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Numerical modelling of high strength steel beams at elevated temperature

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ABSTRACT

High strength steels are increasingly common in structural engineering applications owing to their favourable strength to weight ratio, excellent sustainability credentials and attractive physical and mechanical properties. However, these grades are under-used in structures owing to a lack of reliable information relating to their structural performance, particularly at elevated temperature. This paper presents a review of high strength steels in structural applications including the key design considerations. Particular focus is given to the lateral torsional buckling response of laterally unrestrained beams. A finite element model is developed to investigate this behaviour at ambient and elevated temperature. A series of beams between 500 and 4500 mm in length are studied in order to develop buckling curves which are comparable with current design provisions. At ambient temperature, it is shown that all of the buckling curves currently included in Eurocode 3 Part 1-1 give unsatisfactory and potentially unsafe predictions. In elevated temperature conditions, the buckling curves presented in Eurocode 3 Part 1–2 depict the behaviour reasonably well but, at relatively high slenderness values, the standard does not always provide a safe prediction. Revised bucking curves are proposed for high strength steel beams for laterally unrestrained beams made from high strength steel.

1. Introduction

High strength steels (HSS) are defined as materials with a nominal yield strength of 460 N/mm^2 or above. They have been increasingly used in recent years due to their high strength-to-weight ratio and efficiency. When employed in appropriate applications, HSS can offer environmental benefits owing to the reduced material usage which also leads to aesthetic advantages as architects and designers tend to favour lean and unobtrusive structural elements. Besides these advantages when compared with ordinary steel, the main disadvantages of HSS include the greater initial cost and the high yield strength to Young's modulus ratio which can lead to stability issues, as well as more limited deformation capacity.

The most important feature of HSS for structural design is the high strength-to-weight ratio, which leads to smaller section sizes for similar load capacities compared with using ordinary mild steel. This helps to reduce the dead load acting on the structure and allows long spans to be achieved. A lighter structure requires smaller foundations as well as shorter transportation and construction times. Hence, HSS can offer a very economically efficient solution when used in appropriate applications. In addition to cost advantages, the reduction in material weight requirements also lead to reduced CO$_2$ emissions and energy use both in terms of steel production and transportation.

An excellent example of an appropriate application for HSS is the Friends Arena Stadium in Solna, Sweden, which was built using grade S690 HSS. This led to savings of 15% in weight and €2.2 million in cost compared with using S355 steel [1,2]. Another example is the Oresund Bridge between Sweden and Denmark which saved €22 million by using HSS rather than mild steel for some components [1,3]. As mentioned before, aesthetic considerations and environmental efficiency are further reasons for using HSS since the thin and lightweight elements are architecturally desirable.

The main concern which engineers must consider when specifying HSS in structural components is the increased likelihood of stability problems when compressive stresses are present. HSS has a higher yield strength compared with mild steel but a similar Young's modulus, which can lead to serviceability and stability issues owing to the limited deformation capacity of HSS. Even if the overall buckling strengths of high strength steel elements are improved when compared with the ordinary steel elements on a non-dimensional basis, buckling is still the major problem for HSS elements because of the higher yield ratios. For loading conditions causing inelastic deformations, such as fire and earthquake, this high yield ratio and limited deformation capacity can be particularly important. Moreover, as stated before, HSS sections tend to be thinner than ordinary steel sections, for the same load-carrying capacity, and hence are more likely to experience buckling.

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In fire conditions, unprotected steel members experience a loss of strength and stiffness with increasing temperature owing to the rapid temperature development in the structural members which is exacerbated by the high thermal conductivity of steel and high surface area to volume ratio of the section. Thus, recent years have seen an increase in research activity in the area of fire engineering for steel structures, especially after high profile events such as the collapse of the World Trade Centre towers in 2001. Although the design of normal steel structural members at room and elevated temperatures is well known, there is lack of information about the design of high strength steel structures at elevated temperatures.

Therefore, it is important and necessary to investigate the behaviour of high strength steel structural elements under elevated temperature conditions. Whilst some researchers have investigated the response of HSS structural members, the focus has mainly been given to the ambient temperature behaviour, particularly on subjects such as material characteristics (e.g. [4–7]), residual stresses (e.g. [4–7]), flexural buckling (e.g. [4,8,9]), local buckling (e.g. [5,6]) and beam behaviour (e.g. [6,7,10]). The behaviour of HSS members under fire conditions has received considerably less attention until recently. Previous studies have mainly focussed on the material properties at elevated temperature (e.g. [11–15]), column behaviour [16] and connections [15] with little attention given to beams.

In this context, the current paper is concerned with the behaviour of HSS beams during fire conditions. These elements can be susceptible to lateral torsional buckling (LTB) if sufficient lateral restraint is not provided. The LTB behaviour of normal strength steel beams both at ambient and elevated temperature is well understood and incorporated into design codes (e.g. [17,18]). However, HSS beams have not received the same amount of attention in terms of their lateral-torsional buckling resistance under fire conditions, mainly as they are still quite a novel construction form. It is only in recent years, when the demand for buildings to be environmentally and economically sustainable has continued to grow, that HSS has really become an attractive solution.

Despite the different mechanical properties of high strength and normal strength steels, including their response to elevated temperature, the Eurocode design approach is identical, including in fire conditions. In this context, the aim of the current study is to investigate the lateral-torsional buckling behaviour of HSS beams with a yield strength of 690 N/mm^2 at elevated temperatures. Numerical simulations are performed on high strength steel beams with different buckling lengths under fire conditions using the materially and geometric non-linear finite element analysis software ABAQUS [19]. The results obtained from the numerical analyses are validated against available test data and then compared with the Eurocode predictions [18] to assess the applicability of current design specification for laterally unrestrained HSS beams in fire conditions.

2. High strength steel in structures

2.1. Strengthening mechanisms

The key to strengthening steel is to restrict or reduce the movement of metallographic imperfections known as dislocations through the material [1]. Inelastic deformations are due to the movement of these dislocations. Therefore, by restricting their mobility, the dislocations require more stress to move through the iron crystal lattice resulting in an increase in yield strength [20]. The movement of dislocations can be reduced 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 discontinuities.

Commercial HSS typically achieves this through a combination of strengthening mechanisms. These include:

- Grain refinement - the process of producing a microstructure with fine grains which, in turn, results in more grain boundaries. Fine grains lead to an increase in yield strength because the greater number of grain boundaries tends to relax the movement of dislocations through the material.
- Solid solution strengthening –when the movement of dislocations is slowed through active distortion of the iron crystal lattice.
- Precipitation hardening – increasing the strength due to the precipitates directly obstructing the motion of dislocations as opposed to indirectly through distorting the iron crystal lattice as in solid solution strengthening.
- Strain hardening – introduction of dislocations into the crystal lattice through plastic strain.

2.2. Production routes for HSS

There are a number of different production routes for HSS materials using a variety of heat treatments and rolling procedures to achieve the most desirable properties for a particular application. The addition of alloying elements such as carbon or niobium can add substantial strength also. HSS is traditionally hot rolled in the austenitic region which is typically above 900 ºC. The steel is then cooled at a specific rate to achieve the desired mechanical properties [1].

The structural steel grades in Europe (e.g. S355N, S460Q, etc.) are generally 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. More information on these processes is available elsewhere [1].

2.3. Material properties of HSS at ambient temperature

For high strength structural steels with a yield strength greater than 460 N/mm^2, the quench and tempering heat treatment method is the most common production process employed. The European material standard for hot-rolled structural steel [21] includes seven different HSS quench and tempered (Q) grades, namely S460Q, S500Q, S550Q, S620Q, S690Q, S890Q and S960Q. The current study focusses on the quenched and tempered HSS grade S690Q which is selected because it is the highest strength grade currently included in Eurocode 3 and is

Table 1
Chemical composition for quenched and tempered steels [21].

Grade	C % max	Si % max	Mn % max	P % max	S % max	N % max	B % max	Cr % max	Cu % max	Mo % max	Nb % max *	Ni % max	Ti % max *	V % max *	Zr % max *
S690Q	0.2	0.8	1.7	0.03	0.02	0.02	0.005 0	1.5	0.5	0.7	0.06	2	0.05	0.12	0.15

*Depending on the thickness of the product and the manufacturing conditions, the manufacturer may add one or several alloying elements up to the maximum values given in order to obtain the specified properties.