BEHAVIOUR OF HIGH-STRENGTH STRUCTURAL STEEL S420M AT ELEVATED TEMPERATURES

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ABSTRACT

The main purpose of this research was to develop a real fire design model for structural steel S420M at elevated temperatures. The models represented in this report are based upon transient state tensile test results. The test results are modelled using the calculation method given in Eurocode 3: Part 1.2 and the material model developed by W.Ramberg and W.R.Osgood.

INTRODUCTION

Wide experimental research has been carried out during the years 1994-1996 in the Laboratory of Steel Structures at Helsinki University of Technology for investigating mechanical properties of various structural steels and steel sheets at elevated temperatures. This kind of basic material research is becoming more important as the significance of the fire design of steel structures is growing and new steel materials, including high-strength steels and stainless steels, are going to be used more widely in steel structures in the future.

The latest research in the Laboratory of Steel Structures at Helsinki University of Technology has concentrated on high-strength structural steel S420M. The main purpose of this research was to develop a real fire design model for the behaviour of structural steel S420M under fire conditions. The research has been carried out by using transient state tensile test method. As it is well known, strain rate in the tensile tests at elevated temperatures has a significant effect upon the test results. Therefore the studied material has also been tested with steady state tensile test method to have a proper basis for comparison of the test results from different testing methods.

The test results are used as a basis for evaluation of the existing fire design models. Test results are also modelled by using the calculation method given in Eurocode 3(EC3): Part 1.2 /1/ and the material model developed by W.Ramberg and W.R.Osgood /5/.

Test results of structural steel S420M from transient state tensile /3/ tests show clearly that the calculation method given in EC3 is not applicable to structural steel S420M. The stress-strain curves determined from the transient state tensile test results are mainly 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 W.Ramberg and W.R.Osgood are applicable also for structural steel S420M by using parameters based upon the transient state tensile test results in the calculation process.

TESTING FACILITIES

Test specimen

Test pieces were cut out from a hot-rolled steel sheet longitudinally to rolling direction. Steel material is in accordance with the requirements of the European standard SFS-EN 10 113-3 /9/ for structural steel S420M.The test specimen having so called proportional circular cross-section was in accordance with the standard EN 10 002-5 /8/. The test specimen is shown in Fig. 1.

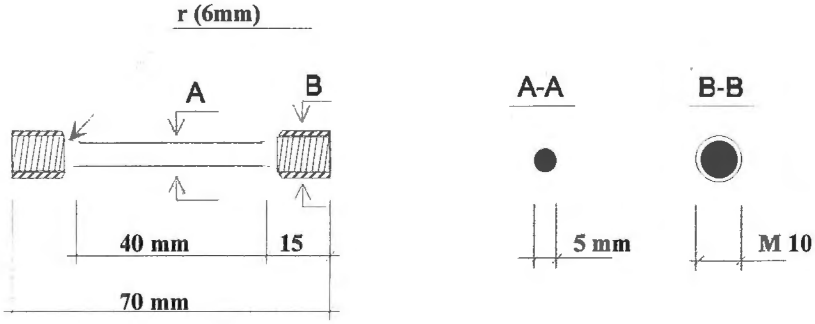

Fig. 1. *Test specimen*

TEST RESULTS

Tensile tests at room temperature

Five tensile tests were carried out at room temperature to determine the mechanical properties of the test material at room temperature. Test results from the tensile tests are compared in Table 1 with reported test values of inspection certificate and the minimum values given by the manufacturer.

Table 1. Test results, reported test value 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)	205138	not measured	206000
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

Thermal elongation

Thermal elongation of the test material was determined with five tests at load level of $3N/mm^2$. Test specimen was heated with heating rate of 10°C/min until temperature was 750°C. In the Laboratory of Steel Structures at Helsinki University of Technology, thermal elongation has been measured earlier for structural steels S235, S355 and for structural steel sheet S350GD+Z /4/. Comparison of the thermal elongation of structural steels S235, S355 and S420M and thermal strain according to EC3 is shown in Fig.2.

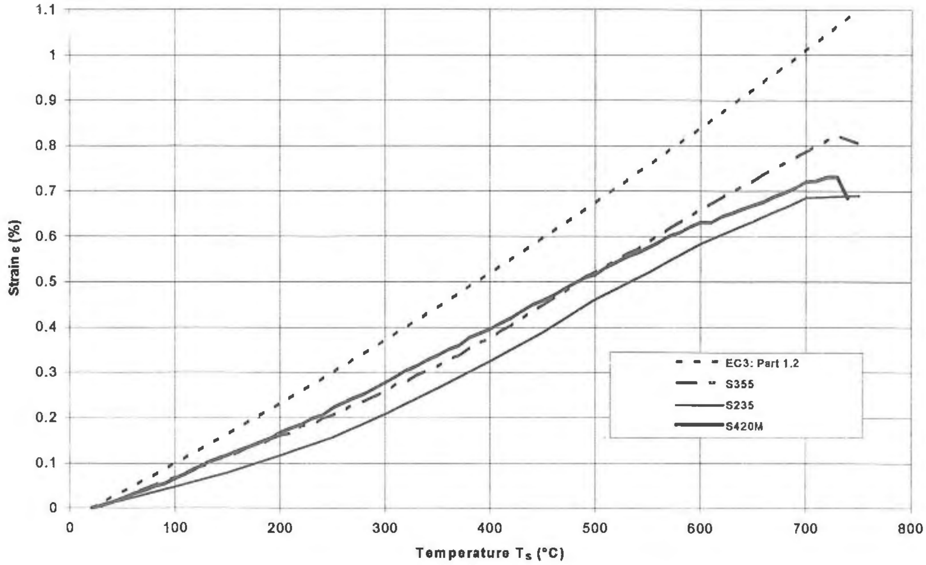

Fig.2. *Thermal elongation determined for structural steels S235, S355 and S420M compared with thermal elongation according to EC3.*

The test results show clearly that there is a notable difference between thermal elongation of different steels. All test results are below the EC3 curve.

Transient state tensile tests

Transient state tensile tests were carried out with two equal tests 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. Heating rate in the transient state tests was 10°C min^{-1}. In the temperature-strain relationship, thermal elongation was subtracted from the total strain. The final results were converted into stress-strain curves.

Steady state tensile tests

Steady state tensile tests were carried out for the test material S420M with loading rate 5N/mm^2/s at each temperature 400°C, 500°C and 600°C. Tensile tests were carried out as stress rate-controlled. Stress-strain curves from the steady state tests at temperatures 400°C, 500°C and 600°C are compared with transient state test curves in Fig. 3.

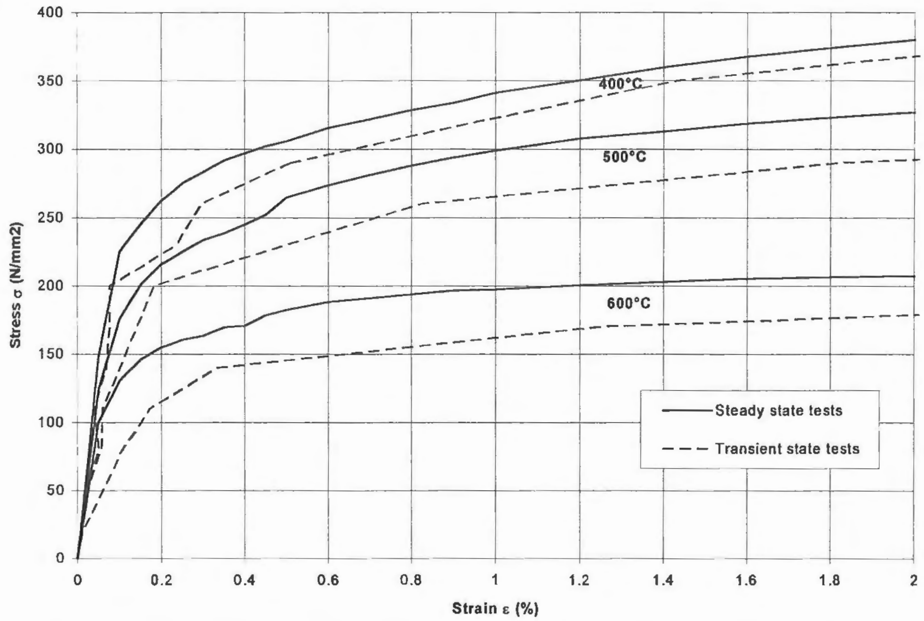

Fig. 3 Measured steady state stress-strain curves for steel S420M at temperatures 400°C, 500°C and 600°C compared with the measured transient state curves.

The strain rate in the steady state tests is lot higher than in the transient state tests and the difference caused by this can be seen clearly from fig.3.

FIRE DESIGN MODELS

Eurocode 3: Part 1.2

Fire design code Eurocode 3: Part 1.2 provides a simple calculation method for determining stress-strain relationship of structural steels at elevated temperatures. The stress-strain curves of EC3 are mostly above the stress-strain curves of structural high-strength steel S420M determined from the transient state tensile test results. Therefore the calculation parameters used in the research of structural steel S420M were modelled using transient state tensile test results.

Mechanical properties of steel S420M at elevated temperatures

Simple formulas for calculating the mechanical properties of steel S420M at elevated temperatures, based on transient state test results, are given in eqns (1) - (7). These equations were used instead of the reduction factors given in EC3.

Modulus of elasticity E(T):

$E_T = E \cdot k_{E,T}$ (1)

$k_{E,T} = -3.5 \cdot 10^{-10} \cdot T^3 - 1.9 \cdot 10^{-6} \cdot T^2 + 0.00028 \cdot T + 1.0$, for $20°C < T \leq 700°C$ (2)

where

E_T is elasticity modulus (N/mm^2) at temperature T ,

E is elasticity modulus (N/mm^2) at room temperature,

$k_{E,T}$ is reduction factor for elasticity modulus and

T is steel temperature (°C).

Proportional limit f_p:

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

$k_{p,T} = 2.9 \cdot 10^{-9} \cdot T^3 - 2.9 \cdot 10^{-6} \cdot T^2 - 0.00064 \cdot T + 1.0$, for $20°C < T \leq 700°C$ (4)

where

$f_{p,T}$ is proportional limit (N/mm^2) at temperature T,

f_y is yield strength (N/mm^2) at room temperature,

$k_{p.T}$ is reduction factor for proportional limit and

T is steel temperature (°C).

Yield strength f_y ($R_{t2.0}$):

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

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

$$k_{y,T} = 2.2 \cdot 10^{-8} \cdot T^3 - 0.000038 \cdot T^2 + 0.0191 \cdot T - 2.09 \quad , \text{for } 400°C \leq T \leq 700°C \quad (7)$$

where

$f_{y,T}$ is yield strength (N/mm²) at temperature T,

f_y is yield strength (N/mm²) at room temperature,

$k_{y,T}$ is reduction factor for yield strength and

T is steel temperature (°C).

Reduction factors for the mechanical properties of steel S420M calculated with eqns (1)-(7) are compared with the test results in Fig.4.

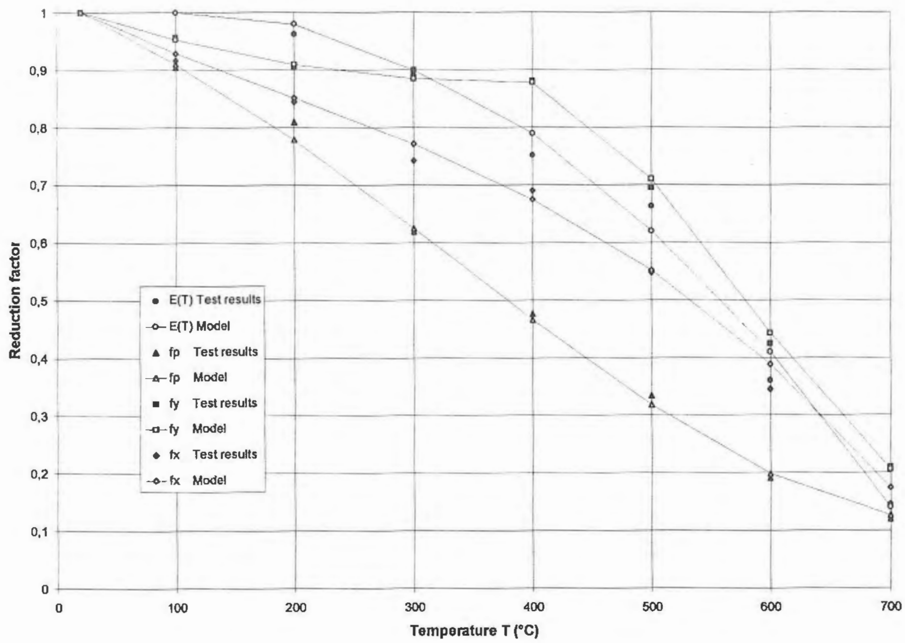

Fig.4. *Reduction factors for elasticity modulus E(T), proportional limit f_p and yield strength f_y and f_x of steel S420M compared with the test results.*

Stress-strain relationship for steel S420M at elevated temperatures

Stress-strain relationship for steel S420M at elevated temperatures was modelled by applying the calculation method given in EC 3 to the transient state tensile test results[4]. Stress-strain curves were determined with the formulas given in EC 3 using the calculation parameters given in eqns. (1)-(7). The modelled stress-strain curves at temperatures 400°C-700°C compared with the test results are illustrated in Fig. 5.

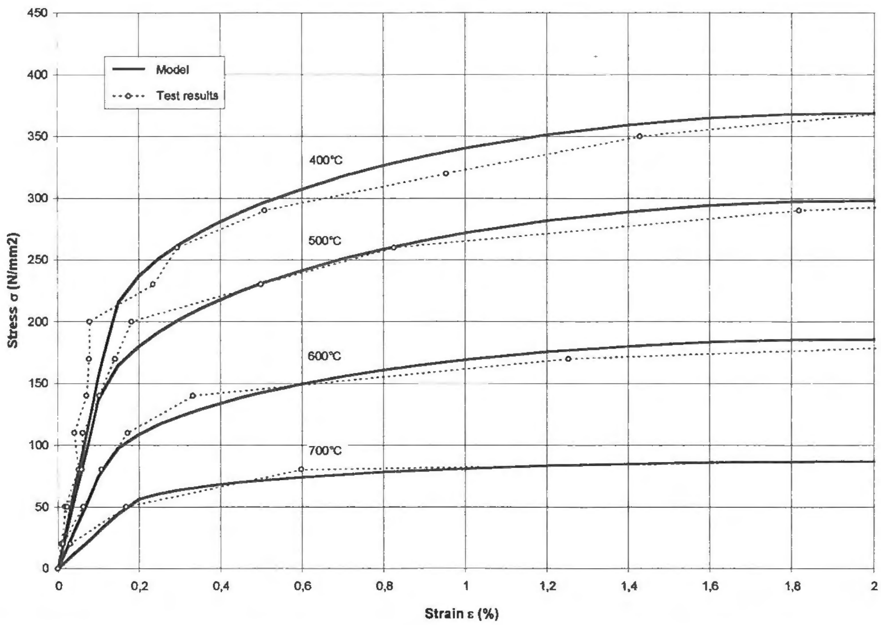

Fig. 5. *Stress-strain curves of steel S420M modelled by using the calculation method given in EC 3 and compared with the test results at temperatures 400°C - 700°C.*

Modelled stress-strain relationship for steel S420M compared with the stress-strain relationship given in EC 3

Mechanical properties for steel S420M at elevated temperatures in the preceding model are based on transient state tensile tests. Comparison between the stress-strain curves of the modified model and EC3 is illustrated in Fig.6 for structural steel S420M.

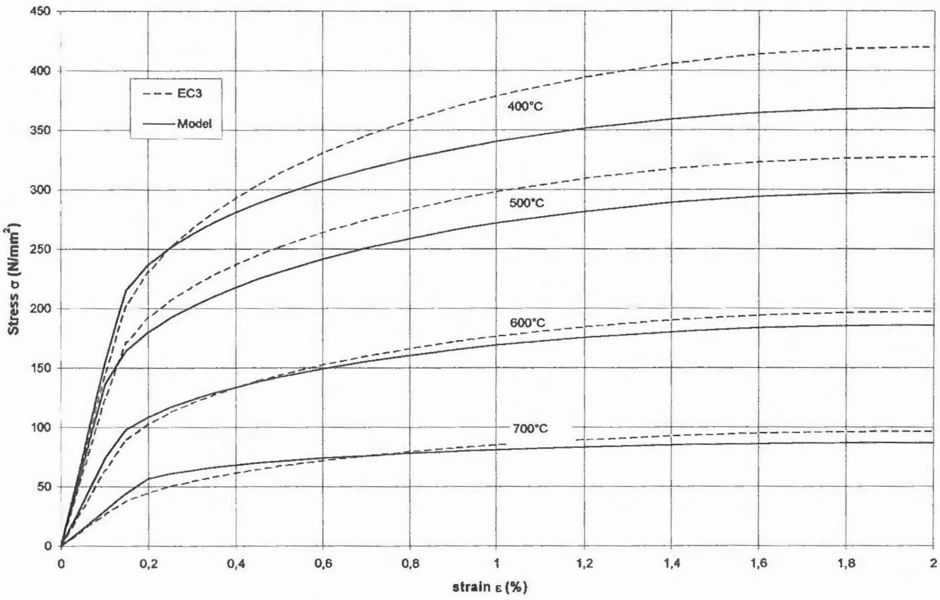

Fig. 6. Comparison between stress-strain curves of the modified model and EC3 for steel S420M at temperatures 400 °C - 700 °C.

It can be seen from Fig. 6 that the stress-strain curves for 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 is not safe for structural steel S420M.

Ramberg-Osgood model

The stress-strain relationship for steel S420M at elevated temperatures based upon transient state tensile test results was modelled by using the calculation method developed by W.Ramberg and W.R.Osgood. The equation for calculating the stress-strain values of steel at elevated temperatures with this method is given in eqn. (8).

$$\varepsilon_i = \frac{\sigma_i}{E(T)} + \beta \cdot \left(\frac{\sigma_y(T)}{E(T)}\right) \cdot \left(\frac{\sigma_i}{\sigma_y(T)}\right)^{n(T)} \quad (8)$$

where

β is 3/7

ε_i is total strain at temperature T,

σ_i is stress (N/mm^2),

E(T) is modulus of elasticity (N/mm^2) at temperature T,

$\sigma_y(T)$ is yield strength (N/mm^2) at temperature T and

n(T) is a temperature-dependent factor.

The values of elasticity modulus E(T) are calculated with eqns (1) and (2). The values of yield strength σ_y ($\sigma_{p0.2}$) are calculated with eqn (9). Values of parameter n(T) at temperatures 20°C-700°C is given in Table 2. Intermediate values can be calculated by using linear interpolation. In this model the value of β in eqn (8) is 6/7.

$$\sigma_y(T) = \sigma_y \cdot (-0.000001 \cdot T^2 - 0.00052 \cdot T + 1.01), \quad \text{for } 20°C \le T \le 700°C \quad (9)$$

where

$\sigma_y(T)$ is yield strength (N/mm^2) at temperature T,

σ_y is yield strength (N/mm^2) at room temperature

T is steel temperature (°C).

Table 2. Parameter n(T) at temperatures 20°C - 700°C for steel S420M.

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

Modelled stress-strain curves of steel S420M at temperatures 400°C -700°C are compared with the test results in Fig. 7.

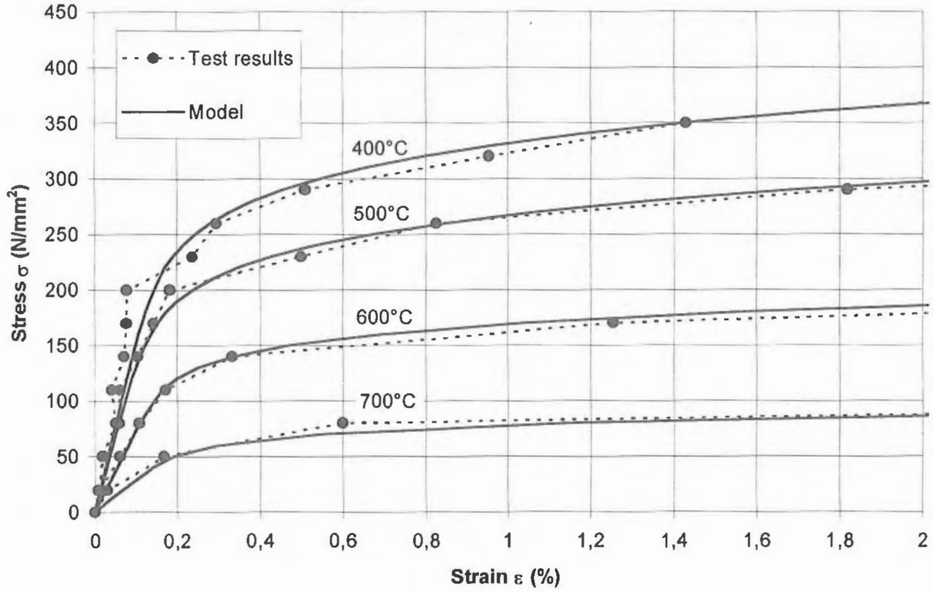

Fig 7. Stress-strain curves for steel S420M determined by using the modified Ramberg-Osgood model compared with the test results at temperatures 400°C - 700°C.

CONCLUSIONS

The main purpose of this research was to develop a real fire design model for the behaviour of structural steel S420M under fire conditions. In the Laboratory of Steel Structures at Helsinki University of Technology experimental research has also been performed on structural steels S235, S355 and structural steel sheets S320GD+Z and S350GD+Z using transient state tensile test method. The test results of different steel grades differ considerably from each other.

Test results of structural steel S420M from transient state tensile tests show clearly that the calculation method given in EC3 is not applicable to steel S420. The stress-strain curves determined from the test results are mainly 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 W.Ramberg and W.R.Osgood are applicable for structural steel S420M by using the transient state tensile test results and therefore it should be of great interest for the steel manufacturers to carry out experimental research for all high-strength steel grades by using transient state tensile test method.

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