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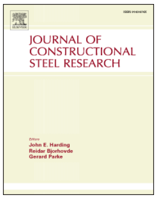

Behaviour of high strength steel columns under fire conditions

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ABSTRACT

With the scarcity of performance data on HSS columns at elevated temperature, a numerical model, which considered geometric imperfections and material non-linearity has been developed in ABAQUS (2014) and validated using experimental data on HSS at ambient temperature and mild steel grades at elevated temperature. After the model was validated, parametric studies incorporating material properties of two different steel grades: S690QL and S700MC were done, in order to determine the influence of the steel grades on the buckling behaviour and assess the suitability of the Eurocode fire resistance design rules for HSS columns. The results showed that the Eurocode generally provides conservative (i.e. safe) results with respect to the buckling coefficients and safely predicts the buckling resistance of columns made from S700MC, while a lower buckling curve may be needed for columns made from S690QL. In addition, because of the various alloying and production routes employed to produce HSS, variations in the stress-strain responses was also observed, in turn, this influenced the buckling response and highlighted possible unconservativisms (i.e. unsafe) in the Eurocode design approach as a result of generalising the material response.

Notation

A	cross-section area of the structural member
A_{eff}	effective cross-sectional area
b	width of the cross-section
h	depth of the cross-section
E_a	elastic modulus
$E_{a,\theta}$	elastic modulus at temperature θ
$E_{0.2}$	tangent modulus at 0.2% proof strength
f_{cr}	elastic critical buckling stress of the most slender constitute plate element in the section
$f_{0.2p,20}$	0.2% proof strength at ambient temperature
$f_{0.2p}$	0.2% proof strength
$f_{p,\theta}$	proportional limit at temperature θ
$f_{1.0p}$	1.0% proof strength
f_y	nominal or design yield strength
$f_{y,20}$	effective yield strength based on 2% total strain at ambient temperature θ (20 °C)
$f_{y,\theta}$	effective yield strength based on 2% total strain at temperature θ
$k_{0.2p,\theta}$	reduction factor for the 0.2% proof strength at steel temperature θ
$k_{y,\theta}$	reduction factor for the effective yield strength at steel temperature θ
$k_{Ea,\theta}$	reduction factor for elastic modulus at steel temperature θ
L	column length
m	strain hardening exponent determined from the points ($f_{0.2p}$, $\varepsilon_{0.2p}$) and ($f_{1.0p}$, $\varepsilon_{1.0p}$).
n	strain hardening exponent
$N_{b,fi,tRd}$	design buckling resistance at time t of a compression member
r_i	internal radius of curvature
t	thickness of cross-section
α	imperfection factor
$\gamma_{M,fi}$	the partial safety factor, for fire situation the recommended value is 1.0
ε	parameter used to determine cross section classification or strain
$\varepsilon_{0.2p}$	total strain at 0.2% proof strength $f_{0.2p}$
$\varepsilon_{1.0p}$	total strain at 1.0% proof strength $f_{1.0p}$
ε_{nom}	engineering strain
ε_{pl}^{ln}	log plastic strain
$\varepsilon_{p,\theta}$	strain at the proportional limit
$\varepsilon_{t,\theta}$	limiting strain for yield strength
$\varepsilon_{y,\theta}$	yield strain
$\varepsilon_{u,\theta}$	strain at ultimate tensile strength
θ	temperature
σ	stress
σ_{nom}	engineering stress
σ_{true}	true stress

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$\overline{\lambda}$	non-dimensional slenderness at ambient temperature
$\overline{\lambda}_\theta$	non-dimensional slenderness at temperature θ
φ_θ	parameter used to calculate χ_{fi}
χ_{fi}	reduction factor for the flexural buckling in the fire
ω_0	local imperfection amplitude

1. Introduction

High strength steels (HSS) are defined herein as steel grades with a yield strength between 460 and 700 N/mm^2 in accordance with Eurocode 3 Part 1–12 [1]. These grades are increasingly being utilised in structural applications, in particular for long span structures and high-rise buildings where there are environmental and economic benefits of using these grades over conventional steel grades (e.g. S355). The benefits of HSS compared with steels with a yield strength below 460 N/mm^2 have been well documented in the literature [2–7]. To summarise, economic savings are gained through the potential reduction in the construction time, as lighter structures can be quicker to erect and require smaller foundations, and the reduction in section sizes results in smaller cross sections to weld and inspect. Additional benefits can be derived from reduced fabrication costs and raw material consumption as well as a reduction in CO_2 emissions and energy use as a result of transporting lighter structural components and processing less material.

There are several documented instances where HSS have been successfully used in structures such as the Taipie 101 Tower in Taiwan and the roof trusses of the Sony centre in Berlin [5, 8]. 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 [9]. In addition the use of HSS in the long span Oresund bridge between Sweden and Denmark resulted in cost savings more than €22 million [8].

Despite their increasing popularity, one of the main barriers to more widespread use of HSS in construction is a lack of usable design information which allows designers to fully harness their advantages. In this context, and owing to the ever-increasing demands for more sustainable construction, there has been an increase in research activity on the subject of HSS structures in recent years including major European collaborative projects [10, 11], as well as studies into beams [12], columns [13, 14] and also different extreme loading scenarios [15–17].

In the case of a fire, structures should meet the legal requirements for fire resistance (i.e. the ability of a structure to maintain its function for a prescribed amount of time in a fire [18]), and this involves having an understanding of how structural elements perform in such an event. There is a considerable amount of information in the literature on the buckling behaviour of steels with a yield strength below 460 N/mm^{2}at elevated temperatures (e.g. [19–28]). Most of this work, which includes experiments and numerical modelling, has contributed towards the current structural fire design guidelines given in Eurocode 3 Part 1–2 [29]. Although the Eurocode was derived from data on steels with yield strengths <460 N/mm^2, these guidelines are currently applicable to HSS with no additional design comments. Further research is necessary to assess the applicability of these design rules, specifically to ensure that the standards are reliable and economical. To date, there are very limited performance data and studies on the buckling behaviour of HSS columns under fire conditions [30–32], mainly owing to the significant expense associated with high temperature structural testing as well as the lack of reliable material properties which are needed for analysis and design [33].

In this paper, a numerical study is carried out to investigate the structural performance and design of HSS columns for fire conditions. The paper proceeds with a discussion on the metallurgical characteristics, in particular the strengthening mechanisms employed, and the various production routes used to produce HSS and will also comment on how these are affected by temperature. The various mathematical representations of the stress-strain response are described and the modified Ramberg-Osgood model proposed by Gardner and Nethercot [34] is used to characterise the stress-strain response of S690QL and S700MC at elevated temperatures, obtained from a previous study [35]. Results from that experimental study showed that S700MC has better strength retention properties than S690QL at temperatures up to 800 °C, mainly owing to the alloying content and production route of these steels. S700MC is thermomechanically control processed (M) and suitable for cold forming (C), whilst S690QL is quench and tempered (Q) and meets the minimum impact energy of 30 J at −40 °C (L). Finally, the general purpose finite element analysis software ABAQUS [36] is used to develop and validate numerical models for predicting the ultimate loads of the columns at ambient and elevated temperatures. A parametric study is then conducted, which incorporates the elevated temperature stress-strain relationships of S690QL and S700MC. The aim of this study is to generate data on the structural performance of Class 1 and Class 3 columns made from these steel grades at temperatures up to 800 °C and assess the suitability of the Eurocode buckling curves [29] for HSS columns in fire conditions.

2. Material and metallurgical properties of high strength steels

2.1. Strengthening mechanisms

There are a number of different strengthening mechanisms used to make high strength steels. Most of these involve restricting or reducing the movement of metallographic imperfections known as dislocations through the material. Plastic deformation is due to the movement of these dislocations and so, by restricting their mobility, the dislocations require more stress to move, resulting in an increase in yield strength. 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 grades of HSS are typically strengthened through a combination of mechanisms rather than just one isolated approach. The most commonly employed of these strengthening mechanisms, as well as how they are affected by elevated temperature, are summarised as:

- *Grain refinement*: the process of producing a microstructure with fine grains which, in turn, results in more grain boundaries. In general, between 400 and 700 °C, grain growth occurs which reduces the amount of grain boundaries. However, it has been shown that the yield strength becomes almost independent of grain size at temperatures above 600 ± 50 °C [37].
- *Solid solution strengthening*: by distorting the iron crystal lattice, the movement of dislocations is reduced resulting in an increase in yield strength. It has been shown [38] that solid solution strengthening does not adversely affect the ductility and is largely unaffected by temperature.
- *Precipitation hardening*: this method 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. Chromium, molybdenum, niobium, vanadium, tungsten and titanium carbonitrides used in steel form at about 500–650 °C [39] and, hence, precipitation hardening is a useful strengthening mechanism at elevated temperature [38].
- *Strain hardening*: this is when dislocations are introduced into the crystal lattice through plastic strain. Since dislocations are obstacles to each other, an increase in the dislocation density leads to an increase in strength. 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 [40].