TRANSIENT STATE TENSILE TEST RESULTS OF STRUCTURAL STEEL S355 (RAEX 37-52) AT ELEVATED TEMPERATURES

Jyri Outinen
Pentti Mäkeläinen

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ABSTRACT

An experimental research is carried out for investigating mechanical properties of structural steel S355 at elevated temperatures. Test values of thermal elongation, modulus of elasticity and yield stress and stress-strain curves are compared with the values and curves given in Eurocode 3 /1/, in the European Recommendations for the Fire Safety of Steel Structures /2/ and in the Finnish Code of Steel Structures /10/.

INTRODUCTION

The main purpose of this research was to examine the mechanical properties of structural steel S355 at temperatures 20°C..700°C using transient state tensile test method. Transient state tensile tests have not been done before this in Finland for structural steel S355 and therefore a comprehensive experimental study was of great importance.

Experimental work was carried out during September and October 1994 at Helsinki University of Technology in the Laboratory of Steel Structures. Financing for the research was provided by Rautaruukki Oy.

Results of this study are compared with the values of mechanical properties given in Eurocode 3 /1/, in the European Recommendations for the Fire Safety of Steel Structures /2/ and in the Finnish Code of Steel Structures /10/.

STEEL MATERIAL S355 (RAEX 37-52)

Test material used in this research was hot-rolled structural steel S355 (RAEX 37-52) manufactured by Rautaruukki Oy. Test specimens were cut out from a hot-rolled steel sheet with nominal thickness of 12mm, longitudinally to rolling direction. Structural steel material is in accordance with the requirements of the European standard SFS-EN 10 025 /9/ for structural steel S355.

Mechanical properties of the test material at room temperature

Four tensile tests were carried out at room temperature to determine the mechanical properties of the test material at room temperature. Results from the transient and steady state tests were compared with these results. Six tensile tests were carried out to determine modulus of elasticity for the test material. Tensile tests were carried out as stress rate-controlled. The rate of loading was 0.52 $(N/mm^2)/s$ which caused a rate of strain of 0.003 min^{-1} to the test specimen. Stress-strain curves were used to determine the tensile properties for each test specimen.

Test results from the tensile tests are compared in Table 1 with the minimum values given by the manufacturer and the measured values given in the test report of the inspection certificate of the test material .

Table 1. Test results, minimum values given by the manufacturer and measured values given in the test report of the inspection certificate.

	Measured value	Minimum requirement	Reported test value of inspection certificate
Modulus of elasticity E (N/mm^2)	210 600	206 000	not measured
Yield stress R_{eH} (N/mm^2)	406.1	355	416
Ultimate stress R_m (N/mm^2)	526.9	490-630	548

Chemical composition of the test material

Chemical composition of the test material including comparisons with maximum values given by the manufacturer is presented in Table 2.

Table 2. Chemical composition of the steel material S355 (RAEX 37-52).

Elementary substance		Measured value (%)	Maximum value (%)
Carbon	C	0.150	0.180
Silicon	Si	0.180	0.500
Manganese	Mn	1.410	1.600
Niobium	Nb	0.010	0.050
Sulphur	S	0.011	0.020
Phosporus	P	0.019	0.025
Aluminium	Al	0.041	minimum 0.020

TESTING FACILITIES

Test specimen

The test specimen having so called proportional circular cross-section was in accordance with the standard EN 10 002-5 /5/. The test specimen is shown in Fig. 1. Dimensions of the test specimen are given in Table 3.

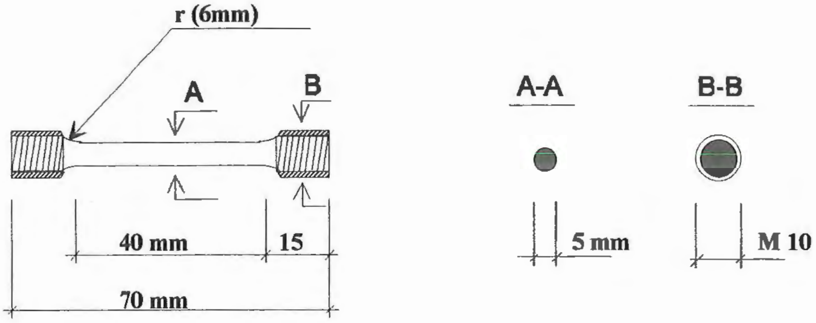

Fig. 1. Test specimen

Table 3. Dimensions of the test specimen.

Total length	L_t	70 mm
Parallel length	L_c	40 mm
Original gauge length	L_0	25 mm
Diameter	d	5 ±0.040 mm
Metric screw thread M10		10 mm
Radius of curvature	r	6 mm

Testing device

The tensile testing machine used in this research was manufactured by the German company Roell+Korthaus. Testing machine is verified in accordance with the standard EN 10 002-2 /6/. Loading range can be chosen between 0..50 kN and 0..250 kN. Loading range used in these tests was 0..50 kN. Maximum load used was about 11 kN. Maximum loading capacity of the machine is 250 kN. Maximum error of the load cell is ±0.05kN by the use of maximum loading capacity.

Gauge length of the extensometer used in this research was 25mm with elongation range of 0..2.5mm. The extensometer has an accuracy of ±0.003mm. The extensometer is in accordance with the standard EN 10 002-4 /7/.

The heating device was manufactured by the German company Maytec GmbH. The device is in accordance with the standard EN 10 002-5 /8/. The oven in which the test specimen is situated during the tests was heated by using three separately controlled resistor elements. The temperature-controlling unit is manufactured by the British company Eurotherm Ltd. 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 temperature-detecting element that was fastened to the specimen during the heating. The temperature-measuring device has an accuracy of ± 3°C. The testing device is shown in Fig.2. The difference between the air temperature and the steel temperature during the tests is given in Table 4.

Table 4. Measured temperature of the test specimen compared with the measured air temperature in the heating oven.

Steel temperature (°C)	**Air temperature (°C)**	**Steel temperature (°C)**	**Air temperature (°C)**
20	20	400	432
50	96	450	470
100	173	500	509
150	226	550	551
200	268	600	600
250	310	650	650
300	352	700	700
350	392	750	750

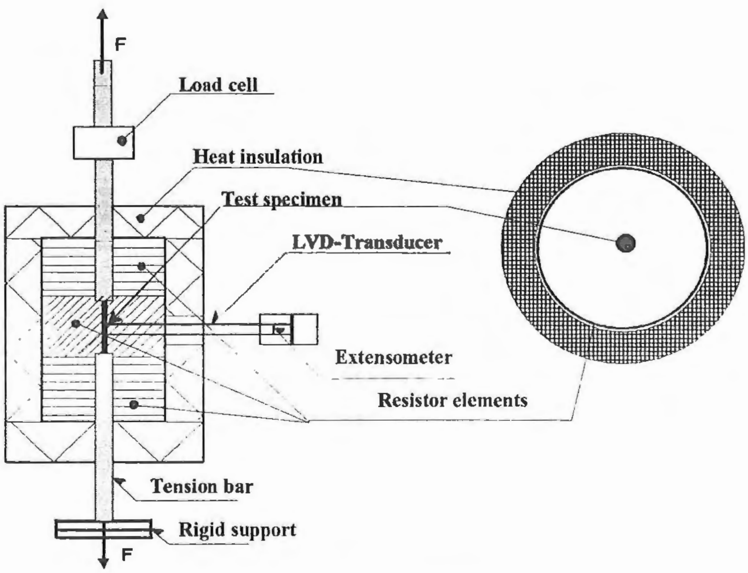

Fig.2. The transient state tensile testing device.

TEST RESULTS

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 and 350 N/mm^2. Thermal elongation of the structural steel was determined with five tests at load level of 3N/mm^2.

Heating rate in the transient state tests was 10°C min^{-1}. Temperature was measured accurately from the test specimen during the heating.

Test specimen was heated until the temperature was 750°C or until breaking of the test specimen. In the temperature-strain relationship, thermal elongation was subtracted from the total strain. Final results were converted into stress-strain curves using the method given in /5/. The test method was in accordance with the standard /8/.

Temperature-strain relationships

Thermal elongation ε_{th} has been considered by subtracting it from the total strain ε_{tot} :

$$\varepsilon_{Ti} = \varepsilon_{tot,Ti} - \varepsilon_{th,Ti} \quad (1)$$

where

ε_{Ti} is elongation at temperature T_i,

$\varepsilon_{tot,Ti}$ is total elongation at temperature T_i and

$\varepsilon_{th,Ti}$ is thermal elongation at temperature T_i.

Measured temperature-strain curves at stress levels of 20-200 N/mm^2 are shown in Fig. 3 and at stress levels of 230-380 N/mm^2 in Fig. 4.

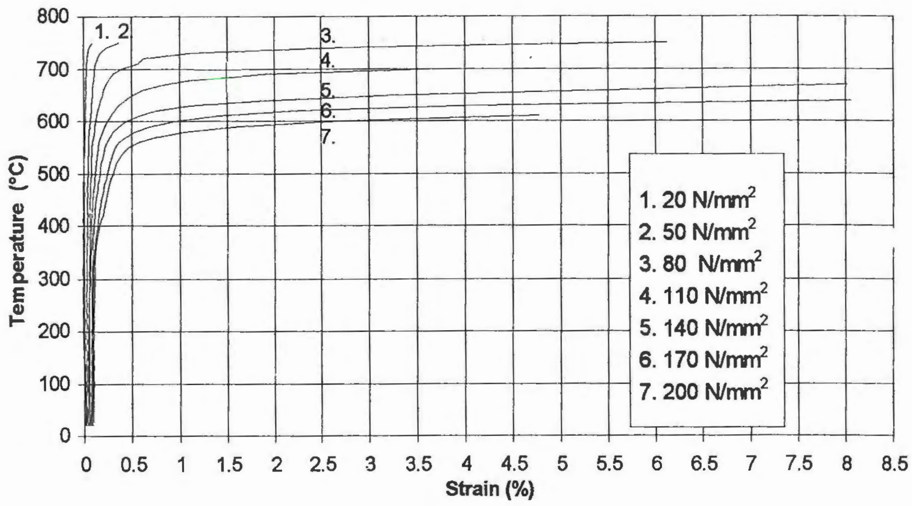

Fig. 3. Temperature-strain curves at stress levels of 20-200 N/mm^2.

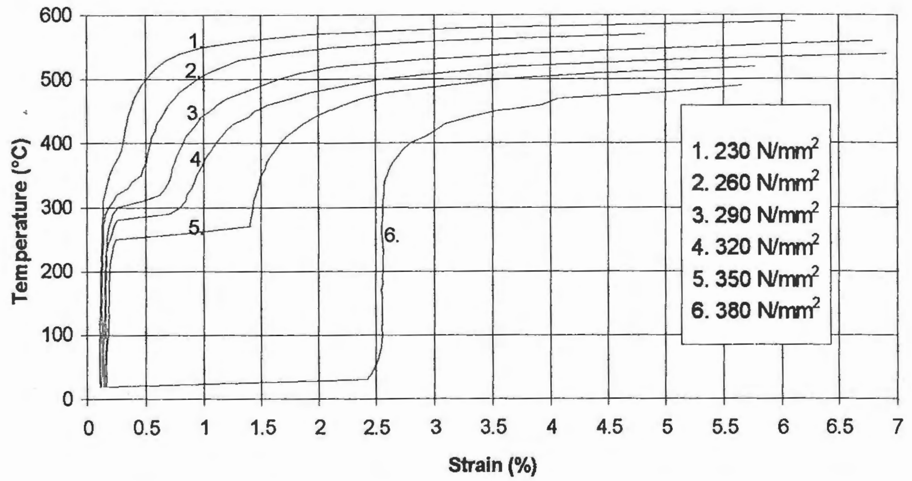

Fig.4. Temperature-strain curves at stress levels of 230-380 N/mm^2.

Thermal elongation

Thermal elongation of the structural steel 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. Thermal elongation was measured during the heating process.

An analytical expression was fitted into the average test values by following equation:

$$\Delta l/l = 5\times10^{-9}\,T_S^{\,2} + 0.8\times10^{-5}T_S - 0.000197 \qquad (2)$$

where

$\Delta l/l$ is relative thermal elongation and

T_S is steel temperature.

The regression coefficient for equation (1) is 0.9981. Results of the five tests and the average are shown in Fig. 5. Average thermal elongation values of the five tests are compared with the analytical expression in Fig. 6.

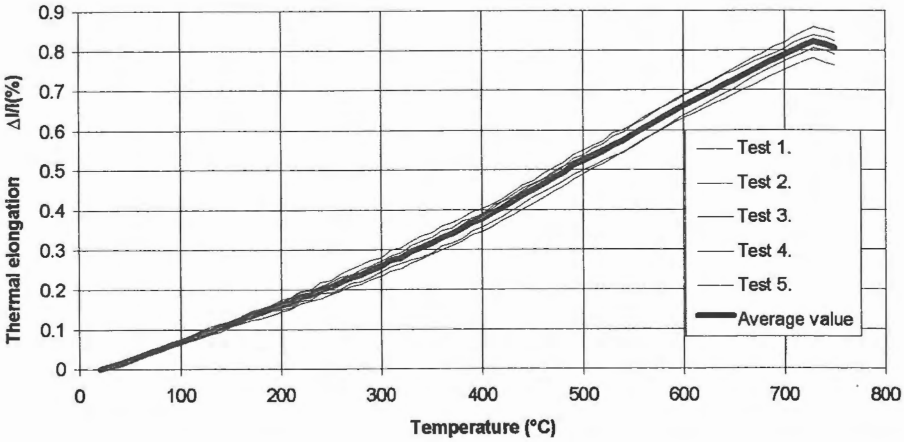

Fig. 5. Temperature dependence of thermal elongation of structural steel S355 (RAEX 37-52): Curves from five tests and the average curve.

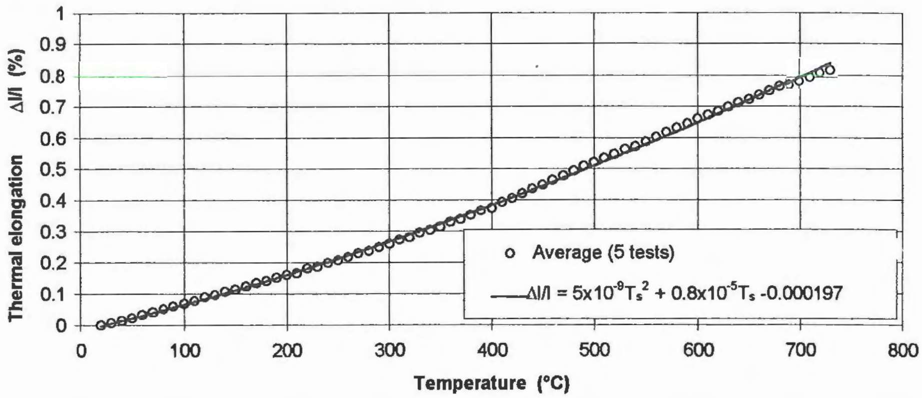

Fig. 6. Temperature dependence of thermal elongation of structural steel S355 (RAEX 37-52): The average curve and an analytical expression fitted into the average curve.

In the Laboratory of Steel Structures at Helsinki University of Technology, thermal elongation has been measured earlier for structural steel S235 (Fe360) and for cold-formed sheet steel Z32. In this research it was measured for structural steel S355 (RAEX 37-52). The thermal elongation of all these steels differs from the values given in Eurocode 3: Part 1.2 for structural steels. Comparison of the thermal elongation of these three materials is shown in Fig. 7. The results for structural steels S235 and S355 are compared with the thermal strain according to Eurocode 3: Part 1.2 in Fig. 8.

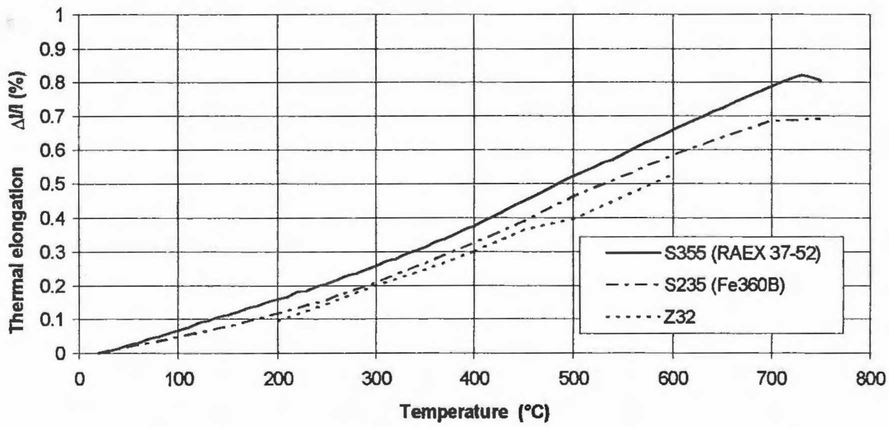

Fig 7. Thermal elongation determined for structural steels S235 (Fe360) and S355 (RAEX 37-52) and for cold-formed steel Z32.

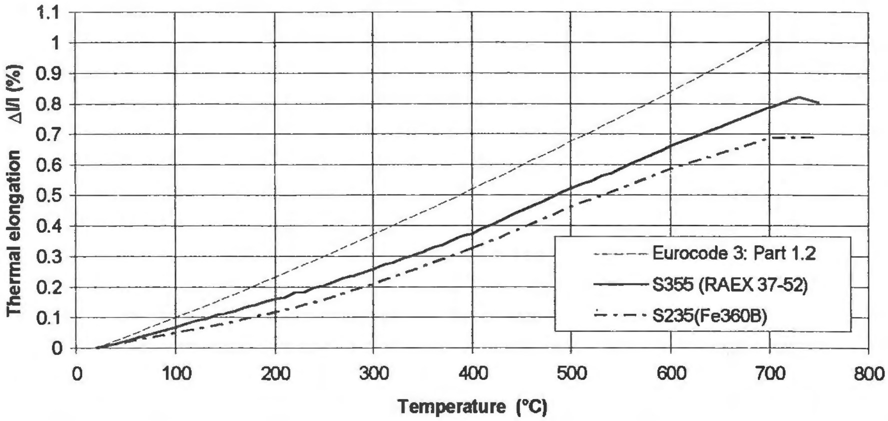

Fig. 8. Thermal elongation of structural steels S235 (Fe360) and S355 (RAEX 37-52) compared with thermal elongation according to Eurocode 3: Part 1.2.

Stress-strain relationships

The transient state tensile test results converted into stress-strain curves at temperatures 100°C-700°C are shown in Fig. 9. Stress-strain curves for test material S355 (RAEX 37-52) at temperatures 300°C-700°C are compared in Fig.10 with stress-strain curves given in Eurocode 3: Part 1.2 /1/.

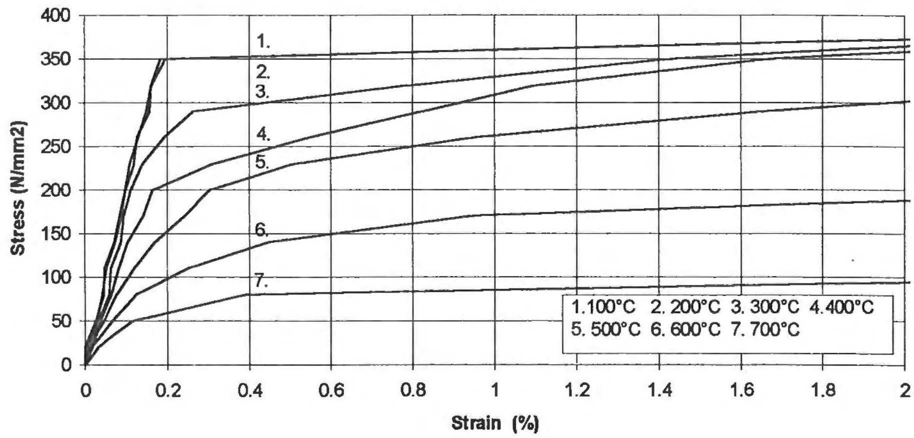

Fig.9. Stress-strain curves for test material S355 (RAEX 37-52) at temperatures 100°C-700°C.

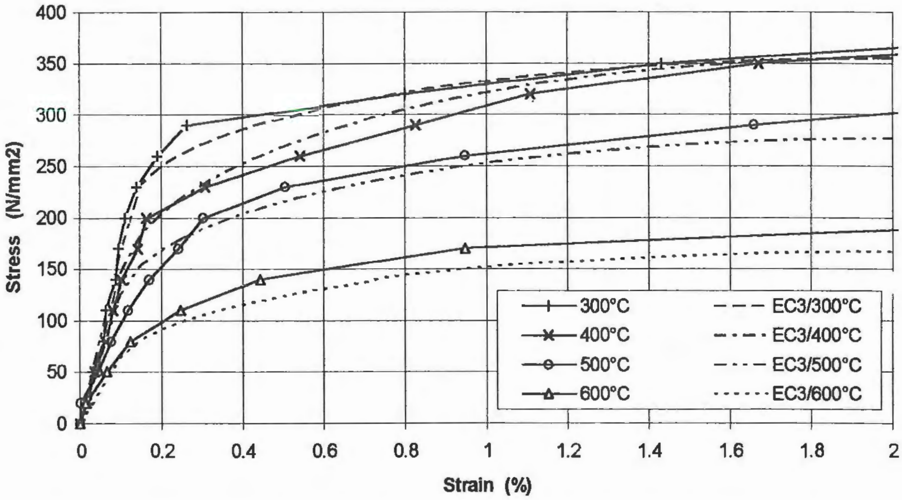

Fig. 10. Stress-strain curves for test material S355(RAEX 37-52) at temperatures 300°C-700°C compared with stress-strain curves of Eurocode 3: Part 1.2 .

Modulus of elasticity

Modulus of elasticity of structural steel S355 (RAEX 37-52) was determined from the stress-strain curves which were converted from the transient state test results. The modulus of elasticity was determined as an initial slope of the stress-strain curves.

The modulus of elasticity for the steel material S355 (RAEX 37-52) at room temperature was determined with six tensile tests and the average value of these tests was 210 600 N/mm^2. The value given by the manufacturer is 206 000 N/mm^2. The experimental value is used as a reference value in analysing the transient state test results .

Test results at temperatures 20°C - 700°C are compared in Fig. 11 with the values of mechanical properties given in Eurocode 3 /1/, in the European Recommendations for the Fire Safety of Steel Structures /2/ and in the Finnish Code of Steel Structures /8/ .

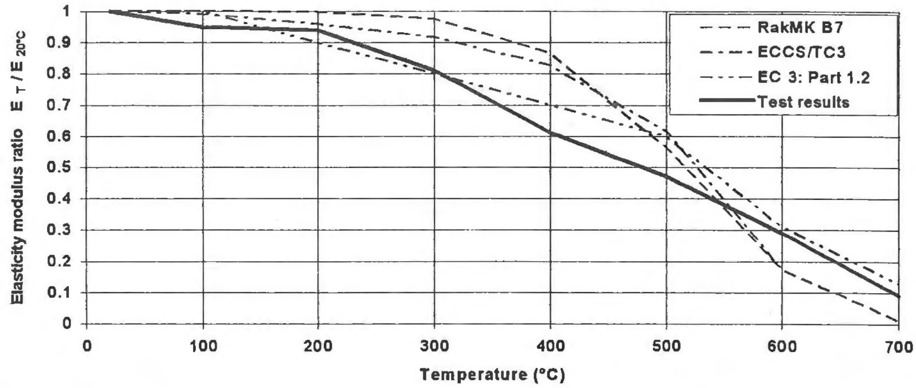

Fig. 11. Comparison of elasticity modulus ratio $E_T/E_{20°C}$ at temperatures 20°C -700°C.

Yield stress

Yield stress was determined for the test material S355 (RAEX 37-52) from the stress-strain curves based on the transient state test results. Test results for yield stress $\sigma_{0.2}$ ($R_{p0.2}$), based upon 0.2% non-proportional extension as defined in /8/, are shown in Fig.12. Test results are compared with the values for $\sigma_{0.2}$ according to the Eurocode 3 /1/ and with the values according to the Finnish Code /10/. Test results for yield stress $\sigma_{0.5}$,$\sigma_{1.0}$ and $\sigma_{2.0}$, based upon total extension of 0.5%, 1.0% and 2.0 % , are shown in Figs. 13, 14 and 15. Test results are compared with the values for $\sigma_{0.5}$,$\sigma_{1.0}$ and $\sigma_{2.0}$ according to the Eurocode 3: Part 1.2 /1/. The reduction factors for effective yield strength given in Eurocode 3 are based on values of yield stress $\sigma_{2.0}$.

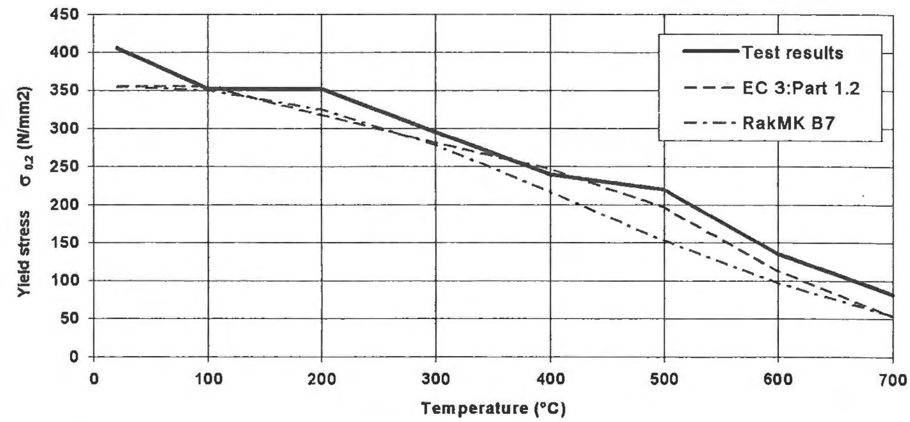

Fig 12. Yield stress $\sigma_{0.2}(R_{p0.2})$ for steel S355(RAEX 37-52) at temperatures 20°C-700°C.

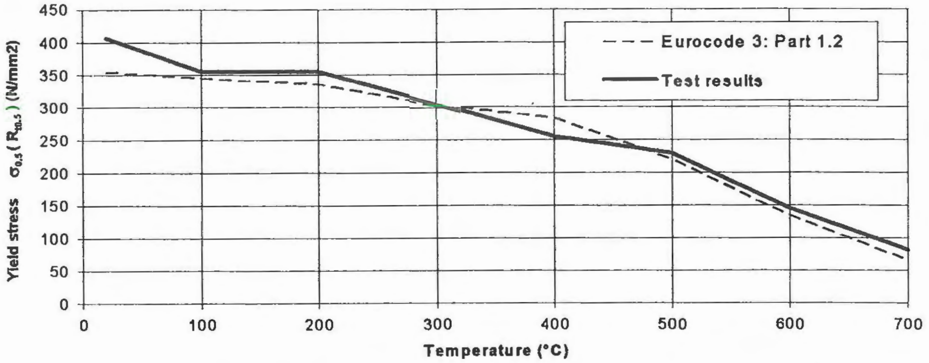

Fig. 13. Yield stress $\sigma_{0.5}$ ($R_{t0.5}$) for steel S355(RAEX 37-52) at temperatures 20℃-700℃.

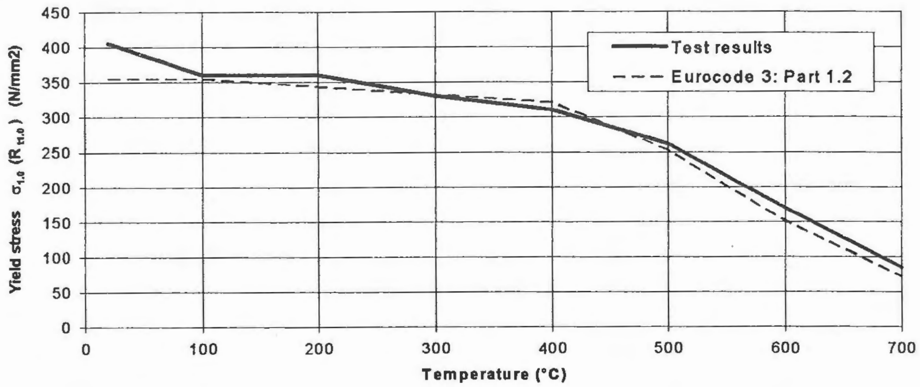

Fig. 14. Yield stress $\sigma_{1.0}$($R_{t1.0}$) for steel S355(RAEX 37-52) at temperatures 20℃-700℃.

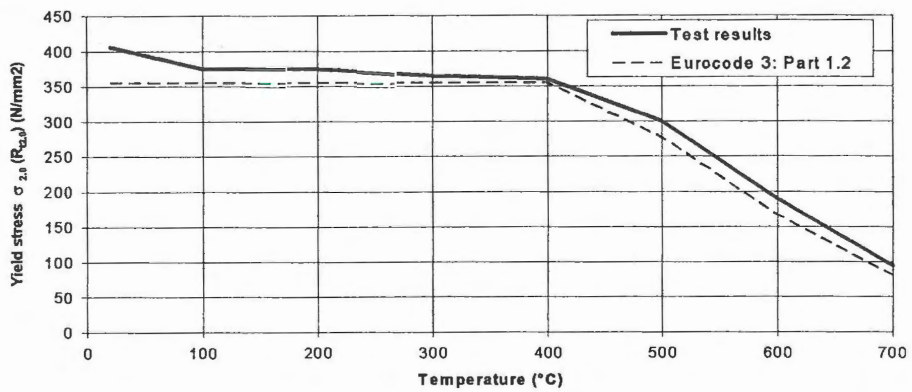

Fig. 15. Yield stress $\sigma_{2.0}$ ($R_{t2.0}$) for steel S355(RAEX 37-52) at temperatures 20℃-700℃.

Steady state tests

Steady state tensile tests were carried out for the test material S355 (RAEX 37-52) with two equal tests at each temperature 400°C, 500°C and 600°C.

Tensile tests were carried out as stress rate-controlled. The rate of loading was 0.52 $(N/mm^2)/s$ which caused a rate of strain of 0.003 min^{-1} in the test specimen.

Stress-strain relationships

Stress-strain curves measured from the steady state tests at temperatures 400°C, 500°C and 600°C are shown in Fig. 16. Stress-strain curves from the steady state tests are compared with transient state test curves in Fig. 17.

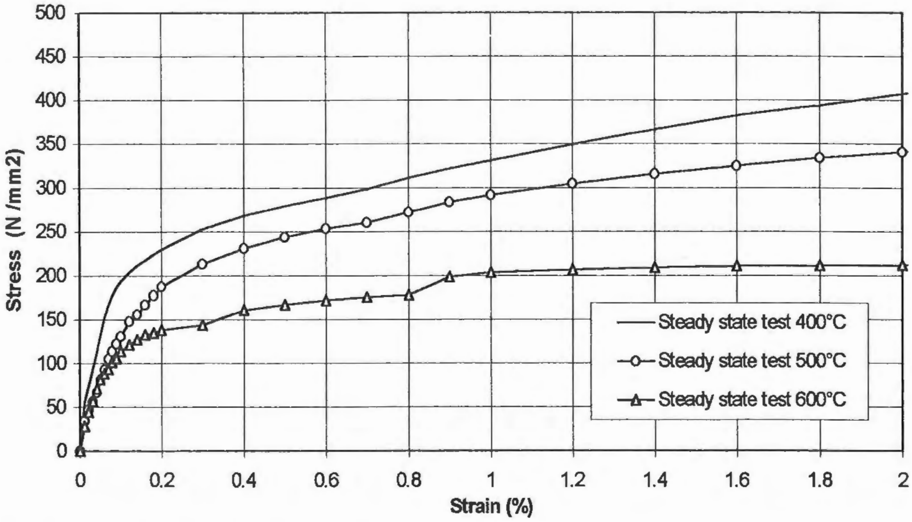

Fig. 16. Stress-strain curves for steel S355 (RAEX 37-52) measured in the steady state tests at temperatures 400 °C, 500 °C and 600 °C.

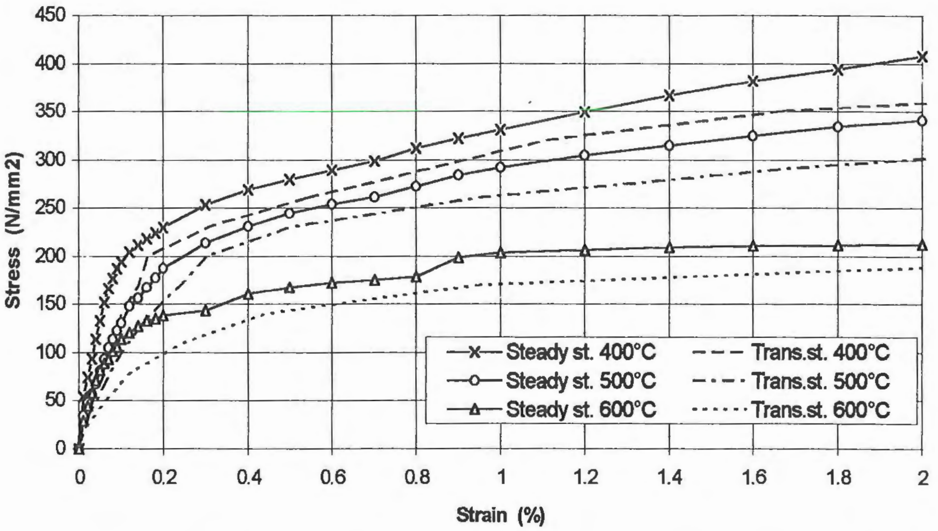

Fig. 17. Measured steady state stress-strain curves for steel S355 (RAEX 37-52) at temperatures 400°C, 500°C and 600°C compared with the measured transient state curves.

<u>Mechanical properties of the test material based on steady state data</u>

Mechanical properties of the test material S355 (RAEX 37-52) determined with the steady state data are given in Table 5.

Table 5. Mechanical properties of the test material S355 (RAEX 37-52) at temperatures 400°C, 500°C and 600°C based on steady state data.

Temperature (°C)	Yield stress $\sigma_{0.2}$ (N/mm^2)	Yield stress $\sigma_{0.5}$ (N/mm^2)	Ultimate stress f_u (N/mm^2)
400	249.5	280.0	515.0
500	230.2	245.0	380.0
600	167.8	170.0	226.0

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Jyri Outinen, Graduating student
Laboratory of Steel Structures
Helsinki University of Technology

Pentti Mäkeläinen, Professor, Dr. Tech.
Laboratory of Steel Structures
Helsinki University of Technology