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Elevated temperature mechanical properties of solid section structural steel

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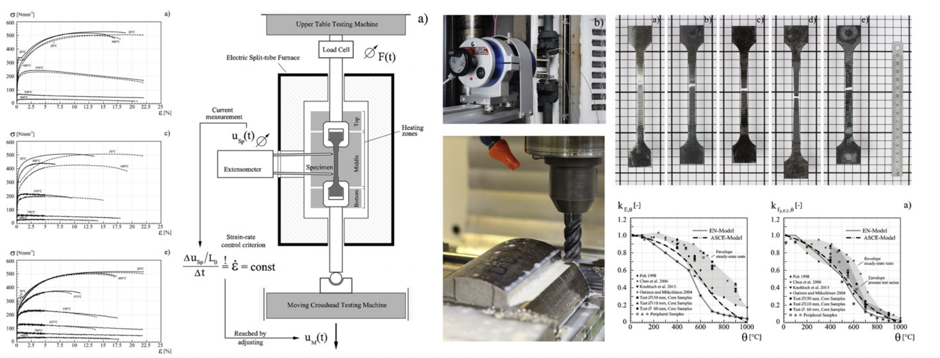
HIGHLIGHTS

- Extensive closed-loop strain-rate controlled tensile tests of solid section steels.
- Novel and accurate temperature-dependent data for advanced structural fire design.
- Novel investigation on temperature-dependence of inhomogeneities of YS and UTS.
- Inhomogeneities in YS and UTS in solid sections vanish with increasing temperature.
- Inhomogeneities in YS and UTS in thick as-rolled solid sections less significant.
- Existing code models also suitable to predict degradation of solid section steels.

GRAPHICAL ABSTRACT



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ABSTRACT

In structural fire design thick solid steel sections are often used for steel columns without fire protection or more recently in innovative composite column systems as for example concrete-filled steel tube columns with solid steel core. The data in the literature on the mechanical properties of commercially available solid section mild carbon steel used in structural fire engineering is scarce and limited to investigations at ambient temperature, showing high inhomogeneity in the yield strength between peripheral and core material, especially in the as hot-rolled condition. This paper presents the results of an extensive series of closed-loop strain-rate controlled tensile tests, performed at elevated temperatures of 400, 475, 550, 626, 700 and 900 °C under steady-state conditions and at ambient temperature with coupon specimens of core and peripheral material of commercially available mild carbon steel from round solid sections of various diameters. The resulting temperature-dependent relations for the yield strength and ultimate tensile strength (1) indicate for normalised small sections and as hot-rolled thick sections only a moderate difference between core and peripheral material that vanishes with increasing temperatures, and (2) can be predicted reasonably well by the European and North American design code models for structural steels at elevated temperature.

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1. Introduction

Solid steel sections are often used in structural fire engineering design as steel columns without special fire protection or in novel composite column systems as e.g. concrete-filled steel tube columns with solid steel core. These innovative composite columns are increasingly used in high-rise building practice because of their high load-bearing capacity and exceptional structural fire behaviour. Combined experimental and numerical studies [1–5] have shown that high fire resistances can be achieved with these columns, because the concrete infill substantially retards that the steel core reaches the range of critical temperatures where marked degradation of stiffness and strength sets in. The solid steel core is therefore the principal structural component that assures during a fire the global stability and strength of the entire composite column. In summary it follows that it is crucial for structural fire engineering design, to have a thorough understanding of the elevated-temperature constitutive behaviour of solid section structural steels in the range of critical temperatures.

Studies on the structural fire behaviour of unprotected solid section steel columns in the 1980's by Kordina and Klingsch [6] showed however a significant influence of the manufacturing process on the fire resistance. Columns in the as hot-rolled condition failed prematurely compared to forged columns. This behaviour was related to the potential inhomogeneity in the yield strength distribution over the thickness of the cross-section and residual stresses arising in the cooling phase after hot-rolling. In the case of core material from solid sections in the as hot-rolled condition, tensile tests at ambient temperature revealed yield strength values significantly below the required minimum by the grading of the steel, whereas in the case of forged solid sections the yield strength was constant over the entire thickness of the cross-section and met with the requirements of the steel grading [7]. Also, numerical investigations of Ref. [8] showed that substantial residual compressive stresses develop in the peripheral parts of solid steel sections during the cooling phase after hot-rolling.

To account for production related inhomogeneity in the material, the characteristic value of the yield strength of structural steel is reduced in current European design practice with respect to the thickness of the structural element and the steel product type [9]. Based on the steel's yield strength at ambient temperature, the temperature-dependence of the mechanical properties of a structural steel and its stress–strain relationships at elevated temperatures can be considered according to the models given in Eurocode 3 for example [10]. For solid steel sections, used in structural fire engineering designs usually in the as hot-rolled condition, these rules to establish the temperature-dependent constitutive behaviour are equally applicable. However, this approach remains afflicted with uncertainty, considering the available test data at ambient temperature [6]. In view of the scarcity of this data and its possible outdatedness due to technological advances in the steel production as well as the lack of corresponding experimental investigations at elevated temperatures, there is room for a test program on the elevated-temperature mechanical properties of today's commercially available solid section structural steel. The objectives of the test program are: (1) to establish novel temperature-dependent constitutive data for advanced numerical modelling in structural fire engineering, and (2) to provide a principal investigation on the temperature-dependence of the potential inhomogeneity in the mechanical properties in solid sections, in order to assess the relevance of this question for structural fire engineering practice.

This paper presents the results of an extensive tensile test program at various elevated temperatures with commercially available grade S355 steel specimens, extracted from the peripheral and core material of round solid sections of three different diameters, used in full-scale fire test specimens of concrete-filled steel tube columns with solid steel core [2]. The paper is divided into two main parts. In the first part (Section 2), the relevant details of the experimental program are outlined, by specifying the test material, the specimen fabrication, the test apparatus and procedure, as well as the methods used to evaluate the raw test data. In the second part (Section 3), the results are presented and discussed by comparing the derived temperature-dependent mechanical properties to the predictions of the currently used European and North American design code models and to available test series from the literature. Moreover, possible influences of the applied test method on the resulting mechanical properties are discussed in this comparison. Finally, specific characteristics of the elevated-temperature stress–strain response are related to available literature on the influence of the chemical composition and of the heat treatment on the mechanical behaviour.

2. Experimental program

The test program performed within the framework of the present study, consisted of a series of strain-rate controlled steady-state tensile tests at elevated temperatures of 400, 475, 550, 625, 700 and 900 °C to provide novel elevated-temperature constitutive data of solid section structural steel for advanced numerical analysis in structural fire engineering. The tensile tests were performed with coupon specimens from core and peripheral material of three different commercially available round solid sections with diameters of 60, 110 and 150 mm respectively, in order to examine the temperature-dependence of the potential material inhomogeneity in the mechanical properties of solid steel sections. At every temperature level, the tensile tests were repeated three times with both peripheral and core samples.

2.1. Test method

In the literature there are two generally accepted test methods to determine the elevated-temperature mechanical properties of steel for use in structural fire engineering design: (1) The total deformation test (force controlled), during which the specimen deformation is continuously recorded as it is held under a constant load and simultaneously exposed to increasing temperature at a given rate until failure; and (2) The tensile test at elevated temperature (strain-rate controlled), where the unloaded specimen is first heated to target temperature and then strained until failure, while keeping the temperature constant. In the commonly adopted nomenclature of Anderberg [11], the total deformation test belongs to the transient-state tests and the tensile test at elevated temperature to the steady-state tests, where steady or transient refer to the heating conditions.

The transient test method is often regarded to give more realistic mechanical property data for use in structural fire engineering design, since the steel specimen is tested under conditions similar to those experienced by steelwork when exposed to a fire [12,13]. The stress–strain curves at elevated temperatures, derived from the total strain–temperature curves of the total deformation tests at various load levels, implicitly contain (after deduction of the thermal expansion determined from a reference test with an unloaded specimen) creep strains or high-temperature creep strains. When the heating rate in the transient tests is similar to a mean heating rate of a structural steel member exposed to fire, then these stress–strain lines are an invaluable simplification for the structural analysis with beam theory of steel structures exposed to fire, where temperature gradients within the cross-sections need not to be considered. This concept of implicitly considering high-temperature creep effects is also contained in the