Journal of Constructional Steel Research 147 (2018) 87–102

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

# An empirical component-based model for high-strength bolts at elevated temperatures

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ARTICLE INFO

*Article history:*
Received 3 October 2017
Received in revised form 15 March 2018
Accepted 27 March 2018
Available online xxxx

*Keywords:*
Bolts
Steel
Shear
Elevated temperatures
Fire
Component-based

ABSTRACT

High-strength structural bolts are used in nearly every steel beam-to-column connection in typical steel building construction practice. Thus, accurately modeling the behavior of high-strength bolts at elevated temperatures is crucial for properly evaluating the connection capacity, and is also important in evaluating the strength and stability of steel buildings subjected to fires. This paper uses a component-based modeling approach to empirically derive the ultimate tensile strength and modulus of elasticity for grade A325 and A490 bolt materials based on data from double-shear testing of high-strength 25 mm (1 in.) diameter bolts at elevated temperatures. Using these derived mechanical properties, the component-based model is then shown to accurately account for the temperature-dependent degradation of shear strength and stiffness for bolts of other diameters, while also providing the capability to model load reversal.



## 1. Introduction

Steel buildings subjected to structurally significant fires experience thermal assault comprising elevated temperatures and non-uniform thermal gradients, which may induce both temperature-dependent degradation and large unanticipated loads in the steel building components, including connections. The effects of the fire on steel connections are important because, in addition to resisting gravity loads, connections provide critical lateral bracing to the columns. Consequently, failure of steel connections could lead to column instability potentially resulting in local or widespread collapse. High-strength bolts are used in nearly every beam-to-column connection in typical steel building construction practice. Thus, accurately modeling the behavior of the bolts under elevated temperatures is crucial for properly evaluating the connection capacity, and by extension, important in evaluating the strength and stability of steel buildings subjected to fires.

Fire effects on steel structures can produce failures of connections, including fracture of connection plates, shear or tensile rupture of bolts, and bolt tear-out failure of beam webs or connection plates. Seif et al. [1,2] examined such failure modes for typical steel gravity and moment connections at elevated temperatures, using high-fidelity finite element analyses. These studies showed that the potential for failure of connections in fire may result not only from degradation of material strength under the sustained gravity loads, but also on the additional loads and deformations that can be developed through 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 accommodate thermal expansion and allow for redistribution of loads after failure of one or more individual connection components.

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https://doi.org/10.1016/j.jcsr.2018.03.034
0143-974X/© 2018 Published by Elsevier Ltd.

A key issue in predicting the response of structural systems to fire-induced effects is the proper modeling of connection components at elevated temperatures. Gowda [3], Luecke et al. [4], and Hu et al. [5] have examined the behavior of commonly used structural steels at elevated temperatures. Kodur et al. [6] studied the influence of elevated temperatures on the thermal and mechanical properties of high-strength bolts by conducting shear and tensile coupon testing of 22 mm (7/8 in.) diameter high-strength bolts at eight elevated temperatures between ambient temperature and 800 °C. Yu [7] studied the influence of elevated temperatures on bolted connections, work which included tests of high-strength bolts under shear loading. Yu [7] observed that bolts did not experience appreciable degradation in their shear resistance until heated in excess of their tempering temperature. More recently, Fischer et al. [8] tested single-lapped bolted splice joints at temperatures of 400 °C and 600 °C, and Peixoto et al. [9] tested a large number of high-strength bolts at elevated temperatures under double-shear loading. The tests by Peixoto et al. [9] used fixtures fabricated from thick heat-treated high-strength plates to minimize the influence of bearing deformations (i.e., to isolate the bolt-shear deformations) which have been significant in previous studies. These recent results by Peixoto et al. [9] provide sufficient data needed for the development and formulation of reliable component-based models.

This paper describes the development of a reduced-order component-based modeling approach for the shear behavior of high-strength bolts at elevated temperatures that is capable of capturing temperature-induced degradation in bolt-shear strength and stiffness. Semi-empirical models for both ASTM A325 [10] and ASTM A490 [11] 25 mm (1 in.) diameter bolts are developed, based on the comprehensive dataset from Peixoto et al. [9]. Using the component-based model, degradation in the ultimate tensile strength and modulus of elasticity of the bolt materials is linked to the corresponding degradation in the bolt double-shear strength and initial stiffness of the bolt load-deformation response, respectively. By calculating the elevated-temperature-induced degradation in the mechanical properties of the bolt steels, the results of the 25 mm (1 in.) diameter bolts can be generalized to calculate the behavior of bolts with other diameters or lap-configurations.

## 2. Summary of experimental data

The component-based model presented in this paper was formulated based on the results of recent double-shear tests of high-strength bolts at elevated temperatures [9], which covered two bolt grades, three bolt diameters, and five temperatures. The bolt grades were either ASTM A325, with a specified nominal yield strength of 635 MPa (92 ksi) and specified nominal ultimate tensile strength of 825 MPa (120 ksi), or ASTM A490, with a specified nominal yield strength of 895 MPa (130 ksi) and specified nominal ultimate tensile strength of 1035 MPa (150 ksi). For each bolt grade, three diameters of bolts were tested (19 mm (3/4 in.), 22 mm (7/8 in.), and 25 mm (1 in.)) at five temperatures (20 °C, 200 °C, 400 °C, 500 °C, and 600 °C). The limiting elevated temperature of 600 °C was chosen so that the results would not be overly sensitive to strain rate effects. At least three nominally identical tests were conducted for each combination of parameters.

The double-shear loads were applied using testing blocks designed to resist loads much larger than the bolts' nominal shear capacity. These blocks 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 [12] steel, with a specified minimum yield strength of 250 MPa (36 ksi), and the second set was manufactured using heat-treated AISI/SAE 8640 alloy steel, with a specified minimum yield strength of 560 MPa (81 ksi). The configuration and dimensions of the testing blocks used to test the 25 mm (1 in.) diameter bolts is shown in Fig. 1.

For each test, the entire test setup, including the bolt specimen, was pre-heated to the specified temperature using an electric furnace, and then the loading block (see Fig. 1) was compressed downward with a universal testing machine until the bolt fractured in double-shear. For all tests, both shear planes were located in the unthreaded region of the bolts. The influence of including threads in the shear plane was not considered in this study. Each tested bolt was assigned a unique name, which includes the bolt diameter (specified in mm), bolt grade, temperature level (in °C), and test number. Thus, Test 19A325T20-1 had a diameter of 19 mm (3/4 in.), an ASTM A325 grade, and was tested at a temperature of 20 °C (ambient temperature), with the numeral 1 after the hyphen indicating that it was the first test in a set of three nominally identical specimens. Detailed descriptions of the test specimens, test setup, and instrumentation used in the tests are available in Peixoto et al. [9]. Results showed that the shear strength of the bolts was only slightly degraded at a temperature of 200 °C, but the degradation was more significant at higher temperatures. For example, at temperatures of 400 °C, 500 °C, and 600 °C the A325 bolts retained an average of approximately 82%, 60%, and 35% of their initial double-shear strength, respectively. Uncertainties in the measured bolt double-shear load-deformation behavior are reported in Peixoto et al. [9].

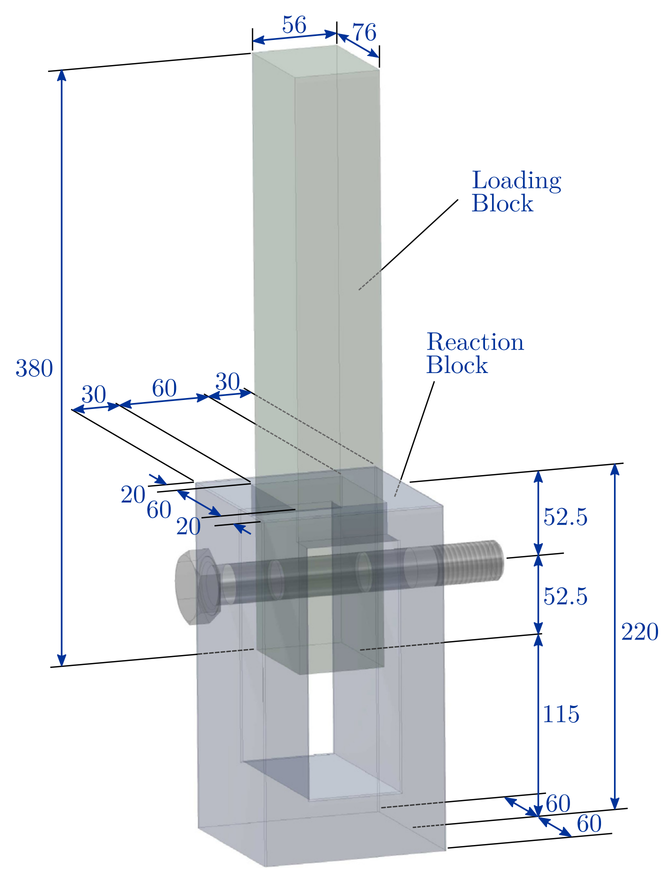


**Fig. 1.** Schematic of bolt double-shear test assembly (dimensions in mm).