FE simulations, concluding that the latter shows closer agreement when compared with full-frame results. The efficiency of the double cantilever test method was also confirmed by Prabha et al. [16]. Moreover, the EN 15512 [2] suggests that the separate values for the stiffness and strength should be obtained for both right and left hand connectors and the mean value used in design. In the cantilever test method, the left and right hand connectors can only be tested in two separate testing arrangements. By contrast, the double cantilever test combines the testing of the left and right hand side connectors in one testing arrangement, thereby easily obtaining the separate strength and stiffness values of these connectors at less cost, minimized time consumption and reduced manual effort.

This test method restrains the shear displacement in the column, allowing it to behave as a rigid body. Deformation takes place only in the BCC, following the rotation of the connected beam. The beam end connector is subjected to moment, shear, and axial pull similar to an actual frame and appropriately estimates the shear and moment ratio [14].

This study followed the testing arrangement based on the double cantilever test method. Despite providing a number of benefits, this test method has been rarely used by the researchers. Since cantilever test method has been used by several investigators, one of the purpose of choosing this test method in this study is to verify the validity of double-cantilever method for the experimental testing of SPRBCCs.

In this study, three different temperature ranges were selected and used (450 °C, 550 °C, and 700 °C) in different tests. This temperature range was adopted because the strength reduction factor for CFS structures defined by Eurocode (EC) 3 [23] at different temperatures provides no significant degradation up to 300 °C. However, the strength degradation beyond this temperature becomes considerable, and the behavior of the CFS members varies with different types of deformation.