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

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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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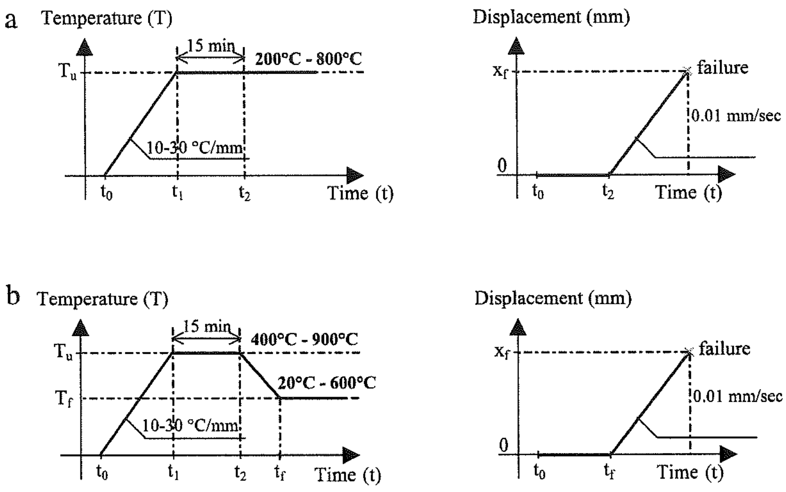

Fig. 1. Steady-state (a) and natural fire (b) tests procedures for bolts experiments.

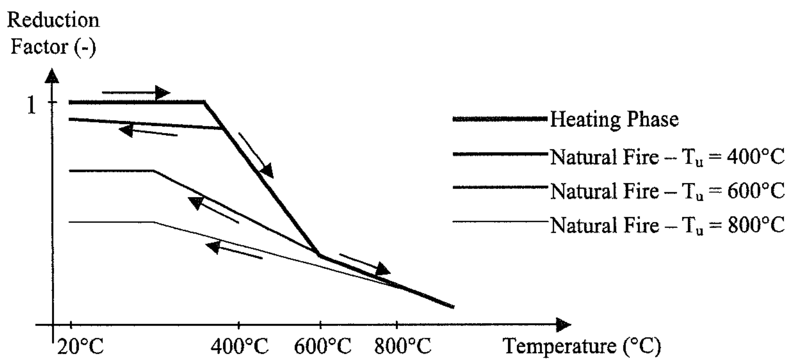

Fig. 2. Possible schematic presentation of the results given by the tests.

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):

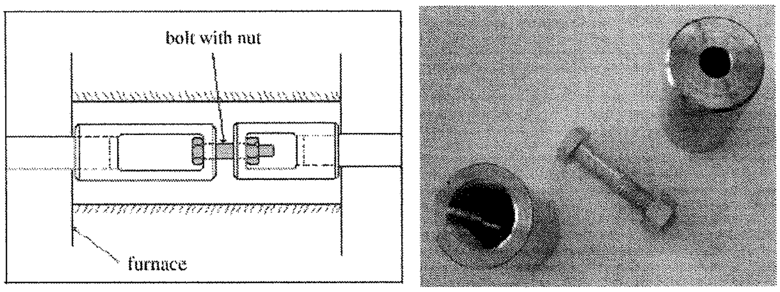

Fig. 3. Bolt–nut assembly and clamps for tensile tests.

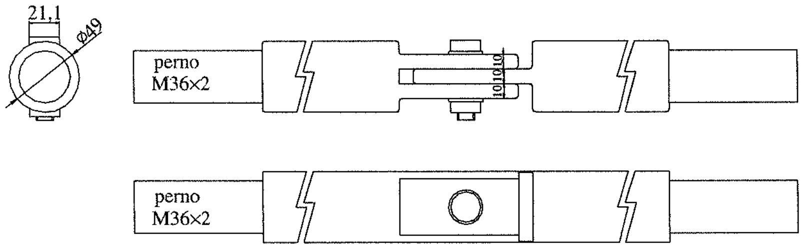

Fig. 4. Bolted connection design for shear tests at elevated temperature.

Table 1
Detailed programme of tensile and shear tests performed on bolts.

Steady-state tests		Natural fire tests		
$T_u = T_f$ (°C)	n-tests	T_u (°C)	T_f (°C)	n-tests
200	1		200	2
400	1	400	100	1
600	1		20	1
800	1		400	1
			300	1
		600	200	2
			100	1
			20	1
			600	1
			400	1
			300	1
		800	200	2
			100	1
			20	1
		900	20	1

- 2 tests on bolts at room temperature;
- 4 steady-state tests performed to compare the results obtained on M12 bolts with the values of Eurocode 3 that have been derived from tests performed on M20 bolts;
- 18 natural fire tests.

Fig. 5 shows all the bolts tested in tension after a natural fire with T_u = 600 °C and cooled down at different T_f before the mechanical load was applied. One of the two tests in which T_f = 200 °C has been missed and that bolt is not shown. Bolts are positioned according to the test temperature T_u (from 20 °C on the left to 400 °C on the right).

5. Test results

5.1. Treatment of experimental results

Test results require pre-treatment of the raw data in order to account for two types of out-of-control phenomena:

- For low load levels, the presence of connection clearance induces some displacements, and the force–displacement graph is not linear whereas the behaviour of the material should be elastic.
- The components of the test rig develop their own elongation during loading. Because the elongation was measured between two referential points located outside the furnace, this elongation of the test rig must be evaluated in order to correctly measure the elongation of the bolt.

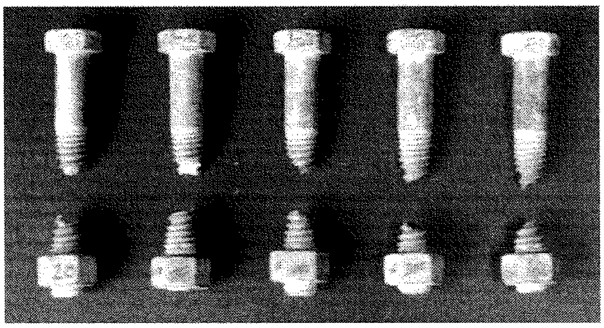

Fig. 5. Bolts tested in tension after natural fire at different T_f temperatures after reaching T_u = 600 °C.

The first operation of the data pre-treatment is a horizontal displacement of the origin of the force–displacement graph so that the parasitic displacements due to the initial adjustments of the rig are eliminated. The origin shift s is evaluated by calculating the slope of the straight line joining the points related to $N = 1/4N_{max}$ and $N = 3/4N_{max}$, and the new origin of the graph is the intersection between this line and the axis of displacements, see Fig. 6.

The second operation of the data pre-treatment consists of removing the spurious displacements caused by the deformations of the test rig during the test. For tensile tests, the variation of length has been measured between two points situated outside the furnace. Consequently, the measured values include the deformation of the bolt and the deformation of the test rig. The deformation of the tested bolt has been obtained by the assumption, afterwards experimentally confirmed, that the Young's modulus of bolts at elevated temperature is given by

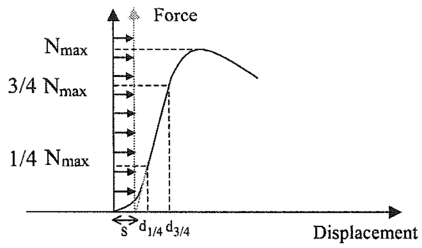

Fig. 6. Horizontal shift of the F-d origin.

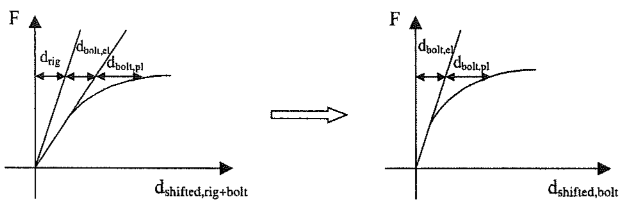

Fig. 7. Elimination of the spurious displacements due to the deformations of the test rig.

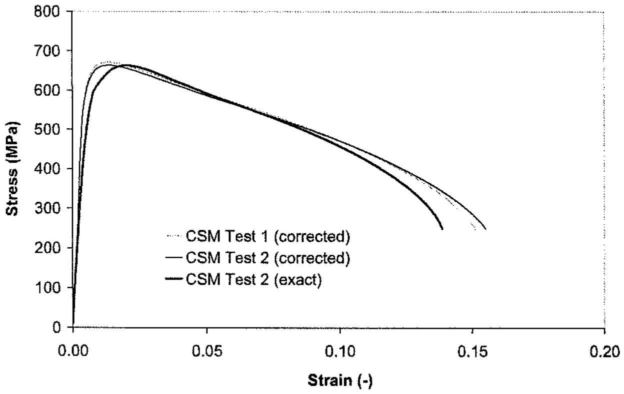

Fig. 8. Stress–strain diagram of bolts at $T_u = T_f = 400$ °C.

the recommendations of Eurocode 3 for carbon steel and the consideration that the test rig remains elastic during the complete mechanical test. Comparison between the measured deformations in the elastic domain and the elastic deformation of the bolt calculated using Eurocode values allows for a determination of the elastic stiffness of the test rig. As a result, elastic deformations of the test rig can be subtracted from the complete experimental curve, see Fig. 7.

A specific additional steady-state test (Test 2) has been performed at 400 °C in order to verify the validity of this procedure. Both the variation of the bolt length and the variation of the distance between the external measuring points have been measured by means of an extensometer designed for high temperature tests. Fig. 8 shows that the elongation measured on the bolts inside the furnace (Test 2 exact) compares very well with the elongation measured at the external points and corrected with the elastic hypotheses (Test 2 corrected). The third curve (Test 1 corrected) represents the stress–strain diagram of the previous test performed at 400 °C, after corrections based on elastic hypotheses.

5.2. Experimental results

Fig. 9 shows the reduction factor k_b defined as the ratio between the bolts strength at elevated temperature $f_{y,Tu=Tf}$ obtained by the steady-state tests performed on M12 bolts and the yield strength

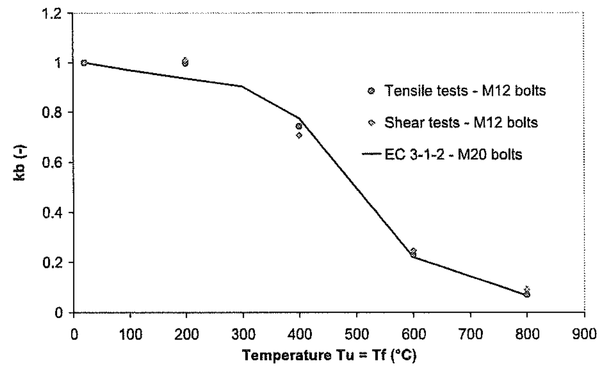

Fig. 9. Comparison between k_b values given by steady-state tests and Eurocode 3.

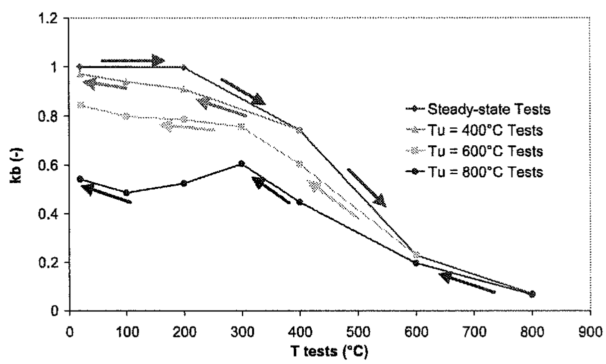

Fig. 10. Tensile tests—reduction factor of bolts strength.

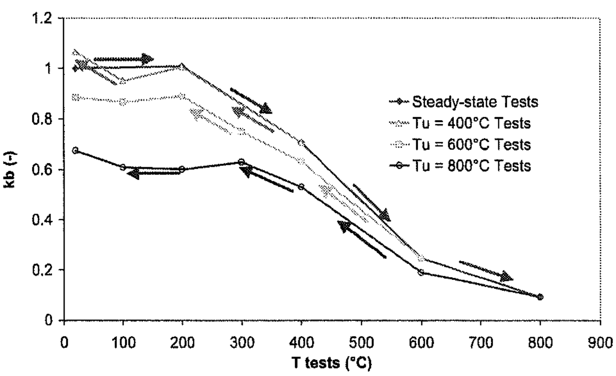

Fig. 11. Shear tests—reduction factor of bolts strength.

at room temperature $f_{y,20\,°C}$. Even when slight differences are observed at 200 °C, the comparison with the values of strength reduction factor k_b proposed in Eurocode 3 and developed on the basis of M20 bolt tests [5] indicates that the diameter of the bolt was not a major influence on tests results.

The total reduction factors of bolt strength k_b obtained experimentally in the natural fire tests for three different maximum temperatures ($T_u = 400$ °C, 600 °C and 800 °C) are plotted on Figs. 10 and 11. The heating phase is represented by a test at room temperature and four steady-state tests realised at four different temperatures. The other three curves, representing the behaviour of bolts during the cooling phase, have been obtained by natural fire tests performed at different temperatures T_f after reaching the same maximal temperature T_u equal to 400 °C, 600 °C or 800 °C. When two tests have been performed under the same conditions, see Table 1, the average value of both results has been used in the figures.

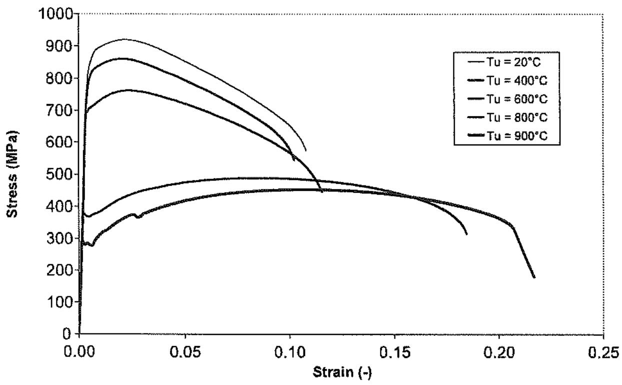

Fig. 12. Experimental stress-strain relationships—$T_f = 20$ °C.

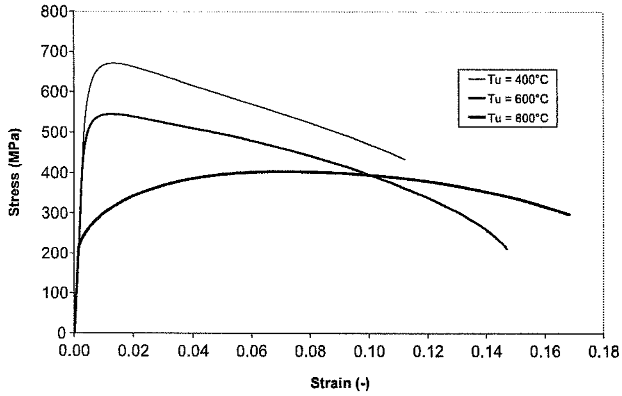

Fig. 13. Experimental stress-strain relationships—$T_f = 400$ °C.

Figs. 12 and 13 give an overview of the stress–strain relationship from several tensile tests performed at the same temperature ($T_f = 20$ °C or $T_f = 400$ °C) after reaching different maximal temperature T_u. The bolts seem to have a more ductile behaviour in tests when the maximal temperature T_u has reached 800 °C than for lower values of T_u. When the maximum temperature reached is lower than or equal to 600 °C, the peak stress strain is lower (around 2%) and there is no horizontal yield plateau in the stress–strain diagram.

6. Analytical models

In order to integrate the stress–strain relationship of bolts during a natural fire into numerical programs (including the heating and the cooling phase), a mathematical model has been proposed and compared with the experimental results. This model is based on the assumption that the bolt has a constant cross-section area equal to the reduced area. In reality, the deformations will be localised to the threaded part of the shank while in the model the elongation is uniformly distributed through the shank, but this does not affect the elongation value. Firstly, a method is given to calculate the yield strength as a function of the maximum temperature reached at the end of the heating phase T_u and the temperature T_f at the time considered. Secondly, a model for the stress–strain relationship of bolts is proposed.

6.1. Evolution of the yield strength

A new ratio k_{nr} is defined in the case of tensile and shear tests as the ratio between the yield strength in steady-state tests (direct heating until the temperature $T_u = T_f$) and the yield strength at T_f during cooling (Eq. (1)).

$$k_{nr}(T_f, T_u) = \frac{f_y(T_f \neq T_u)}{f_y(T_f = T_u)} \leq 1. \quad (1)$$

This ratio has been plotted as individual points for each test on Fig. 14. The following observations can be made:

- For T_f below 500 °C, k_{nr} remains constant whatever the maximum temperature T_u. This means that the permanent loss of strength induced by cooling is fully developed when the temperature returns to 500 °C.
- When the maximum temperature T_u is not higher than 500 °C, k_{nr} is approximately equal to 1. This means that no permanent loss of strength occurs if the temperature does not exceed 500 °C.
- Shear tests seem to give slightly higher k_{nr} values than tensile tests.

Based on the experimental results, the residual resistance f_y (T_f; T_u) during the cooling phase should be calculated according to the following method:

a. EN 1993-1-2 [8] gives the reduction of the bolt strength $k_b(T_f)$ without considering the effect of cooling;

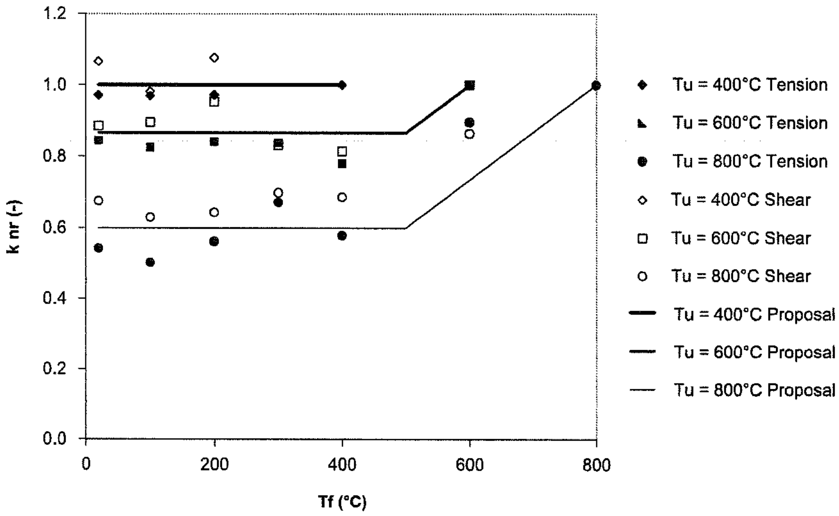

Fig. 14. Tensile and shear tests—reduction factor for yield strength due to non-reversible behaviour.

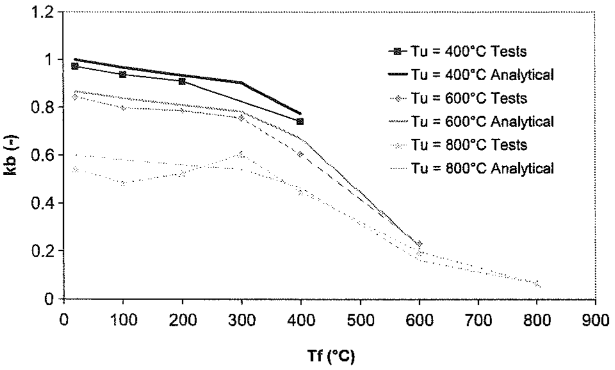

Fig. 15. Tensile tests—comparison between experimental and analytical reduction factor for yield strength.

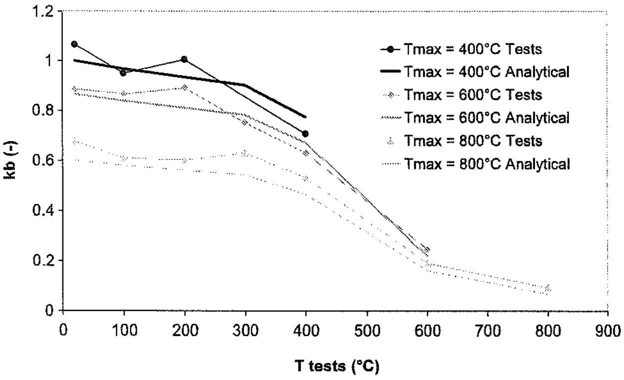

Fig. 16. Shear tests—comparison between experimental and analytical reduction factor for yield strength.

b. The additional effect of cooling, k_{nr}, is calculated from Eqs. (2)(a) and (b).

$$\begin{cases} T_u \leq 500\ ^\circ\text{C} \rightarrow k_{nr} = 1 \quad (a) \\ 500\ ^\circ\text{C} < T_u \leq 800\ ^\circ\text{C} \rightarrow k_{nr} \\ \quad = 1 - 1.33.10^{-3}.(T_u - \max(T_f; 500)) \quad (b). \end{cases} \tag{2}$$

c. Finally, the value of the bolt yield strength accounting for the non-reversible behaviour of steel is given by Eq. (3).

$$f_y(T_f, T_u) = k_b(T_f).k_{nr}(T_f; T_u).f_y(20\ ^\circ\text{C}). \tag{3}$$

It has been decided to use the same expressions for shear and for tension which will simplify the verification of bolts subjected simultaneously to tension and to shear. Analytical expressions are compared with the experimental values obtained from both tensile and shear tests on Fig. 14.

Figs. 15 and 16 show the comparison between the reduction factors for the bolt strength during the cooling phase obtained experimentally and analytically. In the shear tests, the analytical result seems to be a little bit too conservative but lower values would be unsafe in the case of tensile tests.

6.2. Stress–strain diagram

In the mathematical model proposed by Riaux for bolts at elevated temperatures (see Fig. 17), the failure strain ε_u is equal to 0.35. In the tests realised by C.S.M., ε_u varies between 0.1 and 0.2. In order to get a good correlation with C.S.M. tests, the model proposed by Riaux has been adapted. In this new model, there is no horizontal plateau ($\varepsilon_{y,\theta} = \varepsilon_{10,\theta}$) and the values of the characteristic parameters are modified as explained underneath.

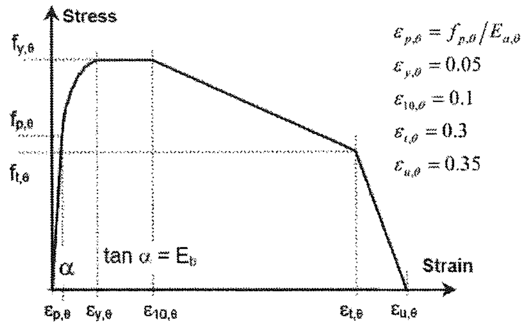

Fig. 17. Mathematical model proposed by Riaux [6].

Table 2
Ratio k_p between the proportional limit f_p and the bolt strength f_y.

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

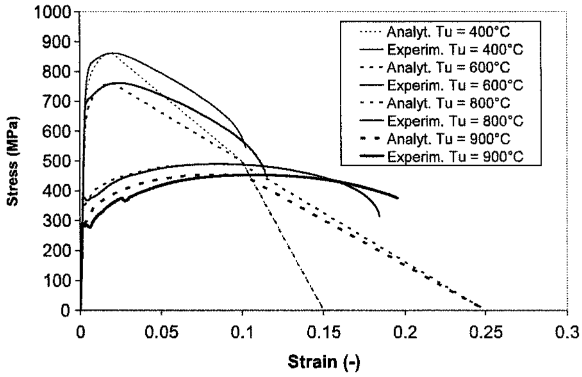

Fig. 18. Comparison between analytical model and experimental results—T_f = 20 °C.

When values are defined for a limited number of temperatures, it is assumed that linear interpolations are accepted for other temperatures.

- $f_{y,\theta}$.
  The calculation of the bolt strength has been set out in the previous paragraph.
- $f_{p,\theta}$.
  The ratio k_p between the proportional limit $f_{p,\theta}$, and the yield strength $f_{y,\theta}$ only depends on the maximum temperature T_u reached at the end of the heating phase. Table 2 gives the value of this ratio for different values of T_u.
- $\varepsilon_{y,\theta}$.
  The yield strain is fixed equal to 0.02.
- $\varepsilon_{t,\theta}$ and $f_{t,\theta}$.
  An analysis of the experimental curves shows that all curves pass on the point (σ = 500 MPa; ε = 0.1), or ($\sigma = f_{y,\theta}$; ε = 0.1) when the yield strength $f_{y,\theta}$ is smaller than 500 MPa.
- $\varepsilon_{u,\theta}$.
  In the tests when T_u = 800 °C, $\varepsilon_{u,\theta}$ = 0.25. In cases when T_u < 600 °C, $\varepsilon_{u,\theta}$ = 0.15.

Curves from the analytical model and experimental results are compared in Figs. 18 and 19.

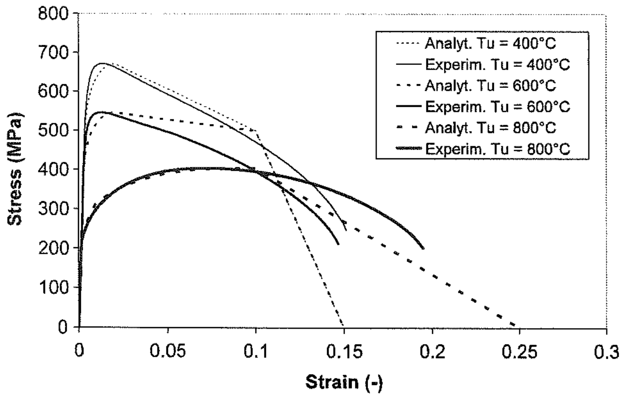

Fig. 19. Comparison between analytical model and experimental results—T_f = 400 °C.

7. Conclusions

The tensile and shear tests performed show that a heating–cooling cycle has a significant effect on the mechanical behaviour of Grade 8.8 bolts. After the bolt temperature has reached values higher than 500 °C, its yield strength decreases and its ductility increases. Based on the experimental results of the tests performed at the Centro Sviluppo Materiali, a model has been proposed for the strength of bolts and the stress–strain diagram of bolts during cooling. The non-reversible behaviour of bolts at elevated temperatures has been quantified by the definition of a new coefficient k_{nr} that depends on the maximum temperature reached during the heating phase T_u and the temperature of the test T_f.

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