Cover page

Title: *Experimental investigations and analytical model for the behavior of Grade 8.8 bolts and butt welds under heating and subsequent cooling*

Authors: François Hanus
Giuliana Zilli
Jean-Marc Franssen

ABSTRACT

The present article describes the experimental tests undertaken on bolts and welds at the Centro Sviluppo Materiali during heating or subsequent cooling, presents a model for the stress-strain diagram of bolts during a natural fire that integrates the influence of the temperature history, and gives values of strength reduction factors for the cooling phase.

INTRODUCTION

Recent full-scale experimental tests performed on steel and composite structures have demonstrated that the development of tensile forces in axially-restrained beams during the cooling phase of a natural fire can lead to the failure of bolts situated in the joint zone. 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 and welds, during both the heating and cooling phases.

Up to now, mechanical models of bolts and welds have been proposed essentially for elevated temperatures, without consideration of a cooling phase. Eurocode 3 Part 1-2 proposes strength reduction factors as a function of 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 and Latham, on hexagonal head bolts, strength class 8.8, and on fillet and butt welds at temperatures up to 800°C. However, the residual resistance of bolts and welds after a heating-cooling cycle has not been investigated yet (see Figure 1).

The behavior of carbon steel is usually assumed as reversible in usual fire design applications, see for example [1]. Due to the manufacturing process of bolts, the mechanical behaviors of bolts and carbon steel differ noticeably at elevated temperatures. Up to now, investigations about the mechanical properties of bolts and welds have essentially been founded on the results of isothermal tests performed on specimens heated up to different temperatures.

François Hanus (corresponding author), Research Engineer, Structural Engineering, University of Liège, Belgium.
Giuliana Zilli, Research Engineer, Centro Sviluppo Materiali, Rome, Italy.
Jean-Marc Franssen, Professor, Structural Engineering, University of Liège, Belgium.

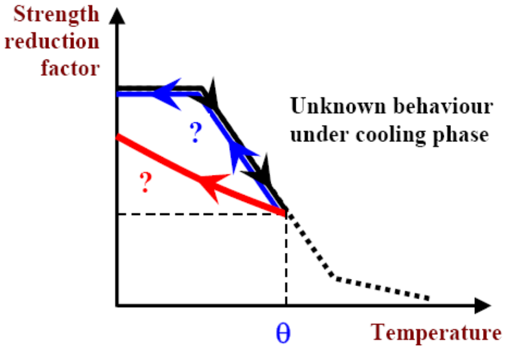

Figure 1. Objective of the tests performed on bolts and welds

The first series of tests performed on bolts were displacement-controlled tests realized by Riaux at temperatures between 20°C and 700°C, showing the existence of a descending branch in the force-displacement diagram before the full breaking of bolts [2]. The strength reduction factors mentioned in EN 1993-1-2 [3] have been determined on the basis of the experimental work carried out at British Steel on Grade 8.8 M20 bolts at temperatures up to 800°C [4]. Tests in tension have highlighted that problems of premature failure by thread stripping are caused by the lack of fit between the nut and the bolt rather than the insufficient capacity of one component. The measured reductions of resistance showed similar patterns in tension and shear. In recent researches, tests performed on Grade 10.9 bolts have underlined the significant effect of creep on the behavior of bolt material at high temperatures [5].

To the knowledge of the authors, the unique available data about the evolution of welds resistance at elevated temperatures is the series of tests performed by British Steel [6] that lead to the reduction factors defined in EN 1993-1-2.

On the basis of this review of existing data, new tests have been performed at the Centro Sviluppo Materiali and are presented in this article. These tests are aimed at characterizing the mechanical behavior of bolts and welds during both the heating and cooling phases of a fire. A stress-strain model is also proposed for bolts during both the heating and cooling phases of a fire.

TEST METHODOLOGY

The experimental programme undertaken on bolts and welds at the Centro Sviluppo Materiali includes three different types of isothermal tests:

- Room temperature tests performed in order to get the reference strengths
- Steady-state tests performed at elevated temperatures in order to obtain the strength evolution of bolts/welds during the heating phase (see Figure 2a)
- Steady-state tests performed at various failure temperatures T_f after heating to temperature T_u, in order to investigate the strength behavior of bolts and welds during the cooling phase (see Figure 2b).

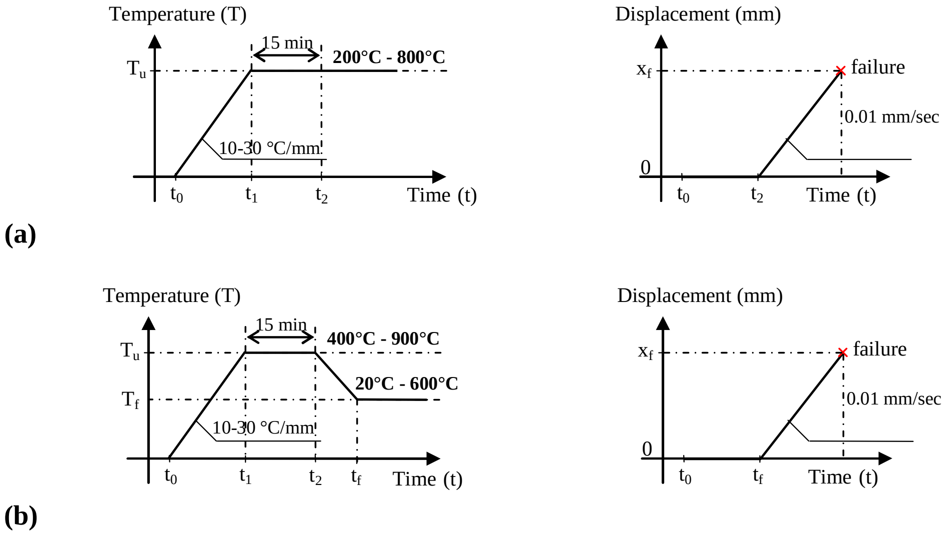

Figure 2. Test processes for bolt experiments after heating (a) or heating and subsequent cooling (b)

In all the tests performed at elevated temperatures, the tested specimens were heated and cooled down at a speed of 10-30°C/min. Temperature has been stabilized during 15 minutes after reaching the temperature T_u and the failure temperature T_f.

EXPERIMENTAL TESTS PERFORMED ON GRADE 8.8 BOLTS.

The resistance of bolts in tension and shear are evaluated separately in the design codes. Consequently, two different test set-ups have been designed to investigate separately the mechanical behavior of bolts in tension and shear (see Figure 3). Due to the limited loading capacity of test equipment, size M12 bolts have been tested. Clamps for both tensile and shear tests have been fabricated using the NIMONIC 115 heat resistant alloy so that their behavior remains elastic during the complete test and prying actions due to clamps deformations are limited.

All the tensile tests have been caracterised by a ductile yielding of the threaded shank and no nut stripping failure occurred (Figure 4).

The correlation between the results obtained from tests performed at the up temperature $T_u = T_f$ and the Eurocode recommendations demonstrated that the diameter has a limited influence on the reduction of bolt resistance (Figure 5).The reduction factors k_b obtained experimentally for T_u = 400°C, 600°C and 800°C are plotted on Figure 6.

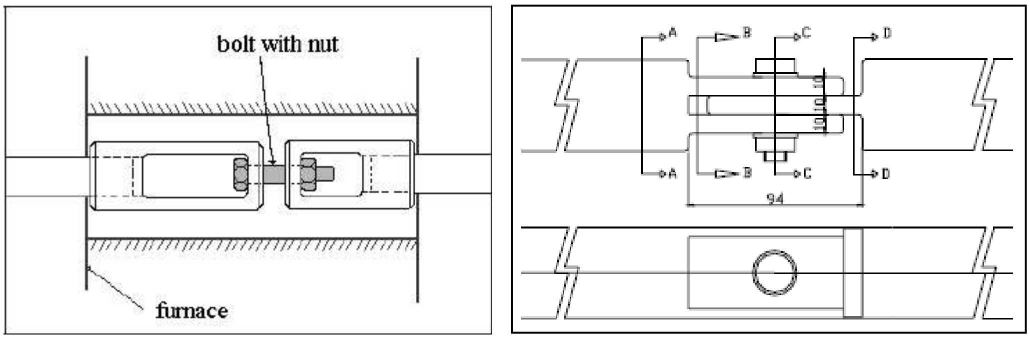

Figure 3. Test set-ups for tensile and shear tests performed on bolts

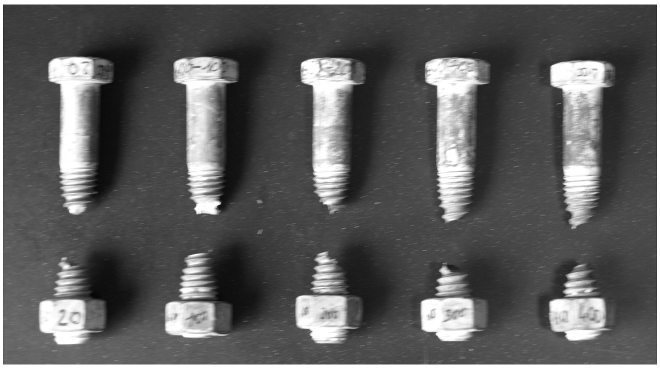

Figure 4. Bolts tested in tension (T_u = 600°C)

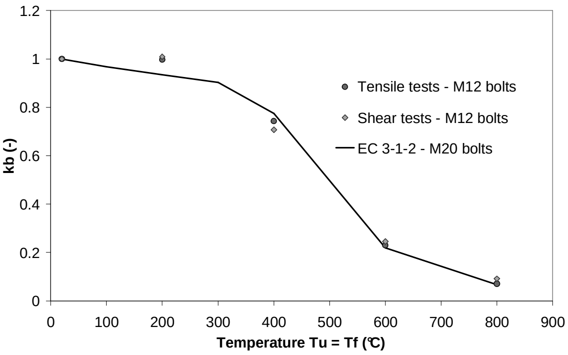

Figure 5. Comparison of the strength reduction factor for M12 and M20 bolts

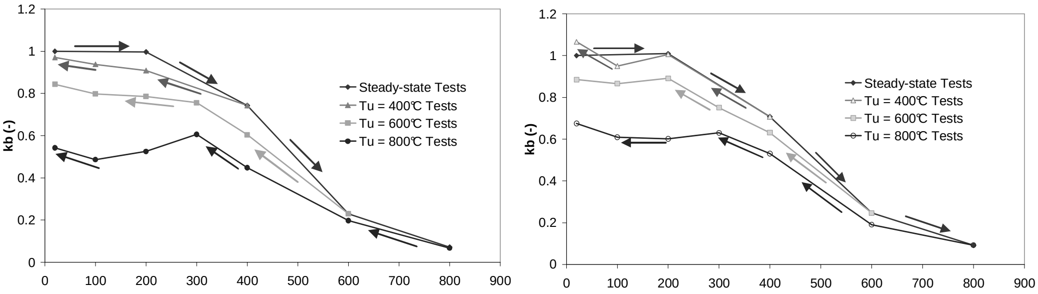

Figure 6. Reduction factor for bolt strength k_b in tension (left) and shear (right)

STRESS-STRAIN LAW FOR GRADE 8.8 BOLTS UNDER NATURAL FIRE

The ultimate bolt strength $f_{ub,Tf,Tu}$ at a temperature T_f after the temperature has reached T_u at the end of the heating phase is given by Eq. 1, where k_b is the reduction factor for bolt strength during the heating phase (from EN 1993-1-2) and k_{nr} is a parameter accounting for the non-reversible behavior of bolts during the cooling phase (Eq. 2). The latter coefficient is equal to 1 if T_u is lower than 500°C and equal to 0.6 for T_u higher than 800°C; a linear interpolation is proposed between these two values. The analytical and experimental values of the reduction factor k_b are plotted on Figure 7.

$$f_{ub}\left(T_f,T_u\right)=k_b\left(T_f\right).\,k_{nr,b}\left(T_f\,;T_u\right).\;f_{ub,20°C} \tag{1}$$

$$k_{nr,b}\left(T_f\,;T_u\right)=\min\left(1\,;1-\frac{0.4}{300}\left(T_u-\max\left(T_f\,;500°C\right)\right)\right) \tag{2}$$

The general shape of the stress-strain diagram proposed for bolts is given on Figure 8 and is composed of an elastic branch, an elliptic branch and a bilinear descending branch. The parameters $f_{p,\theta}$, $f_{t,\theta}$, $\varepsilon_{p,\theta}$, $\varepsilon_{u,\theta}$, $\varepsilon_{t,\theta}$, and $\varepsilon_{0,\theta}$ are defined in Eqs 3 to 7. The Young modulus E_{Tf} is supposed to be the same as the one of carbon steel at the temperature T_f and the coefficient k_p is given in Table 1. The analytical method is compared to experimental results on Figure 9.

$$f_{pb}\left(T_f,T_u\right)=k_p\left(T_u\right).\;f_{ub,20°C} \tag{3}$$

$$f_{tb}=\max\left(f_{ub}\;;500\,MPa\right) \tag{4}$$

$$\varepsilon_{pb}=f_{pb}/E_{Tf} \tag{5}$$

$$\varepsilon_{yb}=0.02 \tag{6}$$

$$\varepsilon_{0b}=0.15+\max\left(0\;;0.1*\frac{\left(\max\left(T_u\;;800°C\right)-600°C\right)}{200°C}\right) \tag{7}$$

T_u (℃)	$k_{p,\theta}$ (-)
20	0.9
200	0.8
400	0.75
600	0.75
800	0.6
900	0.6

Table 1. Values of the factor k_p as a function of T_u

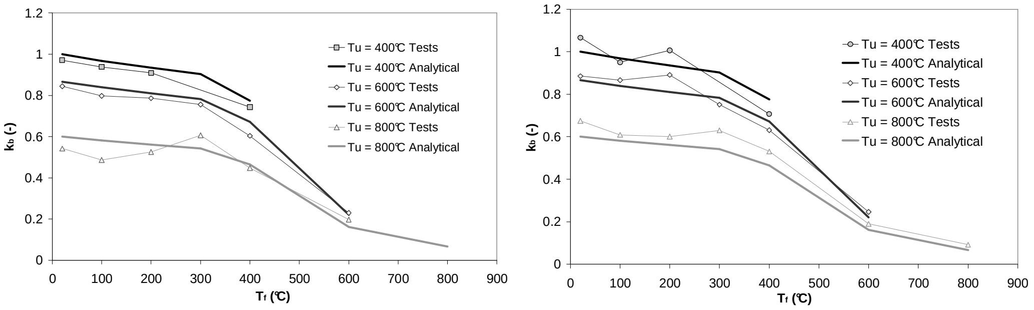

Figure 7. Reduction factor for bolt strength k_b in tension (left) and shear (right)

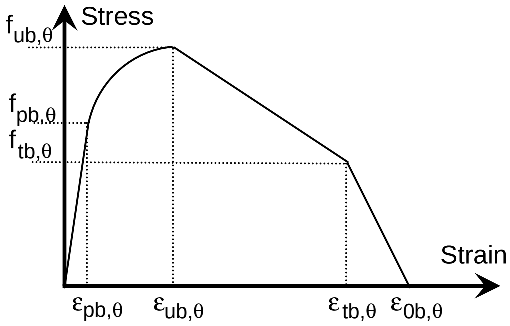

Figure 8. General shape of the stress-strain diagram for bolts

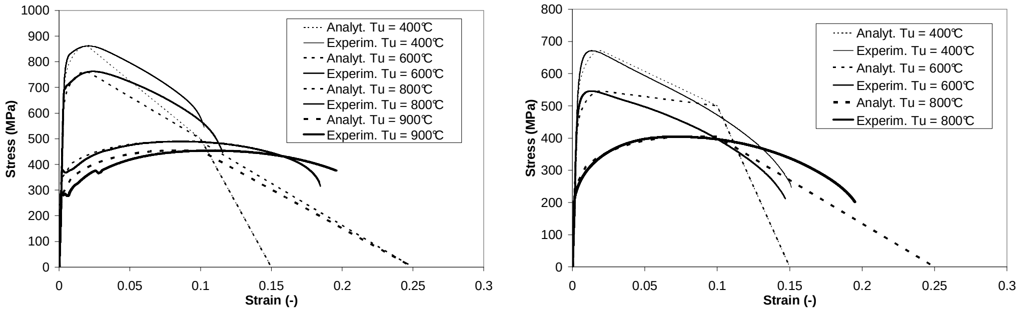

Figure 9. Comparison between analytical and experimental stress-strain curves: T_f = 20°C (left) and T_f = 400°C (right)

EXPERIMENTAL TESTS PERFORMED ON BUTT WELDS.

Tests have been performed on butt welds joints subjected to transversal tensile forces in order to characterize the evolution of welds resistance during a natural fire (Figure 10). For temperatures T_u lower than or equal to 600°C, welds recover their initial strength f_{uw} (Figure 11). When T_u is equal to 800°C or 900°C, the reduction of the ultimate strength after a complete heating-cooling cycle is around 20% of the initial ultimate strength. The ultimate strength of welds $f_{u,welds}$ during the cooling phase is expressed by Eq. 8, where the coefficient for the non-reversible behavior of welds $k_{nr,welds}$ is given by Eq. 9. The analytical values of the reduction factor for welds k_w and the factor accounting for the non-reversible behavior of welds $k_{nr,welds}$ are compared to experimental results on Figures 11 and 12.

$$f_{u,welds}\,(\,T_f\,,T_u\,) = k_w\,(\,T_f\,)\,.\,k_{nr,welds}\,(\,T_f\,,T_u\,)\,.\,f_{u,welds}\,(\,20°C\,) \qquad (8)$$

$$\begin{cases} T_u \le 600°C & \rightarrow \quad k_{nr,welds} = 1 \\ 600°C < T_u \le 800°C & \rightarrow \quad k_{nr,welds} = 1 - 0.2 \times (\,T_u - \max\,(T_f\,;600)\,) \\ 800°C < T_u \le 900°C & \rightarrow \quad k_{nr,welds} = 1 - 0.2 \times (\,800 - \max\,(T_f\,;600)\,) \end{cases} \qquad (9)$$

Figure 10. Specimen submitted to transversal tensile forces during weld tests

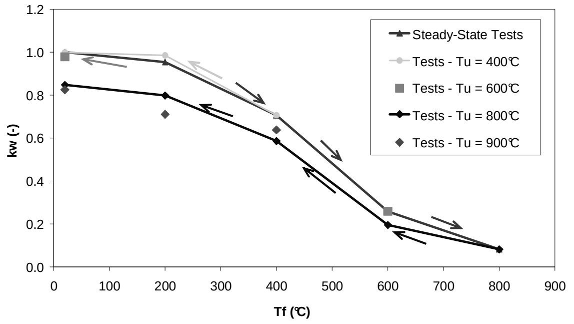

Figure 11. Experimental value of the reduction factor k_w during both the heating and cooling phases

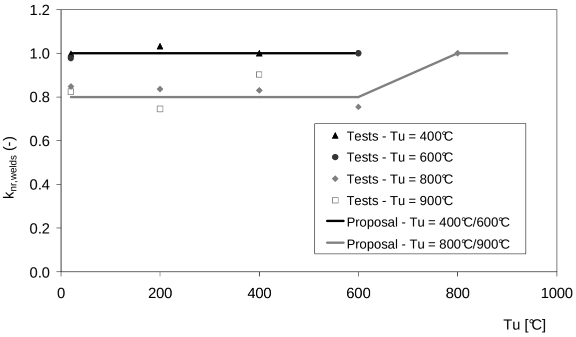

Figure 12. Comparison between the coefficients for non-reversible behavior of welds $k_{nr,welds}$ obtained experimentally and analytically

CONCLUSIONS

Tensile and shear tests performed on bolts have demonstrated that a heating-cooling cycle implies two major modifications in the mechanical behavior of bolts. Firstly, the ultimate strength of bolts starts to reduce in a non-reversible manner when the temperature of bolts has reached 500°C. This reduction can be 40% of the initial bolt strength when the temperature has reached 800% during the heating phase. Secondly, the ductility of bolts under tensile forces is significantly increased when the temperature T_u goes from 600°C to 800°C.
Tests on welds have also shown a reduction in strength but the reduction of ultimate strength of welds after a complete heating-cooling cycle is limited to 20% of the initial ultimate strength.

ACKNOWLEDGEMENTS

The article describes a part of the output of the COSSFIRE Research Project. The Research Fund for Coal and Steel is gratefully acknowledged for its financial support. Dr Bin Zhao from CTICM (France), Dr George Koutlas (UK) and Arnoud Breunese from Efectis Netherlands (NL) are also thanked for their active collaboration in the work presented by this article.

REFERENCES

1. Lapwood D.G. “The Effect of Fire Damage on the Mechanical Properties of Structural Steels Assessed Using Laboratory Heat Treatment Simulations”, British Steel Report No T/RS/1189/8/80/C (1980).
2. Riaux H. “Comportement à l’incendie des assemblages simples boulonnés” (in French), Ph.D. Thesis, INSA Rennes, France (1980).
3. EN 1993-1-2 – Eurocode 3 “Design of steel structures – Part 1-2: Structural fire design”, European Committee for Standardization, CEN, Brussels (2004).
4. Kirby, B.R. “Behaviour of High-Strength Grade 8.8 Bolts in Fire”, Journal of Constructional Steel Research, Vol. 33, pp. 3-38 (1995).
5. Gonzalez F., Lange J. “Material Behaviour of High Strength Grade 10.9 Bolts under Fire Conditions”, Fifth Conference on Steel and Composite, Graz, Austria (2008).
6. Latham D.J., Kirby B.R. “Elevated Temperature Behavior of Welded Joints in Structural Steelwork”, Contract ECSC 7210 SA 824 (1993)