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Influence of the strain-rate on the mechanical properties of mild carbon steel at elevated temperatures

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ABSTRACT

This paper presents an experimental study on the influence of the temperature and especially the strain rate on the stress–strain relationship of mild carbon steel with regard to fire conditions. The study shows that the level of strain rate has a marked effect on the material behaviour at elevated temperatures. An accurate prediction of the elevated temperature material stress–strain response is a key factor for an appropriate assessment of the structural fire resistance in engineering practise. The material characteristics of mild carbon steel at elevated temperatures differ from those at ambient temperature. Under fire conditions, the strength and stiffness reduce with increasing temperature, the clearly defined yield point and the pronounced yield plateau – characteristically for mild carbon steel at ambient temperature – vanish and the stress–strain curve becomes distinctly nonlinear. Many material test series performed in recent years did not specifically focus on the influence of strain or heating rates on mechanical properties at elevated temperatures. Therefore an experimental study focusing on the influence of the strain rate was performed.

On the basis of the presented test results, a comparative study has also been performed. It has been found that the reduction factors for material properties given in current European and American fire design rules fit quite well for high strain rates (short fire duration times) but do slightly overestimate the material properties for low levels of strain rate (long fire duration times). Finally the test results are compared to existing stress–strain models. The study revealed that a description of the stress–strain relationship by means of an adapted exponential (similar to the Ramberg–Osgood model) formulation is able to model the stress–strain relationship for fire design.

1. Introduction

Accurate material properties are essential for structural fire design methods. Under fire conditions, the strength and stiffness of steel reduce with increasing temperature. Additionally, the clearly defined yield point and the pronounced yield plateau of mild structural carbon steel at ambient temperature vanish and the stress–strain relationship becomes distinctly nonlinear. Thus, traditional structural design concepts adapted from ambient temperature design considering the initial stiffness and the yield stress are inappropriate. Moreover, the shape of the nonlinear stress–strain curve has an important effect on the structural stability behaviour like global [1] and local buckling [2]. The concept of "effective yield stress" [3], typically used in structural fire engineering, which cuts of the stress–strain curve for a certain strain level for simplification, is often not sufficiently accurate for modelling the structural behaviour in fire. In addition to the deterioration of mechanical properties in fire, thermal creep may become significant in design for temperatures above approximately 400 °C and is affected by the stress level and fire exposure time.

Mechanical properties of steel under fire conditions are normally analysed with tensile material coupon tests either with steady-state or transient-state conditions using an electric furnace [4]. In steady-state tests the specimens are heated to the target temperature and mechanical load is applied as soon as the temperature of the specimen has been stabilized. In transient-state tests a constant load is applied to the test specimen and the temperature is then gradually increased.

Under fire conditions structural steel elements experience a temperature and relative stress increase which both vary with fire duration. In steady-state tests the strain and in transient tests the heating rate have a distinct effect on the test results. Therefore, the modelling of the structural fire behaviour or of fire tests requires mechanical properties which were determined in a way that is consistent with the anticipated fire exposure or failure time in tests. Many steady state and transient state test series – performed on mild (e.g. [5,6]), high-strength (e.g. [7–10]), and cold-formed steel (e.g. [11,12]) – as well as creep [13] and stress relaxation test series [14] performed in recent years did not specifically study the influence of strain or heating rates

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on mechanical properties at elevated temperatures nor were appropriate strain and heating rates studied with regard to typical fire situations. However, Poh [15] performed steady-state tests with strain rates of $3.33 \times 10-5$/s (0.20%/min) and $8.00 \times 10-4$/s (4.80%/min). Thus, 600 s (10 min) and 25 s, respectively, were required to reach a total strain level of 2% which is often used as the strain level to define the "effective yield strength" in fire design [16]. However, a comprehensive comparative study which focuses on the influence of the strain rate on the mechanical properties of steel for fire design has not been performed so far.

The paper first presents a comprehensive experimental study on the influence of the strain rate on the material properties of steel. The experimental analysis focused on steady-state temperature conditions. Therefore, the influence of the heating rate on the elevated temperature stress–strain response is not studied. Then, the test results are compared to results of steady-state tensile material coupon tests given in the literature [15] and to current European and American fire design rules. Finally, a comparative study considering common analytical material models for nonlinear behaviour is performed and an adapted model is derived from the test results.

2. Experimental study

2.1. Test programme and specimens

Material coupon tests were carried out to determine the elevated temperature stress–strain response of carbon steel at specified and controllable strain rates. In addition to the overall stress–strain relationship, the mechanical parameters, in particular modulus of elasticity $E0,_{\theta}$, proportional limit $fp,_{\theta}$, 0.2%-proof stress $fp0.2,_{\theta}$ and effective yield strength $fx,_{\theta}$ at defined strain levels were obtained from test results. Thus, closed-loop strain controlled steady-state both compressive and tensile material coupon tests were performed at ETH Zürich in conjunction with a structural furnace test series on stub and slender columns and beam-columns with three different cross-sections (hot-finished square hollow sections SHS 160·160·5, rectangular hollow sections RHS 120·60·3.6 and hot-rolled wide-flange section HEA 100) of steel grade S355 (minimum yield stress of 355 N/mm2). Table 1 gives a summary of the test programme of the material coupon tests. Details of the test series are given in [17].

2.1.1. Compressive tests

The test series M5 and M6 comprised test specimens of the SHS 160·160·5 and the RHS 120·60·3.6 material and were conducted as compressive tests at the Institute of Virtual Manufacturing at ETH Zürich. The ambient temperature and steady-state tests at 400 °C, 550 °C and 700 °C were executed with constant levels of strain rate of 0.01/s (60%/min), 0.05/s (300%/min) and 0.25/s (1500%/min). These strain rates were chosen according to the capacity of the test setup, correspond to typical very high strain rates used for metal forming and are much higher than common strain rates in fire design practise. Each test was repeated three to five times to obtain a redundancy of the data.

Table 1
Material coupon test series [17].

Test series[a]	Cross-section	Material coupon tests		Strain rates		Time duration to reach 2% strain		Temperatures (°C)
				(10^{-5}/s)	(%/min)	(s)	(min)	
M5	Square hollow section SHS 160·160·5	Compressive test	Steady-state	1000, 5000, 25000	60, 300, 1500	2, 0.4, 0.08	0.033, 0.0067, 0.0013	20, 400, 550, 700
M6	Rectangular hollow section RHS 120·60·3.6	Compressive test	Steady-state	1000, 5000, 25000	60, 300, 1500	2, 0.4, 0.08	0.033, 0.0067, 0.0013	20, 400, 550, 700
M7	Square hollow section SHS 160·160·5	Tensile test	Steady-state	0.333, 1.67, 8.33	0.02, 0.10, 0.50	6000, 1200, 240	100, 20, 4	20, 400, 550, 700
M8	Rectangular hollow section RHS 120·60·3.6	Tensile test	Steady-state	1.67	0.10	1200	20	20, 400, 550, 700
M9	Wide flange section HEA 100	Tensile test	Steady-state	1.67	0.10	1200	20	20, 400, 550, 700

[a] Labelling of test series corresponds to [17].

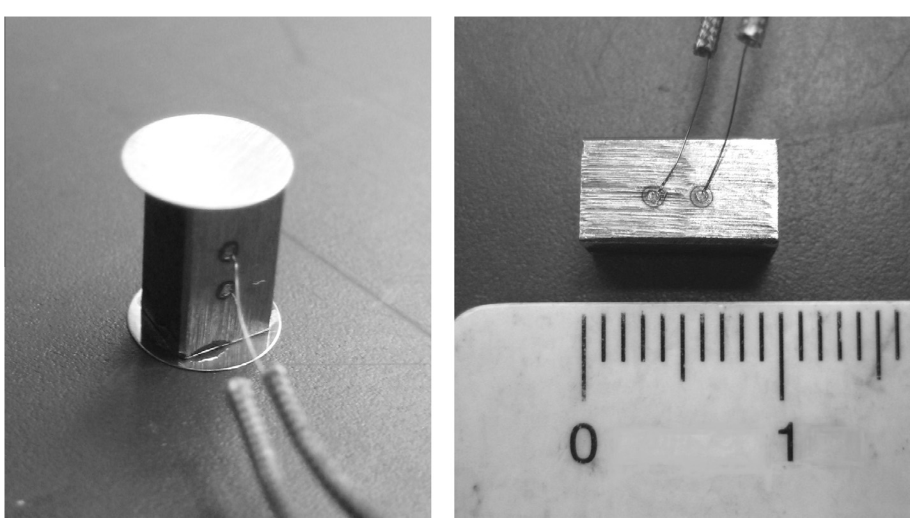

Fig. 1. Compressive test specimen of the test series M5 and M6 with aluminium discs and temperature sensor.