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Residual mechanical properties of high strength steel bolts subjected to heating-cooling cycle

Venkatesh Kodur [a,*], Mahmood Yahyai [b], Abbas Rezaeian [c], Mohamadreza Eslami [a], Alireza Poormohamadi [b]

[a] Civil and Environmental Engineering, Michigan State University, United States
[b] Civil Engineering Department, K.N. Toosi University of Technology, Iran
[c] Civil Engineering Department, Shahid Chamran University of Ahvaz, Iran

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ABSTRACT

This paper presents results from experimental studies on residual mechanical properties of Grade 8.8 bolts exposed to elevated temperatures. The residual mechanical properties including stress-strain response, elastic modulus, yield and ultimate strengths, as well as failure modes of bolts are evaluated after exposure to various target temperatures. The effect of temperature level, chemical composition of feedstock steels and heat treatment characteristics in production process of Grade 8.8 bolts on residual mechanical properties is studied. Data from the tests indicate that bolts experience rapid reduction in residual strength when heated to temperatures beyond 400 °C and reaches to 50% of ultimate strength after exposure to 800 °C. Apart from temperature amount of carbon content in steel and tempering temperature in bolt production process significantly influence residual properties of Grade 8.8 bolts. Data from the tests is utilized to propose a set of predictive equations for evaluating temperature dependent residual mechanical properties of Grade 8.8 bolts.

1. Introduction

Connections in a structural system play a critical role in transferring forces from one member to the other. The integrity of a structural system may be compromised in the event of connections failure, leading to damage or even collapse of the structure. The role of bolted connections in steel structures is much more crucial under fire conditions; as significant fire-induced forces have to be withstood [1–3]. Observations from past fire incidents and full-scale fire experiments indicate that significant temperature induced tensile forces gets induced in axially-restrained beams during the cooling phase of fire and this could result in the failure of bolts after cool down to room temperature (Santiago et al. [4]). Therefore for evaluating realistic residual capacity of steel structures after exposure to fire, the post-fire material properties of all components including bolts is essential.

A number of experimental studies are reported in the literature on temperature induced degradation of mechanical properties of different grades of structural steel [5–11]. However, there is very limited data on the residual mechanical properties of high-strength structural steels after exposure to elevated temperature and cooled down to ambient temperature. Lapwood [12], based on residual strength tests on some steel grades, reported no decrease in strength when steel is heated to temperatures up to 600 °C and cooled down, but inferred degradation in strength after heating-cooling cycle of 600 °C and above. Gunalan and Mahendran [13] pointed out reduction in residual strength of cold-formed steels (G300, G500 and G550) to occur after heating to temperatures above 300 °C. Wang et al. [14] reported significant degradation of elastic modulus and yield and ultimate strengths in high-strength Q460 steel after exposure to temperatures exceeding 600 °C. Also, the behavior of prestressing (high strength) steels after fire has been studied by some researchers [15,16]. They found that prestressing steels are very sensitive to temperatures, and can induce significant decrease in strength properties.

Eurocode3: Part 1.2 [17] specifies temperature dependent strength reduction factors for evaluating strength degradation in bolts under fire conditions. These factors have been proposed on the basis of limited experimental work by Kirby [18] on grade 8.8 hexagonal head bolts, at temperatures up to 800 °C. Also, Kodur et al. [19] proposed relations for variation of thermal and mechanical properties of Grade A325 and A490 steel bolts at temperatures up to 800 °C. These relations for degradation in strength of bolts are derived by considering heating phase conditions only, and without due consideration to the cooling phase which can be critical in determining residual properties [20,21].

Grade 8.8 bolts are produced by quenching and tempering high strength alloy steels, containing higher carbon content together with molybdenum and chromium. The different chemical compositions of high-strength steels influence the temperature induce degradation of mechanical properties of Grade 8.8 bolts. Limited research studies are

* *Corresponding author.
E-mail addresses: kodur@egr.msu.edu (V. Kodur), yahyai@kntu.ac.ir (M. Yahyai), rezaeian_a@scu.ac.ir (A. Rezaeian), eslami@msu.edu (M. Eslami).

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reported on behavior of these bolts after exposure to temperature [18]. Specifically, there is no available data on residual mechanical properties of Grade 8.8 bolts after subjecting to heating and cooling phase, as encountered in realistic fire scenarios. To overcome these limitations, an experimental study is carried out on Grade 8.8 bolts to evaluate residual mechanical properties. The test variables included heating (temperature) level, and chemical composition of steel used in bolts. Data from the tests is utilized to discuss the effect of heating-cooling phase on residual stress-strain response, elastic modulus, yield and ultimate strength, as well as failure modes in bolts.

2. Experimental program

Two types of tests were carried out on full size bolts to evaluate residual mechanical properties. Room temperature tensile strength tests were undertaken to evaluate the reference strength of unheated bolts. Also, residual tensile strength tests, in which bolts were first heated up to a pre-specified temperature, then cooled down to ambient temperature, and were tested to failure by subjecting them to tensile loading.

2.1. Test specimens

High-strength Grade 8.8 bolts are fabricated through either hot or cold forging process, followed by a quenching and tempering heat treatment, to achieve required strength and stiffness properties in bolts. Three sets of bolts were considered in the current test program. The first two sets of bolts M16 and M18, were selected from cold forging of SAE 10B38 steel bar, followed by quenching from an austenitising temperature of 870 °C and subsequently tempering at 530 °C. The third set of bolts (M22), was taken through cold forging SAE 10B21 steel bar, quenched from 870 °C and tempered at 475 °C. To provide a consistent basis for comparing their behavior after temperature exposure, the bolts within each set were taken from a single production batch, using the same bar feedstock, forging operation, and subsequent heat treatment conditions. In total, tensile tests on 99 bolts were carried out. All specimens were Hexagon cap screwed partly threaded bolts, produced by ITC Company, in compliance with DIN 931 standard [22]. The main characteristics of three types of bolts used in the tests are given in Table 1.

The chemical compositions of bolts were determined using FOUNDRY-MASTER UV metal analyzer (Fig. 1), which is a laboratory spectrometer for qualitative and quantitative element analysis of metallic samples, based on Optical Emission Spectroscopy (OES). Chemical compositions of both sets of Grade 8.8 bolts are given in Table 2.

2.2. Test procedure

An electric furnace, with manual adjustment of power, was used for heating the bolts (Fig. 2). Two K-type thermocouples, one mounted on the specimen and the other in the furnace, recorded the temperature of the specimen and the furnace, respectively. The bolts were heated from ambient temperature to specific target temperature at a rate of 10 °C/min. Ten target temperatures (T_u), of 300, 400, 500, 600, 650, 700, 750, 800, 850 and 900 °C were selected for heating. The heating-cooling temperature regime used in the tests is shown in Fig. 3. Once the specimen was heated to the target temperature, it was stabilized for a period of 15 min to ensure uniform (steady) temperature distribution throughout the bolt. In the cooling phase, the furnace was switched-off and the bolt specimen was allowed to cool down to room temperature naturally. The cooling rate was approximately 10 °C/min. Following air cooling, tensile strength test was performed on bolt specimens at ambient temperature.

Fig. 1. FOUNDRY-MASTER UV metal analyzer.

The tensile strength tests were conducted using SANTAM universal testing machine, as shown in Fig. 4. STM-600 system is a fully computerized servo electro-mechanical operation system capable of exerting as much as 600 kN of tensile force. All tensile tests were conducted at room temperature, according to the ASTM E8 [23] test procedure. Three repeat tests were conducted for each bolt under the same conditions to ensure reproducibility of results. A displacement-controlled quasi-static load, with a displacement rate of 0.02 mm/s, was applied on the specimens until failure occurred. A high resolution axial extensometer gauge was used to measure the strain in the central region of the bolt. Data from tests was recorded through a computer and visual observations were also taken at various times during the tests.

The test set up utilized in this test program is for evaluation of residual mechanical properties; namely stress-strain response, elastic modulus, yield and ultimate strengths, and failure modes of bolts exposed to various target temperatures. In this test set up only partial creep effects can be captured. Generally, creep deformations in steel become noticeable at temperatures above 400 °C [24,25] and to capture full creep response, different heating rate and test procedure is to be adopted. Thus, full high temperature creep effects could not be captured in the current paper.

3. Experimental results

Based on the results from tests, the effect of heating-cooling phase on residual stress-strain response, post heating strength and elastic modulus is deduced.

Table 1
Characteristics of test specimens.

Bolt ID	Bolt grade	Bolt size	Material	Yield strength F_y (MPa)	Ultimate strength F_u (MPa)	Elasticity modulus E (GPa)	Rockwell hardness (HRC)	Number of tests
M16(10B38)	8.8	M16	SAE 10B38	834	951	210	29	33
M18(10B38)	8.8	M18	SAE 10B38	831	945	211	29	33
M22(10B21)	8.8	M22	SAE 10B21	986	1079	202	30	33