Experimental Tests and Analytical Models for Welds and Grade 8.8 Bolts under Heating and Subsequent Cooling

F. Hanus[a], G. Zilli[b] and J.-M. Franssen[a]
[a]Department of Architecture, Geology, Environment and Construction, University of Liege, 1 Chemin des Chevreuils, 4000 Liege, Belgium. francois.hanus@ulg.ac.be
[b]Centro Sviluppo Materiali s.p.a, 100 Via del Castel Romano, 00128 Roma, Italy

ABSTRACT

The present article describes experimental tests performed on bolts and welds at the Centro Sviluppo Materiali under heating and subsequent cooling. Force-displacement laws, calibrated on these tests, are proposed afterwards for bolts in tension, bolts in shear and butt welds in shear during a natural fire. These laws can be integrated into models representing the global behaviour of steel and composite joints, based on the Component Method.

1. INTRODUCTION

Large-scale experimental tests performed on steel and composite structures have lead to bolt failures in connections due to development of large tensile forces in axially-restrained beams during the cooling phase of the fire. In order to understand the origins of these ruptures and to design structures that are not prone to such a failure mode, it is essential to have a good knowledge of the material behaviour of all components, including bolts and welds, during both the heating and cooling phases.

Up to now, mechanical models for 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 Grade 8.8 bolts and welds at temperatures up to 800°C. However, the residual resistance of bolts and welds after a heating-cooling cycle has not been investigated (Figure 1).

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

The first series of tests performed on bolts were displacement-controlled tests realized by Riaux at temperatures between 20°C and 700°C have shown 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 behaviour of bolt material at high temperatures [5].

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

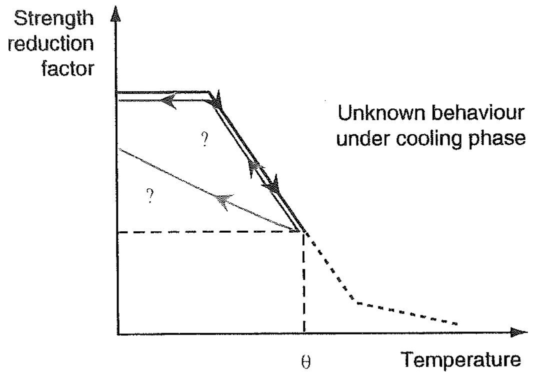

Figure 1. Objective of the tests performed on bolts and welds.

New tests have been performed at the Centro Sviluppo Materiali and are presented in this article. These tests are aimed at characterizing the mechanical behaviour of bolts and welds during both the heating and cooling phases of a fire. Force-displacement models representing the behaviour of bolts (subjected to tension or shear) are proposed for both the heating and cooling phases of a fire. Similarly, analytical expressions have been established to extend the use of strength reduction factor for welds to cooling.

2. TEST METHODOLOGY

The experimental programme followed for tests 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 resistances
- Steady-state tests performed at elevated temperatures in order to obtain the evolution of bolts/welds resistance during the heating phase (Figure 2a)
- Steady-state tests performed at various failure temperatures T_f after heating to an upper temperature T_u, in order to investigate the evolution of the resistance of bolts and welds during the cooling phase (Figure 2b).

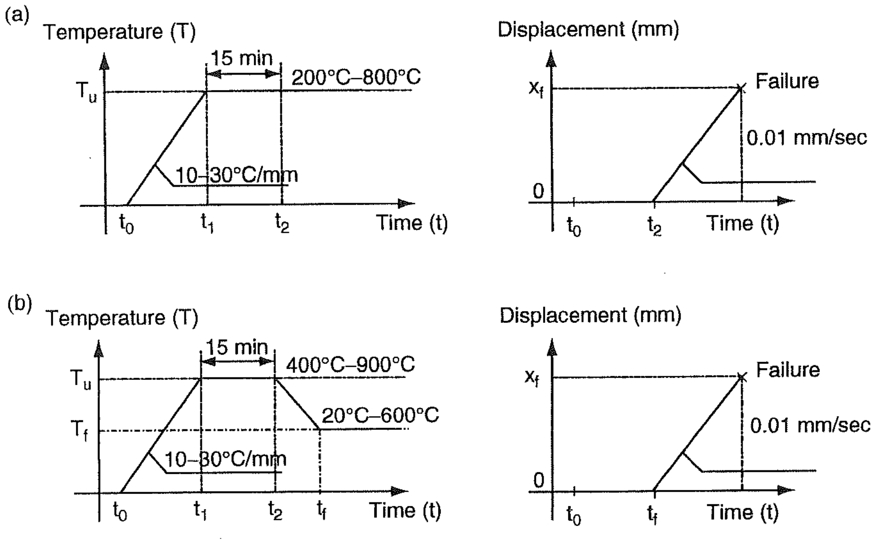

Figure 2. Test procedure for experiments on bolts and welds after heating (a) or heating and subsequent cooling (b).

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

3. EXPERIMENTAL TESTS PERFORMED ON GRADE 8.8 BOLTS

The nominal properties of bolts are given on Tables 1 and 2.

The tested M12 × 50 bolts are hexagonal-head and half-threaded bolts in accordance with the requirements of DIN 931 Norm. The value of the bolt strength f_{ub} has been roughly evaluated by hardness tests on two bolt shank sections. The mean value of the Rockwell Hardness A is 64.5 RHA (see Table 3), suggesting an approximate value of the ultimate tensile stress equal to 930 MPa. The ultimate tensile strength has also been estimated by a more accurate procedure: tensile tests have been performed on specimens machined from bolts according to the UNI EN ISO 898-1 standard (Figure 3). The results of these tensile tests are listed on Table 4.

As the resistance of bolts under tensile and shear forces are evaluated separately in the design codes, two different test set-ups have been designed to investigate separately the mechanical behaviour of Grade 8.8 bolts in tension and in shear (Figure 3). Clamps for both tensile and shear tests have been fabricated using the NIMONIC 115 heat resistant alloy so that prying actions due to deformations of clamps are limited. Due to the limited loading capacity of test equipment, size M12 bolts have been tested. The tensile and shear tests performed on bolts are listed in Tables 5 and 6.

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

Table 1. Nominal and reduced cross-section areas of typical bolt classes

Bolt class	M12	M16	M20	M24
Nominal section area (mm^2)	113	201	314	452
Reduced section area (mm^2)	84.3	157	245	353

Table 2. Nominal yield and ultimate strength of typical bolt grades

Bolt grade	4.6	5.6	6.8	8.8	10.9
Yield strength (N/mm^2)	240	300	480	640	900
Ultimate tensile strength (N/mm^2)	400	500	600	800	1000

Table 3. Results of hardness tests performed on tested Grade 8.8 M12 bolts

Specimen ID	Location ID	Rockwell Hardness (RHA 60 kg)
	Close to the surface	64
P1	Center	64
	Close to the surface	65
	Close to the surface	65
P2	Center	64
	Close to the surface	65
Mean value		64.5

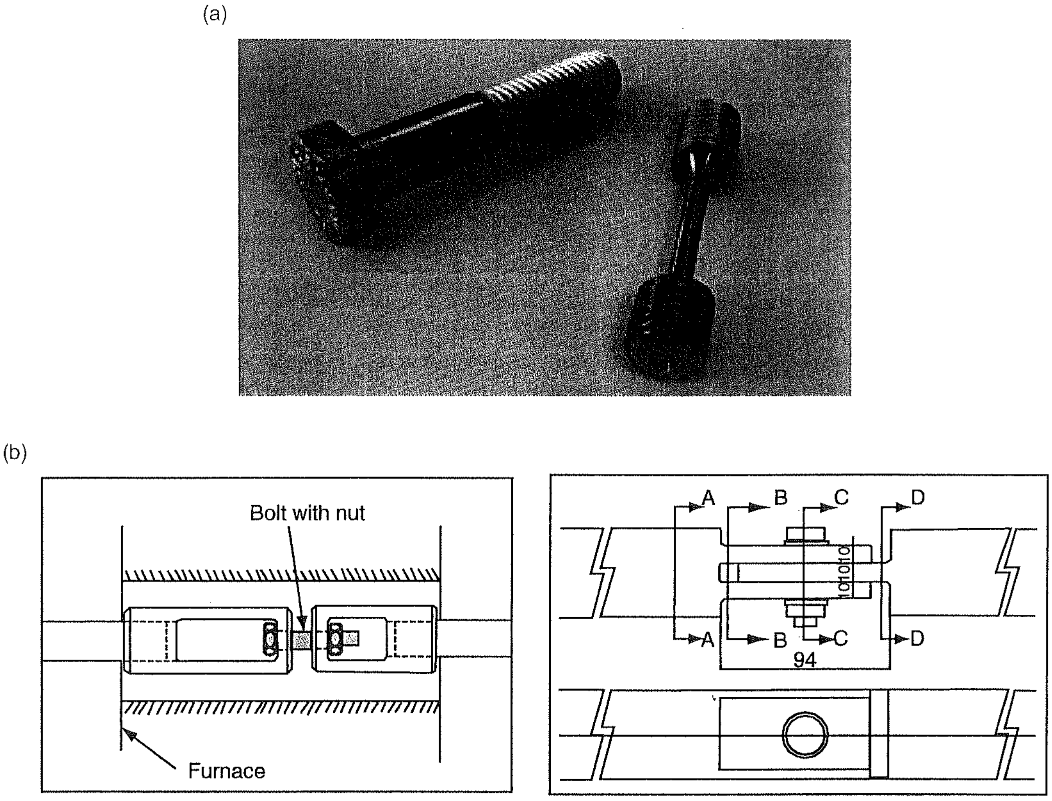

Figure 3. (a) Intact bolt and specimen machined to characterize the bolt material, (b) Test set-ups for tensile and shear tests performed on bolts.

Table 4. Results of the tensile tests performed on machined specimens

Test ID	YS [MPa]	UTS [MPa]
T1	914	952
T2	912	953
T3	882	956
T4	916	962
Mean values	906	956

The correlation between the results obtained from tests performed at the upper 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 at different failure temperatures T_f for T_u = 400°C, 600°C and 800°C are plotted on Figure 6.

4. FORCE-DISPLACEMENT LAWS PROPOSED FOR GRADE 8.8 BOLTS UNDER NATURAL FIRE

A reduction factor for the non-reversibility of bolts strength $k_{nr,b}$ is defined as the ratio between, on one side, the bolt ultimate strength f_{ub} at a temperature T_f after heating until T_u and, on the other side, the bolt ultimate strength after direct heating to T_f ($T_f = T_u$).

Table 5. Test program for bolts in tension

Tests before cooling		**Tests during the cooling phase**		
$T_u = T_f$ [°C]	*n.* **tests**	T_u [°C]	T_f [°C]	*n.* **tests**
20	2	400	200	2
200	1		100	1
400	1		20	1
600	1	600	400	1
800	1		300	1
			200	2
			100	1
			20	1
		800	600	1
			400	1
			300	1
			200	2
			100	1
			20	1
		900	20	1

Table 6. Test program for bolts in tension

Tests before cooling		**Tests during the cooling phase**		
$T_u = T_f$ [°C]	**n. tests**	T_u [°C]	T_f [°C]	**n. tests**
20	2	600	400	1
200	1		300	1
400	1		200	2
600	1		100	1
800	1		20	1
		800	600	1
			400	1
			300	1
			200	2
			100	1
			20	1
		900	20	1

When the temperature at the end of the heating phase T_u is not higher than 500°C, no permanent loss of resistance are observed and $k_{nr,b} = 1$. When temperatures higher than 500°C are reached, the reduction factor for the non-reversibility of bolts strength $k_{nr,b}$ decreases until the temperature comes back to 500°C. Then, the factor $k_{nr,b}$ remains constant during the rest of the cooling phase. The analytical expression of $k_{nr,b}$ is given by Eq. 1 and 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. 2, where k_b is the reduction factor for bolt strength during the heating phase (from EN 1993-1-2) and $k_{nr,b}$ is the parameter accounting for the non-reversible behaviour of bolts during the cooling phase (Eq. 1).

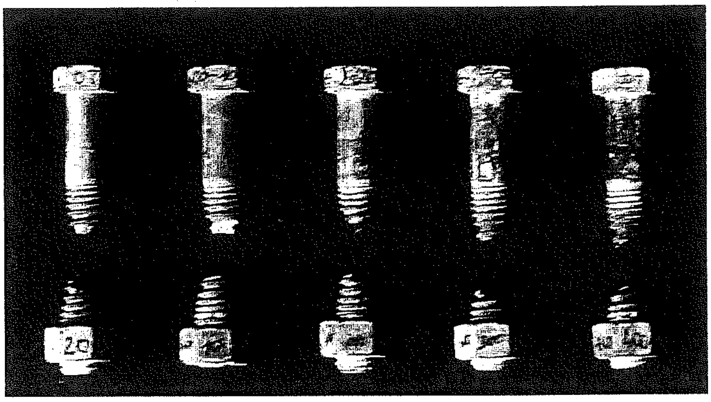

Figure 4. Bolts tested in tension (T_u = 600°C).

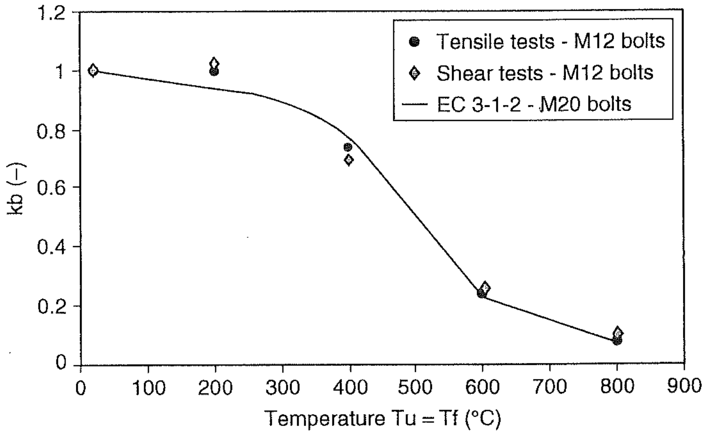

Figure 5. Comparison of the strength reduction factor for M12 and M20 bolts.

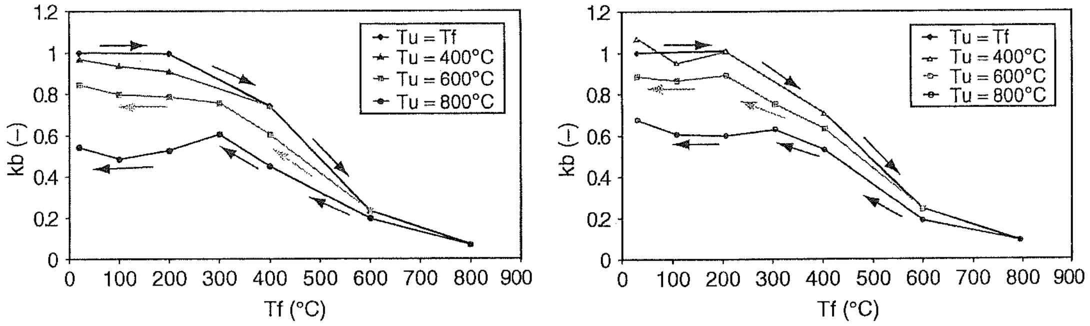

Figure 6. Reduction factor for bolt strength k_b in tension (left) and shear (right).

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

$$f_{ub}\left(T_f,T_u\right)=k_b\left(T_f\right).\,k_{nr,b}\left(T_f\,;T_u\right).\,f_{ub,20°C} \tag{2}$$

A force-displacement diagram composed of an elastic branch, a non-linear branch and a bilinear descending branch is proposed for characterizing the behaviour of Grade 8.8 bolts under tensile forces (Figure 7). The parameters F_{ub}, F_{pb}, F_{tb}, d_{pb}, d_{yb}, d_{tb} and d_{ub} of this diagram are given in Eqs 3 to 9. The reduction factor k_{pb} is given in Table 7 and k_E is the reduction factor for Young's modulus of carbon steel. This diagram is compared to experimental measurements on Figures 8 and 9.

$$F_{ub,T_u,T_f}=k_{b,T_f}.k_{nr,b,T_u,T_f}.f_{ub,20°C}.A_s \tag{3}$$

$$F_{pb,T_u,T_f}=k_{pb,T_f}.F_{ub,T_u,T_f} \tag{4}$$

$$F_{tb,T_u,T_f}=\min(F_{tb,T_u,T_f}\,;A_s{*}500\ N/mm^2) \tag{5}$$

$$d_{pb,T_u,T_f}=F_{pb,T_u,T_f}/(k_{E,T_f}\,.\,E\,.\,A_S) \tag{6}$$

$$d_{yb,T_u,T_f}=1\ mm \tag{7}$$

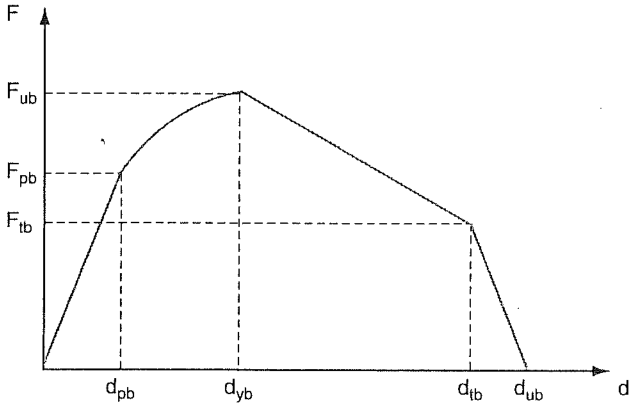

Figure 7. Force-displacement diagram for bolts in tension.

Table 7. Values of the reduction factor for proportional limit k_{pb}

T_u (°C)	$K_{pb,Tf(-)}$
20	0.9
200	0.8
400	0.75
600	0.75
800	0.6
900	0.6

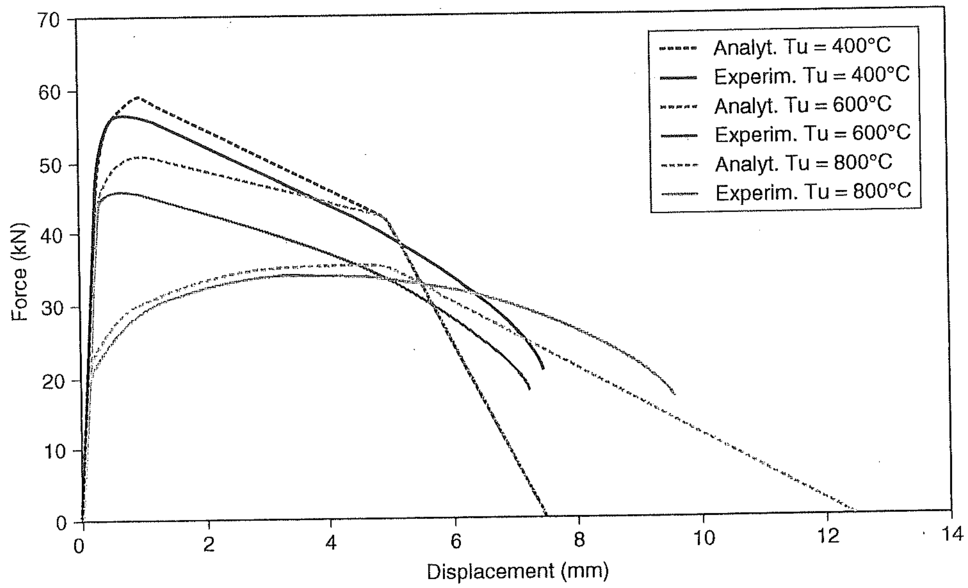

Figure 8. Comparison between test results and models for bolts in tension ($T_f = 400°C$).

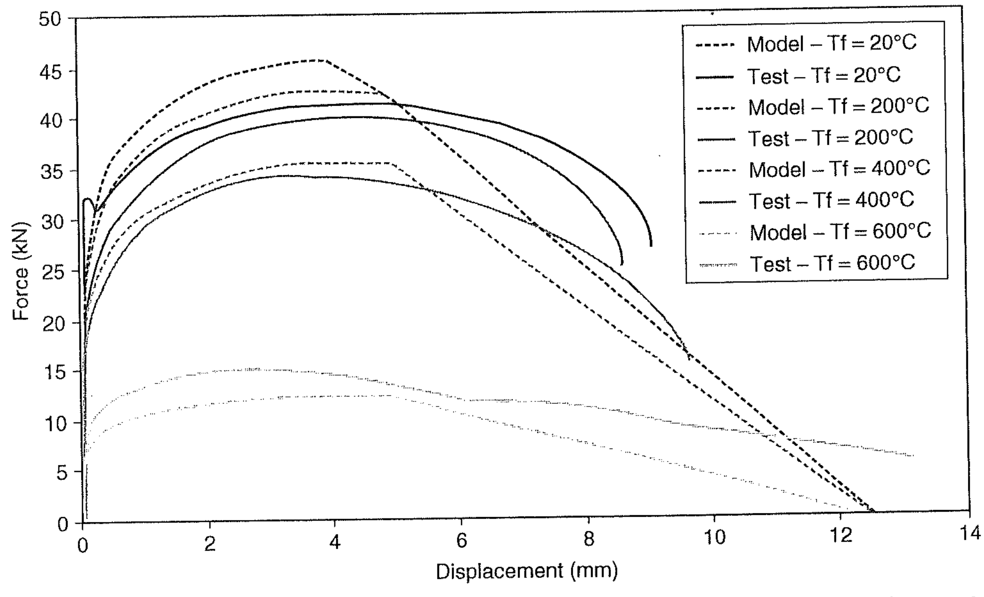

Figure 9. Comparison between test results and models for bolts in tension ($T_u = 800°C$).

$$d_{tb,T_u,T_f} = 5\ mm \tag{8}$$

$$d_{ub,T_u,T_f} = \max(7.5\ mm;\ 7.5\ mm + (T_u - 600) / 200*5\ mm) \tag{9}$$

The response of bolts subjected to shear forces at room temperature has been investigated and a model has recently been proposed by Henriques [7] on the basis of experimental double-shear tests performed on bolts of different grades (5.8, 8.8 and high-strength bolts) and different diameters (M16, M20 and M24 bolts) [8]. This model has been used as a basis for the model proposed here for elevated temperature. In order to avoid any confusion with the parameters used for the model of bolts in tension, the parameters R and δ used by Henriques will be kept in this article for the model of bolts in shear.

Two differences exist between the Henriques model at room temperature and the one proposed here for the heating and cooling phases of a fire. Firstly, an elliptic branch is used in the elasto-plastic domaine and second, a linear descending branch is added at the end of the yield plateau (Figure 10). The expressions of all the parameters used in the new force-displacement diagram are given hereafter (Eqs 10 to 14).

$$R_{b,T_u,T_f} = k_{b,T_f} \cdot k_{nr,b,T_u,T_f} \cdot \alpha_v \cdot f_{ub,20°C} \cdot A \tag{10}$$

where A is the tensile stress area of the bolt and α_v is, according to the recommendations of the EN 1993-1-8 [9], taken equal to 0.5 for Grade 8.8 bolts where the shear plane is situated in the threaded part of the bolt.

$$S_{b,T_u,T_f} = k_{E,T_f} \cdot \frac{8\,d^2\,f_{ub}}{d_{M16}} \tag{11}$$

where d_{M16} is the reference diameter of a M16 bolt.

$$R_{ub,T_u,T_f} = \kappa_f \cdot \kappa_u \cdot R_{b,T_u,T_f} \tag{12}$$

where the factors κ_u and κ_f respectively take into consideration the influences of temperatures T_u and T_f (Table 8).

$$S_{st,b,T_u,T_f} = \beta_f \cdot \beta_u \cdot S_{b,T_u,T_f} \tag{13}$$

where the factors β_u and β_f respectively take into consideration the influences of temperatures T_u and T_f (Table 9).

$$\delta_{ub,T_u,T_f} = \eta_f \cdot \eta_u \cdot \frac{R_{b,T_u,T_f}}{S_{b,T_u,T_f}} \tag{14}$$

where the factors η_u and η_f respectively take into consideration the influences of temperatures T_u and T_f (Table 10).

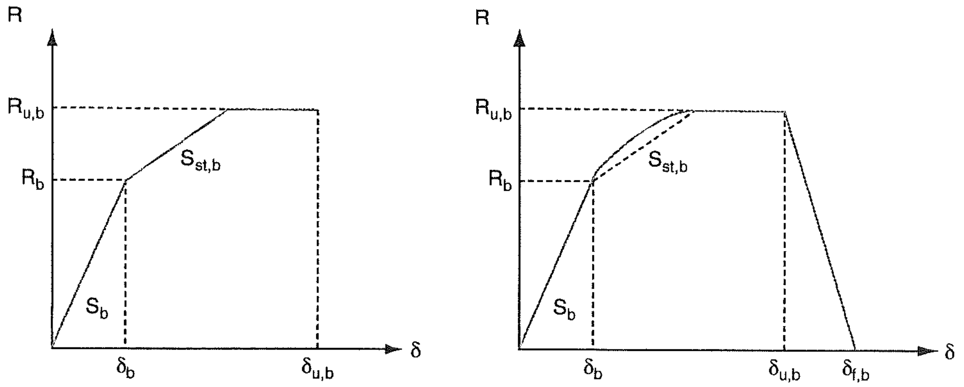

Figure 10. Henriques tri-linear law and modified non-linear law for bolts in shear.

Table 8. Values of the factors κ_f (a) and κ_f (b) at elevated temperatures

a)

T_f (°C)	κ_f
20	1.2
200	1.2
400	1.2
600	1.4
800	1.75
900	–

b)

T_u (°C)	κ_u
20	1
200	1
400	1
600	1
800	1.1
900	1.1

Table 9. Values of the factors β_f (a) and β_u (b) at elevated temperatures

a)

T_f (°C)	β_f
20	5
200	5
400	5
600	4
800	3
900	–

b)

T_u (°C)	β_u
20	1
200	1
400	1
600	1
800	2
900	2

Table 10. Values of the factors η_f (a) and η_u (b) at elevated temperatures.

a)

T_f (°C)	η_f
20	4
200	5
400	6
600	6
800	6
900	-

b)

T_u (°C)	η_u
20	1
200	1
400	1
600	1
800	1.25
900	1.25

Finally, the failure displacement $\delta_{fb,Tu,Tf}$ only depends on the temperature T_u reached at the end of the heating phase (Table 11).

5. EXPERIMENTAL TESTS PERFORMED ON BUTT WELDS

Tests have been performed on butt weld joints subjected in order to characterize the evolution of welds resistance during a natural fire (Figure 13). In these tests, the Grade S355JR butt weld specimens are submitted to shear stresses. The numbers of tests performed under the different thermal conditions are given in Table 12.

The deformability of welds is negligible and the resistance of a weld component depends on the ultimate strength of the weld material.

For temperatures T_u lower than or equal to 600°C, welds recover their initial strength f_{uw} after cooling (Figure 14). 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. 15, where the coefficient for the non-reversible behaviour of welds $k_{nr,welds}$ is given by Eq. 16. The analytical values of the reduction factor

Table 11. Values of the factors δ_{fb} at elevated temperatures

T_u (°C)	$\delta_{f,b,Tu}$ (mm)
20	6
200	6
400	7
600	11
800	15
900	–

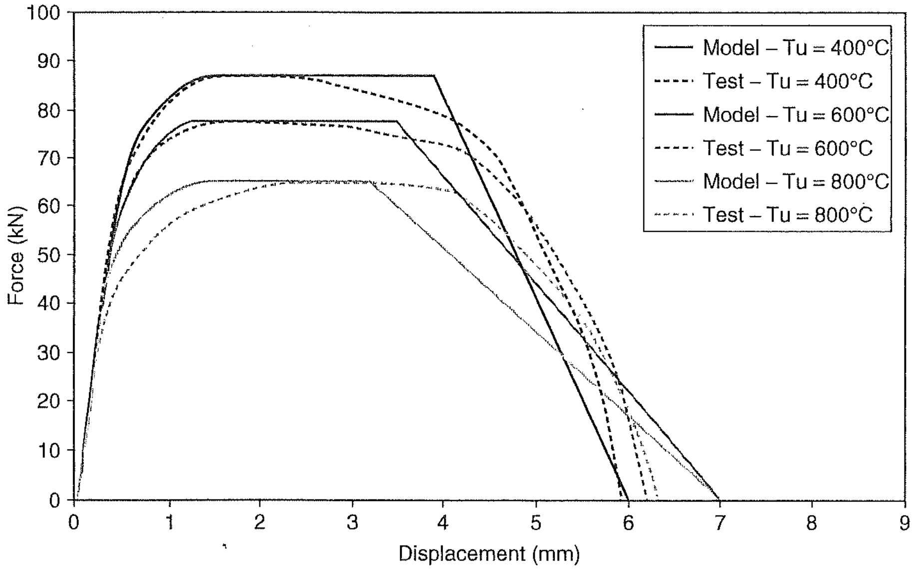

Figure 11. Comparison between test results and models for bolts in shear (T_f = 400°C).

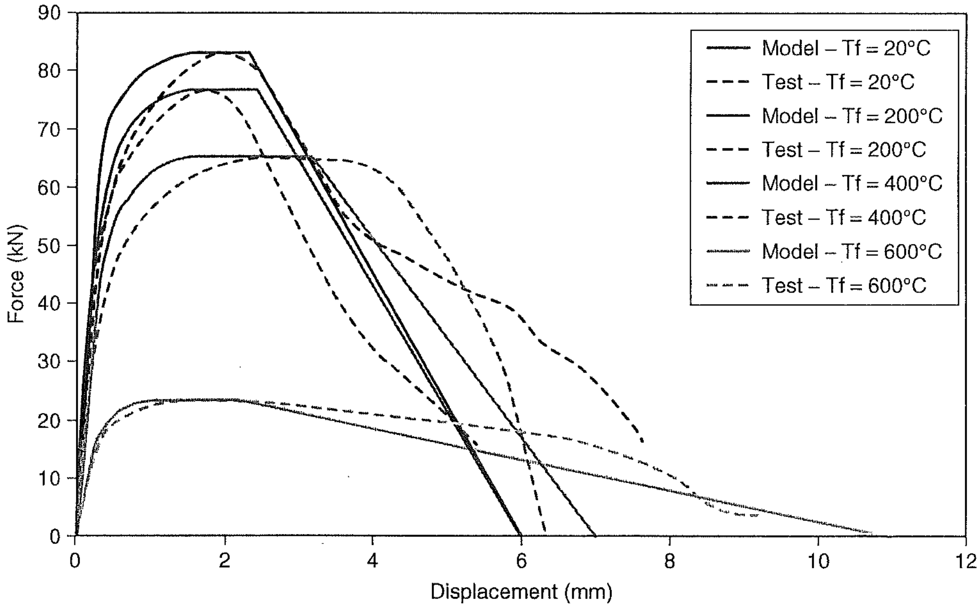

Figure 12. Comparison between test results and models for bolts in shear (T_u = 800°C).

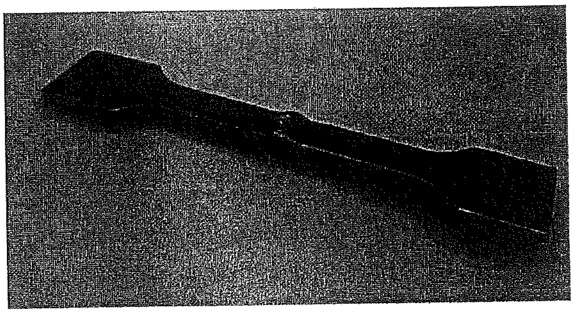

Figure 13. Specimen used for tests performed on butt welds.

Table 12. Test program for tests performed on butt welds

Tests before cooling		Tests during the cooling phase		
$T_u = T_f$ [°C]	n. tests	T_u [°C]	T_f [°C]	n. tests
20	1	400	200	1
200	1		100	1
400	1		20	1
600	1	600	400	–
800	1		200	–
			20	1
		800	600	1
			400	1
			200	1
			20	1
		900	400	1
			200	1
			20	1

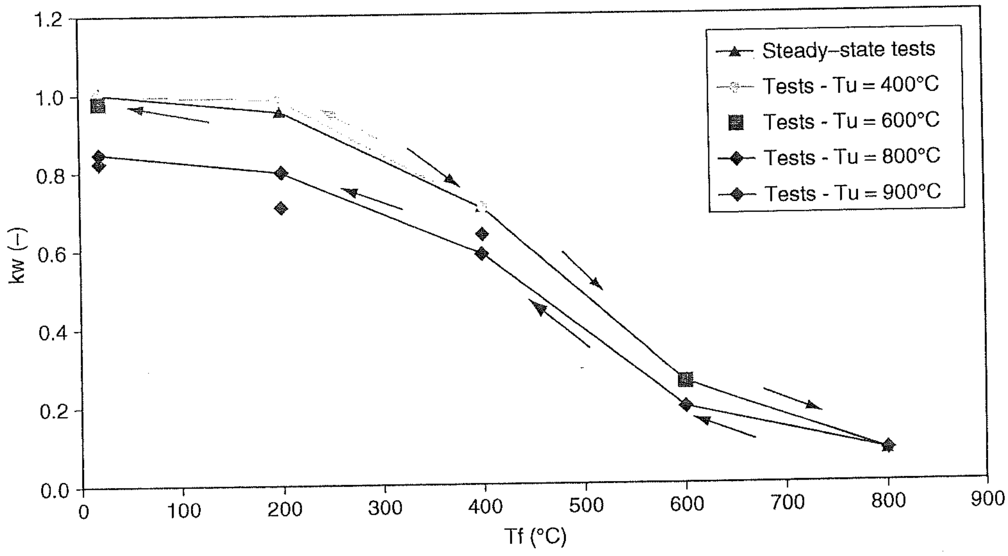

Figure 14. Experimental value of the reduction factor k_w during both the heating and cooling phases.

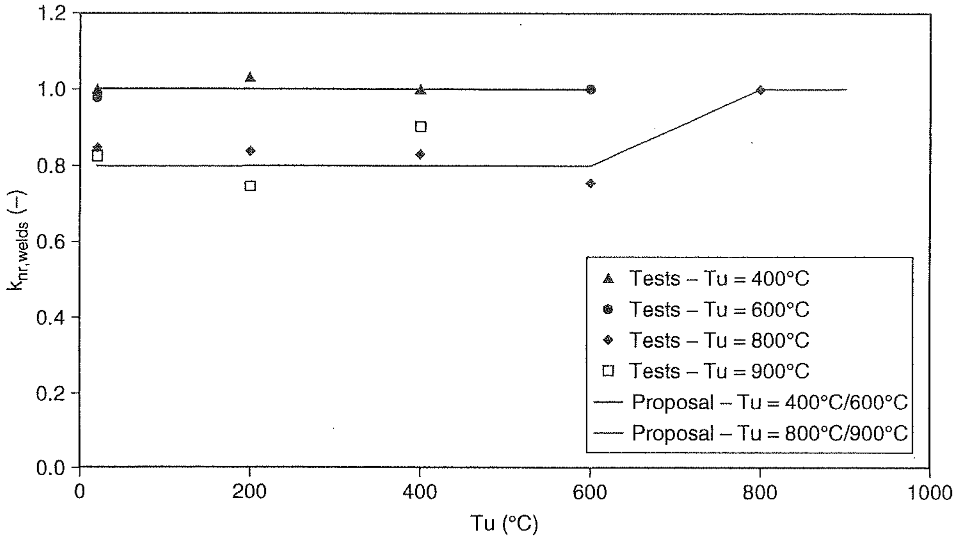

Figure 15. Comparison between the coefficients for non-reversible behaviour of welds $k_{nr,welds}$ obtained experimentally and analytically.

for welds k_w and the factor accounting for the non-reversible behaviour of welds $k_{nr,welds}$ are compared to experimental results on Figures 14 and 15.

$$f_{uw}(T_f, T_u) = k_w(T_f) \,.\, k_{nr,w}(T_f, T_u) \,.\, f_{uw,20^\circ C} \tag{15}$$

$$k_{nr,w}\left(T_f\,;T_u\right) = \min\left(1\,;1 - \frac{0.2}{200}\left(\min\left(T_u\,;\,800^\circ C\right) - \max\left(T_f\,;\,600^\circ C\right)\right)\right) \tag{16}$$

7. CONCLUSIONS

Tensile and shear tests performed on bolts have demonstrated that a heating-cooling cycle creates two major modifications in the mechanical behaviour of bolts. Firstly, the resistance of bolts starts to reduce in a non-reversible manner when the temperature of bolts has reached 500°C. The reduction of resistance can be 40% of the initial bolt resistance when a temperature of 800% is reached at the end of 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 shown that the reduction of welds resistance after a complete heating-cooling cycle is limited to 20% of the initial resistance.

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 Behaviour of Welded Joints in Structural Steelwork", Contract ECSC 7210 SA 824 (1993).

[7] Henriques J.A.G. "Ductility requirements in shear bolted connections", Master Thesis, Universidade de Coimbra (2007).

[8] Karmalin V.V., Pavlov A.B. "Load capacity and deformativity of bearing and friction-bearing connections, Proceedings of the International Colloquium on Bolted and Special Structural Connections, Moscow, USSR (1989).

[9] EN 1993-1-8 – Eurocode 3 "Design of steel structures – Part 1–8: Design of joints", European Committee for Standardization, CEN, Brussels (2005).