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Material properties of high strength steel under fire conditions

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ABSTRACT

This paper is concerned with the material characteristics of various commercial high strength structural steels (yield strengths between 460 and 700 N/mm^2) under fire conditions. The paper proceeds with a description of the experimental programme which includes two different grades of high strength steel. The aim of this research is to assess (i) the mechanical properties at elevated temperature through tensile testing to support the safe design of fire resistant structures made from high strength steel and (ii) the effect of chemical composition and processing route on the microstructure through a detailed metallurgical investigation. In this paper, a series of isothermal and anisothermal elevated temperature tests are conducted on two commercially-available steel grades (S690QL and S700MC). Following a detailed description of the tests, the results are analysed to determine strength and stiffness reduction factors at elevated temperatures and these values are compared with literature and EN 1993-1-2 (2005). It was found that the results for S700MC, for which there is limited data in the literature, showed better strength retention properties than S690QL at elevated temperatures. The results also showed that under isothermal conditions, the guidance for the elastic modulus of these materials may be unconservative and overly optimistic.

Keywords: high strength steel, material properties, fire, reduction factors

1 INTRODUCTION

High strength steel (HSS) defined herein as material with a yield strength between 460 and 700 N/mm^2 in accordance with Eurocode 3 [1] are increasingly being employed in structures as an alternative to conventional steel grades (i.e. steel grades with yield strengths below 460 N/mm^2 such as S355, S275 and S235) due to economic and environmental benefits related to weight reduction and material usage. In 2007, supplementary rules for HSS were introduced to the Eurocodes [1] to expand upon existing rules for conventional steel grades based on the limited research available at that time. The enhanced strength of HSS is due to the combination of alloying elements and processing route (including heat treatments). Eurocode 3 Part 1-12 [1] covers HSS in accordance with EN 10025-6 [2] and EN 10149-2 [3] which deal with quench and tempered (QT) and thermomechanically control processed (TMCP) steels for cold forming, respectively.

As HSS are being increasingly utilised in structures, it is important that such structures maintain its function for a prescribed amount of time under extreme conditions such as a fire. The ability to predict the behaviour of HSS structures in fire scenarios requires detailed knowledge of the material properties at elevated temperature. To date, the material properties available for HSS grades are predominately for QT steels (e.g., [4–6]). For TMCP steels there is limited data reported in the literature (e.g., [7]), particularly for the steel grade S700MC where no data is available. In this paper, a series of isothermal and anisothermal elevated temperature tensile tests on two different commercially-available HSS grades (S690QL and S700MC) are described. Based on the findings of this study, preliminary data of the following mechanical properties are presented: 0.2% proof strength ($f_{0.2p,\theta}$), effective yield strength ($f_{y,\theta}$) based on the total strain level at 2% (in accordance with the Eurocode approach) and elastic modulus ($E_{a,\theta}$) and. The results are compared with available data for similar steel grades in the literature and also the Eurocode values [8]. The tests described herein are part of a larger programme which includes detailed metallurgical studies.

2 EXPERIMENTAL INVESTIGATION

Ambient and elevated temperature tensile tests were conducted using a 100 kN electromechanical testing machine and a furnace with 3 heating zones, which was controlled using a closed loop thermal system. Three k-type thermocouples was used to monitor the top, middle and bottom temperature of each tensile specimen. An axial contact extensometer with high purity alumina ceramic rods, compliant with ISO 9513 Class 1 [9], with a gauge length of 25 mm was used to measure the strain. An example of one of the test set-up is shown in Fig. 1.

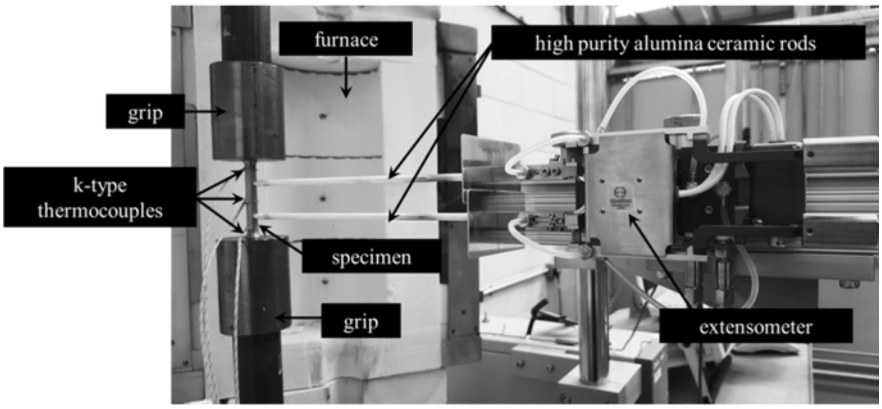

Fig. 1. Experimental set-up (furnace open)

2.1 Materials

Table 1 presents the HSS grades which are included in the experimental investigation. The designations for structural steel grades within EN 10025 [2] and EN 10149 [3] are denoted by an S at the beginning followed by the nominal yield strength (f_y) at ambient temperature and then the production route/delivery condition. Q in the designation S690QL refers to the quench and tempered production process whilst L indicates that the material meets the minimum impact energy requirement of 30 J at -40°C [2]. Likewise, M and C in S700MC indicate TMCP and cold-formed materials, respectively [3]. The chemical compositions of the steels are presented in Table 2. As shown in this table, steel A was alloyed with chromium (Cr), nickel (Ni), boron (B), and molybdenum (Mo) and was also microalloyed with titanium (Ti) and vanadium (V). Steel B had a lower carbon (C), Cr, nitrogen (N), copper (Cu) and Mo content as well as a higher contribution of manganese (Mn) and combined microalloying with Ti, niobium (Nb) and V than steel A.

Round tensile specimens were machined parallel to the rolling direction from each of the plates detailed in Table 1. The dimensions of the specimens were specified in accordance with ISO 6892 Part 1[10] and 2 [11], and are shown Fig. 2. The total length L_t, parallel length L_c and the diameter at three positions along the gauge length L_o were measured for each tensile specimen using a travelling light microscope and digital read out system. The average diameter d_o was then calculated and used to determine the cross-sectional area A_c for each tensile specimen. In total, 64 specimens (31 and 33 for steels A and B respectively) were tested in the current study.

2.2 Ambient temperature

In order to generate ambient temperature tensile data for comparison, six tensile tests (three for each of steels A and B) were conducted following the test procedures detailed in Huang and Young [12], which are summarised in Table 3. In each test two linear strain gauges were attached to the midpoint of each tensile specimen to verify the accuracy of the readings from the extensometer.

The average tensile properties from the three tests for each of steel A and B are presented in Table 4.

Table 1. Grades of commercial HSS included in the programme

	Grade	f_y (N/mm^2)	Nominal plate thickness (mm)	Tensile specimen	Manufacturing process
Steel A	S690QL	690	16	M12	Quenched and tempered
Steel B	S700MC	700	12	M10	TMCP + cold-formed

Table 2. Chemical composition of the HSS included in the programme

	Chemical composition (wt %)											
	C	Mn	Cr	Si	Ni	Cu	Mo	Al	Ti	Nb	V	B
Steel A	0.17	1.29	0.56	0.29	0.460	0.180	0.210	0.037	0.002	-	0.003	0.003
Steel B	0.06	1.98	0.26	0.15	0.033	0.019	0.004	0.046	0.120	0.067	0.014	-

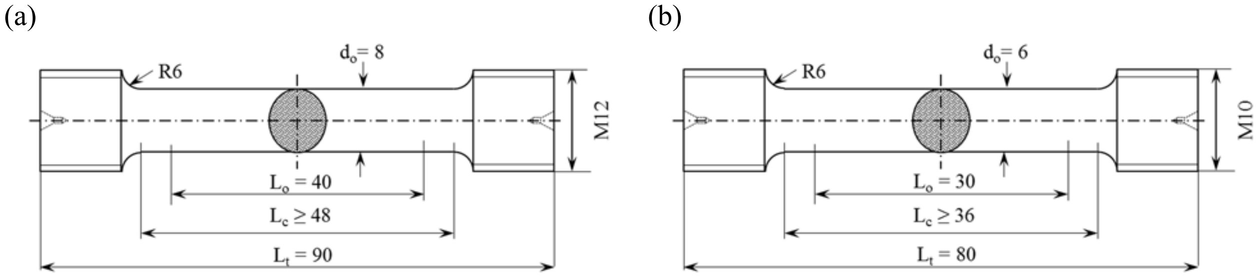

Fig. 2. Dimension of (a) M12 and (b) M10 tensile specimen (all measurements are in mm)

2.3 Elevated temperature testing

Material properties at elevated temperature for structural fire design purposes are obtained from elevated temperature tensile tests conducted under isothermal (steady state) or anisothermal (transient state) conditions. In an isothermal test, the temperature of the specimen is equilibrated at the target temperature before applying an axial load at a controlled rate until failure occurs. In an anisothermal test, the specimen is held at a target tensile load and then the temperature is increased at a controlled rate until failure occurs. The total strain is recorded as a function of temperature θ and this can be converted into stress-strain curves (see Fig. 3(a)) once the effect of thermal expansion has been removed from the data using the appropriate coefficient of thermal expansion.

Isothermal tests are more commonly conducted because of experimental ease and the full stress-strain curves generated can be directly incorporated into complex structural fire resistance analysis [14]. However, anisothermal tests are considered more representative of what steel members would experience in a fire scenario (i.e. constant load, rising temperature) and the current European design guidelines are derived from such tests. In a real fire scenario, the behaviour of steel members is complex due to factors such as creep (time dependent deformation that occurs when a material is subjected to a steady load, below yield [14]), irregular rise in temperature and dynamic loads (and strains) and both methods have limitations. The choice of strain rate in isothermal tests or heating rate in anisothermal tests will influence the material properties at temperatures greater than 400°C due to creep effects [15]. For this reason test parameters should be chosen to be representative of the expected behaviour of steel members under fire conditions. In this investigation both test methods were used.

Table 3. Strain rates used in testing

Strain (%)	Strain rate (/min)
0 – 0.2	0.0009
0.2 – fracture	0.0070

Table 4. Average mechanical properties of steel A and B at ambient temperature

	$f_{0.2p,20}$ (N/mm^2)	$f_{y,20}$ (N/mm^2)	$f_{u,20}$ (N/mm^2)	$E_{a,20}$ (GPa)
Steel A (S690Q)	706.3	739.3	791.8	199.3
Steel B (S700MC)	749.3	800.7	836.3	224.7

2.3.1 Isothermal (steady-state) testing

In the isothermal tests, the temperature of the specimen was equilibrated at the target temperatures of 100, 200, 300, 400, 500, 600, 700 and 800°C before straining to failure at a controlled rate. Tests were repeated at 100, 400, 500 and 600°C. The heating rates used are presented in Table 5. In cases where the target temperature was greater than 400°C, a rate of 10°C/min was employed although this was reduced to 3°C/min when the temperature reached 80% of the target value in order to avoid temperature overshoot and to ensure the prescribed temperature was reached within the limits of ±3°C. This ensured that the entire parallel length of the specimen reached thermal equilibrium by the time the target temperature was achieved. Tests conducted at 100, 200, 300 and 400°C took approximately one hour to reach, and stabilise at, the target temperature. At such temperatures, a one hour heating time is expected to have a minimal effect on the strength or stiffness, as limited microstructural effects would be expected [16]. A strain rate of 0.005 ± 0.002/min was adopted which is consistent with the standards [11], [17] and other researchers (e.g., [5, 6]); this strain rate is considered to include slight creep effects. A contact extensometer was used to measure the strain up to 5% and crosshead displacement was used for the remainder of the test.

2.3.2 Anisothermal (transient state) testing

In anisothermal tests, the specimens were held at a target tensile load for the duration of the test whilst the temperature was increased at a controlled rate of 10°C/min until a temperature of 900°C was reached or the tensile load could no longer be maintained at the 'runaway' strain (which could be correlated to strains reached in steel beams or columns where failure is imminent [18]). This heating rate represents a fully loaded steel member surviving for approximately 1 hour in accordance with the ISO 834 standard fire resistant tests [19]. For such a time frame, some creep will develop but its significance to the overall fire resistance of a steel member is dependent on factors such as boundary conditions (e.g. restrained ends). Nine tensile loads were chosen as multiples of 80, ranging from 80 to 720 N/mm^2 (i.e, 80, 160, 240 N/mm^2 ….etc). For steel B (S700MC), additional tests were conducted at 760 and 800 N/mm^2 in order to obtain suffucient data to determine the effective yield strength at 2.0% total strain at temperatures between 100–700°C. Tests were repeated at 80, 160, 240, 320, 400 and 480 N/mm^2. Throughout the test, the total strain was recorded using the axial contact extensometer as a function of the average temperature θ taken from the top, middle and bottom thermocouples attached within the gauge length of the specimen and includes the following: (i) the mechanical (elastic and plastic) strain introduced when the tensile load was applied at ambient temperature, (ii) the creep strain which is implicitly accounted for and (iii) the thermal strain as a result of thermal expansion [15]. In order to deduct the influence of the thermal expansion from the total strain, separate tests were conducted using minimal load of 1 N/mm^2.

Table 5. Heating rates used in this experimental programme

Target temperature (°C)	Heating rate (°C/min)
100	2
200	3
300	5
>400	10

2.3.3 Key parameters measured during testing

At elevated temperature, the yield strength becomes increasingly difficult to quantify because of the large strains exhibited and material nonlinearity. Eurocode 3 Part 1-2 [8] idealises the stress-strain response at elevated temperature as illustrated in Fig. 3(b). The response is assumed to be linear up to the proportional limit ($f_{p,\theta}$) and this is followed by an elliptical representation until the maximum stress ($f_{y,\theta}$) is achieved at a strain of $\varepsilon_{y,\theta}$, where $\varepsilon_{y,\theta}$ is commonly defined as the total strain level at 2.0% [20]. Following this, a constant strength is assumed between $\varepsilon_{y,\theta}$ and the limiting strain ($\varepsilon_{t,\theta}$) before the stress drops to zero at the ultimate strain ($\varepsilon_{u,\theta}$).

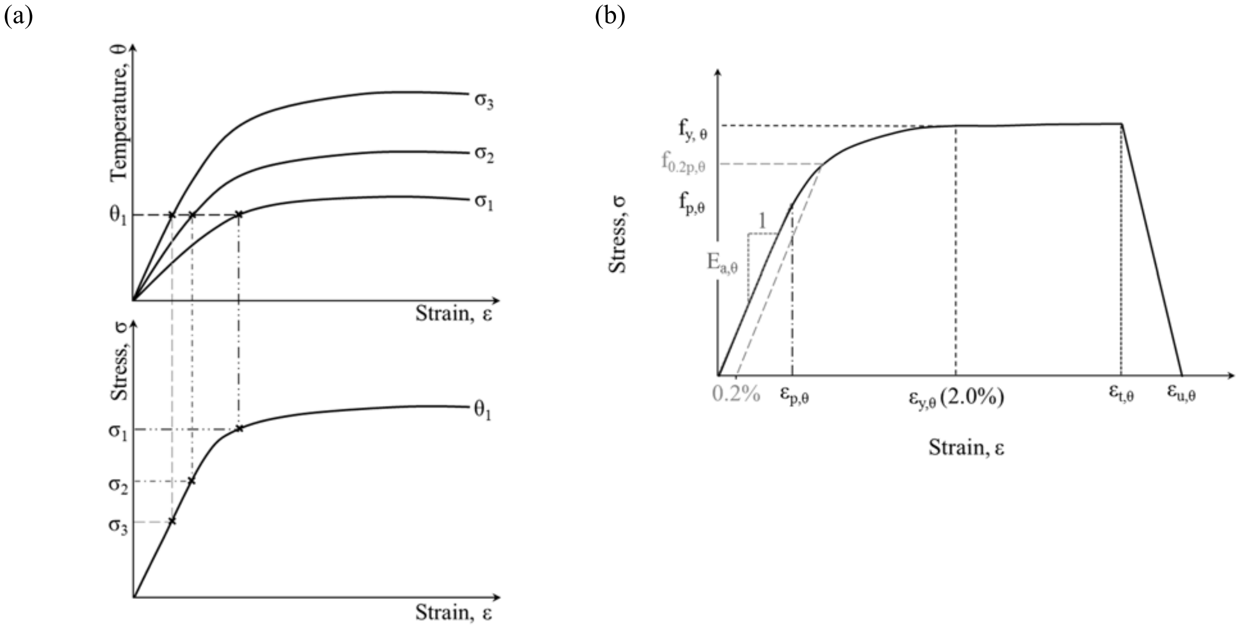

Fig. 3. (a) Converting temperature-strain curves into stress-strain curves from transient test result; (b) Idealised stress–strain curve at elevated temperature adopted from EN 1993-1-2 [8]

3 REDUCTION FACTORS

In this section, the main parameters related to strength and stiffness (i.e. $f_{0.2p,\theta}$,$f_{y,\theta}$ and $E_{a,\theta}$) are assigned reduction factors based, which is the ratio between the property at elevated temperature θ, and the corresponding term at ambient temperature. The results presented in Table 6 and Table 7 are later compared with published data for similar steel grades where tests were similarly conducted under isothermal or anisothermal conditions (e.g. [5–7]) and the design curves given in Eurocode 3 Part 1-2 [8]

3.1 0.2% proof strength

As the yield stress is difficult to identify in materials with a non-linear stress-strain response where no distinctive yield point is observed (e.g. TMCP steel and stainless steel), the yield strength at ambient temperature is usually defined in terms of a proof stress at a particular offset strain, typically 0.2% strain (see Fig. 3(b)). The 0.2% proof stress is often used in the design of class 4 (slender) steel members, where local buckling will occur before the yield strength is reached in one or more parts of the cross-section [23]. Fig. 4(a) and Fig. 4(b) depict the reduction values for the 0.2% proof strength at elevated temperatures (i.e. $k_{0.2p,\theta} = f_{0.2p,\theta}/f_{0.2p,20}$) under isothermal and anisothermal (which in Figs. 4–6 are abbreviated as iso and aniso, respectively) conditions along with data from the literature (i.e. [5–7]) and Annex E of the Eurocode [8]. From Fig. 4(a), it can be seen that generally, the reduction factors provided in the Eurocode are conservative and adequate for depicting the reduction in the 0.2% proof strength at temperatures greater than 100°C under isothermal conditions and 200°C under anisothermal conditions for steel A (S690QL) and B (S700MC). With reference to Fig. 4(b), steel A (S690QL) and B (S700MC) follow the same trend with the steels from literature [5–7]. Similar to steels A (S690QL) and B (S700MC) under both isothermal and anisothermal conditions, the Eurocode curves are conservative at temperatures greater than 200°C, with the exception of S690QL tested by Qiang et al. [6] at 700°C. Only HSA800 tested by Choi et al. [7] under isothermal conditions met or exceeded the $k_{0.2p,\theta}$ reduction factors from the Eurocode at all temperatures.

Table 6. Reduction factors for strength and stiffness under isothermal (steady state) conditions

θ, Temperature (°C)	Steel A (S690Q)			Steel B (S700MC)		
	$f_{0.2p,\theta}/f_{0.2p,20}$	$f_{y,\theta}/f_{y,20}$	$E_{a,\theta}/E_{a,20}$	$f_{0.2p,\theta}/f_{0.2p,20}$	$f_{y,\theta}/f_{y,20}$	$E_{a,\theta}/E_{a,20}$
20	1.00	1.00	1.00	1.00	1.00	1.00
100*	0.98	0.97	0.95	0.99	0.97	0.91
200	0.95	0.95	0.96	0.94	0.94	0.97
300	0.92	0.97	0.92	0.98	1.02	0.94
400*	0.91	0.93	0.89	0.92	0.99	0.91
500*	0.80	0.84	0.89	0.81	0.86	0.85
600*	0.63	0.66	0.75	0.68	0.71	0.79
700	0.32	0.34	0.38	0.47	0.45	0.63
800	0.10	0.11	0.27	0.23	0.21	0.39

*repeated tests

Table 7. Reduction factors for strength and stiffness under anisothermal (transient state) conditions

θ, Temperature (°C)	Steel A (S690Q)			Steel B (S700MC)		
	$f_{0.2p,\theta}/f_{0.2p,20}$	$f_{y,\theta}/f_{y,20}$	$E_{a,\theta}/E_{a,20}$	$f_{0.2p,\theta}/f_{0.2p,20}$	$f_{y,\theta}/f_{y,20}$	$E_{a,\theta}/E_{a,20}$
20	1.00	1.00	1.00	1.00	1.00	1.00
100	0.92	0.95	0.98	0.91	0.95	0.97
150	0.91	0.94	0.95	0.89	0.94	0.95
200	0.88	0.94	0.96	0.88	0.94	0.96
250	0.88	0.93	0.95	0.89	0.94	0.97
300	0.89	0.92	0.91	0.87	0.93	0.96
350	0.88	0.92	0.90	0.87	0.93	0.92
400	0.90	0.91	0.89	0.87	0.93	0.85
450	0.86	0.88	0.86	0.86	0.92	0.79
500	0.79	0.85	0.80	0.82	0.90	0.70
550	0.71	0.79	0.75	0.76	0.81	0.65
600	0.60	0.66	0.64	0.61	0.71	0.58
650	0.46	0.55	0.46	0.54	0.61	0.46
700	0.24	0.37	0.44	0.43	0.50	0.37
750	0.14	0.22	0.16	0.30	0.32	0.27
800	0.11	0.11	0.04	0.15	0.22	0.19

3.2 Effective yield strength

In Eurocode 3 Part 1-2 [8], the effective yield strength at elevated temperature ($f_{y,\theta}$) is defined as the stress level at which the stress-strain curve is truncated to provide a yield plateau, as shown earlier in Fig. 3(b). In practice, this has been consistently based on the total strain level at 2.0%, which is a high working strain for structural steels at ambient temperature [20] but in a fire scenario, large strains are accepted as it is assumed that structural members are likely to be either repaired or replaced once exposed to the fire [23]. Fig. 5(a) presents the reduction factors for the effective yield strength (i.e. $k_{y,\theta} = f_{y,\theta}/f_{y,20}$) obtained from isothermal and anisothermal tests with the reduction curve taken from the Eurocode [8] whilst Fig. 5(b) presents these reduction factors with data from the literature (i.e. [5–7]). From Fig. 5(a), there is little disparity between the data obtained from isothermal and anisothermal tests for steels A (S690QL) and B (S700MC) compared to the 0.2% proof strength, which is comparable with the findings from other researchers (e.g., [18]) who found that at relatively higher strains (e.g. ≥2%), the disparity between isothermal and anisothermal tests reduced. The Eurocode is reasonable and conservative at depicting the strength retention behaviour at temperatures greater than 400°C. Below 400°C, the data are unconservative in relation to the Eurocode curve with the exception of Steel B (S700MC) at 300 and 400°C under isothermal conditions where the strength increases. This strength increase is not observed in the corresponding anisothermal tests.

With reference to Fig. 5(b), the Eurocode is shown to provide unconservative reduction factors for the effective yield strength compared with the values tested and reported in the literature, with the exception of HSA800 tested by Choi et al.[7] at 300°C and BISPLATE 80 (S690Q) tested by Chen et al. [5] between 500 and 700°C. Both steel A (S690QL) and B (S700MC) demonstrate better strength reduction factors from 500 to 800°C than the steels from literature. Steel B, a thermomechanical control processed material had the better strength reduction properties compared to steel A (S690QL) at all tested temperatures. This steel contains niobium and titanium and also had the highest reported vanadium content of the tested steels (see Table 2) which suggests that this steel may contain a stable, fine dispersion of niobium or vanadium carbonitrides, or even form these as the temperature increases. Such precipitates play a crucial role in retention of steel strength at temperatures up to 650°C [24].

3.3 Elastic modulus

The elastic modulus is a very important property in structural engineering as it is used to determine the stiffness of a structural element and is particulary relevant for stability. The elastic modulus at ambient and an elevated temperature θ (i.e. $E_{a,20}$ and $E_{a,\theta}$, respectively) were determined from the test results based on the tangent of the initial linear elastic region of the stress-strain curve (Fig. 3(b)). It is noteworthy that at temperatures above 700°C, the linear elastic region of the stress-strain curve was small, particularly under anisothermal conditions where there was a limited number of data points available to determine the elastic modulus at small strains (i.e. below 0.2%).

Fig. 6(a) and Fig. 6(b) illustrates the reduction factors determined from the test programme (i.e. $k_{E,\theta} = E_{a,\theta}/E_{a,20}$) and compares these with equivalent values taken from the literature (i.e. [5–7]) and the Eurocode [8] under isothermal and aniosthermal conditions. Accordingly, in Fig. 6(a), the Eurocode curve is conservative and sufficiently depict the reduction in the elastic modulus of steel A (S690QL) and B (S700MC) at all temperatures with the exception of both steels at 100°C under isothermal and anisothermal conditions and steel A (S690QL) at 800°C under anisothermal conditions. The reduction factors obtained from isothermal and anisothermal tests for both steels are similar up to 400°C. Above 400°C, reduction factors obtained from isothermal tests are overly conservative compared to reduction factors obtained from anisothermal tests. At temperatures greater than 400°C, creep effects are particularly evident and suggest that a given load, the additional influence of creep deformation may possibly account for the lower elastic modulus. Kirby and Preston [18] stated that the difference is clearly due to experimental technique and the elastic modulus derived from anisothermal data could be considered more appropriate for structural fire design purposes. This suggests that relying only on isothermal data could compromise the ability to safely predict the buckling behaviour of HSS structures under fire conditions. From the results presented in Fig. 6(b), the elastic modulus for steels A and B follow a similar trend to those in the published literature (i.e. [5–7]) and the reduction factors are generally rather unconservative in relation to the Eurocode curve with the exception of BISPLATE 80 (S690Q) tested by Chen et al. [5] under aniosthermal conditions below 600°C, S690QL tested by Qiang et al. [6] at 200°C (under both isothermal and anisothermal conditions) and 700°C under anisothermal conditions.

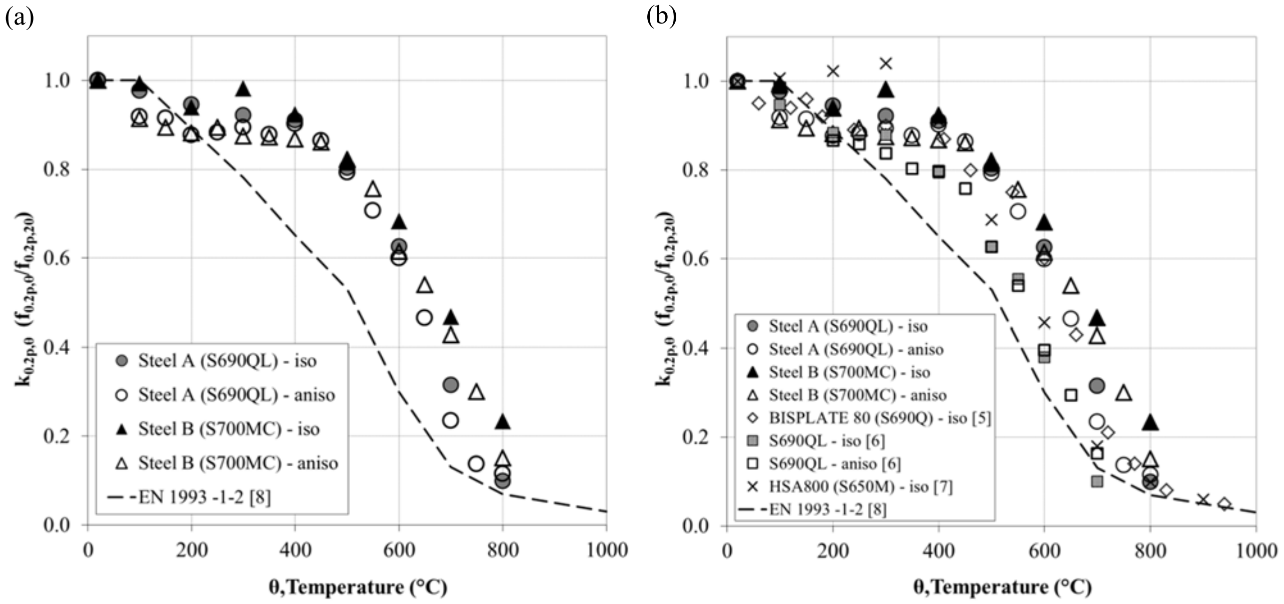

Fig. 4. Comparison of the reduction factors for 0.2% proof strength ($k_{0.2p,\theta} = f_{0.2p,\theta}/f_{0.2p,20}$) with (a) EN 1993-1-2 [8] and (b) available literature [5–7] and EN 1993-1-2 [8]

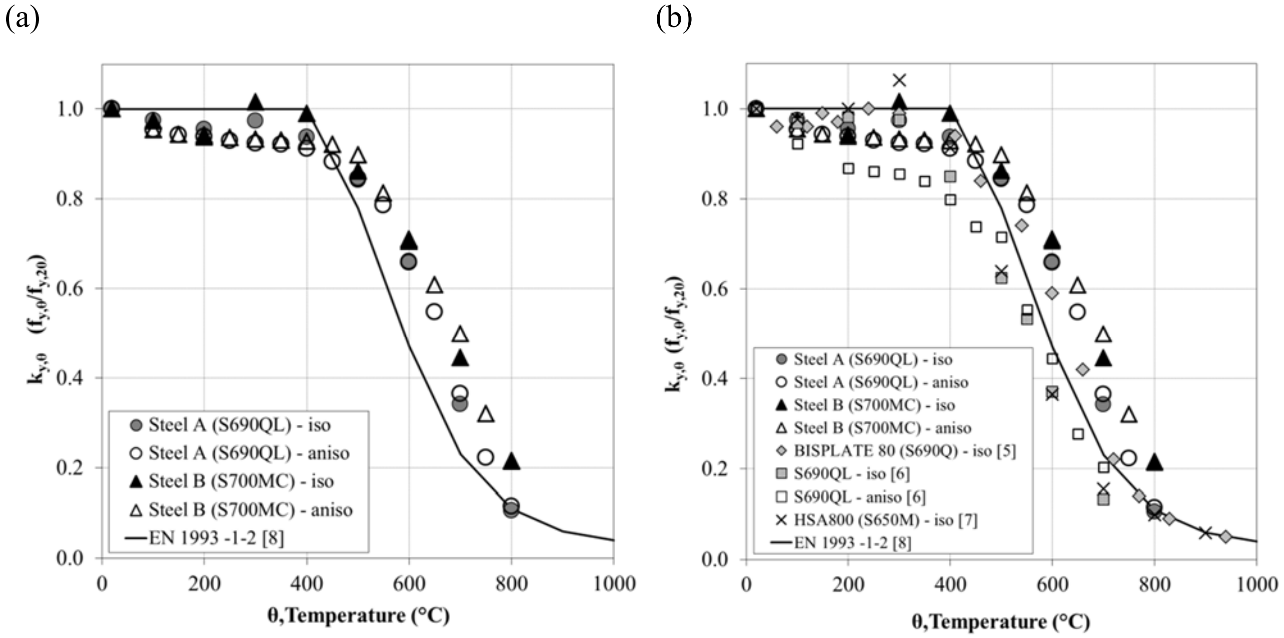

Fig. 5. Comparison of the reduction factors for the effective yield strength ($k_{y,\theta} = f_{y,\theta}/f_{y,20}$) with (a) EN 1993-1-2 [8] and (b) available literature [5–7] and EN 1993-1-2 [8]

4 SUMMARY AND FUTURE WORK

The 0.2% proof strength ($f_{0.2p,\theta}$), effective yield strength ($f_{y,\theta}$) and elastic modulus ($E_{a,\theta}$) were obtained from ambient, isothermal and anisothermal tensile tests on two commercially available HSS (S690QL and S700MC) at temperatures between 20 and 800°C for structural fire deign purposes. The results were presented as reduction factors and compared to available literature [5–7] and EN 1993-1-2 [8]. The results highlight that the Eurocodes can be unconservative for predicting the 0.2% proof strength, effective yield strength and elastic modulus for different HSS grades at temperatures up to 800°C. The disparity between data derived from isothermal and anisothermal tests was much smaller for the effective yield strength compared to the 0.2% proof strength and the elastic modulus at temperatures greater than 400°C. The reduction factors under isothermal conditions were unconservative and overly optimistic compared to reduction factors obtained from anisothermal tests. Hence, only relying on data from isothermal tests in structural fire analysis could result in overestimating the performance of HSS members, particularly in scenarios where stability (i.e. buckling) is critical. Steel B (S700MC) had better strength reduction factors compared with steel A (S690QL) and it is clear from the results presented in Table 2, Table 6 and Table 7 that there are significant differences in the performances of high strength steels from different sources and it is likely that the chemical composition and production route are influential on the material performance at elevated temperatures.

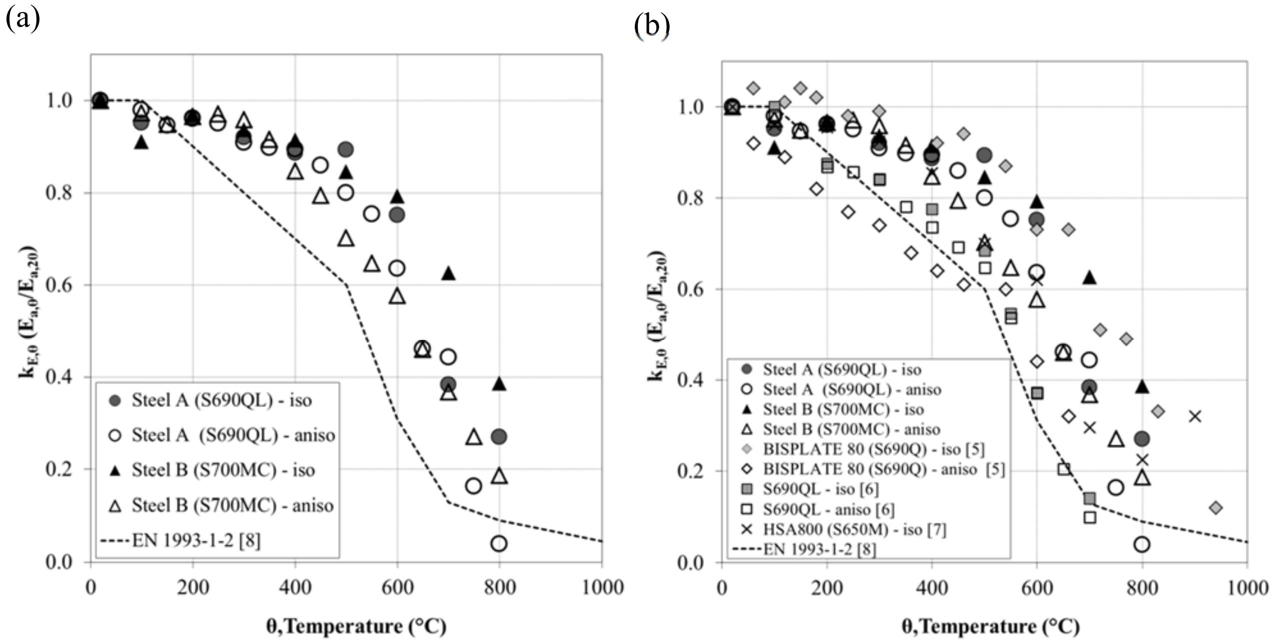

Fig. 6. Comparison of the reduction factors for the elastic modulus ($k_{E,\theta} = E_{a,\theta}/E_{a,20}$) with (a) EN 1993-1-2 [8] and (b) available literature [5–7] and EN 1993-1-2 [8]

The loss of strength and stiffness of steel during a fire is inevitable, but the chemical composition and processing routes employed to acquire high strengths may influence the rate at which this occurs. From a practical perspective, steels which retain strength and/or stiffness for longer or to higher temperatures as a result of metallurgical effects such as secondary (or precipitation) hardening could allow additional valuable evacuation time in the event of a fire. As part of a wider research programme a detailed metallurgical study will be conducted, focused on the influence of microstructural effects on the mechanical properties of the steels.

5 ACKNOWLEDGMENT

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