Journal of Constructional Steel Research 67 (2011) 1292–1298

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Behaviour of Grade 8.8 bolts under natural fire conditions—Tests and model

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ARTICLE INFO

Article history:
Received 22 October 2009
Accepted 6 March 2011

Keywords:
Bolts
Material law
Non-reversibility
Cooling
Natural fire

ABSTRACT

Recent full-scale experimental tests performed on steel and composite structures have demonstrated that the presence of tensile forces in axially-restrained beams during the cooling phase of a fire could lead to bolt failures. In order to understand this observation and design structures that are not prone to such a failure mode, it is essential to have a deep knowledge of the material behaviour of all the components, including bolts, during both the heating and cooling phase.

In the present article, the test set-ups and the results of the tensile and shear tests performed at the Centro Sviluppo Materiali (Italy) on Grade 8.8 bolts under heating–cooling cycles are described.

Then, material laws are defined for characterising the mechanical behaviour of Grade 8.8 bolts under heating and cooling phases. These laws account for the non-reversibility of the mechanical properties of Grade 8.8 bolts.

1. Introduction

The stability of a steel structure during a fire depends on its ability to withstand mechanical and thermally-induced loads in spite of the reduction of the mechanical properties in structural elements. Until recently, the analysis of structures subjected to fire was in most cases systematically performed under the hypothesis of a nominal fire where the temperature is continuously increasing. Recent full-scale experimental tests have been performed under fire curves including a phase of decreasing temperature that we call a "natural fire" test. It has been observed that, when failure does not occur during the heating phase, the tensile forces induced in axially-restrained beams during the cooling phase, could lead to the failure of bolts situated in the joint zone [1,2]. In order to understand this phenomenon and to design structures that are not prone to such a failure mode, it is essential to have a deep knowledge of the material behaviour of all components, including bolts, during cooling.

The residual strength of several steel grades after heating and cooling has been studied by British Steel. Lapwood [3] reported that no decrease in strength is observed after heating to temperatures up to 600 °C but that some deterioration in properties occurs after heating to higher temperatures. Up to now, mechanical models of bolts have been proposed mostly for elevated temperatures, without the consideration of a cooling phase. Eurocode 3 Part 1–2 [4] proposes strength reduction factors as a function of the temperature for the design of bolts under fire conditions. These factors have been determined on the basis of the experimental work carried out by Kirby on M20 hexagonal head bolts, strength class 8.8 (EN ISO 898-1) at temperatures up to 800 °C [5]. Riaux also carried out six tensile tests in order to determine the mechanical properties of bolts as a function of temperature between 20 °C and 700 °C [6]. The tests by Riaux realised under displacement control showed that a descending branch exists before the full breaking of the bolts. A material model based on these results has been proposed recently to characterise the mechanical behaviour of bolts during heating. In recent researches, Lange performed tests on Grade 10.9 bolts and investigated the effect of creep on the behaviour of bolt material at high temperatures [7].

Due to the manufacturing process of bolts, based on a quenching phase from an austenitising temperature of 800 °C to around 500 °C and a tempering phase, the mechanical behaviour of bolts at elevated temperatures differs noticeably from the mechanical behaviour of carbon steel. The residual resistance and stiffness of bolts are reduced by a heating–cooling cycle.

The present article describes the experimental tests undertaken at the Centro Sviluppo Materiali (C.S.M.) in Italy and presents the values of strength reduction factors after having experienced a natural fire, which means a temperature history including both heating and cooling. A model is also proposed for the stress–strain diagram of bolts during a natural fire (temperature history including both heating and cooling).

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doi:10.1016/j.jcsr.2011.03.012

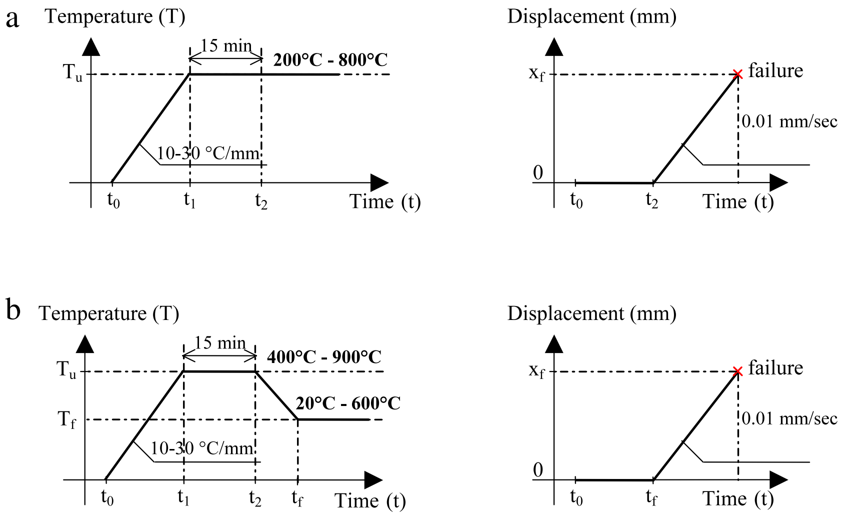

Fig. 1. Steady-state (a) and natural fire (b) tests procedures for bolts experiments.

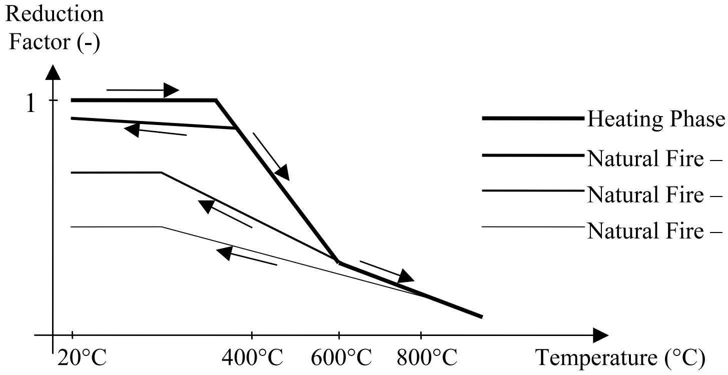

Fig. 2. Possible schematic presentation of the results given by the tests.

2. Test methodology

In this project, three different types of test have been performed on full size bolts:

(a) Room temperature tests, performed in order to get the reference strength.
(b) Steady-state tests at elevated temperatures, performed in order to obtain the strength evolution of bolts during the heating phase.
(c) Natural fire tests: steady-state tests at various elevated temperatures after first heating to a higher temperature, performed in order to investigate the strength behaviour of bolts during the cooling phase.

In the steady-state tests, the bolts were heated unloaded at a speed of 10–30 °C/min until the desired temperature was reached. The load was applied after a stabilisation period of 15 min that ensured a uniform distribution of temperature in the bolt, see Fig. 1(a). In the natural fire tests, the temperature was stabilised at an up-value of temperature T_u during 15 min and decreased until the failure temperature T_f at a speed of 10–30 °C/min. The mechanical loading was applied as soon as the temperature reached T_f, see Fig. 1(b). Temperatures are measured by a thermocouple.

From the steady-state tests, the resistance of bolts during heating in terms of reduction factor (the ratio of bolt resistance after heating to bolt resistance at room temperature) can be plotted as a function of the temperature, see the line printed in bold on Fig. 2. The objective of the present natural fire tests is to obtain the evolution of the bolt resistance as a function of the maximum temperature T_u and the test temperature T_f, see the fainter lines on Fig. 2.

3. Test set-up

Design codes (see for example Eurocode 3) give separate values for the bolt strength in tension and shear so two different test set-ups have been designed to investigate separately the mechanical behaviour of bolts in shear and in tension at elevated temperature.

The furnace used for testing is an electrical furnace with manual adjustment of power. Tests are performed imposing a furnace power that resulted in a heating rate in the range of 10–30 °C/min. At the cooling phase the furnace is switched off and ventilated. The cooling rate is approximately in the same range of 10–30 °C/min.

Due to the limited loading capacity of test equipment, it was decided to use size M12 bolts which are smaller than those used in building structures (minimum M16). Special investigation has been undertaken to check the consequences of this decision.

Clamps for both tensile and shear tests have been fabricated using the NIMONIC 115 heat resistant alloy, see Figs. 3 and 4, so that the behaviour of clamps remains elastic during the complete test and prying actions due to clamp deformations are avoided.

4. Test schedule

For both tensile and shear tests, the following tests have been performed (see also Table 1):