

Appendix A

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Fire Design Model for Structural Steel S355 Based Upon Transient State Tensile Test Results

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ABSTRACT

Experimental research has been carried out during the years 1994–1995 in the Laboratory of Steel Structures at Helsinki University of Technology for investigating mechanical properties of structural steel S355 at elevated temperatures by using the transient state tensile test method. The test results are used here as a basis for modelling the stress–strain relationship of the structural steel S355 at temperatures 20–700°C. Test results are modelled by using the calculation method given in Eurocode 3: Part 1.2 and the material model developed by W. Ramberg and W. R. Osgood. © 1997 Elsevier Science Ltd.

NOTATION

$E_{a,0}$	The modulus of elasticity of steel at elevated temperatures
T_a	The steel temperature
$f_{p,0}$	The proportional limit at elevated temperatures
$f_{y,0}$	The yield strength at elevated temperatures
ϵ_i	Total strain at temperature T_i
σ_i	Stress at temperature T_i
n_0	A temperature-dependent factor

1 INTRODUCTION

In the transient state tests the specimen is under constant load, while the temperature rises. The aim of this method is to study the behaviour of the

material in fire temperatures with a small specimen. In a real fire situation a structure is normally under a constant load and the temperature begins to rise. That is why this method gives us a more realistic picture of the behaviour of the studied material than the most commonly used steady state test method. In the steady state tests the specimen is heated to a constant temperature, after which a tensile test is carried out.

The test results of structural steel S355 were used as a basis for the simple models described in this report. The 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 and 350 N/mm². Thermal elongation was determined with five tests. Heating rate in the transient state tests was 10°C/min.

2 TESTING FACILITIES

2.1 Test specimens

The test specimen having a so-called proportional circular cross-section was in accordance with the standard EN 10 002-5 [1]. The test specimen is shown in Fig. 1.

2.2 Testing device

The tensile testing machine used in these research projects was verified in accordance with the standard EN 10 002-2 [2]. The extensometer is in accordance with the standard EN 10 002-4 [3]. Gauge length of the extensometer used in the research of hot-rolled structural steels was 25 mm. The oven in which the test specimen was situated during the tests was heated by using three separately controlled resistor elements. The air temperature in the oven was measured with three separate temperature-detecting elements. The steel temperature was measured accurately from the test specimen using a tempera-

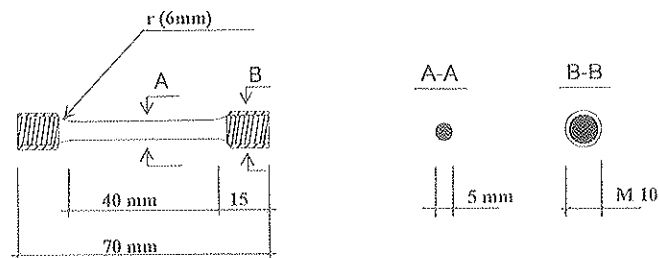


Fig. 1. Test specimen.

ture-detecting element that was fastened to the specimen during the heating. The testing device is shown in Fig. 2.

3 STRESS-STRAIN RELATIONSHIP USING EC3: PART 1.2

3.1 Mechanical properties of steel S355 at elevated temperatures

Simple formulas for calculating the mechanical properties of steel S355 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: Part 1.2 [4].

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

$$E_{a,\theta} = 206,000 - 44.44 \cdot (T_a - 20), \text{ for } 20^\circ\text{C} \leq T_a \leq 200^\circ\text{C} \quad (1)$$

$$E_{a,\theta} = 263,000 - 325 \cdot T_a, \text{ for } 200^\circ\text{C} < T_a \leq 700^\circ\text{C}. \quad (2)$$

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

$$f_{y,\theta} = 350 \text{ N/mm}^2, \text{ for } 20^\circ\text{C} \leq T_a \leq 200^\circ\text{C} \quad (3)$$

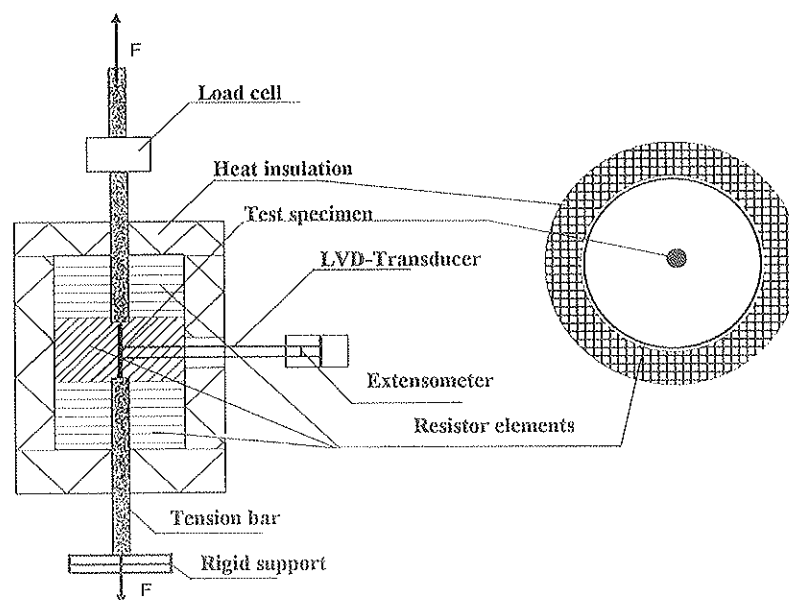


Fig. 2. The transient state tensile testing device.

$$f_{y,\theta} = 350 - 1 \cdot (T_a - 200), \text{ for } 200^\circ\text{C} < T_a \leq 400^\circ\text{C} \quad (4)$$

$$f_{y,\theta} = 150 - 1/3 \cdot (T_a - 400), \text{ for } 400^\circ\text{C} < T_a \leq 700^\circ\text{C}. \quad (5)$$

Yield strength $f_{y,\theta}$:

$$f_y = f_{y20^\circ\text{C}}, \text{ for } 20^\circ\text{C} \leq T_a \leq 420^\circ\text{C} \quad (6)$$

$$f_y = 1.127 \times 10^{-5} \cdot T_a^3 - 0.01942 \cdot T_a^2 + 10 \cdot T_a - 1254.3, \text{ for } 420^\circ\text{C} \leq T_a \leq 700^\circ\text{C}. \quad (7)$$

Reduction factors for the mechanical properties of steel S355 calculated with eqns (1)–(7) are compared with the test results in Fig. 3.

3.2 Stress–strain relationship

The stress–strain relationship for steel S355 at elevated temperatures was modelled by applying the calculation method given in EC3 [4] to the reduction factors based upon the transient state tests given in eqns (1)–(7). The calcu-

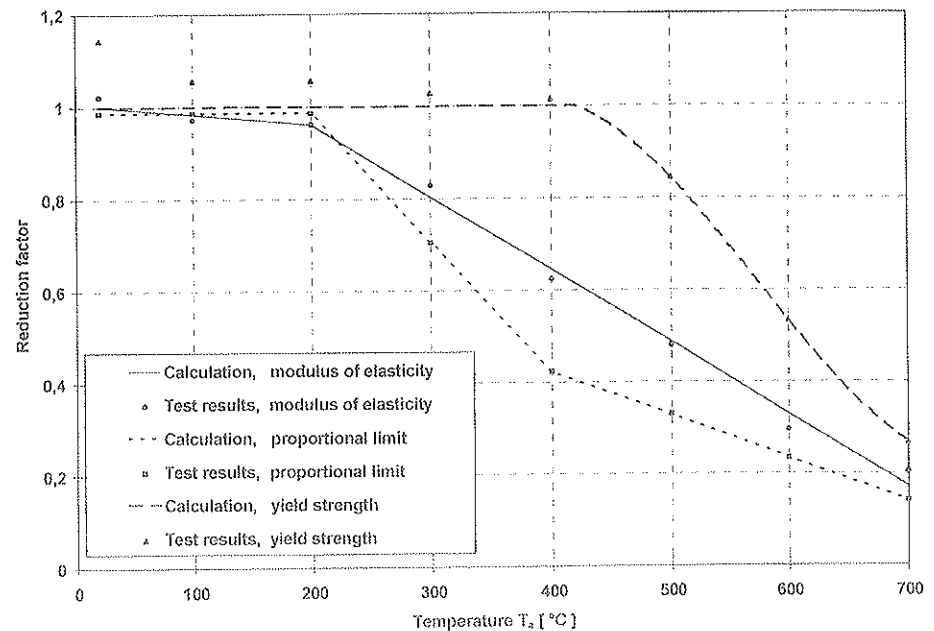


Fig. 3. Reduction factors for elasticity modulus, proportional limit and yield strength of structural steel S355 compared with the test results.

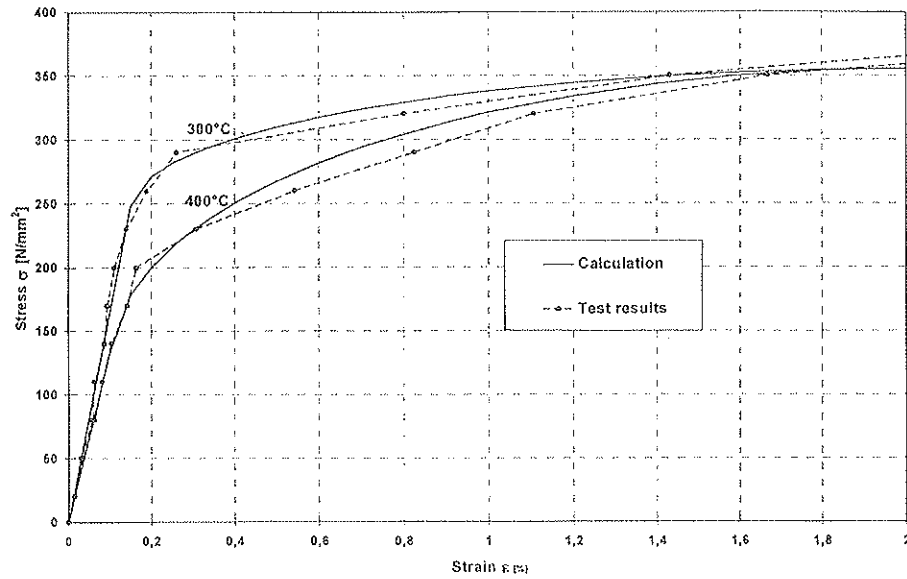


Fig. 4. Stress-strain curves of steel S355 modelled by using the calculation method given in EC 3 compared with the test results at temperatures 300 and 400°C.

lated stress-strain curves at temperatures 300–700°C compared with the test results are illustrated in Figs 4 and 5.

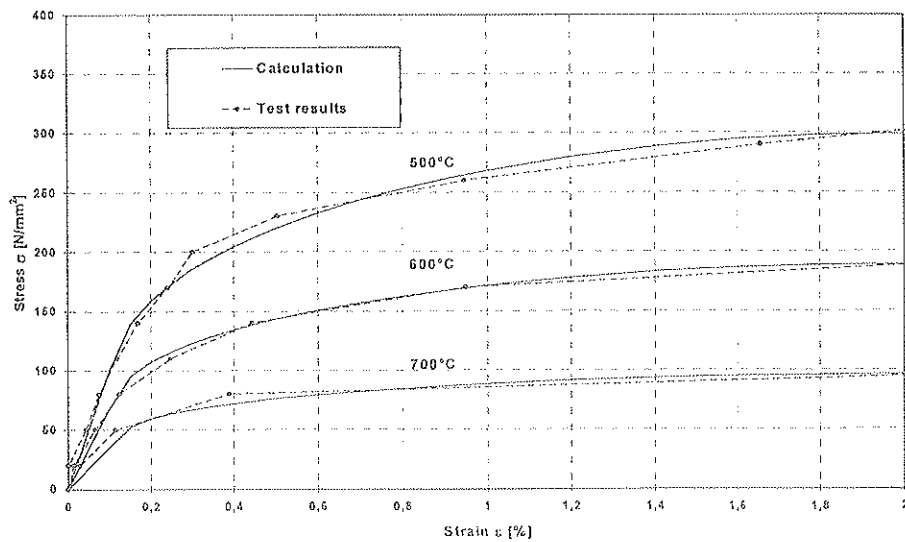


Fig. 5. Stress-strain curves of steel S355 modelled by using the calculation method given in EC 3 compared with the test results at temperatures 500, 600 and 700°C.

4 MODELLED STRESS-STRAIN RELATIONSHIP COMPARED WITH EC3

A comparison between the calculated stress-strain curves using eqns (1)–(7) and the stress-strain curves of the original EC3 at temperatures 300–700°C is illustrated in Fig. 6.

It can be seen that the stress-strain curves for structural steel determined with the method based on transient state tensile tests are mostly above the EC3 curves and therefore the calculations with the model given in EC3 are safe for structural steel S355.

5 CALCULATION METHOD OF W. RAMBERG AND W. R. OSGOOD

5.1 Ramberg–Osgood model

The stress-strain relationship of steel S355 at elevated temperatures based upon transient state tensile test results was also modelled by using the calculation method developed by W. Ramberg and W. R. Osgood [5]. The equation for calculating the stress-strain values of steel at elevated temperatures with this method is usually given as in eqn (8). The value of β is $3/7$.

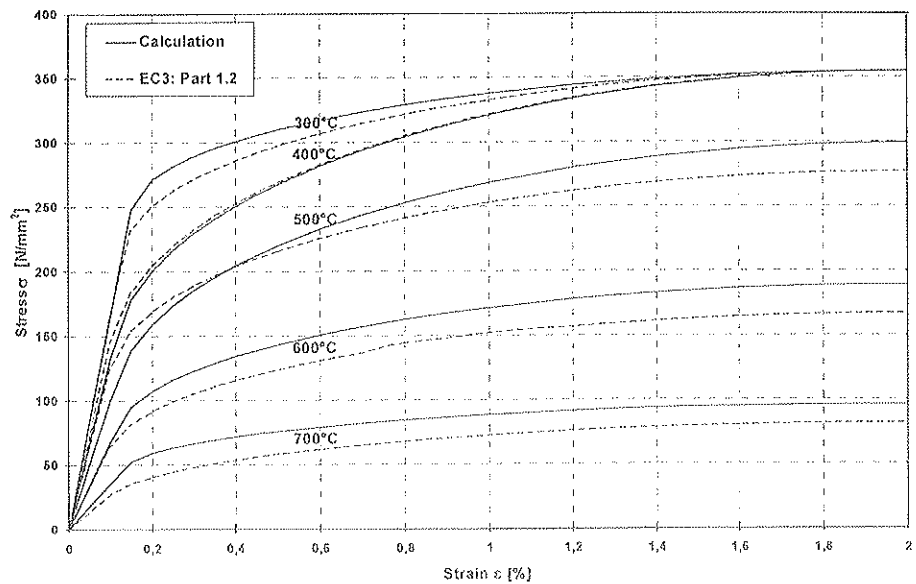


Fig. 6. Comparison between the calculated stress-strain curves and those given in EC3.

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

5.2 Stress–strain relationship for structural steel S355

Simple formulas for calculating the parameters of the Ramberg–Osgood model were determined from the test results. The values of elasticity modulus $E_{a,\theta}$ are calculated with eqns (1) and (2). The values of yield strength $f_{y,\theta}$ are calculated with eqns (9) and (10). In this model the yield strength is based on non-proportional strain 0.2%. Values of parameter n_θ at temperatures 20–300°C are given in Table 1. Intermediate values can be calculated by using linear interpolation. The values for parameter n_θ at temperatures 300–700° are calculated by using eqn (11). In this model the value of β in eqn (8) is 6/7.

$$f_{y,\theta} = f_y - 0.016667 \cdot (T_a - 20), \text{ for } 20^\circ\text{C} \leq T_a \leq 200^\circ\text{C} \quad (9)$$

$$f_{y,\theta} = 352 - 0.54 \cdot (T - 200), \text{ for } 200^\circ\text{C} < T \leq 700^\circ\text{C} \quad (10)$$

$$n_\theta = 0.000231 \cdot T^2 - 0.231 \cdot T + 62.5, \text{ for } 300^\circ\text{C} \leq T \leq 700^\circ\text{C}. \quad (11)$$

Modelled stress–strain curves of steel S355 at temperatures 300–700°C are compared with the test results in Fig. 7.

6 CONCLUSIONS

Stress–strain curves determined for structural steel S355 based upon the transient state tensile test results are mostly above the stress–strain curves given in EC3: Part 1.2 [4]. The modified Ramberg–Osgood model is also applicable

TABLE 1
Parameter $n(T)$ at Temperatures 20–300°C for Steel S355

Temperature T (°C)	Parameter $n(T)$
20	230
100	190
200	140
225	54
250	28
300	14

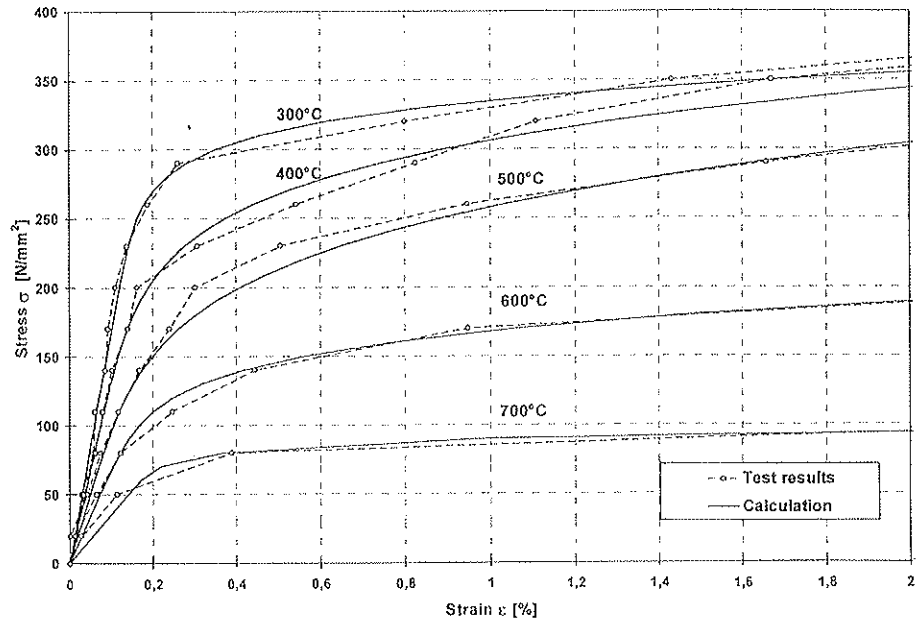


Fig. 7. Stress–strain curves for steel S355 determined by using the modified Ramberg–Osgood model compared with the test results at temperatures 300–700°C.

for use in fire design. The original Ramberg–Osgood model [6] modified by Olawale–Plank [5] is applicable for steel S355 only up to non-proportional strain 0.2%. With bigger strain values, the stress–strain curves rise above the test results.

The main purpose of this research was to study the behaviour of structural steel S355 [7] under fire conditions and to develop simple formulas for calculating the mechanical material properties of the studied material. In the Laboratory of Steel Structures at Helsinki University of Technology there has also been experimental research on structural steels S235 and S420M and on structural sheet steels S320GD + Z and S350GD + Z [8] using the transient state tensile test method. Similar research has also been carried out for one aluminium alloy and for one austenitic stainless steel. The test results of different steel grades vary so considerably from each other that more experimental research is clearly needed to obtain detailed information about mechanical properties at elevated temperatures for all the steel grades used in steel structures.

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