HIGH STRENGTH STEEL IN FIRE

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ABSTRACT

High-performance materials are necessary to meet the future demands of the construction industry, which is strongly influenced by a growing population and depletion of natural resources. Sustainable development is central to research and development into innovative structural materials, and requires solutions to be economically viable whilst equally providing a positive contribution towards environmental and social factors. High strength steels (HSS) have the potential to contribute towards such demands by reducing the weight of structures when employed in appropriate applications. Lighter structures require smaller foundations, shorter transportation and construction times and also lower CO_2 emissions. A particular challenge related to the use of HSS in structures include increased likelihood of stability issues resulting from the reduction in section thickness, and limiting deflection and vibration criteria are also more likely to be critical. Nevertheless, when used appropriately, they can provide a sustainable solution. Their use in structural applications is further hindered by a lack of performance data and design guidance under fire conditions. This paper compares the mechanical properties, particularly strength and stiffness of HSS (yield strengths between 460-700 MPa) and mild steel (yields between 235-460 MPa) at elevated temperatures, through a critical review of published literature. Various alloying and processing routes used to achieve high yield strength are assessed. At the same time, the review considers available information on the strengthening mechanisms that can be utilised to retain the strength and/or stiffness of the material in the event of a fire. Using the information gathered, an extensive testing programme is developed which will enable design guidance for the fire design of HSS structures to be proposed.

1. INTRODUCTION

High Strength Steel (HSS) is defined herein as material with a yield strength between 460 and 700 N/mm^2 in accordance with Eurocode 3 [1]. These materials offer economic, environmental and social benefits when compared to the more commonly used steel grades (e.g. S235, S275 and S355) through a reduction in material usage, weight and section size. Economic savings are gained through reducing the construction time as lighter structures are quicker to erect and easier to transport and the reduced section sizes result in smaller cross sections to weld and inspect. Additional savings can be made because a smaller foundation is needed due to the reduced weight and there are also associated environmental benefits owing to less disruption to the ground. Further environmental benefits include reduced fabrication costs and raw material consumption as well as increased fuel efficiency due to the transportation of lighter structural components and material processing. Moreover, HSS has the potential to create more architecturally pleasing solutions.

The full potential of HSS can be exploited when the design of structural components is governed by strength rather than stiffness. To date the use of HSS in civil engineering has been limited to specific applications such as offshore drilling rigs, heavy industrial plants, bridges and long span trusses. Their use in more common structural engineering structures is limited for reasons such as lack of reliable design guidelines, serviceability issues, different welding procedures and misconceptions on the cost/tonne [2]. Nonetheless HSS are gaining more and more interest in the market of structural steels for civil engineering applications and there are a number of instances where HSS have been successfully utilised in structures. For example the use of HSS in the Friends Arena Stadium in Solna, Sweden resulted in a structure 15% lighter when compared with using S355, €2.2 million savings in costs and 17% savings in greenhouse gas emissions [3]. In addition, the use of HSS in the long span Oresund

bridge between Sweden and Denmark resulted in cost savings of more than €22 million [4].
The European design standard for structural steel (Eurocode 3) initially applied to steel grades S235 to S460 with the most common steel grades being S235, S275 and S355 which are classified as mild steel [5]. These steels are well documented and much research has been done on their performance. The increasing interest in the use of steels with yield strengths greater than 460 N/mm^2 led to an additional part being added to the code in 2007, EN 1993-1-12 [1]. This extension provided additional rules to supplement existing codes for mild steels to cover steel grades up to S700 and was supported by an increase in research focus on the behaviour and design of HSS structures at ambient temperatures.
Under fire conditions, it is expected that, like mild steel, the strength of the material decreases as the temperature increases until eventually it can no longer support the load it was designed to carry. From a metallurgical perspective, understanding the microstructural changes that occur with increasing temperature is of great interest as it can lead to an enhancement in the materials strength retention properties. This is relevant to structural engineers who require an accurate representation of the stress-strain relationship for structural analysis in order to design structures to survive for prescribed time periods in a fire scenario [6]. The design rules for structural fire design (EN 1993-1-2 [7]) are currently applicable to all steel grades up to S700 although the material data presented is based on data from tests on mild steel. There has been limited research into the applicability of the design rules for HSS, mainly owing to the significant expense associated with high temperature structural testing as well as a lack of reliable data on the material properties which are needed to develop computational design models. These factors hinder the use of HSS in structural design.
This paper will discuss the metallurgical characteristics, in particular the strengthening mechanisms employed in steels, and the various production routes used to produce HSS and will comment on how these are affected by temperature. Thereafter, the tensile properties of steel at ambient and elevated temperature are briefly discussed and data showing how the tensile properties of various steel grades change with increasing temperature are extracted from published literature and reviewed. The relationship between the production route and strengthening mechanism employed are discussed in the context of the strength retention properties of high strength steel at elevated temperatures. Finally, the plans for future research are presented.

2. STRENGTHENING MECHANISMS FOR STEELS

The key to strengthening steel is to restrict or reduce the movement of metallographic imperfections known as dislocations, through the material. Plastic deformation is due to dislocation movement and so by restricting the mobility of dislocations, the dislocations require more stress to move through the iron crystal lattice. The result is an increase in yield strength [8]. The dislocation movement can be slowed down by the presence of alloying elements in the form of solute atoms (e.g. molybdenum) or precipitates (e.g. molybdenum carbides), grain boundaries or other dislocations. Commercial HSS typically achieve this through a combination of strengthening mechanisms. The most commonly employed of these strengthening mechanisms are briefly discussed in the following subsections with discussion on how they are affected by temperature.

2.1 GRAIN REFINEMENT

Grain refinement is the process of producing a microstructure with fine grains which, in turn, results in more grain boundaries. Fine grains results in an increase in yield strength because there are more grain boundaries present to slow down the movement of dislocations. The yield strength (f_y) is inversely proportional to the square root of the average grain size (d) as demonstrated in the Hall-Petch relationship [8]:

$$f_y \propto \frac{1}{\sqrt{d}} \quad (1)$$

However, the yield strength steel becomes almost independent of grain size at temperatures above 600 ± 50°C [9] At elevated temperatures (typically between 400 - 700°C [10]), grain growth occurs which reduces the amount of grain boundaries. Thus it is expected that this strengthening mechanism becomes less effective at contributing towards strength at elevated temperatures.

2.2 SOLID SOLUTION STRENGTHENING

By distorting the iron crystal lattice, the movement of dislocations is slowed down resulting in an increase in yield strength. The atoms of the alloying elements sit interstitially between the iron atoms (interstitial solid solution) or replace them by substitution (substitutional solid solution) [8] as shown in Figure 1. Furthermore, it has been shown in the literature(e.g. [11]) that solid solution strengthening does not adversely affect the ductility and is largely unaffected by temperature.

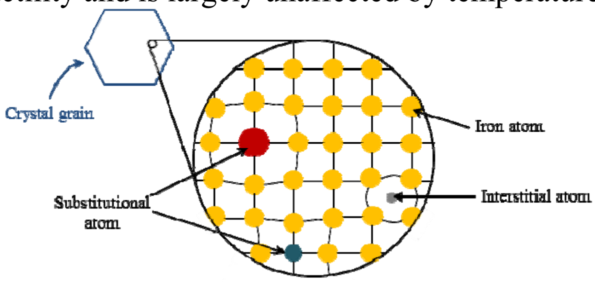

Figure 1 Crystal lattice distortion caused by the presence of solute atoms

2. 3 PRECIPITATION HARDENING

Precipitation hardening differs from solid solution strengthening in that the increase in yield strength is due to the precipitates directly obstructing the motion of dislocations as opposed to indirectly through distorting the iron crystal lattice. Generally, dislocations cut through smaller precipitates and move around bigger precipitates; the latter is known as Orowan Bowing. The extent to which precipitates contribute to the strength of steel is dependent on the composition (as this relates to the thermal stability), size, and the space between them [8]. Chromium, molybdenum, niobium, vanadium, tungsten and titanium carbonitrides used in steel form at about 500–650^{o}C [8]. Moreover, there are instances where the precipitation effect can be delayed until the steel is reheated (such as in a fire scenario) and this is known as secondary hardening. A fine distribution of carbonitrides-containing elements such as vanadium and niobium can be thermally stable at temperatures above 600^{o}C hence precipitation hardening is a useful strengthening mechanism at elevated temperature [11].

2.4 STRAIN HARDENING

Strain hardening is when dislocations are introduced into the crystal lattice through plastic strain. Since dislocations are obstacles to each other increasing the dislocation density leads to an increase in strength [12]. This strengthening mechanism is commonly used to obtain adequate strength in wires and rods but strength is achieved at the expense of ductility. Recovery occurs at elevated temperature where the amount of dislocations introduced through plastic strain is reduced and so the impact of this strengthening mechanism reduces [12].

3. PRODUCTION ROUTES FOR HSS

Production routes for steels utilise various heat treatments and rolling regimes to manipulate the microstructure to get optimum properties for a given application. Alloying elements, such as carbon and niobium also play an important role in manipulating the microstructure through the different strengthening mechanisms mentioned in Section 2. HSS are traditionally hot rolled in the austenitic region which is typically above 900^{o}C but this temperature is dependent on the chemical composition. The steel is then cooled at different rates to get the desired mechanical properties. The steel grades for structural steels in Europe are denoted by an S at the beginning of their designation followed by the minimum yield strength in N/mm^2 and then the production route/delivery condition, where N, Q, M and C are used for materials that are normalised (N), quench and tempered (Q), thermo-mechanically rolled or thermo-mechanically control processed (M) and cold-formed (C), respectively. The most common processing routes used to produce high strength steel at ambient temperature and the elevated temperature effects of the steel are summarised hereafter.

3.1 NORMALIZED (N) STEEL

Normalizing steel involves reheating the steel to a fully austenitic state where the temperature is typically about 100^{o}C above the upper transformation temperature to limit grain growth. The steel is then air cooled and the result is a microstructure of fine grain size. This heat treatment is often used after hot rolling, where the high finishing temperature (≥ 900°C) can lead to a coarse microstructure [8]. Due to the thermal stability of its microstructure, normalized steels are expected to have good strength retention properties at elevated temperatures.

3.2 QUENCHED AND TEMPERED (Q and Q&T) STEEL

After hot rolling in the austenitic region the steel is quenched or rapidly cooled to ambient temperature. The result is the formation of martensite or bainite which is a very hard structure in which the carbon has no time to diffuse resulting in a supersaturated microstructure with high strength and low ductility. Quenching is usually followed by tempering where the supersaturated carbon diffuses into the matrix and forms fine carbide precipitates within the grains and on the grain boundaries and hence some ductility is restored with moderate sacrifice in strength [8]. Heating such steels above their tempering temperature (typically between 580 - 620°C) will result in a change in microstructure and perhaps rapid strength degradation. Hence careful selection of the post weld heat treatment (PWHT) temperature is important [13].

3.3 THERMOMECHANICAL CONTROL PROCESS (M, TM and TMCP) STEEL

Thermomechanical control process (TMCP) is a production process that uses thermomechanical rolling and sometimes accelerated cooling to produce a fine grained microstructure that cannot be achieved or repeated by heat treatment alone [14]. TMCP steels are differentiated from other production techniques by their ability to achieve high strength through the implantation of deformation bands during the hot rolling process, which become nucleation sites for new grains. Grain growth is suppressed through the use of accelerated cooling and the addition of niobium, titanium and vanadium which form carbonitrides. In addition to restricting the opportunity for grain growth also the latter gives further carbonitrides precipitation which adds further to the strengthening. This means that reduced levels of alloying elements such as carbon are needed to contribute to the strength, resulting in improved weldability compared to normalised steel [15]. The European standards [14] recommend not to heat TMCP steels (with yield strengths below 700 N/mm^2) above 580°C to minimise any adverse effects on the mechanical properties. This suggests that the strength retention properties of TMCP steels degrade rapidly after 580°C because of grain growth.

3.4 COLD-FORMED (C) STEEL

Cold-formed steel is material that has been bent into shape (e.g. a channel or tube shape) at ambient temperature. It is typically thin gauge steel (i.e. 1-3 mm thick) and is very common in structural applications [16]. These steels are plastically deformed during the forming process, resulting in strength enhancement through strain hardening discussed in Section 2.4. Thus it is expected that the strength will degrade with increasing temperature because of recovery.

4. TENSILE PROPERITES OF HSS AT AMBIENT TEMPERATURE

The tensile strength and elastic modulus (E) of steel are obtained by conducting tensile tests. The results are presented on a stress-strain curve and the shape of that curve is influenced by the steels chemical composition and production route.

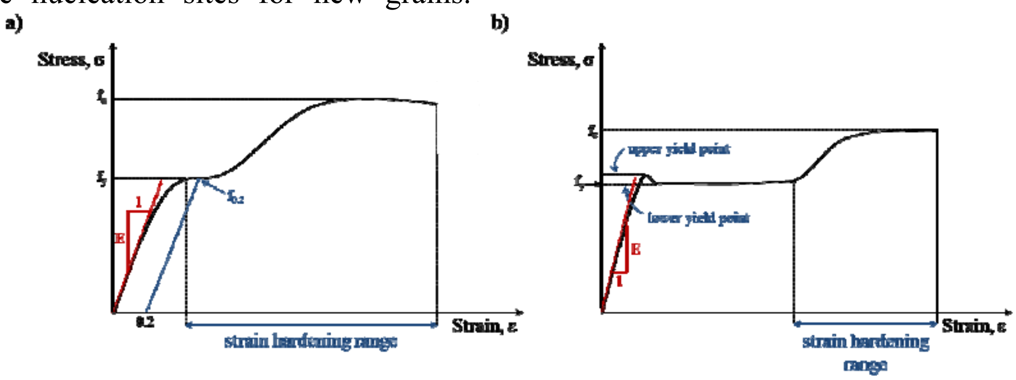

Figure 2 Stress –strain relationship for HSS at ambient temperature showing a) the 0.2% proof strength and b) the upper and lower yield point based on [5, 17]

Figure 2 shows typical stress-strain curves for HSS. As shown, at ambient temperature the stress-strain curve can show a distinctive plateau point (f_y). When there is no distinctive yield plateau the 0.2% proof strength ($f_{0.2}$) 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% offset yield strength. There are instances where an upper and lower yield point is present and this is typically dependent on the amount of carbon and nitrogen in solid solution. In most cases the 0.2% proof strength is the lower yield point. HSS may strain harden when plastically deformed (as stated in Section 2.4), resulting in an increase in strength beyond the 0.2% proof strength. The maximum stress is known as the tensile strength (f_u).

5. TENSILE PROPERTIES OF HSS AT ELEVATED TEMPERATURE

At elevated temperatures, the yield strength becomes increasingly difficult to quantify because of the large strains exhibited and material nonlinearity. The Eurocode [7] idealises the stress-strain response at elevated temperature as a linear relationship up to the proportional limit ($f_{p,\theta}$) followed by an elliptical representation until the maximum stress ($f_{y,\theta}$) is achieved at a strain of $\varepsilon_{y,\theta}$, as depicted in Figure 3. Following this, a constant strength is assumed between $\varepsilon_{y,\theta}$ and $\varepsilon_{t,\theta}$ before the stress drops to zero at the ultimate strain $\varepsilon_{u,\theta}$. The main parameters related to stiffness and strength (i.e. $E_{a,\theta}$, $f_{p,\theta}$ and $f_{y,\theta}$) are assigned reduction factors for increasing temperatures. Owing to the difficulty in defining the yield strength in tensile tests, different approaches are adopted in the codes. In EN1993-1-2, the effective yield strength ($f_{y,\theta}$) is based on the total strain level at 2.0% [6] whilst BS 5950 [18] gives different reduction factors of

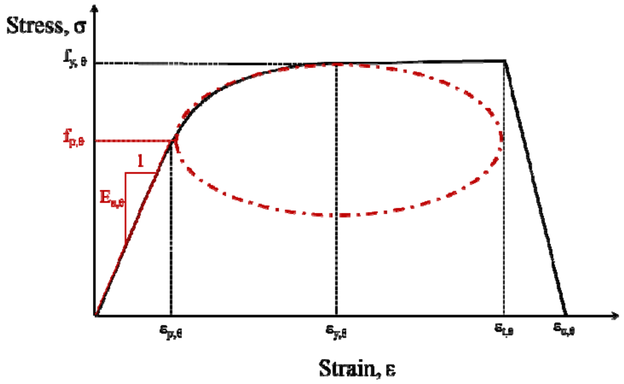

Figure 3 Stress–strain curve at elevated temperature

yield strength for 0.5, 1.5 and 2.0% strains, based on lines drawn perpendicularly from the to the strain axis to the stress-strain curve at those strains. Tensile testing at elevated temperature may be conducted either isothermally or anisothermally, also known as steady-state and transient-state testing, respectively. In steady-state testing, the material coupon is heated to a specified test temperature. Once thermal equilibrium has been reached, the specimen is loaded until failure. Steady-state tests are typically strain-controlled whereby the strain rate is kept constant at a prescribed value, e.g. ASTM Standard E21-09 recommends a value of 0.005/min ± 0.002/min [19], although load control can also be used.

On the other hand, in transient-state testing, the tensile load is kept constant whilst the temperature increases at a steady rate that is representative of real fires. This typically is between 5°C/min for a steel member with heavy insulation to 50°C/min for a non-insulated steel member [20]. The total strain is recorded at various temperatures which can be converted into stress-strain curves (see Figure 4) once the effect of thermal expansion has been removed from the data using the appropriate coefficient of thermal expansion. In both types of elevated temperature tensile test, the strain is measured using a high temperature extensometer and thermocouples are employed to monitor the temperature of the specimen.

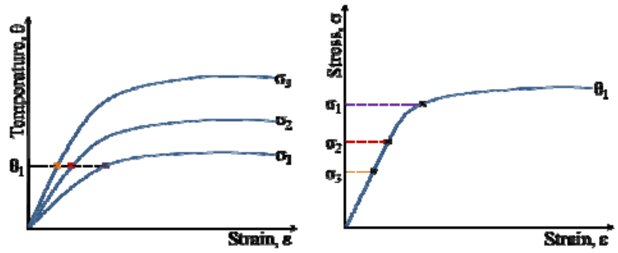

Figure 4 Converting temperature-strain curves into stress-strain curves from transient test result

The advantages of the steady-state test method are that it is easier to conduct and continuous stress-strain curves are produced that could be more favourable for potential complex structural fire resistance analysis in the future [21]. The advantage of the transient-state method is that it gives a more realistic representation of the steel's behaviour under fire conditions [22] but the complexity of the method compared to the steady-state means that it is less commonly used. Researchers have compared data taken from steady- and transient-state tests for mild steels at

0.2 and 1.0% proof strength [6]. The results for 0.2% proof strength from transient-state tests were at least 10% below the minimum steady-state range between 400 and 800°C. This is because during transient-state testing, creep strains become increasingly influential above 400°C [23]. However, for 1.0% proof stress there was good agreement between the two test methods. Moreover, Kirby and Preston [22] concluded that when the strain approaches the values corresponding to the limits of deflection or instability under fire conditions, the temperature derived from either test methods can be used to predict limiting temperatures. Preference over which method to use is not currently standardized [19, 24]. However, the reduction factors presented in Eurocode 3 were developed on the basis of transient-state testing [6].

5.1 REDUCTION FACTORS

5.1 (a) GENERAL COMMENTS

Reduction factors are typically used to express how the strength and stiffness properties degrade with increasing temperature and are defined as the ratio between the mechanical property being considered at elevated temperature and the equivalent value at ambient temperature. The acceptance criteria for structural steel components at elevated temperature are set to ensure that the structural integrity is maintained for a sufficient period of time to allow for safe evacuation. The criteria are then normally defined as a minimum temperature (typically 550°C) at which the reduction factor is 0.6, or when a limiting strain or deflection has been reached [13]. Alternatively performance may be required to exceed a reduction curve over the temperature range.

In this subsection, the reduction factors for yield strength and the elastic modulus were extracted from the available literature and compared with the design curves given in EN 1993-1-2 [7] and AISC 360-10 [25]. The test method (i.e. steady- or transient- state) is stated where this information is known and the chemical composition and the production route of the steel grades taken from the available literature are presented in Table 1. In the instances where steady-state testing was conducted, strain-control was used to investigate the strain rate and was compliant to ASTM Standard E21-09. In the transient tests the heating rates where either 10 or 20°C/min. Outinen [26] investigated the effect of heating rates between 10 and 30°C/min on the temperature–strain curve at a low stress level (20 N/mm^2), and the results showed very little difference irrespective of the heating rate. It should also be noted that in this paper, L in the steel designation S690QL stands for the impact energy at a minimum temperature of -40 °C.

5.1 (b) YIELD STRENGTH

Figure 5 shows the reduction factors for the 0.2% proof strength for steels between S650 and S700 whilst Figure 6 shows the same property for steels between S350 and S460. The equivalent factors for the 2% yield strength are shown in Figure 7 (steels between S650 and S700) and Figure 8 (steels between S350 and S460). Also included in the plots are the reduction factors for $f_{p,\theta}$ and $f_{y,\theta}$ from EN 1993-1-2 and $f_{y,\theta}$ from AISC 360-10.

It is clear from Figures 5 and 6 that in many cases the $f_{y,\theta}$ reduction factors are unconservative and the values for $f_{p,\theta}$ are more appropriate, although it is noteworthy that at low temperatures (< 200°C) even the $f_{p,\theta}$ reduction factors are slightly unconservative and do not depict the loss in strength accurately. On the other hand, the reduction factors at 2% strain (i.e. $f_{y,\theta}$ in Figures 7 and 8) showed relatively good agreement with the Eurocode values although in many cases, the code values were rather unconvervative and underestimate the loss in strength that occurs at elevated temperature.

With reference to Figures 5 and 7 (S650 to S700), the reduction factors for S690QL (measured by Qiang [5]) under both steady-state and transient conditions show that this material had poorer strength retention than BISPLATE 80 (S690Q), S700QL and reheated quenched and tempered S690 tested by other authors, especially between 200 and 400°C. At higher temperatures (> 450°C), the reheated, quench and tempered S690Q tested by Chiew *et al* [21] demonstrated the poorest strength retention properties.

It is noteworthy that Outinen *et al* [27] used the nominal yield strength provided by the manufacturer to determine the reduction factors rather than measured experimental values. This is inconsistent with the rest of the published literature and means that these results should be

Table 1 Chemical composition and delivery conditions of steels presented in literature

Author	Minimum yield Strength (N/mm^2)/	Production route	Chemical composition (wt %)														
			C	Mn	Cr	Si	Ni	Cu	N	Mo	Al	Ti	Nb	V	B	S	P
Outinen [27]	700	Quench and tempered	0.169	1.01	0.59	0.316	0.19	-	0.004	0.194	0.044	0.02	0.001	0.01	0.0014	0.0001	0.011
Chen [28]	690	Quench and tempered	0.160	1.10	-	0.20	-	-	-	0.20	-	-	-	-	0.001	0.003	0.01
Qiang [5]	690	Quench and tempered	0.160	0.85	0.35	0.21	0.05	0.03	0.003	0.20	0.093	0.006	0.025	-	0.0024	0.001	0.012
Choi [29]	650	Thermo-mechanically rolled	0.200	3.00	0.80	0.55	2.00	1.50	-	0.60	-	-	-	0.12	-	0.01	0.015
Chiew [21]	690	Reheated - quench and tempered	0.140	1.35	0.01	0.4	0.01	0.01	-	0.12	0.035	0.025	0.035	0.05	0.002	0.003	0.012
Lange [30]	460	Normalised	0.190	1.65	0.03	0.44	0.33	0.03	-	-	-	-	-	0.17	-	-	-
Lange [30]	460	Thermo-mechanically rolled	0.096	1.62	0.055	0.5	0.49	0.026	-	-	-	0.017	0.041	0.098	-	-	-
Qiang [5]	460	Normalised rolled delivery condition	0.172	1.5	0.02	0.483	0.018	0.025	0.005	0.002	0.037	0.002	0.046	0.087	-	0.005	0.012
Outinen * [31]	460	Thermo-mechanically rolled	0.16	1.7	-	0.6	0.45	-	0.025	0.20	0.02	0.05	0.05	0.12	-	0.030	0.035
Outinen [32]	420	Thermo-mechanically rolled	0.120	1.41	-	0.29	0.03	-	-	0.003	0.033	0.003	0.04	0.007	-	0.009	0.012
Outinen [26]	355	Cold - rolled steel sheet	0.080	0.99	-	-	-	-	-	-	-	-	-	-	-	-	0.012
Hu* [33]	350	-	0.230	0.50 to 1.60	0.35	0.40	0.45	0.6 0	-	0.15	-	-	0.15		-	0.045	0.035
Chen [28]	350	-	0.220	1.70	0.30	0.55	0.50	0.40	-	0.35	0.10	0.04	0.03		-	0.030	0.040

* based on maximum values

treated with caution. BISPLATE 80 (S690Q) had the best strength-retention properties from 500-650ºC. Insufficient information on compositions or microstructure was provided in the literature to enable a detailed analysis.

With reference to the steel grades S350 to S460 (Figures 6 and 8), it can be seen that S420M steel tested by Outinen *et al* [34] had the poorest strength retention properties of the materials presented. The sample of S460M tested by Lange *et al* [30] had better strength retention properties compared with other similar steels such as S460M [35], S460N [5, 30] and the values given in EN 1993-1-2 [7]. It is clear from the results presented in Figure 5-8 as well as the data in Table 1 that production route and chemical composition are influential to the material performance at elevated temperature. Solid solution strengthening from elements like molybdenum, along with precipitation hardening such as vanadium carbide play crucial roles in retaining the strength at temperatures up to 650ºC [11, 36]. Insufficient data is available to enable a detailed discussion on the relative performances in Figures 7 and 8 but the range of performances does suggest that good fire performances can be achieved through material design.

In two of the materials presented, XLERPLATE (S350) and HSA800 (S650M), a possible beneficial precipitation hardening effect was seen with a strength increase from ambient to around 300ºC (Figures 7 and 8). These two steels had the highest reported molybdenum content as well as some micro-alloying elements. XLERPLATE (S350) also showed the best strength retention properties above 250ºC out of all the steel grades presented. It is expected that secondary hardening from niobium, vanadium and titanium carbides has contributed to the strength around 500-650ºC but microstructural studies would be necessary for confirmation.

5.2. (c) ULTIMATE TENSILE STRENGTH

Figure 9 illustrates the reduction in the ultimate tensile strength as a function of temperature for HSS, taken from the available literature. As before,

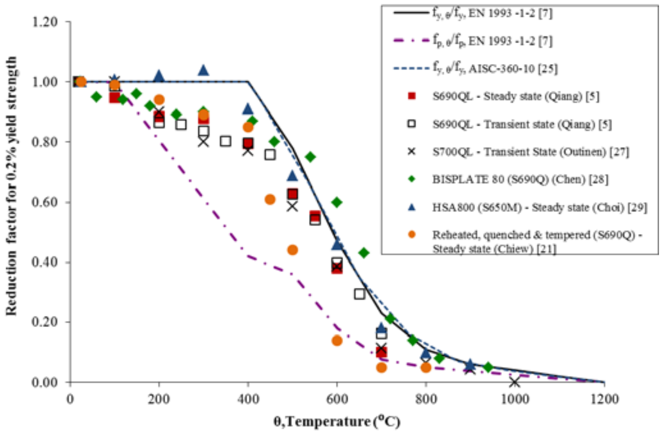

Figure 5 Comparison of reduction factors for 0.2% proof strength for steel grades between S650 and S700

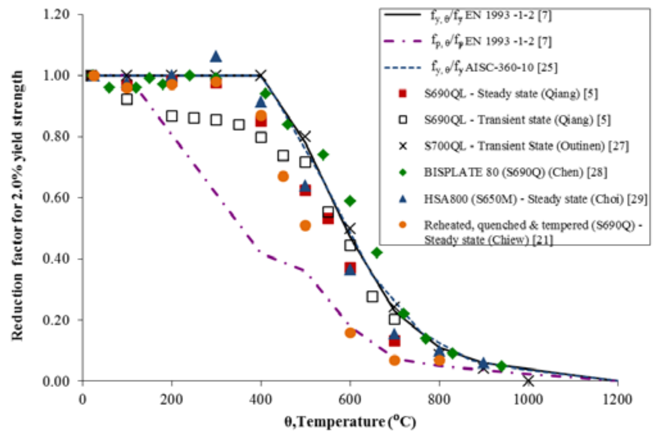

Figure 7 Comparison of reduction factors for 2.0% yield strength for steel grades between S650 and S700

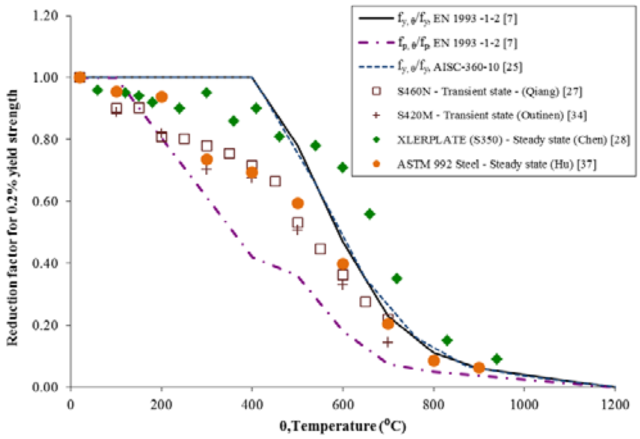

Figure 6 Comparison of reduction factors for 0.2% proof strength for steel grades between S350 and S460

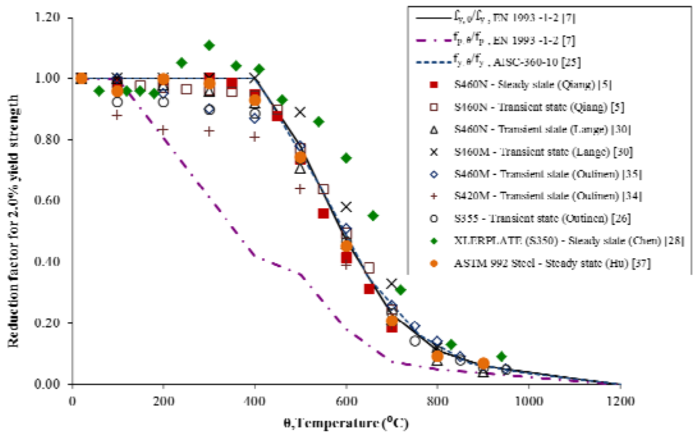

Figure 8 Comparison of reduction factors for 2.0% yield strength for steel grades between S350 and S460

the results are presented as a reduction factor Which normalises the value at elevated temperature to their respective value at ambient temperature ($f_{u,\theta}/f_u$).

The Eurocode [7] does not include reduction factors for $f_{u,\theta}$ whereas in the American Institute of steel [25] gives identical values for $f_{u,\theta}$ and $f_{y,\theta}$ (i.e. effectively the same approach in both codes). This is because these codes assume that the effect of strain hardening at elevated temperatures is negligible and hence the maximum stress level is the yield strength. This is likely only true above 400°C and, for this reason, an alternative stress-strain relationship, which does include strain hardening below 400°C is provided in Annex A of EN 1993-1-2 [7]. It is clear from Figure 9 that almost none of the published data performed as well as the values in AISC 360-10 or EN 1993-1-2. The exceptions to this were BISPLATE 80 between 500 and 950°C and HSA800 (S650M) at approximately 300°C. The reason for the poor relative performance is likely to be because the recommendations in the standards are based on test data from mild steel.

5.2. (d) ELASTIC MODULUS

The elastic modulus is an important material property used to determine the stiffness of a structural element. It is a particularly important property when designing with HSS where serviceability and stability issues may arise. The elastic modulus is determined at various temperatures based on the tangent modulus of the initial linear elastic region of the stress-strain curve. Figures 10 and 11 illustrate reduction factors for the elastic modulus, again normalised by the appropriate value at ambient temperature ($E_{a,\theta}/E$), for steel grades between S650 and S690 and between S350 and S460, respectively, as well as the standardised recommendations. In comparison to the earlier strength plots presented, it is observed that the code values for the elastic modulus reduction factors are generally

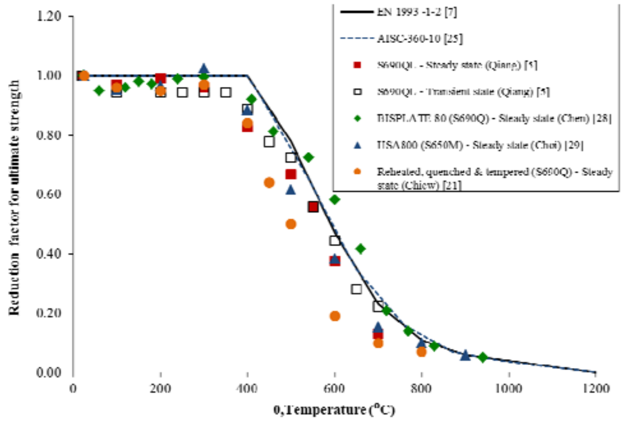

Figure 9 Comparison of reduction factors for ultimate strength

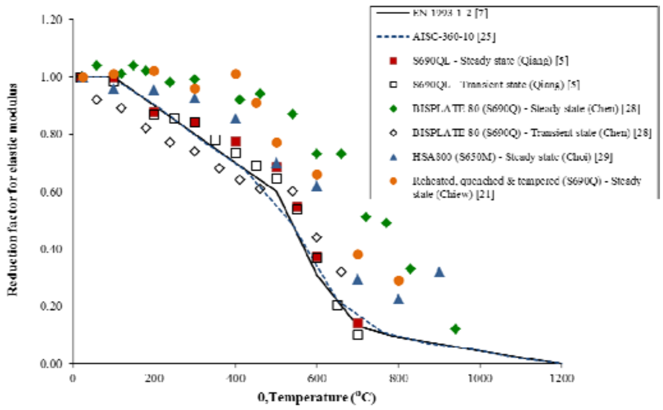

Figure 10 Comparison of reduction factors for elastic modulus for steel grades between S650 and S700

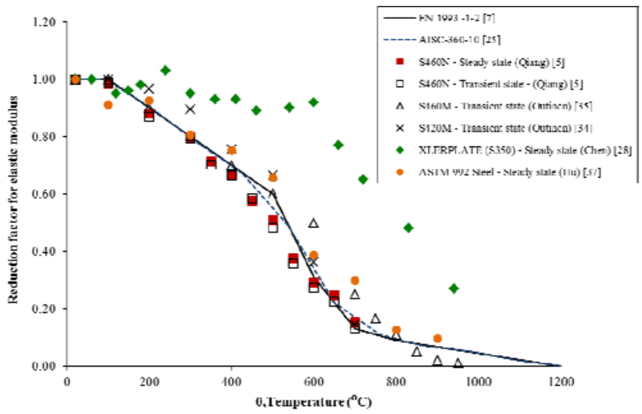

Figure 11 Comparison of reduction factors for elastic modulus for steel grades between S350 and S460

conservative. In particular, the XLERPLATE (S350) material [28] performed significantly better than the standardised values as well as the other materials presented (Figure 11). This steel also performed well in terms of strength as discussed previously.

With reference to Figure 10, the BISPLATE 80 (S690Q) tested by Chen *et al.* [28] showed large discrepancies between the performance during steady- and transient-state testing. On the other hand, the S690QL tested by Qiang [5] showed little difference in the reduction factors obtained between both testing methods. Both reported that the strain rate in the steady-state tests was within the acceptable range (0.005 ± 0.002/min) specified in ASTM Standard E21-09 [19]. In the case of the transient tests, the temperature was varied at a rate representative of a real fire scenario (10^{o}C/min).

It is noteworthy that the reduction factors for elastic modulus given in AISC 360-10 and EN 1993-1-2 demonstrate the more rapid deterioration in stiffness, relative to strength, at relatively low levels of elevated temperature (between 100 and 400^{o}C). This suggests that the failure mode of steel member may change at elevated temperature. For example, a slender steel I-beam designed for plastic-hinge failure at ambient temperature may be more prone to buckling failure at elevated temperature owing to the quicker degradation of stiffness relative to strength with rising temperature.

6. CONCLUSIONS AND FUTURE WORK

This paper has provided an overview of the material behaviour of high strength steels at elevated temperature. A comparison of the reduction factors of various steel grades from the available literature has highlighted that the mechanical properties of HSS at elevated temperatures are directly related to the material composition and the production route employed; both are necessary to ensure adequate strength and stiffness retention properties under fire conditions. Moreover this has highlighted that separate reduction factors for yield strength and elastic modulus may be proposed for different steel grades to maximise the strength and stiffness parameters in design.

The chemical composition and control parameters used by manufacturers of HSS are commercially sensitive information making it difficult to fairly compare their relative performances. Nonetheless, it is clear that the sample of HSA800 (S650M) tested by Choi *et al.* [29] had better strength retention properties at elevated temperatures than other steel grades including the samples of S690QL tested by Qiang [5]. This steel was TMCP and contained molybdenum, vanadium, niobium and titanium. However, in the absence of any detailed microstructural information, it is difficult to comment further on the precise mechanisms leading to this better performance.

It is clear from the literature that research to date has mainly focused on obtaining accurate tensile properties with very limited metallurgical analysis meaning the influence of the microstructural parameters is not clear. As part of the future plans for this wider research project, both steady-state and transient tests from ambient temperature up to 900^{0}C will be conducted on various grades of commercially-available HSS with different alloying combinations and processing routes. The results will contribute towards a database of mechanical properties of HSS at elevated temperature to facilitate a move from prescriptive design to a performance-based approach to structural fire design. The intent is to use the results to suggest appropriate design guidelines for specific HSS grades in structural fire design.

In parallel, a detailed metallurgical investigation will be carried out to characterise the microstructural changes with increasing time and temperature. It is of particular interest to explore which combination of alloying elements and production routes gives an optimum balance between high strength at ambient and elevated temperatures. Moreover, the scope to further develop chemistries and production routes which might slow the loss of strength and stiffness at elevated temperature will be studied.

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