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Behaviour 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) at elevated temperatures. These steels vary in chemical composition and production route but have similar tensile properties at ambient temperature. Preliminary data of the following: proportional limit ($f_{p,\theta}$), elastic modulus ($E_{a,\theta}$), effective yield strength ($f_{y,\theta}$) based on the total strain level at 2% (in accordance with the Eurocode approach) obtained from isothermal tests are presented as reduction factors and compared with literature and the Eurocode (EN 1993-1-2). The consequences for material selection and design are also discussed.

1. INTRODUCTION

During the conceptual design stage of a project, the selection of materials and structural schemes are often governed by the requirement for solutions to be economically viable whilst equally providing a positive contribution towards the environment and society. High strength steels (HSS, defined here as materials with yield strength between 460 and 700 N/mm^2 in accordance with the Eurocode Part 1-12 [1]) have the potential to make a positive contribution towards these demands by reducing the material usage and hence weight of structural elements when employed in appropriate applications. Lighter structures lead to smaller foundations, reduced transportation costs and potentially reduced construction times and costs, as well as lower CO_2 emissions and energy use during construction.

One of the issues preventing more widespread use of HSS in structures is the lack of reliable information relating to the response of these materials at elevated temperature. Although the Eurocode (does include a section for HSS [1], the guidance for fire design is based on experiments on steel with yield strengths below 460 N/mm^2. For HSS, there are limited data in the literature (e.g. [2, 3]) that present the effects of temperature on the mechanical properties in terms of reduction factors. Whilst the loss of strength and stiffness during a fire is inevitable, a recent review highlighted that the strength and stiffness of HSS at elevated temperature are directly related to the alloying elements and processing route employed [4]. This implies that by choosing particular alloying elements and processing routes, possible metallurgical effects such as secondary (or precipitation) hardening could potentially be utilised to retard the loss of strength and stiffness of HSS during a fire, therefore buying valuable evacuation time. However, because limited metallurgical analysis was presented in the literature, the influence of strengthening mechanisms such as precipitation hardening on the performance of HSS at elevated temperature is not clear. In this context a primary aim of this work is to provide engineers and designers with essential and reliable information to support the safe design of fire resistant structures made from high strength steels (HSS). A further aim of the work is to develop a detailed understanding of the effects of steel alloying and processing routes on the structural response of HSS in fire as these are likely to have a strong influence on the degradation of mechanical properties.

In this paper, a series of isothermal elevated temperature tests on commercially-available HSS grades is described. Based on the findings of this study, preliminary data of the following mechanical properties are presented: proportional limit ($f_{p,\theta}$), elastic modulus ($E_{a,\theta}$) and effective yield strength ($f_{y,\theta}$) based on the total strain level at 2% (in accordance with the Eurocode approach). The results are compared with available results in the literature and also the Eurocode values [5]. The tests described herein are part of a larger programme which includes anisothermal testing as well as detailed metallurgical studies.

1 EXPERIMENTAL INVESTIGATION

Ambient and elevated tensile tests were conducted on an electromechanical testing machine, which has a maximum displacement rate capacity of 100 mm/min. The machine consists of a load frame with a maximum capacity of 100 kN, a three-zone furnace with a temperature controller that has a maximum temperature capability of 1200^{o}C, and testXpert II software that monitors and controls the mechanical and thermal variables of the system through a digital closed loop control. A total of three thermocouples were used to monitor the top, middle and bottom temperature of the tensile specimen and an axial contact extensometer, compliant with ISO 9513 Class 1 [6], was used to measure the strain up to 4% before switching to crosshead displacement to estimate the strain for the remainder of the test.

1.1 TEST MATERIAL AND SPECIMENS

Table I presents the HSS grades which are included in the experimental investigation, covering a range of nominal yield strengths (σ_y) between 690 and 700 N/mm^2 at ambient temperature (note that σ_y is used to describe the nominal yield strength whilst f_y is used later to represents the effective yield strength).

TABLE I. GRADES OF COMMERCIAL HSS INCLUDED IN THE PROGRAMME

	Grade	**σ_y (N/mm^2)**	**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
Steel C	S690QL	690	15	M12	Quenched and tempered

TABLE II. 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	0.46	0.18	0.21	0.037	0.002	-	0.003	0.003
Steel B	0.12	1.98	0.26	0.15	0.033	0.019	0.004	0.046	0.12	0.09	0.2	-
Steel C	0.2	1.44	0.015	0.17	0.17	0.015	-	0.062	0.004	0.06	0.06	0.004

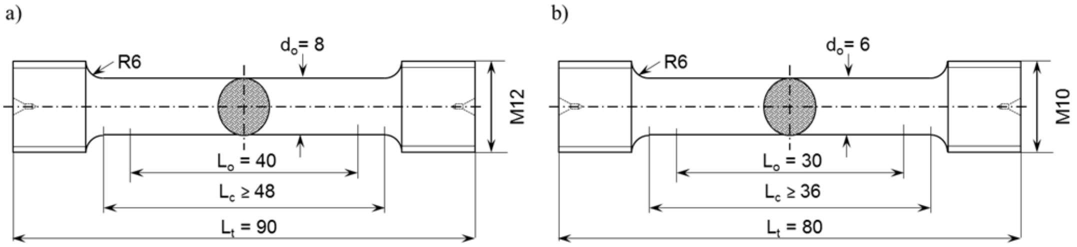

Figure 1. Dimension of a) M12 and b) M10 tensile specimen in mm

The steel grades for structural steels within EN 10025 [7] and EN 10149 [8] are denoted by an S at the beginning of their designation followed by the nominal yield strength (σ_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 at -40^{o}C [7]. Likewise M and C in S700MC indicate thermo-mechanical control processed (M) and cold-formed (C) materials, respectively [8]. It is noteworthy that although steels A and C have the same designation, analysis from optical emission spectroscopy revealed that these steels varied in chemical composition. The results from the analyses are presented in Table II. As shown in this table, steel A was alloyed with chromium (Cr), nickel (Ni), molybdenum (Mo) and boron (B), whereas steel C had a higher carbon content (0.20% vs 0.17%) but lower levels of nickel and boron as well as the microalloying elements niobium (Nb) and vanadium (V). The TMCP steel B had a lower carbon content than the QT steels, a low chromium addition and was microalloyed with titanium (Ti) as well as a high level of niobium and vanadium.

Round M10 and M12 tensile specimens were machined parallel to the rolling direction from each of the plates detailed in Table I. The dimensions of the specimens which follow ISO 6892-1/2 [9, 10] are shown in Figure 1. 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 digitised travelling light microscope. The average diameter d_o was then calculated and used to determine the cross-sectional area for each tensile specimen. The standard gauge length, was calculated using the following formula for proportional tensile specimens (Eq. 1):

$$L_o = 5.65 \sqrt{A_c} \tag{1}$$

where A_c is the cross-sectional area of the tensile specimen. L_o was rounded to nearest multiple of 5 mm, as recommended in ISO 6892-1 [9]. Such approximation is only valid if the difference between the calculated gauge length and approximate gauge length is less than 10%. In total, 27 specimens (9 for each steel type) were tested in the current study.

1.2 ELEVATED TEMPERATURE TESTS

Tensile testing at elevated temperature may be conducted isothermally or anisothermally, also known as steady-state and transient testing, respectively. In an isothermal test, the specimen temperature is equilibrated at the target temperature before straining to failure at a controlled rate. In an anisothermeal test, the specimen is held at a target load and then the temperature is increased at a controlled rate until failure occurs, the strain is recorded to generate a set of load-strain curves for different temperatures. Researchers have compared data taken from isothermal and aniosthermal tests for mild steels at 0.2% and 1.0% proof strength [11]. The results for the 0.2% proof strength from transient-state tests were found to be at least 10% below the minimum steady-state range between 400 and 800^{0}C due to the increasing influence of creep strains above 400^{0}C [12]. However, for the 1.0% proof stress there was good agreement between the two test methods. Moreover, Kirby and Preston concluded that for large strains (i.e. 2% and above), data derived from either test method can be used to predict the behaviour of steel components in a fire [13]. This paper will present data from isothermal tests.

1.2.1 STRAIN RATE

Knobloch *et al.* investigated the influence of strain rate on the stress-strain response of mild steel at 400, 550 and 700^{0}C under isothermal conditions [14]. The strain rates adopted were 0.0002/min, 0.001/min and 0.005/min, which is representative of the range of long to short fire durations. It was found that as the strain rate decreased, a lower effective yield strength ($f_{y,\theta}$) was observed, so the reduction factors from the experimental data did not correlate well with the European and American fire design guidelines when the strain rate was 0.0002/min or 0.001/min. However, there was good agreement between the experimental data and the reduction factors when the strain rate was 0.005/min. Thus a strain rate of 0.005± 0.002/min was used throughout the current investigation, which is also in agreement with the American standards [15]. The strain rate was indirectly controlled by specifying a crosshead displacement rate (mm/min) v_c, based on Eq. 2:

$$v_c = \dot{\varepsilon}_{L_c} \times L_c \tag{2}$$

where $\dot{\varepsilon}_{L_c}$ and L_c are the target strain rate and parallel length of the tensile specimen, respectively. This method gave strain rates that were compliant with ASTM E21-09.

1.2.2 HEATING RATE

In structural fire design, heating rates for steel should be within the range of 2 to 50^{0}C/min as specified in EN 1993-1-2 [5] in order to reflect real fire behaviour. In this study the temperature was increased at a steady rate of 10°C/min, which represents a fire resistance time of 1 hour based on the standard ISO 834 fire curve [13]. This heating rate has also been consistently used in literature (e.g [13, 16]). To avoid any temperature overshoot and to reach the prescribed temperature within the limits of ±3°C, the heating rate decreased steadily to 3°C/min when the temperature reached 80% of the target temperature. This ensured that the entire parallel length of the specimen reached thermal equilibrium by the time the target temperature was reached. Two tensile specimens were tested at each of 400, 500 and 600°C.

2 RESULTS AND DISCUSSION

In this subsection, the main parameters related to strength and stiffness (i.e. $f_{p,\theta}$, $f_{y,\theta}$ and $E_{a,\theta}$) are assigned reduction factors, which is the ratio between the property at elevated temperature and the corresponding term at ambient temperature. The results presented in Table III are compared with literature where tests were conducted under isothermal conditions [2, 3, 16] and the Eurocode [15].

2.1 PROPORTIONAL LIMIT

The proportional limit ($f_{p\ \theta}$) is defined as the point where the stress-strain curve changes from linear to non-linear. As this is difficult to identify in materials with no distinctive yield point such as high strength steel or stainless steel, the 0.2% offset value is widely used. This is the point where the proportional line offset at 0.2% strain intersects the stress strain curve and is also known as the 0.2% proof stress or the 0.2% offset yield strength. In Figure 3, the reduction values for the 0.2% proof strength at elevated temperatures ($f_{p,0.2,\theta}/f_y$) are presented along with data from literature [2, 3, 16] and the reduction factors for the proportional ($f_{p,\theta}/f_y$) and effective yield strength ($f_{y,\theta}/f_y$) from EN 1993-1-2 [5]. From Figure 3 it can be seen that in many cases the $f_{y,\theta}/f_y$ reduction factors are unconservative, except for steel B (S700MC) at all temperatures tested, HSA800 (S650M) tested by Choi *et al* [16] between 20 – 300°C and BISPLATE 80 tested by Chen *et al* [2] between 500 – 700°C. Hence $f_{p,\theta}$ is more appropriate, although it is noteworthy that at temperatures below 200°C even $f_{p,\theta}$ reduction factors are slightly unconservative and do not depict the loss in strength accurately.

2.2 EFFECTIVE YIELD STRENGTH

In the Eurocode EN 1993-1-2, the effective yield strength ($f_{y,\theta}$) is based on the total strain level at 2.0% [11] (depicted in Figure 2) . In Figure 4 the reduction values for the effective yield strength at elevated temperatures ($f_{y,\theta}/f_y$) are presented along with data from literature [2, 3, 16]and the reduction curve taken from the Eurocode. Generally it is observed that the Eurocode is conservative at predicting the effective yield strength for all three steels, with the exception of steel A (S690QL) and C (S690QL) at 400°C.

TABLE III. REDUCTION FACTORS OF YIELD STRENGTHS AND ELASTIC MODULUS

θ, Temperature (^{0}C)	Steel A			Steel B			Steel C		
	$\mathbf{f_{p,0.2,\theta}/f_y}$	$\mathbf{f_{y,\theta}/f_y}$	$\mathbf{E_{a,\theta}/E_a}$	$\mathbf{f_{p,0.2,\theta}/f_y}$	$\mathbf{f_{y,\theta}/f_y}$	$\mathbf{E_{a,\theta}/E_a}$	$\mathbf{f_{p,0.2,\theta}/f_y}$	$\mathbf{f_{y,\theta}/f_y}$	$\mathbf{E_{a,\theta}/E_a}$
20	0.96	1.00	1.00	0.98	1.00	1.00	0.99	1.00	1.00
400	0.80	0.86	0.72	0.91	0.99	0.81	0.84	0.93	0.85
500	0.78	0.84	0.70	0.83	0.87	0.82	0.74	0.80	0.83
600	0.57	0.66	0.73	0.62	0.69	0.40	0.51	0.54	0.60

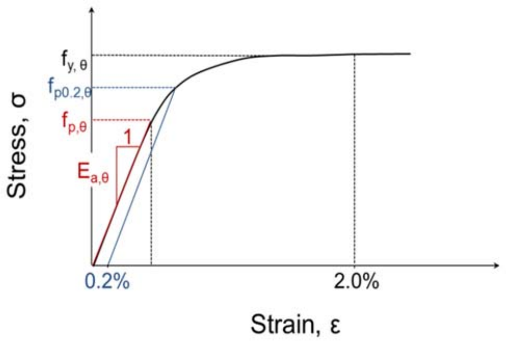

Figure 2. Stress–strain curve at elevated temperature

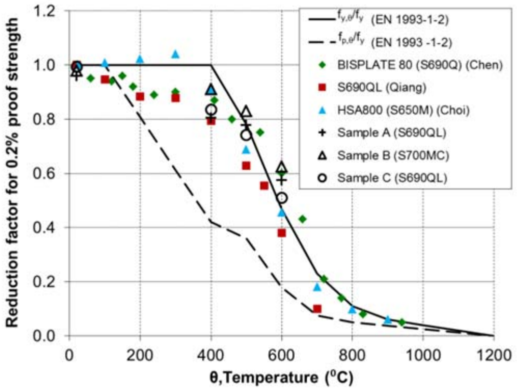

Figure 3. Reduction factors for the 0.2% proof strength

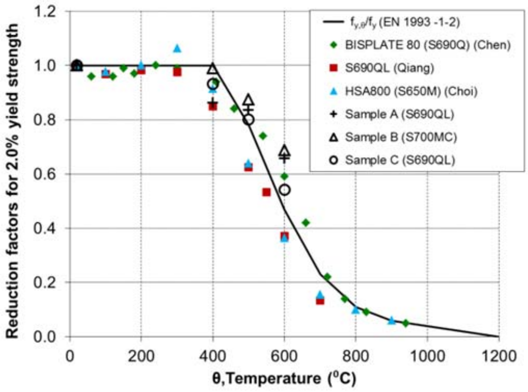

Figure 4. Reduction factors for the 2% yield strength

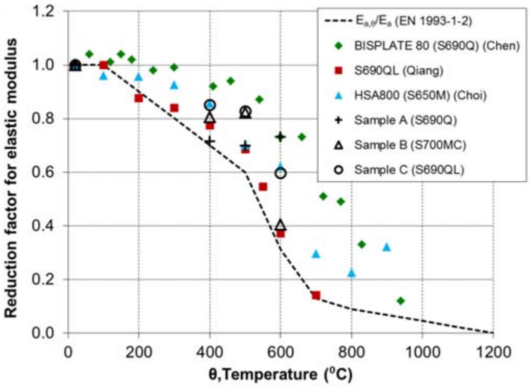

Figure 5. Reduction factors for the elastic modulus

In comparison the Eurocode is unconservative at predicting the reduction factors of the effective yield strength for the steels in literature, with the exception of HSA800 tested by Choi *et al* [16] at 300^{0}C and BISPLALTE 80 (S690Q) tested by Chen *et al* [2] between 500 and 700^{0}C. Steel B, a thermomechanical control processed and cold formed material had the best strength reduction properties compared to all other steels at the tested temperatures. This steel contains niobium and titanium and also had the highest reported vanadium content of the tested steels (see Table II) which suggests that this steel may contain stable precipitates of niobium or vanadium carbonitrides. Such precipitates play a crucial role in retention of steel strength at temperatures up to 650^{0}C [17]. Steels A and C are both quenched and tempered materials that vary in chemical composition. Steel A contains molybdenum and substantially more chromium than steel C, which could be linked to its better strength retention properties by comparison with steel C but further research is needed to confirm this.

2.3 ELASTIC MODULUS

The elastic modulus, E_a is used to determine the stiffness of a structural element and hence its load bearing capacity [3]. E_a and $E_{a,\theta}$ (i.e. the elastic modulus at a temperature θ) were determined based on the tangent modulus of the initial linear elastic region of the stress-strain curve (Figure 2). Figure 5 illustrates the reduction factors for the elastic modulus ($E_{a,\theta}/E_a$) from the experimental study compared with literature [2, 3, 16] and the Eurocode (EN 1993-1-2) [5]. From the results it can be seen that the elastic modulus follows a similar trend to the other steels tested in literature and the reduction factors are generally conservative. Some of the results should be treated with caution, particularly the elastic modulus for steel A which will require further testing to ensure consistent results.

3 CONCLUSIONSAND FUTURE WORK

This paper has presented preliminary results as part of an experimental study on the material properties of three commercial HSS at elevated temperatures. The 0.2% proof strength ($f_{p0.2,\theta}$), effective yield strength ($f_{y,\theta}$) and elastic modulus ($E_{a,\theta}$) were obtained from ambient and isothermal tests at 400, 500 and 600^{o}C. The results were presented as reduction factors and compared to literature [2, 3, 16] and EN 1993-1-2 [5]. The results suggest that the Eurocode provides conservative predictions for the proportional limit at temperatures greater than 200^{o}C and the elastic modulus at all temperatures for the steels tested. Steel B had the best strength reduction factors compared with steels A and C. On the other hand, steel C had the poorest strength retention properties. It is clear from the results presented in Figure 3 and Table II 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. Elements such as niobium, vanadium, and molybdenum have a positive influence on the strength retention properties at temperatures as high as 650^{o}C [17] but further research is required to find out, for instance the metallurgical influences that result in steel B having better strength retention properties than steel A or C. Hence future plans for this wider research project will include a detailed metallurgical investigation with the aim of characterising the microstructural changes in terms of time and temperature. In particular, the influence of grain size and precipitates on the mechanical properties at elevated temperature will be studied. The HSS presented in Table I will be heat treated to replicate isothermal tensile tests.

Thereafter, a technique called electron backscatter diffraction (EBSD) will be used to characterise the grain size of the heat treated samples and compared with the sample at ambient temperature. Future work will include transmission electron microscope (TEM) studies to characterise precipitates and microstructure. Such information will support further material developments to optimise the ambient and elevated temperature properties by providing steel producers with preliminary guidance on the effects that chemical composition and processing routes have on the elevated temperature performance. The steels will also be tested to get a full temperature profile from 20 – 900^{0}C under isothermal and anisothermal conditions. The data from this project will be incorporated into ABAQUS models to evaluate the behaviour of HSS structural members during a fire

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