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Double-shear tests of high-strength structural bolts at elevated temperatures

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ABSTRACT

The behavior of high-strength structural steel at elevated temperatures, especially under shear loading, is not well established in the literature. This paper presents results from recently conducted tests on high-strength structural bolts subject to double shear loading at elevated temperatures. The parameters varied between tests included the bolt grade, bolt diameter, and temperature. Bolt grades A325 and A490 were tested. For each bolt grade, three different diameters were tested (19 mm (3/4 in), 22 mm (7/8 in), and 25.4 mm (1 in)) at five different temperatures (20 °C, 200 °C, 400 °C, 500 °C, and 600 °C). At least three tests were conducted for each combination of parameters. Degradations in the mechanical and material properties including stiffness, strength, and deformation at fracture, are characterized and presented herein. The results from these experiments fill a critical knowledge gap currently present in the literature regarding the behavior of high-strength structural bolts under shear loading at elevated temperatures. These data will ultimately provide a thorough understanding of the overall behavior of structural steel systems under realistic fire loading by clarifying the (i) shear behavior of high-strength structural steel bolts at elevated temperatures, and (ii) degradation in the mechanical and material properties of high-strength steel bolts with increasing temperatures.

1. Background

Fire effects on steel structures can produce failures of connections, including fracture of connection plates, shear rupture of bolts, and bolt tear-out failure of beam webs or connection plates. Seif et al. [1] and [2] examined such failure modes for typical shear and moment connections at elevated temperatures, based on explicit high-fidelity finite element analyses. Whether such failures occur depends not only on the loads that can be sustained by the various components of a connection, but also on the deformations that can be accommodated prior to fracture, since fire-induced forces result from the restraint of thermal expansion or contraction. The ductility of steel components plays an important role in the performance of connections at elevated temperatures. Sufficient ductility can potentially allow redistribution of loads after failure of one or more connection components.

Thus, a key issue in evaluating the response of structural systems to fire effects is the proper representation of material behavior, including fracture, at elevated temperatures. Temperature-dependent material behavior of structural plate materials (such as ASTM A36, ASTM A572, and ASTMA992), has been studied both experimentally and numerically (e.g., Seif et al. [3,4], and Hu et al. [5]). However, the behavior of high-strength structural bolts at elevated temperatures, especially under shear loading, is not well established in the literature. The current lack of reliable experimental data has made proper characterization of the temperature-dependent material behavior of bolts impossible, forcing researchers to use alternative approximations. Seif et al. [4] proposed a simple multi-linear representation of the temperature-dependent true stress-strain behavior for high-strength bolts.

Kodur et al. [6] studied the influence of elevated temperatures on the thermal and mechanical properties of steel bolts, including a limited number of experiments on bolts under tensile loading at different temperatures. Yu [7] studied the effect of high temperatures on bolted connections. His work included a few experiments on bolts under shear loading, and he noted that if a bolt is not heated up past its tempering temperature, its shear resistance is not affected. However, the experiments were limited to a small set of data, with excessive bearing deformations imbedded in the results. Thus, a more comprehensive set of test data was needed in order to provide a fuller understanding of the behavior of high-strength bolts under shear loading at elevated temperatures, which will ultimately lead to a fuller understanding of the overall behavior of structural steel systems under realistic fire loading. The following sections describe the details of this experimental study along with the results and discussion.

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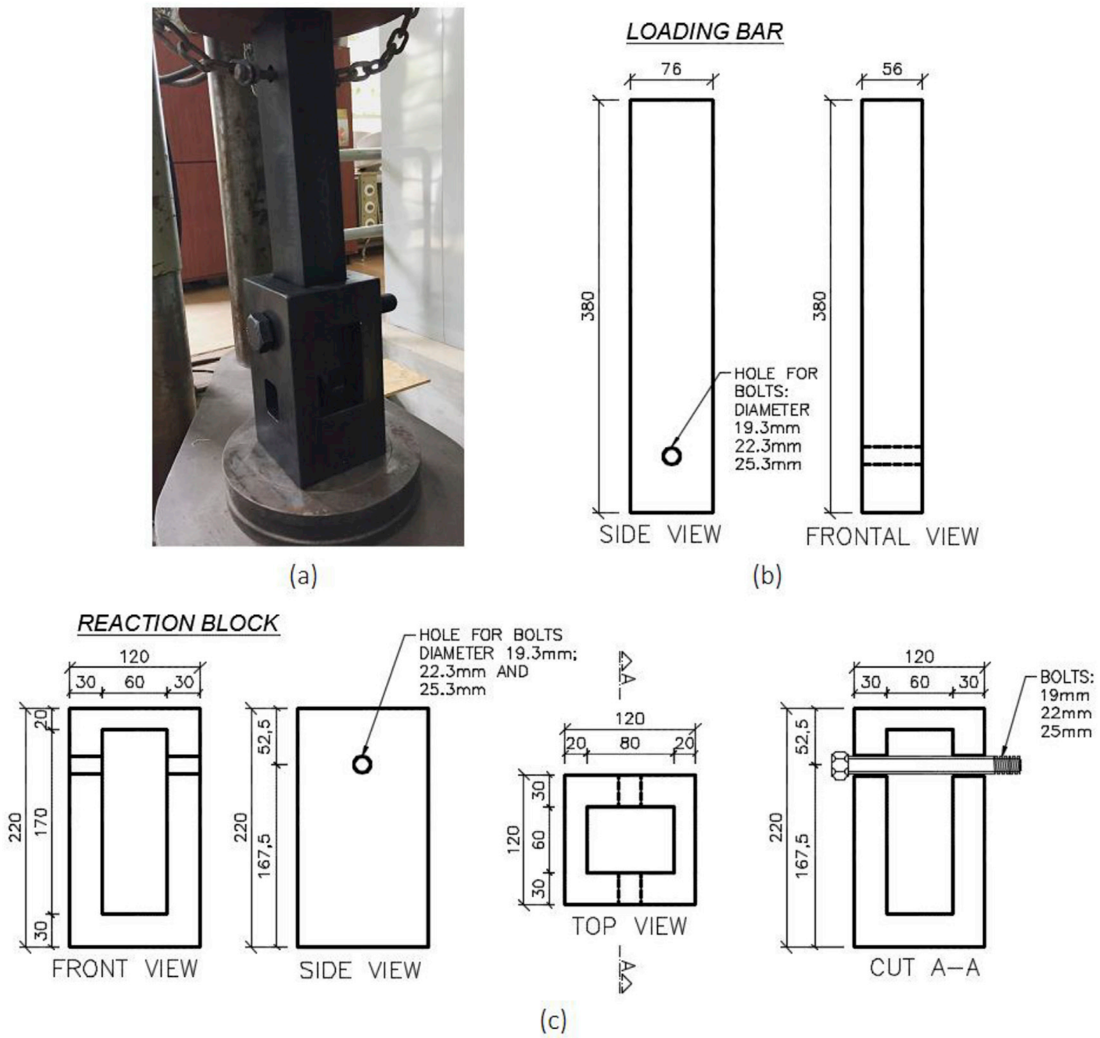

Fig. 1. Test block: (a) photo of actual setup, (b) and (c) dimensions. All dimensions are in mm (1 in = 25.4 mm).

2. Test parameters and setup

The parameters varied between tests included the bolt grade, bolt diameter, and temperature. Bolt grades ASTM A325 [8] (specified nominal yield strength of 635 MPa (92 ksi) and specified nominal ultimate strength of 825 MPa (120 ksi)) and ASTM A490 [8] (specified nominal yield strength of 895 MPa (130 ksi) and specified nominal ultimate strength of 1035 MPa (150 ksi)) were tested. For each bolt grade, three different diameters were tested (19 mm (3/4 in), 22 mm (7/8 in), and 25.4 mm (1 in)) at five different temperatures (20 °C, 200 °C, 400 °C, 500 °C, and 600 °C). At least three tests were conducted for each combination of parameters. Degradations in the mechanical and material properties including stiffness, strength, and deformation at fracture, were documented and are presented in the following sections.

All specimens were tested in a specially manufactured testing blocks, heated to the specified temperature, and then subjected to double-shear loading. The testing blocks were designed to resist loads much higher than the bolts' nominal shear capacity, and were reused for multiple tests. Two sets of testing blocks were manufactured: one set for the 19 mm (3/4 in) and 22 mm (7/8 in) diameter bolts, and one set for the 25 mm (1 in) diameter bolts. The first set was manufactured using ASTM A36 steel [9] (yield strength of 250 MPa (36 ksi) and ultimate strength of 400 MPa (58 ksi)), and the second was manufactured using the heat treated AISI/SAE 8640 alloy steel [10] (yield strength of 560 MPa (81 ksi) and ultimate strength of 750 MPa (109 ksi)). For the 19 mm (3/4 in) and 22 mm (7/8 in) bolt diameter tests, the same set of testing blocks was used and only the hole necessary to pass the bolt was enlarged after all the 19 mm (3/4 in) bolts were tested. The configuration and dimensions of the testing blocks are shown in Fig. 1. Refer to section 4.1 for further discussion on the blocks.

The specified temperature for each test was reached by placing the entire test setup in an electric furnace which was capable of achieving a maximum temperature of 1200 °C. A rate of temperature loading of 20 ºC/min was used for all tests and the entire test setup was free to expand. One thermocouple type K was placed inside the furnace to control the furnace temperature and three additional thermocouples type K were strategically placed on the bolt specimens (touching the bolt surface) to ensure that the target temperature had been achieved in the bolt at the initiation of the shear loading. As stated by the thermocouple manufacturer, the precision of the measured temperature at 0 °C is of 2.2 °C. The shear loading on the bolt specimen was applied using a universal testing machine, which had a capacity of 980.7 kN (220.5 kip) and an uncertainty of measurement at 10 kN (2.25 kip) of ±0.1 kN, at a level of confidence of 95%. Compression loading was applied at a rate of approximately 60 kN/min (13.49 kip/