Appendix B

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Fire design model for structural steel S420M based upon transient-state tensile test results

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Abstract

A wide-ranging experimental research project was carried out during 1994–1997 in the Laboratory of Steel Structures at Helsinki University of Technology to investigate the mechanical properties of various structural steels and sheet steels at elevated temperatures. This kind of basic materials research is becoming more important as the significance of fire design of steel structures is growing and new steel materials, including high-strength steels and stainless steels, are expected to be used more widely in steel structures in the future. One of the latest investigations in the Laboratory of Steel Structures at Helsinki University of Technology has concentrated on the high-strength structural steel S420M. The main purpose of this research was to develop a realistic model for the behaviour of structural steel S420M under fire conditions. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Fire design model; Structural steel; Transient-state; Tensile testing; Mechanical properties; Elevated temperatures; Material properties

Notation

$E_{a,\theta}$	Modulus of elasticity of steel at temperature θ_a
$f_{p,\theta}$	Proportional limit at temperature θ_a
$f_{y,\theta}$	Yield strength at temperature θ_a
$k_{E,\theta}$	Elasticity modulus reduction factor
$k_{p,\theta}$	Proportional limit reduction factor
$k_{y,\theta}$	Yield strength reduction factor (2% total strain)

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n_θ	Temperature-dependent factor
ϵ_i	Total strain at temperature θ_i
σ_i	Stress at temperature θ_i
θ_a	Steel temperature

1. Introduction

One of the latest investigations in the Laboratory of Steel Structures at Helsinki University of Technology has concentrated on the high-strength structural steel S420M. The main purpose of this research was to develop a realistic model for the behaviour of structural steel S420M under fire conditions. The research was carried out by using the transient-state tensile test method. The material was also tested with the steady-state tensile test method to have a proper basis for comparison of test results obtained with different testing methods.

The test results are used as a basis for the evaluation of existing fire design models. Test results are also modelled by using the calculation method given in Eurocode 3(EC3): Part 1.2 and the material model developed by Ramberg and Osgood.

Earlier research projects in the Laboratory of Steel Structures at Helsinki University of Technology focused on the constructional steel grades S235, S355 and S350GD + Z, and an austenitic stainless steel EN 1.4301 (AISI 304). Reports of these projects are available from the Library of Helsinki University of Technology. Some test results from these projects are also presented in this paper.

2. Test methods

The experimental part of this project was carried out mainly with the transient-state tensile test method. The more common test method, the steady-state method, was also used to enable comparison of the test results with those from another test method. Only the transient-state test results were used in the modelling process. The steady-state test results are not presented in this paper. They are presented in the full report of that research project [1].

2.1. Transient-state method

In the transient-state method, the testpiece is under a constant load and a constant temperature rise. Temperature and strain are measured during the test. As a result, a temperature–strain curve is recorded during the test. The results are then converted into stress–strain curves. Thermal elongation is subtracted from the total strain.

The test method was in accordance with standard procedures [2]. Transient state-tensile tests were carried out on two identical specimens at each load level of 3, 20, 50, 80, 110, 140, 170, 200, 230, 260, 290, 320, 350, 380, 410 and 440 N mm^{-2}. The heating rate in the transient-state tests was 10°C min^{-1}. Test specimens were heated until the temperature of 700°C was reached or until they broke. Temperature was measured with a temperature-detecting element fastened to the test specimen.

2.2. Steady-state method

In steady-state tests, the testpiece is heated up to a specific temperature, after which a tensile test is carried out. In the steady-state tests, stress and strain are recorded and, from the stress–strain curves, the mechanical material properties can be determined. The steady-state tests can be carried out under either strain control or load control. In the strain-controlled tests, the strain rate is kept constant and in the load-controlled tests the loading rate is kept constant.

3. Testing facilities

3.1. Test specimens

The test specimens had proportional circular cross-sections in accordance with standard EN 10 002-5 [2]. The test specimen is shown in Fig. 1.

3.2. Testing device

The testing device consists of a tensile testing machine, a heating oven, an extensometer, temperature-detecting elements, two control units and two computers. The tensile testing machine used in the research projects is verified in accordance with standard EN 10 002-2 [3]. The extensometer is in accordance with standard EN 10 002-4 [4]. The extensometer used in the research on hot-rolled structural steels had a gauge length of 25 mm. The oven in which the test specimen is situated during the tests was heated by three, separately controlled, resistor elements. The air temperature in the oven was measured by three separate temperature-detecting elements. The steel temperature was measured accurately during heating by taking readings

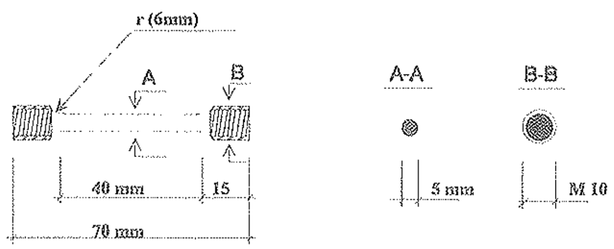

Fig. 1. Test specimen.

from the temperature-detecting element fastened to the specimen. The testing device is shown in Fig. 2.

4. Mechanical material properties at room temperature

4.1. Mechanical properties at room temperature

The steel material used in this research is in accordance with the requirements of European standard SFS-EN 10 113-3 [5] for hot-rolled structural steel S420M. Testpieces were cut from a hot-rolled steel sheet, longitudinal to the rolling direction.

The mechanical properties of S420M at room temperature were determined by four standard tensile tests. The test results were very near to the minimum requirements given by the manufacturer. Test results at room temperature are presented in Table 1.

5. Stress–strain relationships according to EC3: Part 1.2

5.1. Mechanical properties of steel S420M at elevated temperatures

Simple empirical formulae for calculating the mechanical properties of steel S420M at elevated temperatures were determined from the transient-state test results by curve fitting. Eqs. (1)–(7) were used in calculating the model parameters instead

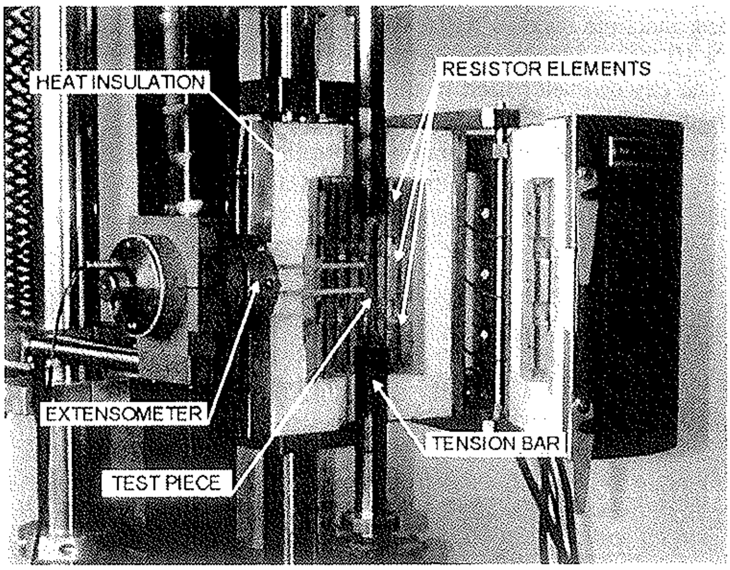

Fig. 2. The transient-state tensile testing device.

Table 1
Test results, reported test values of Inspection Certificate and the minimum values given by the manufacturer

	Measured property	Reported test value of Inspection Certificate	Minimum requirement
Modulus of elasticity, E ($N\ mm^{-2}$)	205,138	not measured	206,000
Yield stress, R_{eH} ($N\ mm^{-2}$)	456	477	420
Yield stress, $R_{p0.2}$ ($N\ mm^{-2}$)	430.2	not measured	420
Ultimate stress, R_m ($N\ mm^{-2}$)	548.8	555	500–660

of using the reduction factors given in EC3 [6]. The test results and the calculated values are presented in Fig. 3.

Modulus of elasticity $E_{a,\theta}$:

$$E_{a,\theta} = E \cdot k_{E,\theta} \quad (1)$$

$$k_{E,\theta} = -3.5 \times 10^{-10}\theta_a^3 - 1.9 \times 10^{-6}\theta_a^2 + 0.00028\theta_a + 1.0, \quad (2)$$

$$\text{for } 20°C < \theta_a \le 700°C$$

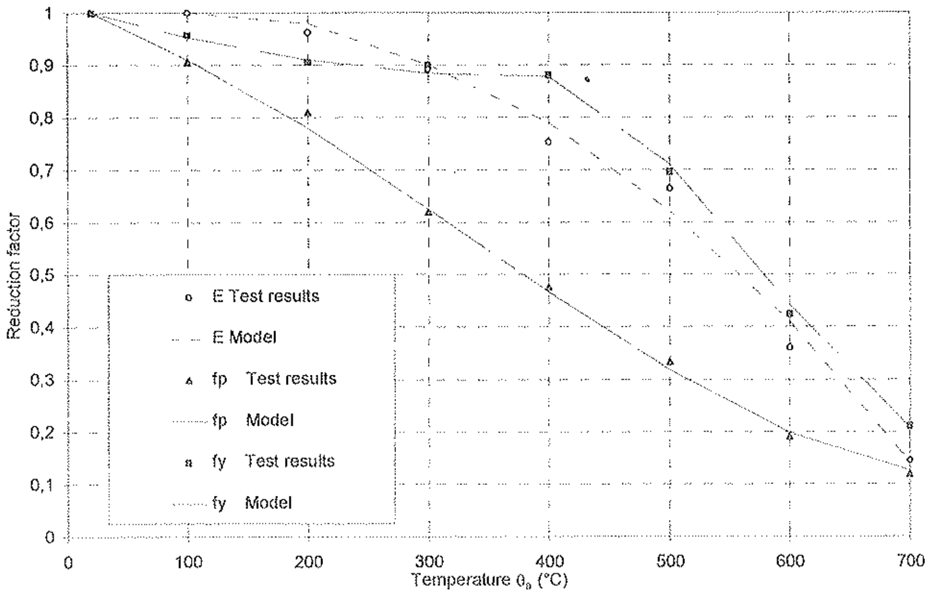

Fig. 3. Reduction factors for elasticity modulus $E_{a,\theta}$, proportional limit $f_{p,\theta}$ and yield strength $f_{y,\theta}$ at temperatures of 20 to 700°C for steel S420M, and comparsion with with test results.

Proportional limit $f_{p,\theta}$:

$$f_{p,\theta} = f_y \cdot k_{p,\theta} \quad (3)$$

$$k_{p,\theta} = 2.9 \times 10^{-9}\theta_a^3 - 2.9 \times 10^{-6}\theta_a^2 - 0.000064\theta_a + 1.0, \quad (4)$$

for $20°C < \theta_a \leq 700°C$

Yield strength $f_{y,\theta}$ ($R_{t2.0}$):

$$f_{y,\theta} = f_y \cdot k_{y,\theta} \quad (5)$$

$$k_{y,\theta} = 9 \times 10^{-7}\theta_a^2 - 0.0007\theta_a + 1.014, \quad \text{for } 20°C \leq \theta_a \leq 400°C \quad (6)$$

$$k_{y,\theta} = 2.2 \times 10^{-8}\theta_a^3 - 0.0000038\theta_a^2 + 0.0191\theta_a - 2.09, \quad (7)$$

for $400°C \leq \theta_a \leq 700°C$

5.2. *Stress–strain relationships for steel S420M at elevated temperatures*

Stress–strain relationships for steel S420M at elevated temperatures were determined by applying the calculation method given in EC3 [6] to the transient-state tensile test results [1]. The calculated stress–strain curves are compared with the experimental curves in Fig. 4. Comparison between the stress–strain curves of the modified calculation model and the original EC3 model is illustrated in Fig. 5.

It can be seen from Fig. 5 that the stress–strain curves for a structural steel determined with the method based on transient-state tensile tests are mostly below the EC3 curves, and therefore the use of the model given in EC3 seems not to be safe for structural steel S420M.

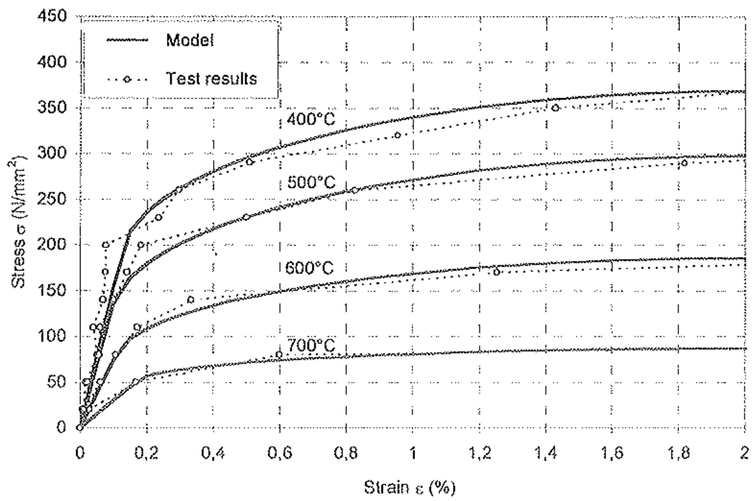

Fig. 4. Calculated stress–strain curves for steel S420M and comparison with experimental curves at temperatures of 400 to 700°C.

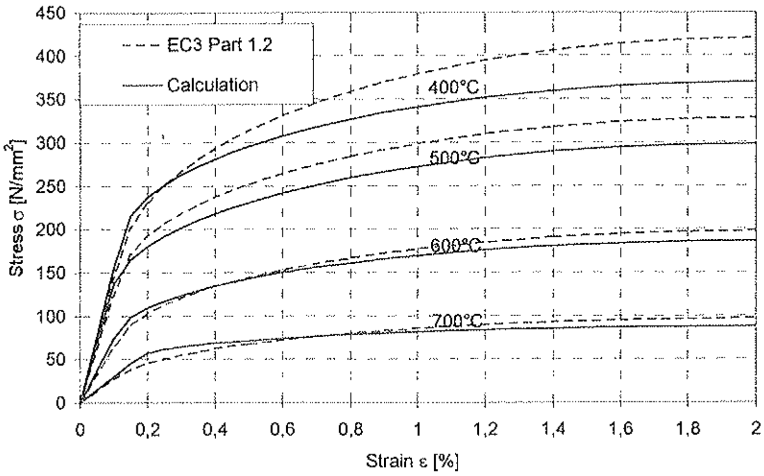

Fig. 5. Stress–strain curves from the modified calculation model and the EC3 model.

6. Calculation method of Ramberg and Osgood

6.1. Ramberg–Osgood model

The stress–strain relationships of steel S420M at elevated temperatures based upon the transient-state tensile test results were modelled by using the calculation method developed by Ramberg and Osgood [7]. In this method, the equation for calculating the stress–strain values of steel at elevated temperatures is:

$$\epsilon_i = \frac{\sigma_i}{E_{a,\theta}} + \beta\cdot\left(\frac{f_{y,\theta}}{E_{a,\theta}}\right)\cdot\left(\frac{\sigma_i}{f_{y,\theta}}\right)^{n}_{\theta} \tag{8}$$

6.2. Stress–strain relationship for structural steel S420M

The test results were used as a basis in modelling the yield strength $f_{y,\theta}$ ($\sigma_{p0.2}$), elasticity modulus $E_{a,\theta}$ and the calculation parameter n_θ. The values of elasticity modulus are calculated with Eqs. (1) and (2). The values of yield strength are calculated with Eq. (9). Values of parameter n_θ at temperatures of 20–700°C are given in Table 2. Intermediate values can be calculated by using linear interpolation. In this model, the value of β in Eq. (8) is 6/7.

$$f_y,\theta = f_y(-0.000001\cdot T_a^2 - 0.00052T_a + 1.01), \quad \text{for } 20°\text{C} \leq T_a \leq 700°\text{C} \tag{9}$$

Modelled stress–strain curves of steel S420M at temperatures from 400°C to 700°C are compared with the test results in Fig. 6.

Table 2
Values of parameter n_θ at temperatures of 20 to 700°C for structural steel S420M

Temperature, θ (°C)	Parameter n_θ	Temperature, θ (°C)	Parameter n_θ
20°C	230	350°C	11
100°C	105	400°C	8
200°C	50	500°C	7.5
250°C	26	600°C	8.8
300°C	17	700°C	7.8

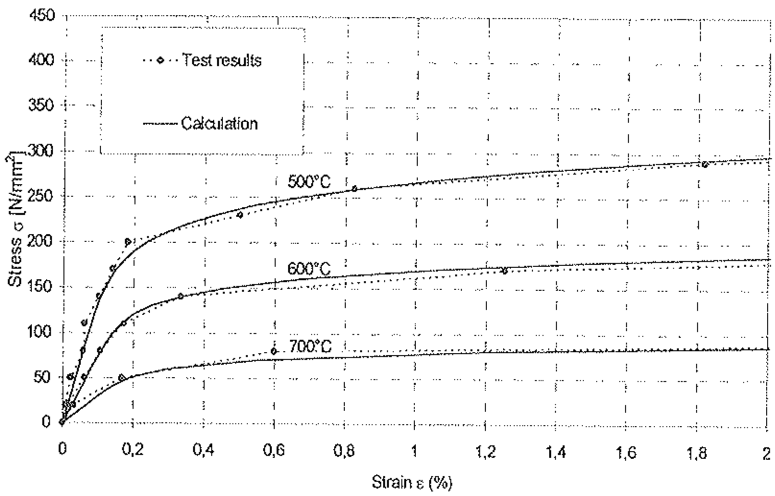

Fig. 6. Stress–strain curves for steel S420M determined with the modified Ramberg–Osgood model, and comparison with test results at temperatures of 400 to 700°C.

7. Test results from other transient-state tests

The earlier research projects in the Laboratory of Steel Structures at Helsinki University of Technology have consisted of tests for structural steels S235, S355 and S350GD + Z [8], and for an austenitic stainless steel named by Polarit 725 (EN 1.4301, AISI 304) [9]. The experimental reduction factors at temperatures up to 700°C relative to the yield strength f_y at room temperature are presented in Fig. 7 for the structural steels studied. Yield strength f_y is based on 2% total strain.

EC3: Part 1.2 can be applied to fire design for the steel materials presented in Fig. 7. The figure shows clearly the large differences between the test results for the

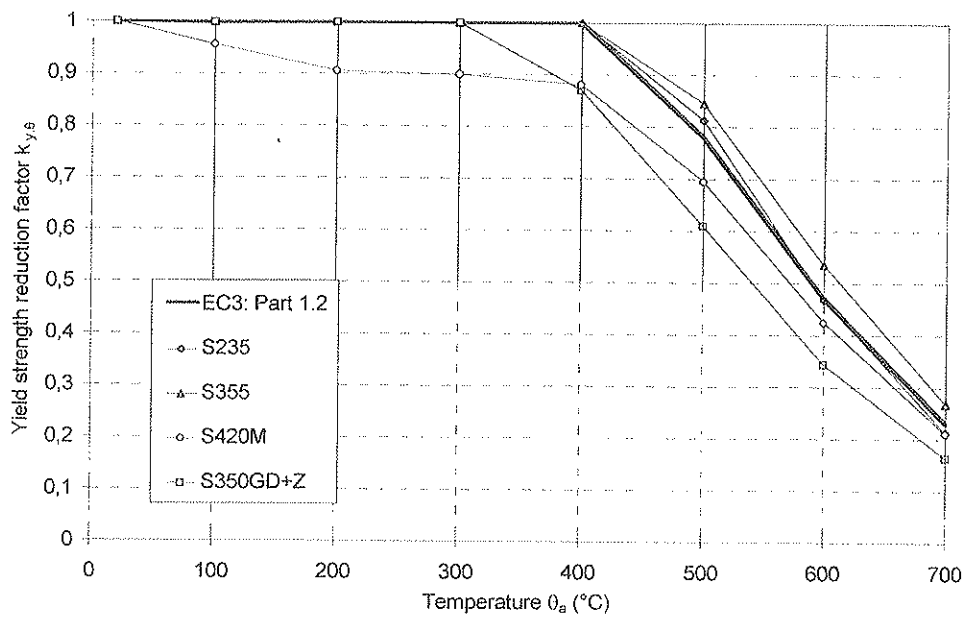

Fig. 7. Yield strength reduction factor $k_{y,\theta}$ for the structural steels studied at temperatures up to 700°C.

steel materials tested. The values for structural steels S350GD + Z and S420M are below the EC3 fire design values.

However, the experimentally determined yield strength of the sheet steel S350GD + Z at temperatures up to 700°C is still well above the design values given, for example, in British and Finnish standards for structural sheet steels. The very common low-carbon structural steel S355 seems to follow the EC3 values very well.

An interesting study was also carried out earlier for structural steel FeE460 (S460M) by ARBED-Recherches [10]. This work consisted of various kinds of test including transient-state beam tests and steady-state tensile tests. The stress–strain curves of steel FeE460 were modelled by using a quadrilinear law. The modelled stress–strain curves, which are based on the steady-state tests, are above the EC3 curves.

8. Conclusions

The main purpose of this research was to develop a realistic model for the behaviour of the basic structural steel grade S420M under fire conditions. In the Laboratory of Steel Structures at Helsinki University of Technology, experimental research has also been carried out on structural steels S235 and S355 and on structural steel sheets

S320GD + Z and S350GD + Z by using transient-state tensile test method. The test results of different steel grades differ considerably from each other. Thus the experimental results give a good basis for evaluating the existing standards and also help in developing new ones.

Test results for the structural steel S420M show clearly that the calculation methods given in EC3 are not directly applicable to all steel grades. The stress–strain curves determined from test results are mostly below the stress–strain curves calculated with the method given in EC3, and therefore the use of this method is not safe for structural steel S420M.

However, the calculation method given in EC3 and the material model developed by Ramberg and Osgood are applicable for structural steel S420M by using experimental test results. Therefore it should be of a great interest for the steel manufacturers to carry out experimental research also for other high-strength steel grades used in steel structures.

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