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Response of high-strength steel beam and single-storey frame in fire: Numerical simulation

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A B S T R A C T

The design principles for high strength steel (HSS) structures exposed to fire are under development. In this paper, the response of HSS structures in fire is studied through numerical simulation of a beam and a two-bay frame. Geometrical imperfections and residual stresses are introduced into the structural models. Deformation limit criteria are used to compare the critical temperatures of the structures made of HSS and mild steel. The comparisons show that HSS structures have higher strength reserve than mild steel structures. Using the mechanical properties at elevated temperatures from literature sources, it is observed that the deflection behaviour of the studied structures depends on the ratio of strength to elastic modulus. The deflection of the studied beam is sensitive to yield strength reduction factors as the beam fails by plastic hinge mechanism. Whereas, the deflection of the HSS frame is sensitive to the reduction factors of the elastic modulus as the frame fails by inelastic instability. The above-mentioned observations on the studied structures are made using a three-stage mechanism which is developed for interpreting the deformation response.

1. Introduction

High strength steel (HSS) has gained popularity in recent years due to its possible applications in the construction industry. Its high strength-to-weight ratio encourages in designing structures with long spans or reduced cross-sections. The comparatively light structure of HSS leads to savings in transportation costs. Slim structures are less obstructive and aesthetically pleasing as well. Despite the obvious advantages, there are certain hurdles regarding structural fire safety design using HSS. The long span structures leading to open space design change the fire exposure. For the available HSS, the elastic modulus is nearly the same as mild steel while the yield strength is twice or more, therefore there is a limitation on the serviceability limit state design. These issues require revision and renewing of the current structural fire safety design (FSD) method. Performance-based FSD takes into account different fire scenarios and complex structural material properties in order to study the structural performance close to reality ([1–3]). The present work particularly focusses on the effect of HSS material properties on the response of structures.

The degradation of mechanical properties of carbon steel at elevated temperature is presented in EN 1993-1-2 [4]. The applicability of the temperature dependent reduction factors has been extended from S460 to S700 grade steel in EN 1993-1-12 [5]. Since the reduction factors in EN 1993-1-2 are provided through research and tests on mild steel (below S460), the advantage offered by the increased strength of HSS is not fully reflected in these reduction factors. Therefore, material tests to obtain the mechanical properties of HSS have been carried out in recent years ([6–13]). Transient and steady state tensile tests were carried out for determining the mechanical properties of S700QL (quenched and low temperature toughened) at elevated temperatures in 2014 by Outinen et al. [6]. The heating rate of 20 °C/min was used for both testing methods. The stress levels used for S700 in transient tests were 30, 45, 60, 80, 120, 170, 230, 280, 350, 420, 490, 560, 630, and 700 N/mm^2. The temperature levels used for S700 in steady state tests were 20, 500, 600, and 700 °C. Yield strength values from tests are taken corresponding to 0.2 and 2% strain offset. Due to limited number of test specimens, the elastic modulus was not measured. The steel used in the tests fulfilled the criteria of the delivery conditions for quenched and tempered steel according to EN 10025-6 [14].The reduction factors of effective yield strength at 2% strain offset obtained from transient and steady-state tests are shown in Fig. 1.

Mechanical properties of steel grades close to nominal yield strength of 700 N/mm^2 at elevated temperatures from different research groups (Outinen et al. [6], Qiang et al. [11], Chen et al. [10], and Chiew et al. [12]) are selected for the current study. Maraveas et al. [15] proposed two equations for the reduction factors which takes into account the available material properties of steels having average yield strength ranging from 510 N/mm^2 to 1300 N/mm^2. One of the proposed equations has been selected for the current study. The reduction factors of yield strength and modulus of elasticity from some of the above-mentioned

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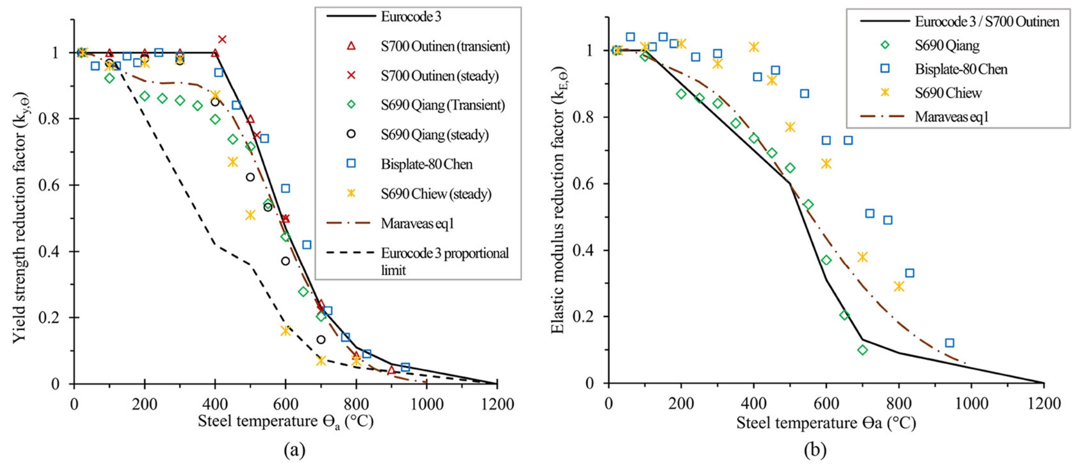

Fig. 1. Comparisons of temperature dependent mechanical properties from literature to EN 1993-1-2 (a) Reduction factors for yield strength (b) reduction factors for modulus of elasticity.

literature are compared with those from EN 1993-1-2 in Fig. 1 (a) and (b), respectively. The yield strength reduction factors are taken at 2% strain offset values for all literatures. Chen et al. [10] did not provide clear information about the test method used for the reduction factors provided by them. Proportional limit reduction factors are also provided by EN 1993-1-2 (Fig. 1), but there is little data available in the literature sources.

The reduction factors of HSS obtained through tensile tests at elevated temperature from above mentioned literature show considerable variations when compared to EN 1993-1-2 reduction factors (Fig. 1). The comparisons show that the results from Outinen et al. [6] (hereafter as Outinen-model) are very close to EN 1993-1-2 values for both yield strength and modulus of elasticity. The yield strength values provided by Qiang et al. [11] (hereafter as Qiang-model) are lower, and the values of modulus of elasticity are close to EN 1993-1-2 values. On the other hand, the values of yield strength provided by Chen [10] (hereafter as Chen-model) are close to those of EN 1993-1-2 but modulus of elasticity values are considerably higher. For the results from Chiew's tests [12] (hereafter as Chiew-model), the yield strength values are lower, while the values of modulus of elasticity are considerably higher than EN 1993-1-2 values. The yield strength is close to the proportional limit after 600 °C. Maraveas et al. [15] (hereafter as Maraveas eq1) has values which lie roughly at the middle of the scatter of the reduction factors of the literature sources. Li [16] has measured the modulus of elasticity of several high strength steels at elevated temperatures using both static and dynamic methods and the results show that the reduction factors provided by current EN 1993-1-2 are overly conservative. Therefore, EN 1993-1-2 provided material properties of HSS at elevated temperature could be further revised taking into account the observed variations from recent tests.

Using the available mechanical properties of HSS at elevated temperature, studies on structural behaviour have been carried out. Varol and Cashell [17] studied the buckling response of S690 grade steel beam at high temperatures using EN 1993-1-2 reduction factors and concluded that buckling curves provided in EN 1993-1-2 are not always safe. HSS connection behaviour [18] and column behaviour [19] [20] at elevated temperature was also studied recently. Elevated temperature behaviour of HSS frames was studied by Shakil et al. [21] in which recent material data from literature was used for material modelling. The studies highlighted the deviations of mechanical properties observed in recent HSS material tests and concluded that the use of reduction factors provided in EN 1993-1-2 for material modelling for HSS frames may lead to underestimation of critical temperatures. Further confirmation studies are therefore necessary, especially dealing with the effect of variations of measured mechanical properties on the deformation behaviour of HSS structures.

In the present study, a 3D finite element (FE) model considering both material and geometrical non-linearity is created firstly for a beam structure with available test results. For the material modelling, stress-strain curves formulation given in EN 1993-1-2 is selected, and then the temperature dependency is introduced with the help of reduction factors. An explicit FE analysis procedure is selected based on the non-linear nature of the problem. The FE modelling is validated against the test values of the selected mild steel beam structure from literature. The possibilities of extending the validated FE modelling of mild steel beam to HSS beam is then studied. After that, the sensitivity of the response for the scattering of the mechanical properties of HSS observed in literature on the behaviour of beams are investigated. Furthermore, similar studies are then extended to the steel frame structure. The study highlights the suitability of the reduction factors provided by EN 1993-1-2 for HSS structural applications. Both geometrical imperfections and residual stresses are considered in creating FE models to study the behaviour of beam and frame structures. The benchmark tests to validate FE models have been performed on steel beams and steel frames, and the studies of this paper focus on the effects of scattering of mechanical properties on the structural response. Therefore, the temperature gradient inside the steel beam due to floor effects has not been taken into account.

2. FE modelling for analysis

Abaqus software version 6.13-3 [22] and its explicit procedure has been selected for numerical simulation. The explicit procedure is preferred in order to avoid convergence issues with non-linear problems with large deformation. Quasi-static events can be simulated using the explicit dynamic solver, which is computationally efficient compared to implicit solvers.

2.1. Structure and meshing

Rubert and Schaumann [23] have performed elevated temperature tests for the beam structure with normal rolled sections. Extensive details of these tests have been provided by the authors in their paper and the results have been widely used by other researchers for validation studies [24–27]. The setup of the beam test and the dimensions of the beam profile (IPE 80) is shown in Fig. 2. The measured yield strength of 399 N/mm^2, i.e. $\sigma_y = 399$ N/mm^2, is provided for the steel beam. In these tests, mechanical load (F) is applied at the center of the beam and is kept constant throughout the experiment. The temperature of the beam is increased uniformly until the beam deforms up to a certain limit. Three different heating rates are used in the tests, and they are intended to simulate the heating of the beam with or without fire