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CSM Report no. 13570R
Progress Report no. 7 (Final report)

STAINLESS STEEL IN FIRE

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CONTENTS

1 WP 5 – Bolts at elevated temperatures

1.1 General objectives

The scope of WP5 is to provide information on mechanical properties at elevated temperature of stainless steel bolted connections.
Experimental data will be generated with the scope of evaluating strength reduction factors for stainless steel bolts in the same format used in Eurocode 3 Part 1-2 for carbon steel bolts.

1.2 State of the art

The standard Eurocode 3 Part 1-2 gives in Table D.1 the reduction factors of bolts design resistance in fire conditions. These reduction factors were determined on the basis of the experimental work carried out by B. R. Kirby (British Steel) on full size M20 bolts (EN ISO 898-1) at temperatures up to 800 °C [1] and assumed valid for stainless steel bolts too.

In his work, Kirby analysed three types of bolts and two types of nuts differing for chemical composition and making procedure, and highlighted some interesting aspects.
First of all, bolt assembly premature failure may occur due to thread stripping; this effect decrease joint performances of about 20%, but it becomes almost negligible at temperatures above 350÷400 °C. Tests suggest this mechanism be controlled by the interaction of the threads between nut and bolt, that is by the degree of fit between these two components: to avoid this type of failure, Kirby recommends to specify nuts and bolts dimensional properties to the tighter tolerance classes. The main role in this phenomenon seems to be played by a weakness shown by nuts produced by cold forging; in the large, bolts performances during and after a fire obviously vary depending upon how they have been manufactured, since high temperatures cause grain modifications inside the steel.
Another remark concerns the influence of heating rate and soaking period: Kirby’s tensile tests shown that these parameters have little influence on ultimate bolts capacity. Finally, both of tensile and shear tests results graphics (capacity vs. temperature) show a plateau between RT and 300 °C.

Presently only data at room temperature are available on stainless steel bolts. They come from a research project partially financed by the ECSC ([2]) in which four tension tests (Table 1) and three shear tests (Table 2) were carried out on individual bolt - nut assemblies at room temperature.

Table 1 – ECSC project tensile tests on stainless steel individual bolt-nut assemblies at room temperature.

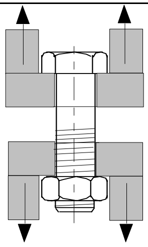
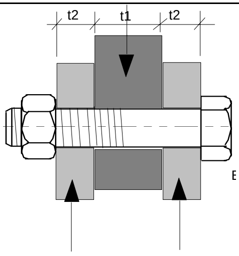
	EN ISO 3506-1		Manufacturer test	ECSC project test [2]			
Bolt	$A_{s,nom}$ [mm^2]	$f_{ub,nom}$ [MPa]	$f_{ub,exp}$ [MPa]	P_{max} [kN]			
				Test 1	Test 2	Test 3	Test 4
M12×40	84.3	800	863	71.5	71.8	70.8	71.1
M16×50	157	800	955	147.6	143.5	147.2	145.1
M20×50	245	800	852	211.1	202.7	208.8	205.4

Table 2 – ECSC project shear tests on stainless steel individual bolt-nut assemblies at room temperature.

	EN ISO 3506-1		Manufacturer test	ECSC project test [2]		
Bolt	$A_{s,nom}$ [mm^2]	$f_{ub,nom}$ [MPa]	$f_{ub,exp}$ [MPa]	P_{max} [kN]		
				Test 1	Test 2	Test 3
M12×40	84.3	800	863	101.2	99.6	96.1
M16×50	157	800	955	184.3	189.8	200.5
M20×50	245	800	852	256	257.2	258.6

The bolts were in austenitic grade A4 and strength class 80 in accordance with EN ISO 3506 standards. Three different diameters were investigated: M12×40 fully coarse threaded (EN ISO 4017), M16×50 38mm coarse threaded (EN ISO 4014) and M20×50 fully coarse threaded (EN ISO 4017). Bolts of a given diameter were from one lot only.
Nuts were in accordance with EN ISO 4032.

1.3 Work undertaken

A total amount of 41 stainless steel bolt assemblies (bolt and nuts; washers were available but not used) machined by Ferriere di Stabio from stainless steel bars produced by Cogne Acciai Speciali have been tested.

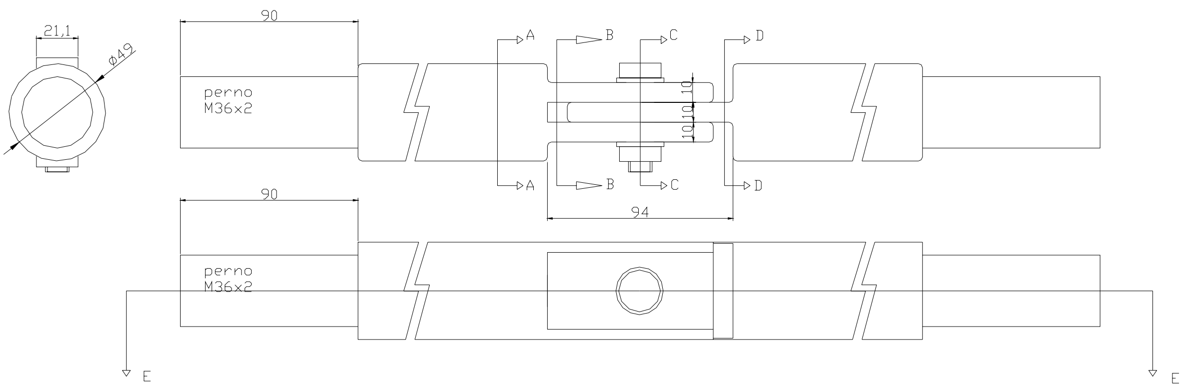
Isothermal tests at 7 different temperatures from RT up to 900°C have been performed loading the above bolt assemblies in tension (21 tests) and shear (20 tests). A detailed performed testing programme is reported in Table 3. Please note, RT tensile test for A4 80 bolt set has been doubled because in the first test, failure occurred by thread stripping; so, it has been decided to validate the result by checking if thread stripping occurrence noticeably decreased bolt resistance. In the second test, failure occurred in thread and the load was very similar to the first one.

Table 3 – Testing programme performed in Task 5.1 of the project.

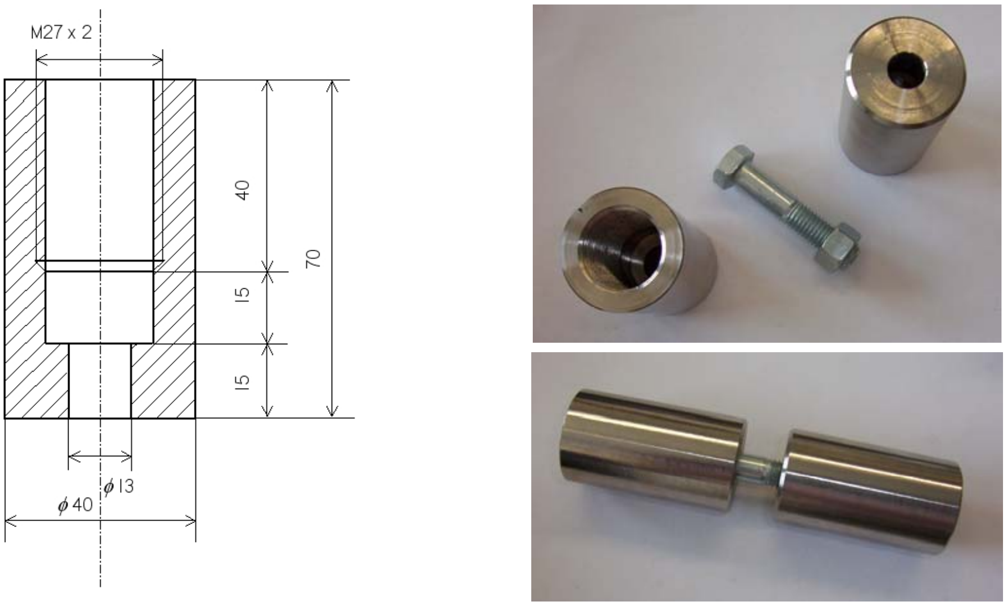
Material grade strength level	Load direction	Test temperature	No. of tests	Material grade strength level	Load direction	Test temperature	No. of tests
A2 70	shear	RT	1	A4 80	shear	RT	1
		200 °C	1			200 °C	1
		300 °C	2			300 °C	2
		400 °C	1			400 °C	1
		500 °C	1			500 °C	1
		600 °C	2			600 °C	2
		800 °C	1			800 °C	1
		900 °C	1			900 °C	1
	tensile	RT	1		tensile	RT	2
		200 °C	1			200 °C	1
		300 °C	2			300 °C	2
		400 °C	1			400 °C	1
		500 °C	1			500 °C	1
		600 °C	2			600 °C	2
		800 °C	1			800 °C	1
		900 °C	1			900 °C	1
			20				21

Bolts are of two different stainless steel grades and strength classes: an austenitic grade A2 at strength class 70 (nominal tensile strength $f_{ub,nom}$ = 700 N/mm²) and an austenitic grade A4 at strength class 80 (nominal tensile strength $f_{ub,nom}$ = 800 N/mm²) as classified in EN ISO 3506 standard; both of them were produced by cold forging and roll threading.
Bolts are hexagonal head M12×50 half threaded in accordance with DIN 931. Nuts are hexagonal too.

Testing set-up is shown in Figure 1; for design of shear connections, see Annex A.



a)



b)

Figure 1 – Connection design for bolts tests at elevated temperature: a) shear test; b) tensile test. Dimensions are in [mm].

On the basis of Eurocode 3 Part 1-8 the single bolt connections shown in Figure 1 are classified as:

a) <u>Category A</u> non-preloaded shear resistant single bolt connection; the shear resistance of the bolt at elevated temperature ($\mathbf{F_{v,Rd}}$) has been measured during the test.

b) <u>Category D</u> non-preloaded tension resistant single bolt connection; the tensile resistance of the bolt ($\mathbf{F_{t,Rd}}$) has been measured during the test.

Material used for grips is the heat resistant alloy NIMONIC 115 so as to ensure the failure occurs in the bolted connection itself and not in the connection elements; this choice also allowed to avoid prying effects noticed by Kirby during his shear tests, that raised tensile stresses causing the bolt thread to extend.

The testing procedure defined on the basis of the experimental work performed by B. R. Kirby on carbon steel bolts at elevated temperature, is reported in Figure 2 in terms of displacement and heating rates.
The tests are carried out in displacement control measuring machine crossbeam displacement.

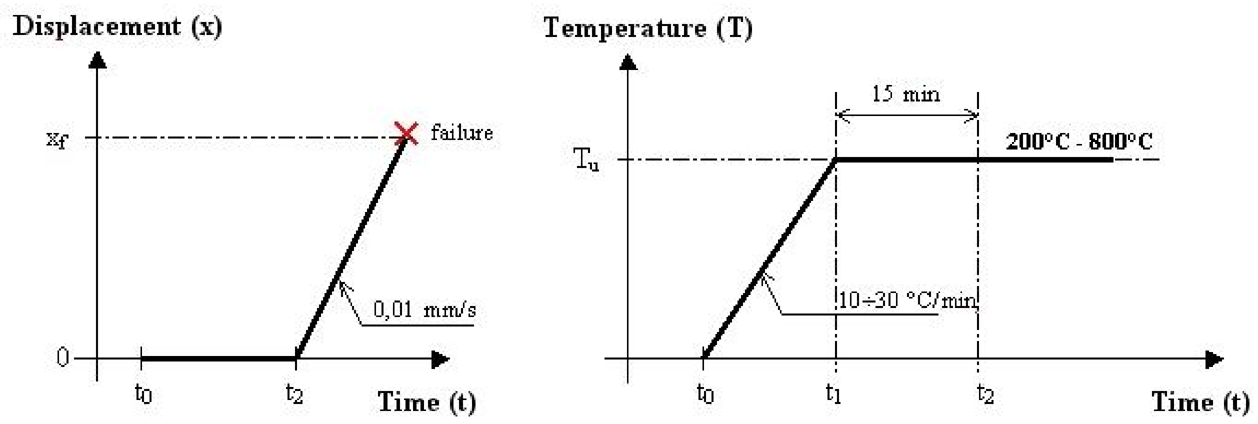


Figure 2 – Testing procedures for bolted connections at elevated temperature: displacement rate on the left and heating rate on the right.

Temperature is feedback-controlled by a thermocouple applied inside the furnace; another thermocouple is applied on the bolt itself and allows to check temperature differences between the two zones (see Figure 3).

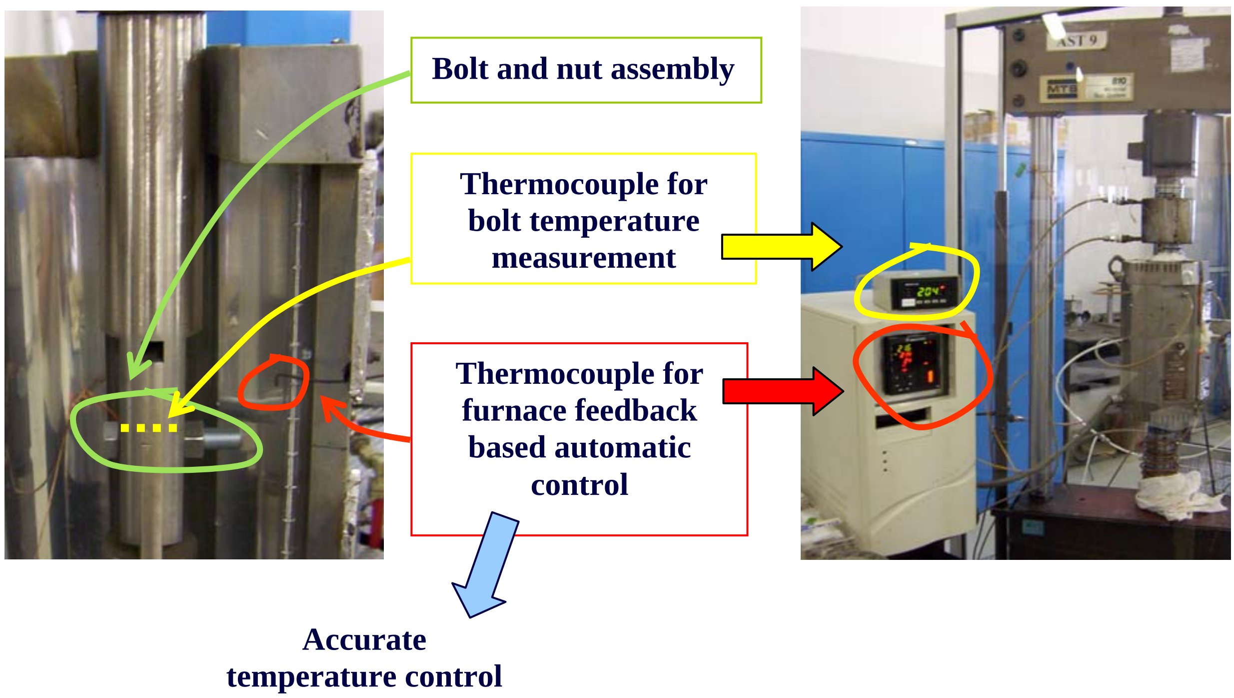


Figure 3 – Bolt-nut assembly in the furnace (left) and high temperature testing appliance (right).

1.4 Results

Detailed tests results at several temperatures are shown in Table 4 and in Table 5, respectively for A2 70 and for A4 80 bolts.

Tensile tests up to T = 300÷400 °C highlighted an ambiguous behaviour of bolts, that was not noticed by Kirby: the failure sometimes occurred in the shank rather than in the thread, even if the first one has a resistant section larger than the latter. Stainless steel is far more sensitive to cold working than a carbon steel; thus, the abovementioned results can be read by thinking T = 300÷400 °C as a transition temperature, above which cold working effects on stainless steel, that are due to thread making and that increase thread mechanical resistance, disappear for effect of temperature related grain growth.

Figure 4 shows A4 80 bolts after failure at T = 300 °C, in the two cases of shank and thread failure.

Table 6 and Table 7 show tests results in terms of strength reduction factors.

Table 4 – Detailed results of shear and tensile tests carried out on A2 70 bolt-nut assemblies.

	Test temperature	Shear – P_{max} [kN]	Tensile	
			P_{max} [kN]	Failure mode
A2 70	RT	117,3	83,0	thread
	200	84,0	67,2	shank
	300	79,5	64,5	shank
		80,0	63,3	thread stripped
	400	73,8	61,6	shank
	500	68,1	58,1	thread
	600	56,7	49,0	thread
		57,2	47,0	thread
	800	23,6	17,5	thread
	900	12,9	5,6	thread

Table 5 – Detailed results of shear and tensile tests carried out on A4 80 bolt-nut assemblies.

	Test temperature	Shear – P_{max} [kN]	Tensile	
			P_{max} [kN]	Failure mode
A4 80	RT	105,9	73,6	thread stripped
			77,6	thread
	200	75,6	52,4	thread stripped
	300	75,2	60,0	shank
		71,8	60,0	thread
	400	71,2	58,5	thread
	500	64,5	56,7	thread
	600	56,6	49,3	thread
		57,6	49,5	thread
	800	24,4	13,3	thread
	900	13,8	6,3	thread

Figure 4 – A4 80 bolts different failure modes at T = 300 °C.

Table 6 – Resulting strength reduction factors for A2 70 bolt-nut assemblies.

	Test temperature	$K_{b,\theta\ shear}$	$K_{b,\theta\ tensile}$
A2 70	RT	1,00	1,00
	200	0,72	0,81
	300	0,68	0,77
	400	0,63	0,74
	500	0,58	0,70
	600	0,49	0,58
	800	0,20	0,21
	900	0,11	0,07

Table 7 – Resulting strength reduction factors for A4 80 bolt-nut assemblies.

	Test temperature	$K_{b,\theta\ shear}$	$K_{b,\theta\ tensile}$
A4 80	RT	1,00	1,00
	200	0,71	0,69
	300	0,69	0,79
	400	0,67	0,77
	500	0,61	0,75
	600	0,54	0,65
	800	0,23	0,18
	900	0,13	0,08

Figure 5 and Figure 6 show experimental tests results in terms of strength reduction factors, compared with EN standard and Kirby tests results. About the latter ones, it is important to make a clarification.

For his tests, Kirby considered three bolt sets and two nut sets. The first set of bolts was identified by the letter A, it was 100 mm long with thread length of 46 mm and came from cold forging steel bar supplied to BS3111: Part 1: Type 9, quenched from 850 °C and tempered at 450÷500 °C. Bolt set B differed from the first one only for its threaded length, equal to 30 mm. Finally, bolt set C was 100 mm long with a threaded length of 46 mm (like the A set), but it had been hot forged from steel bar supplied to BS970: Part 1: Grade 150M36, quenched from 900 °C and tempered at 600÷620 °C. As for as nut sets concerns, set A had been hot forged from steel bar meeting BS970: Part 1: Grade 080M30, quenched from 870°C and tempered at about 540°C; the set B, instead, was produced by cold forging steel bar meeting BS3111: Part 1: Type O. Due to the different thermo-mechanical treatments, all sets but nut set B (bright) were supplied black For details about chemical composition of bolts and nuts, see [2].

In Figure 5, Kirby set A stays for Kirby type A bolt and nut, while in Figure 6 Kirby set AB stays for type A bolt and type B nut, Kirby set BA stays for type B bolt and type A nut.

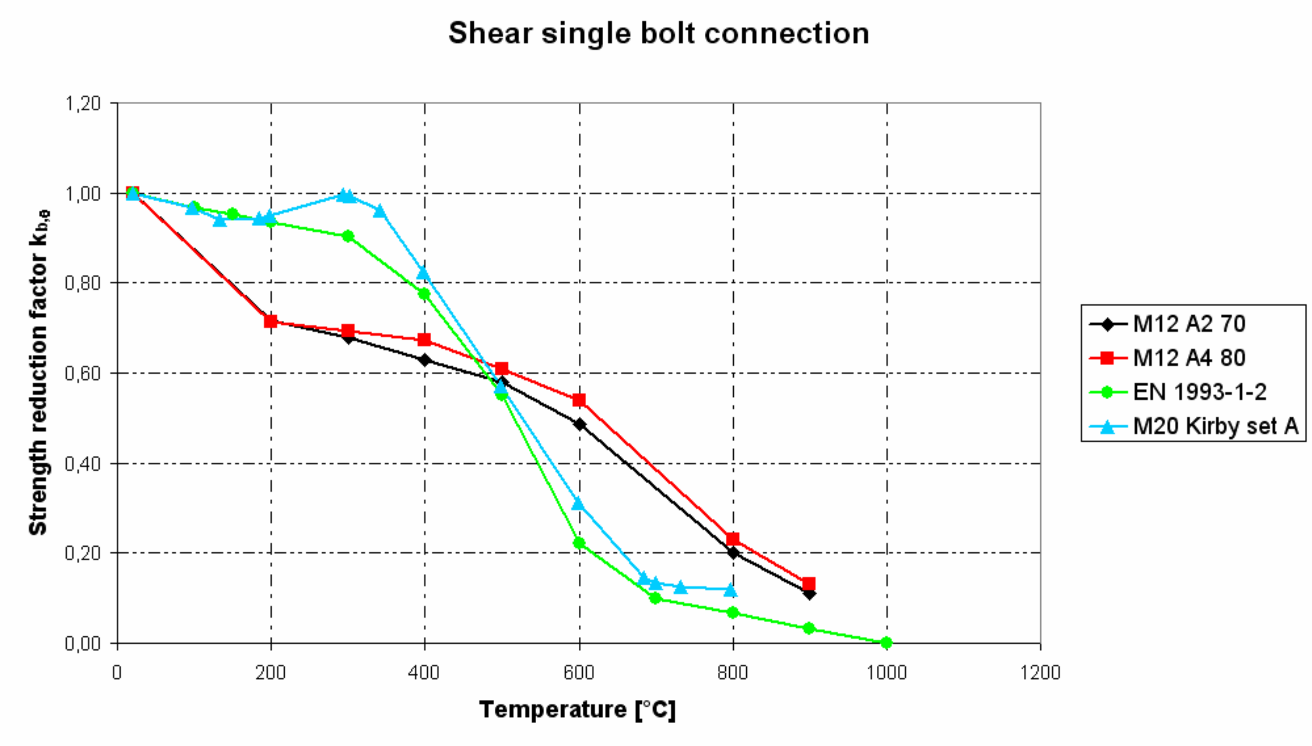


Figure 5 – Shear tests results and their comparison with EN 1993-1-2 standard and Kirby tests results.

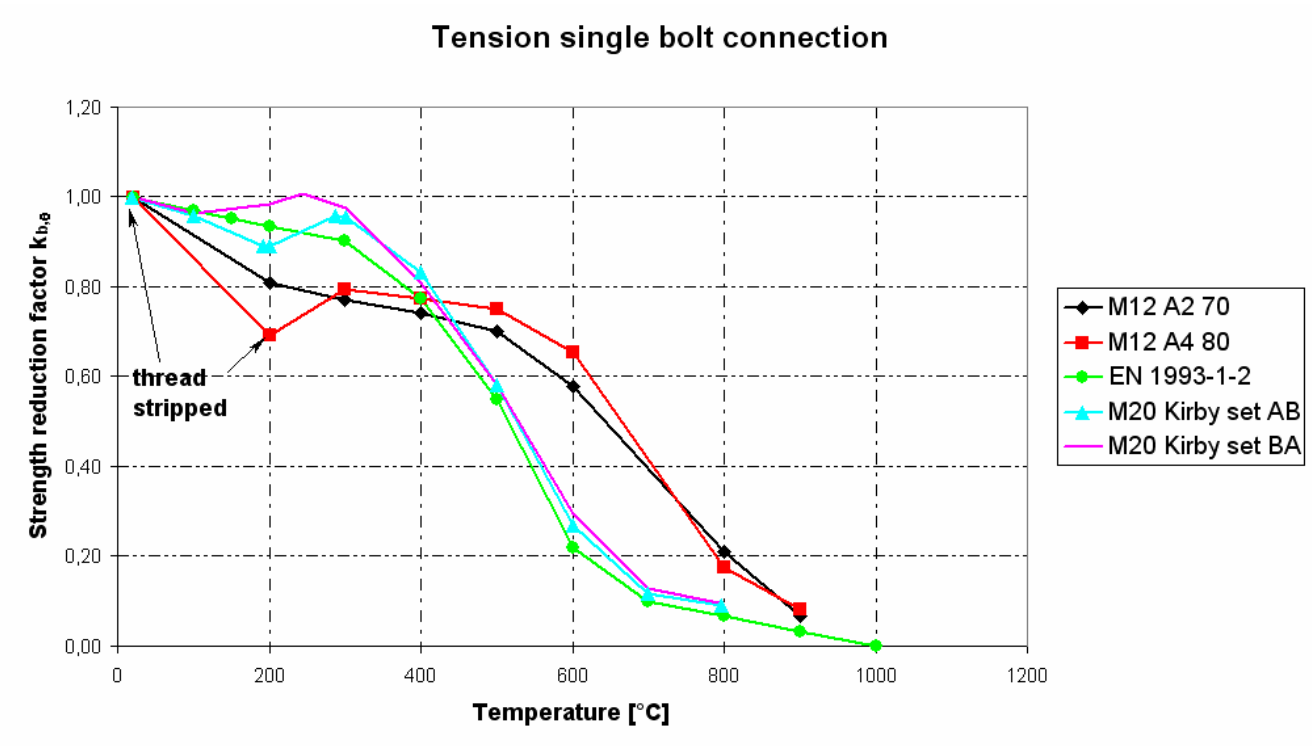


Figure 6 – Tensile tests results and their comparison with EN 1993-1-2 standard and Kirby tests results.

1.5 Conclusions

Carried out high temperature tests highlight that stainless steel acts better than carbon steel at high temperatures, that is beyond 400÷450 °C; this is really the more interesting range when studying fire effects. Omitting A4 80 grade thread stripping at 200 °C, this grade presents a slightly better behaviour than A2 70. It is observed that stainless steel bolts loaded in tension can fail indifferently in the shank or in the thread area at low temperatures (up to 300÷400 °C); this is probably due to the increased resistance of the threaded part after cold working.

The suggested values for strength reduction factors are proposed as the minimum values among all the tensile and shear test data on both of analysed grades, omitting the result for A4 80 tensile test at 200 °C with thread stripping (see Table 8: bold fonts identify results chosen as suggested values); Figure 7 and Figure 8 show the abovementioned factors together with the ones by EN 1193-1-2 standard, compared with tensile and shear tests results, respectively. The slightly higher behaviour of grade A4 80 is considered as negligible in advantage of safety.

Table 8 – Suggested values for stainless steel strength reduction factors, related to experimental tests results.

Test temperature	A2 70		A4 80		Suggested
	$K_{b,\theta\ shear}$	$K_{b,\theta\ tensile}$	$K_{b,\theta\ shear}$	$K_{b,\theta\ tensile}$	$K_{b,\theta}$
RT	**1,00**	**1,00**	**1,00**	**1,00**	1,00
200	0,72	0,81	**0,71**	0,69	0,71
300	**0,68**	0,77	0,69	0,79	0,68
400	**0,63**	0,74	0,67	0,77	0,63
500	**0,58**	0,70	0,61	0,75	0,58
600	**0,49**	0,58	0,54	0,65	0,49
800	0,20	0,21	0,23	**0,18**	0,18
900	0,11	**0,07**	0,13	0,08	0,07

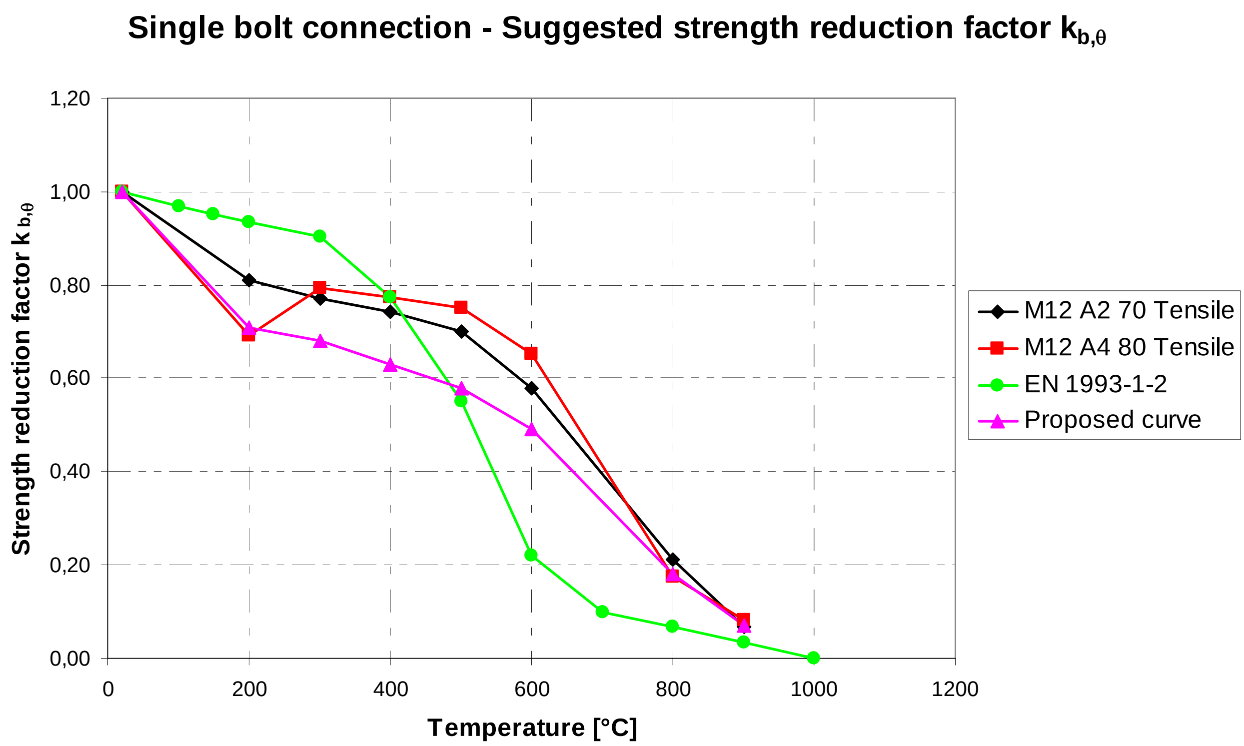


Figure 7 – Single bolt connection suggested strength reduction factor $k_{b,\theta}$ and its comparison with EN 1993-1-2 standard and tensile experimental tests results.

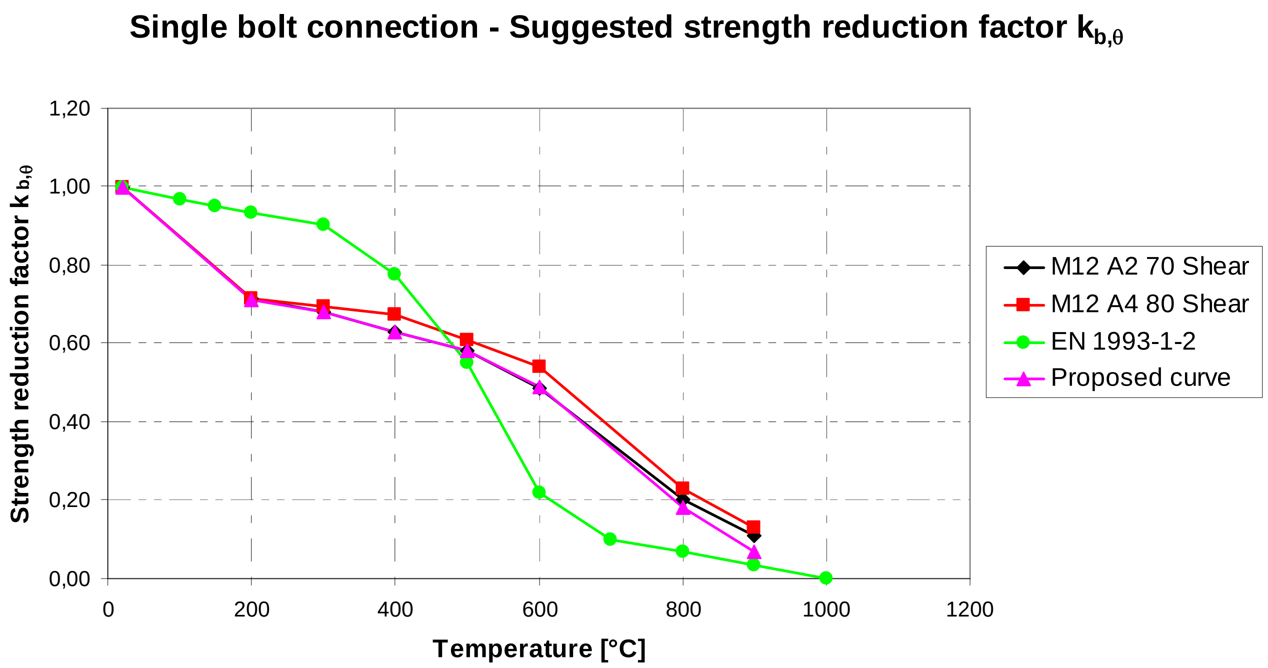


Figure 8 - Single bolt connection suggested strength reduction factor $k_{b,\theta}$ and its comparison with EN 1993-1-2 standard and shear experimental tests results.

1.6 Problems encountered

No problem has been encountered.

A Annex: Design calculation of shear connection

Here below the design calculations of shear connection used during the project and shown in Figure 1 are reported. The calculations are in accordance with EN1993-1-8 and EN 1993-1-4 and are developed for the stronger grade A4 80 only since the scope is to prevent failure occurrence in the grips.

M12 A4 class 80 bolt:

$A = 113\ mm^2$	cross section area of the unthreaded portion of the bolt shank
$A_{s,nom} = 84.3\ mm^2$	cross section area of the threaded portion of the bolt shank
$f_{ub} = 955\ MPa$	ultimate tensile strength (the effective one provided by the steelworker)
$d_0 = 14\ mm$	hole diameter

Cover plates:

$t = 5.5\ mm$
$e_1 = 40\ mm$
$e_2 = 15.18\ mm$
$A_{net} = 356\ mm^2$

Intermediate plates:

$t = 12\ mm$
$e_1 = 40\ mm$
$e_2 = 17.33\ mm$ equivalent values (A_{net}/t)
$A_{net} = 346.5\ mm^2$

Plates material properties (NIMONIC 115)

$f_y = 800\ MPa$	*nominal values*
$f_u = 1150\ MPa$	*nominal values*
$f_{u,red} = 1090\ MPa$	*calculated from nominal values*

Category A (non-preloaded shear resistant) bolt connection in accordance with EN 1993-1-8

shear resistance (2 shear planes, one passes through unthreaded portion of the bolt while the other passes through threaded portion):

$$F_{v,Rd} = 2 \cdot \alpha_v \cdot A \cdot f_{ub} = 113kN \qquad \alpha_v = 0.6 \text{ for stainless steel}$$

bearing resistance:

$$F_{b,Rd} = k_1 \cdot a_b \cdot f_{u,red} \cdot d \cdot t = \begin{matrix} 184kN & \text{cover plates} \\ 192kN & \text{intermediate plate} \end{matrix}$$

where:

$$a_b = \mathbf{min}\ (\alpha_b; \frac{f_{ub}}{f_u}; 1.0)$$

$$\alpha_b = \frac{e_1}{3d_0} \qquad \text{end bolt in the direction of load transfer}$$

$$k_1 = \mathbf{min}\ (2.8\frac{e_2}{d_0} - 1.7; 2.5) \qquad \text{edge bolt perpendicular to the direction of load transfer}$$

net section resistance:

$$F_{u,Rd} = A_{net} \cdot f_{u,red} = \begin{matrix} 388kN & \text{cover plates} \\ 378kN & \text{intermediate plate} \end{matrix}$$

REFERENCES

[1] B.R. Kirby 'The behaviour of grade 8.8 bolts in fire', Journal of Constructional Steel Research 33, pages 3-38 (1995).

[2] Ryan - ECSC Project: Development of the use of stainless steel in construction. Contr. Nr. 7210-SA/842, 327. WP4.2-Bolted connections. Final Report to European Coal and Steel Community. CTICM and UGINE (FR), December 1999.

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PRECEDENTI RIFERIMENTI SULLA COMMESSA
Former internal order references

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12165R	*September 2005*	*E2002002*
12483R	*February 2006*	*E2002002*
12702R	*September 2006*	*E2002002*
13043R	*March 2007*	*E2002002*
13246R	*September 2007*	*EC140003*