Appendix D

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A STUDY FOR THE DEVELOPMENT OF THE DESIGN OF STEEL STRUCTURES IN FIRE CONDITIONS

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SUMMARY

A study for the development of the design of steel structures in fire conditions has been started 1999 in the Laboratory of Steel Structures at Helsinki University of Technology. The objective of this project is to develop the fire engineering design of steel and steel-concrete composite structures using as a starting point the research done at the Technical Research Centre of Finland (VTT) on fire models for different types of buildings. The development of temperature increase in steel structures is studied. Material models in fire conditions based on experimental results are used to determine the load-bearing capacity of structures in fire. The point is to make use of the possibility of performing a more thorough and exact fire design given by, e.g. the Finnish design standards.
In connection to the above, an extensive experimental research program has been carried out during the years 1994-2000 in the Laboratory of Steel Structures at Helsinki University of Technology for the investigation of the mechanical properties of various structural steels at elevated temperatures. The latest research has concentrated on structural steel S355J2H. The tests are carried out for cold-formed material taken from rectangular hollow sections. The purpose of this research is to study the behaviour of this cold-formed steel material at fire temperatures using both transient state and steady state tensile test methods. The test results for this material and also for structural steels with yield strength 355N/mm^2 and 460N/mm^2 and for structural sheet steel with yield strength 350N/mm^2 are presented shortly in this paper.

KEYWORDS

Steel, structural steel, mechanical properties, strength, fire, high-temperature, elevated temperature, cold-formed, material model.

INTRODUCTION

Basic material research of structural steel materials is becoming more important as the significance of fire engineering 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 near future. Extensive experimental research has been carried out during the years 1994-2000 in the Laboratory of Steel Structures at Helsinki University of Technology in order to investigate mechanical properties of several structural steels at elevated temperatures by using mainly the transient state tensile test method. Furthermore one austenitic stainless steel grade and one aluminium alloy have been studied with the same test method. Another method, the steady-state method has also been used in order to create a proper basis for the analyses of the test results.

In this paper the experimental test results for the mechanical properties of the studied steel grades S350GD+Z, S355 and S460M at fire temperatures are presented with a short description of the testing facilities. A test series is also carried out for cold-formed material taken from rectangular hollow sections.

The test results are used to determine the temperature dependencies of the mechanical properties, i.e. yield strength, modulus of elasticity and thermal elongation, of the studied steel materials at temperatures up to 950°C. The test results are compared with the material model for steel according to Eurocode 3: Part 1.2. The test results are presented as simple figures and graphs of the reduction factors of the mechanical properties, i.e. modulus of elasticity, yield strength and the other calculation parameters that are needed in the Eurocode 3 (EC3) model. Some modificatations to existing fire design codes are suggested based on the test results for the mechanical properties of the studied materials.

STUDIED STEEL MATERIALS

S350GD+Z

The studied material was cold-rolled hot dip zinc coated structural steel S350GD+Z (Z35) manufactured by Rautaruukki Oyj. Test pieces were cut out from a cold-formed steel sheet with nominal thickness of 2mm, longitudinally to rolling direction. Steel material is in accordance with requirements of the European standard SFS-EN 10 147.

S355

The steel grade used in this part of the research was hot-rolled structural steel S355 manufactured by Rautaruukki Oyj. Test pieces were cut out from a cold-rolled steel sheet with nominal thickness of 4mm, longitudinally to rolling direction. Structural steel material is in accordance with the requirements of the European standard SFS-EN 10 025 (1993) for structural steel grade S355.

S460M

The tests for structural high-strength steel S460M were carried out using test specimen that were made from 20mm thick steel plate. The pieces were cut out longitudinally to rolling direction. The material fills the requirements given in standard SFS-EN 10113 for structural steel S460M.

S355J2H
The tensile tests for structural steel S355J2H were carried out using test specimens that were cut out from SHS-tubes 50x50x3, 80x80x3 and 100x100x3 longitudinally from the middle of the face opposite to the welded seam. The material is in accordance with the requirements given in standard SFS-EN 10219-1.

TESTING FACILITIES

Test pieces

The tensile test specimens were in accordance with the standard EN 10 002-5 (1992). Strain was measured from the middle of the test piece. The gauge length was 25mm.
The test pieces for base materials were cut out from virgin steel plates. The nominal plate thickness for S350GD+Z was 2 mm , for S355 (base material) it was 3 mm, for high-strength steel S460 it was 20 mm and for the square hollow sections (structural steel S355J2H) the thickness was 3mm.The test pieces were cut out longitudinally to rolling direction.
The test pieces for cold-formed structural steel S355J2H were cut out longitudinally from the middle face opposite to the weld seam of square hollow sections 50x50x3, 80x80x3 and 100x100x3.

Testing device

The tensile testing machine used in the tests is verified in accordance with the standard EN 10 002-2 (1992). The extensometer is in accordance with the standard EN 10 002-4 (1992). The oven in which the test specimen is 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 temperature-detecting element that was fastened to the specimen during the heating.

Test methods

<u>Transient-state test method</u>
In transient-state tests, the test specimen was under a constant load and under a constant temperature rise. Temperature and strain were measured during the test. As a result, a temperature-strain curve was recorded during the test. Thermal elongation was subtracted from the total strain. The transient-state test method gives quite a realistic basis for predicting the material's behaviour under fire conditions. The transient-state tests were conducted with two identical tests at different stress levels. Heating rate in the transient state tests was 20°C min^{-1}. Temperature was measured accurately from the test specimen during the heating.

<u>Steady-state test method</u>
In the steady-state tests, the test specimen was heated up to a specific temperature. After that a tensile test was carried out. In the steady state tests, stress and strain values were first recorded and from the stress-strain curves the mechanical material properties could be determined. The steady state tests can be carried out either as strain- or as load-controlled. In

the strain-controlled tests, the strain rate is kept constant and in the load-controlled tests the loading rate is kept constant.

MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES

Structural sheet steel S350GD+Z

The behaviour of structural steel S350GD+Z at elevated temperatures was studied with 30 high-temperature tests. The test results were combined with an earlier test series that was carried out in the same laboratory. The aim was to add the test results of the mechanical properties at temperatures from 700°C to 950°C to the earlier test results. On the basis of these test results a suggestion concerning the mechanical properties of the studied material was made to a Finnish norm concerning the material models used in structural fire design of unprotected steel members. The suggested reduction factors for modulus of elasticity and yield strength are illustrated in Table 1.

TABLE 1
REDUCTION FACTORS FOR ELASTICITY MODULUS AND YIELD STRENGTH OF STRUCTURAL SHEET STEEL S350GD+Z AT TEMPERATURES 20°C-1000°C

Steel temperature [°C]	$E_{a,\theta} / E_a$ EC 3:Part 1.2	$E_{a,\theta} / E_a$ Proposal	$f_{y,\theta} / f_y$ EC 3:Part 1.2	$f_{y,\theta} / f_y$ Proposal
20	1.0000	1.0000	1.0000	1.000
100	1.0000	1.0000	1.0000	0.970
200	0.9000	0.9000	1.0000	0.932
300	0.8000	0.8000	1.0000	0.895
400	0.7000	0.7000	1.0000	0.857
500	0.6000	0.6000	0.7800	0.619
600	0.3100	0.3100	0.4700	0.381
700	0.1300	0.1300	0.2300	0.143
800	0.0900	0.0900	0.1100	0.105
900	0.0675	0.0675	0.0600	0.067
1000	0.0450	0.0450	0.0400	0.029

The mechanical properties were determined from both transient and steady state test results. In Figures 1 and 2 the measured yield strength and modulus of elasticity are compared with yield strength given in different design codes.

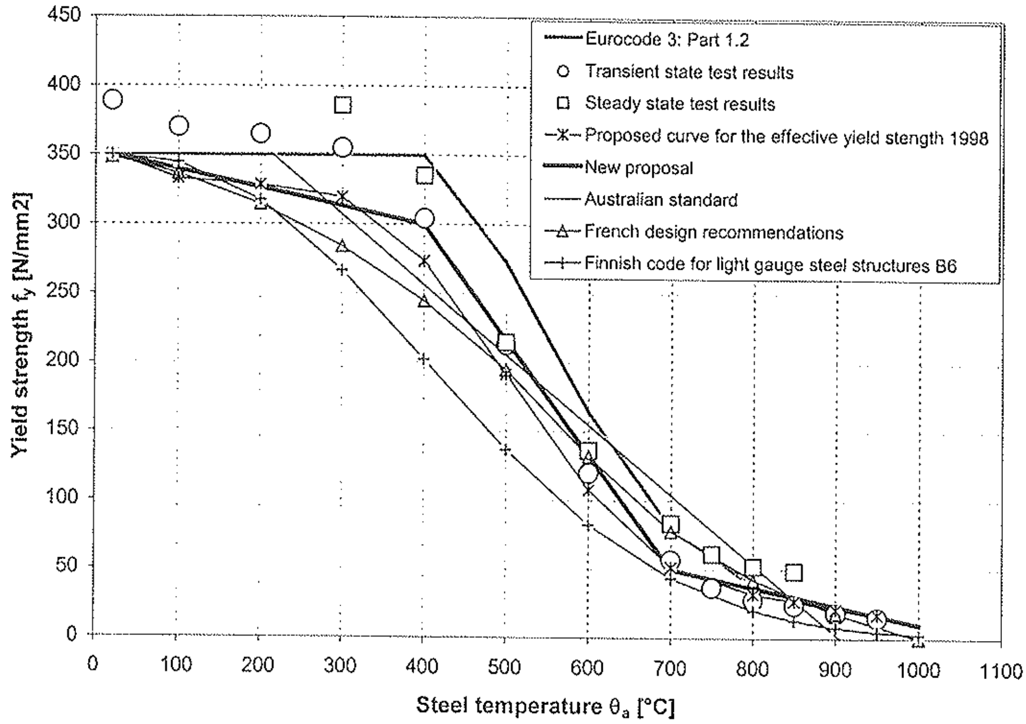

Figure 1:Yield strength of structural steel S350GD+Z determined from test results compared with yield strength given in different design codes.

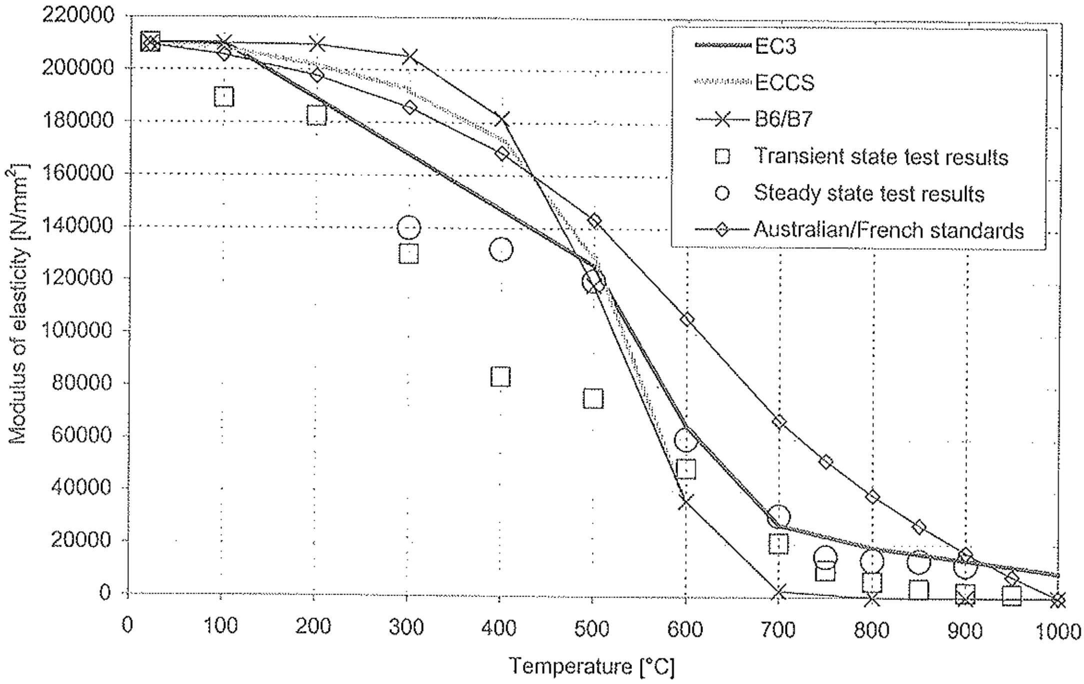

Figure 2: Modulus of elasticity of structural steel S350GD+Z determined from test results compared with yield strength given in different design codes.
Structural steel S355

The high-temperature behaviour of structural steel S355 at elevated temperatures was studied with 30 tensile tests. The test results were combined with an earlier test series that was carried out in the same laboratory. The mechanical properties of sructural steel S355 determined from the transient state tests are illustrated in Table 2.

TABLE 2
MECHANICAL PROPERTIE S OF STRUCTURAL STEEL S355 AT TEMPERATURES 20°C - 950°C

	Modulus of elasticity [N/mm2]		Yield strength f_y [N/mm2]	
Temperature [°C]	EC3: part 1.2	Test results	EC3: part 1.2	Test results
20	210000	210600	355	406
100	210000	200070	355	375
200	189000	197964	355	375
300	168000	170586	355	365
400	147000	128466	355	360
500	126000	98982	276.9	300
600	65100	61074	166.85	190
700	27300	42120	81.65	95
750	23100	18900	60.35	58
800	18900	10500	39.05	44
850	16537.5	5250	30.175	32
900	14175	4200	21.3	22
950	11812.5	3780	17.75	20
1000	9450		14.2	

The tested thermal elongation of structural steel S355 is compared in the next figure with thermal elongation given in Eurocode 3 (EC39. The test results seem to be very near the EC3 values.

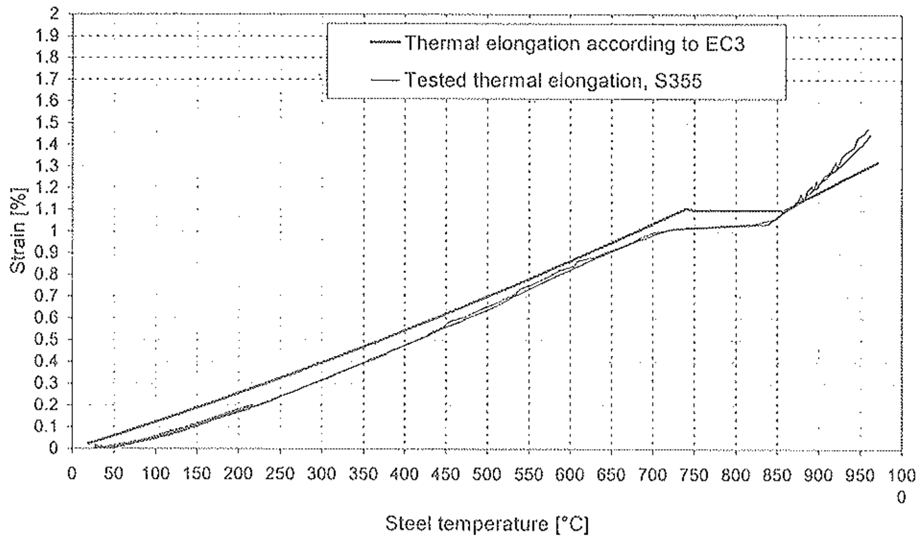

Figure 3: Thermal elongation of structural steel S355 at temperatures 20°C - 950°C

The behaviour of modulus of elasticity and yield strength at elevated temperatures is illustrated in Figures 4 and 5.

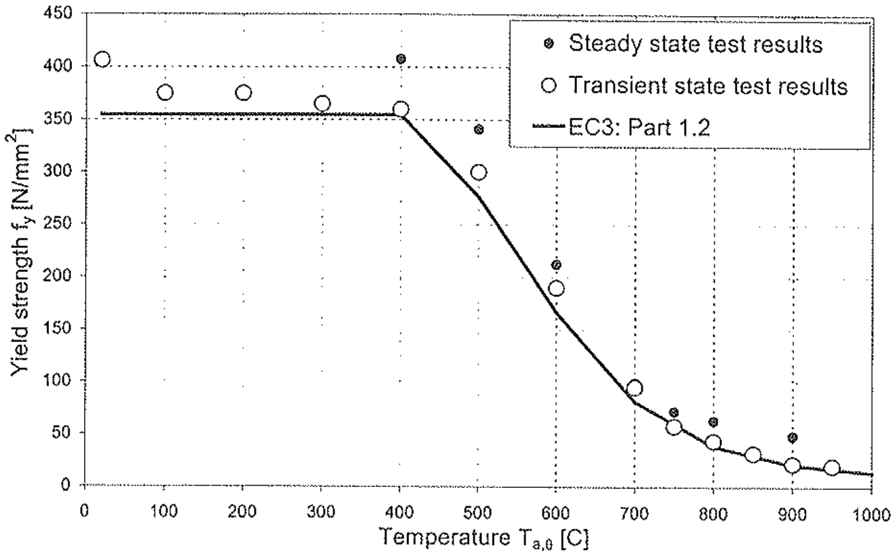

Figure 4: Yield strength of structural steel S355 at temperatures 20°C - 950°C

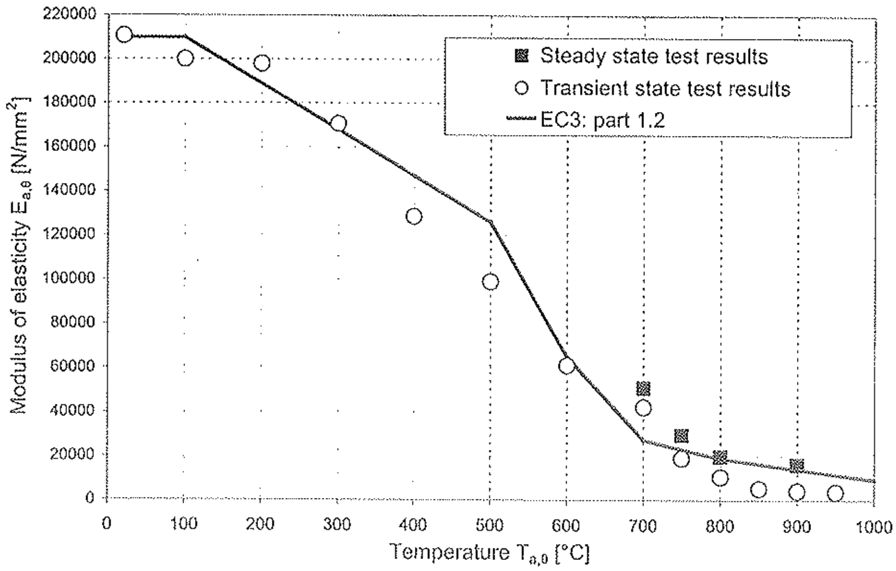

Figure 5: Modulus of elasticity of structural steel S355 at temperatures 20°C - 950°C

The effect of heating rate which also affects the strain rate during tests was studied by carrying out transient state tests at a low stress level. Three different heating rates were used varying from 10°C/min to 30°C/min. The test results within these temperature rates for structural steel did not differ much from each other. In Figure 6 the test results are illustrated as temperature-time curves.

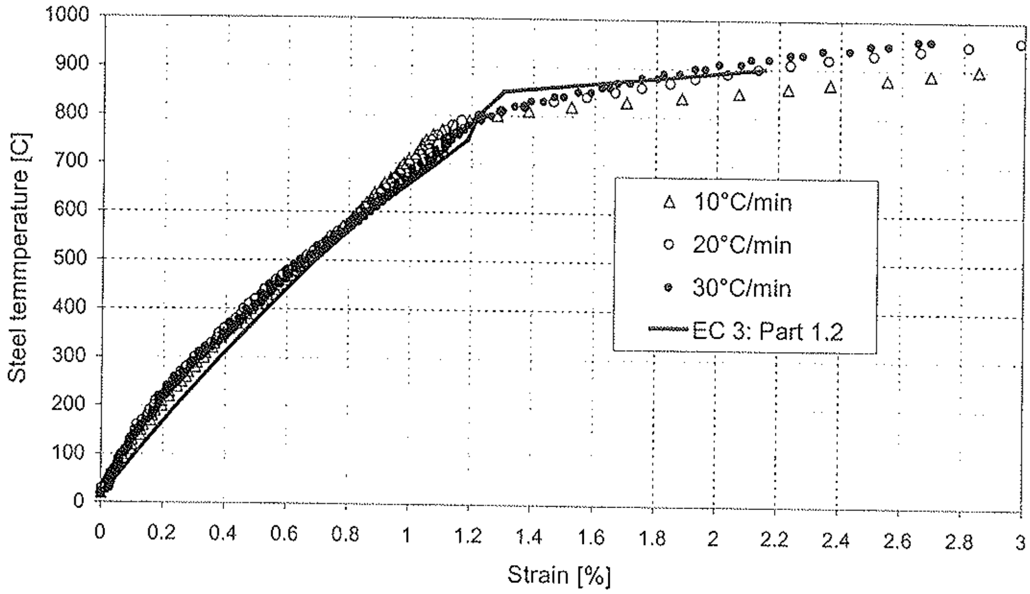

Figure 6: Transient state test results at stress level 20N/mm2 for structural steel S355 with heating rates 10-30°C/min.

The behaviour of structural steel S355 analyzed on the basis of transient state test results seem to be very near the material model given in Eurocode 3: Part 1.2. It can be concluded that within the limits that are given for that model in Eurocode 3 (EC3), the use of it for structural steel S355 is well-grounded in structural fire design of steel structures.

Structural steel S460M

The tests for structural high-strength steel S460M were carried out using test specimen that were made from 20mm thick steel plate. The pieces were cut out longitudinally to rolling direction. The material fills the requirements given in standard SFS-EN 10113 for structural steel S460M. The test pieces were in accordance with the testing standard SFS-EN 10002-5.

A series with 60 test specimen was carried out to study the behaviour of the mechanical properties of structural high-strength steel at elevated temperatures. The tests were carried out using transient state test method. Some steady state tests were also made at temperatures 700°C - 900°C.

The mechanical properties were determined from the stress-strain curves that were converted from the transient state test results.

The yield strength determined on the basis of the test results seems to differ significantly from the Eurocode 3 values at temperatures up until 500°C. At higher temperatures the behaviour follows quite well the Eurocode 3 values.

The experimentally determined modulus of elasticity follows the EC3 values at temperatures up until 500°C. At higher temperatures there is a notable difference between the test results and EC3. The reduction factors for the modulus of elasticity and yield strength are illustrated in Figures 7 and 8.

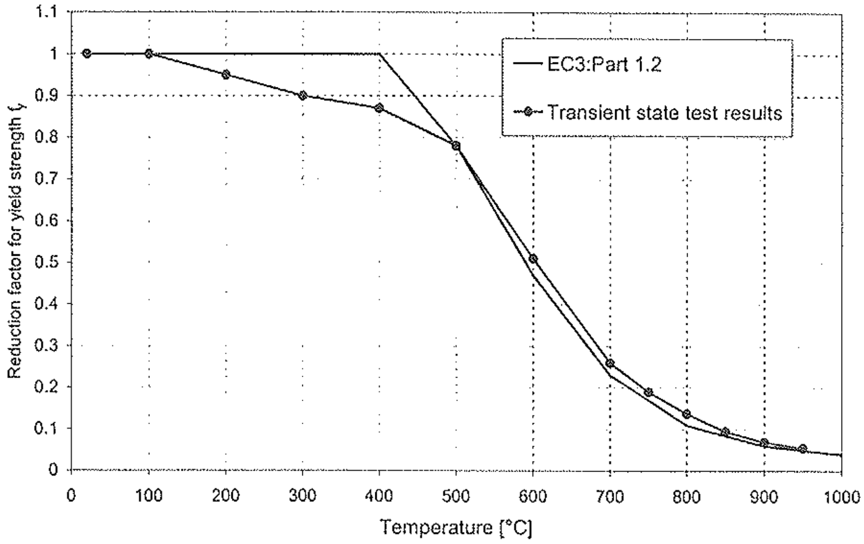

Figure 7: The behaviour of yield strength of structural steel S460M at high temperatures

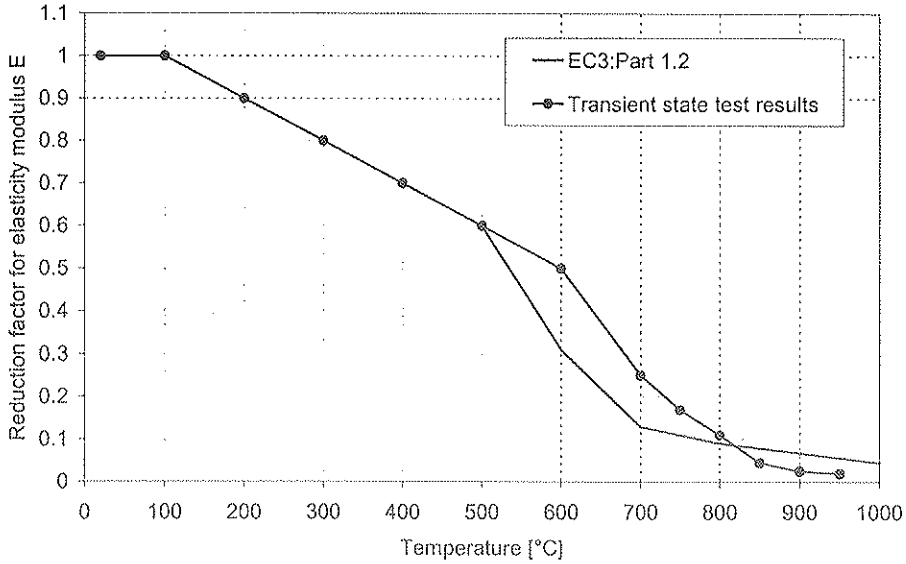

Figure 8: The behaviour of modulus of elasticity of structural steel S460M at high temperatures

The strain rate in the transient state tests before yielding is about 0.004 - 0.001 min^{-1}. In the high-temperature testing standard SFS-EN 10002-5 the strain rate limit is set to 0.003min^{-1}. Some steady state tests were carried out to check the effect of the strain rate to test results. In figure 12 it can clearly be seen that the test results from tests with a high strain rate are significantly higher than the test results determined according the European standard. The strain rate in these tests varies between 0.006..0.01 min^{-1} in the elastic range. The test results are illustrated in Figures 9-11.

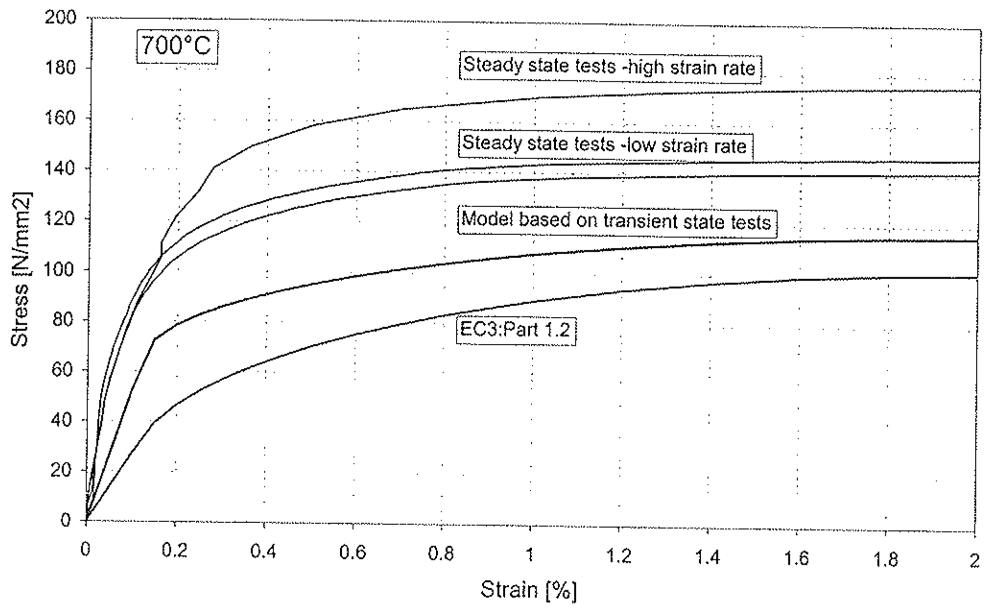

Figure 9: Steady state test results of structural steel S460M at temperature 700°C compared with the transient state tests and Eurocode 3: Part 1.2

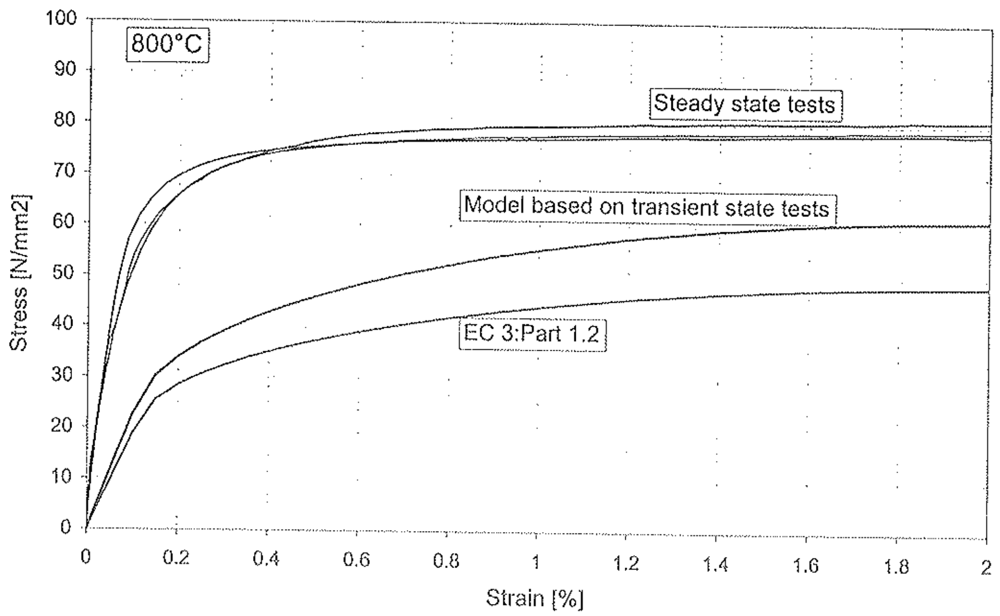

Figure 10: Steady state test results of structural steel S460M at temperature 800°C compared with the transient state tests and Eurocode 3: Part 1.2

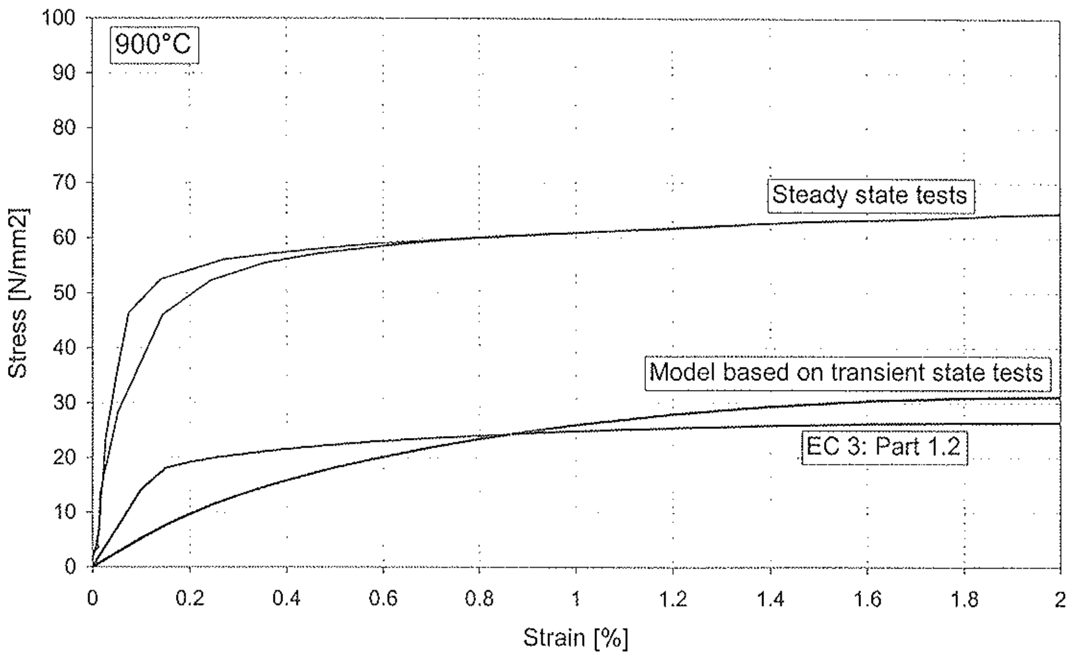

Figure 11: Steady state test results of structural steel S460M at temperature 900°C compared with the transient state tests and Eurocode 3: Part 1.2

Structural steel S355J2H

Most of the transient state tests for this material have been carried out for the material taken from SHS 50x50x3. A few tests have also been performed to the materials taken from SHS 80x80x3 and SHS 100x100x3. The heating rate in the tests was 20°C/minute. Some tests were also carried out with 10°C/minute and 30°C/minute.

The transient state tests have so far been carried out with stress levels 5...460N/mm^2 for the material taken from SHS 50x50x3. Two tests have also been performed for the material taken from SHS 80x80x3 and for SHS 100x100x3 at stress level 100N/mm^2.

The test results have been fitted into the EC3: Part 1.2 material model using the calculation parameters determined from the transient state tests. The modified stress-strain curves are presented in the next Figures 12 and 13.

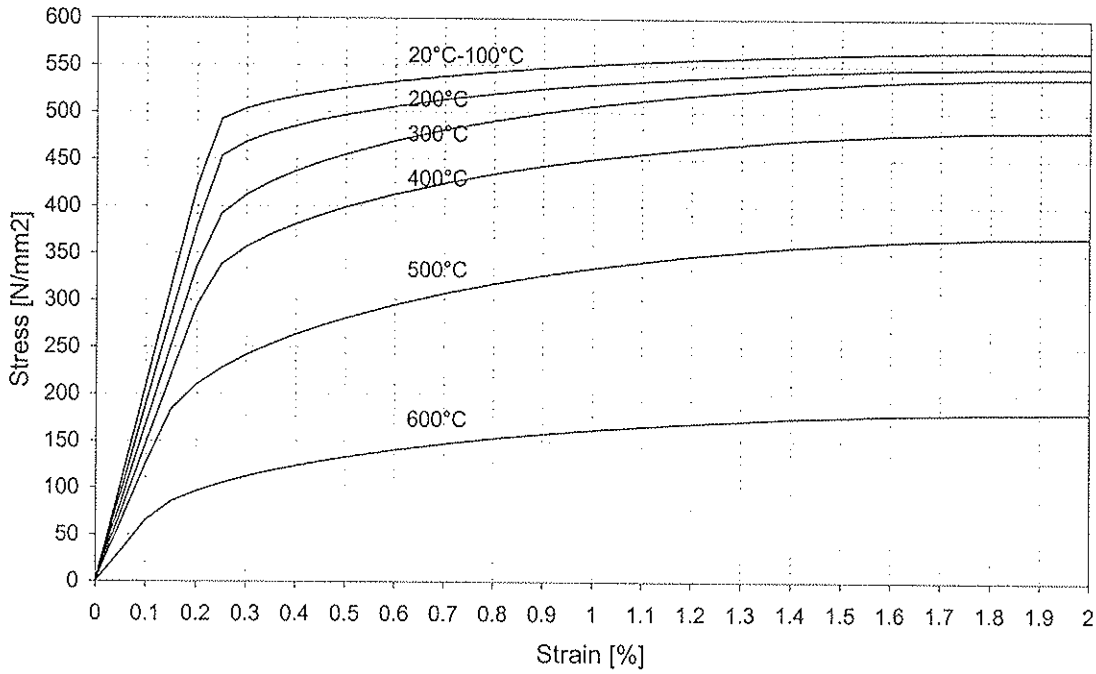

Figure 12: Stress-strain curves of structural steel S355J2H at temperatures 20°C - 600°C. Test pieces taken from SHS 50x50x3.

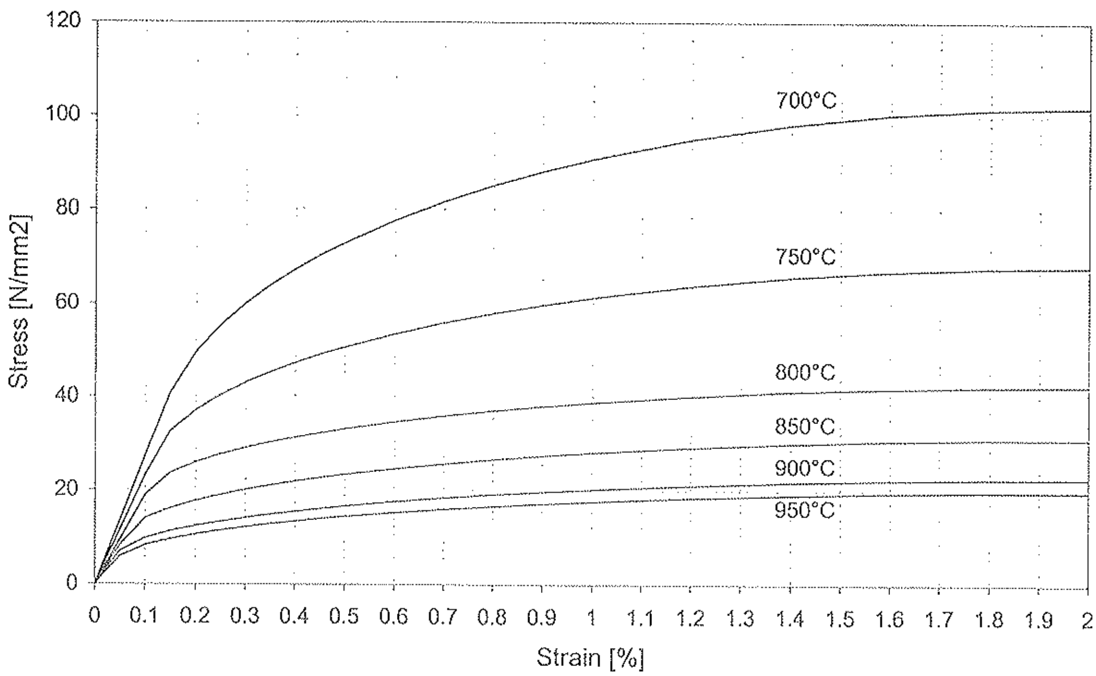

Figure 13: Stress-strain curves of structural steel S355J2H at temperatures 700°C - 950°C. Test pieces taken from SHS 50x50x3.

The test results for yield strength f_y, $R_{p0.2}$ and $R_{t0.5}$ determined from the transient state tests are compared with EC3 material model in the next figure.

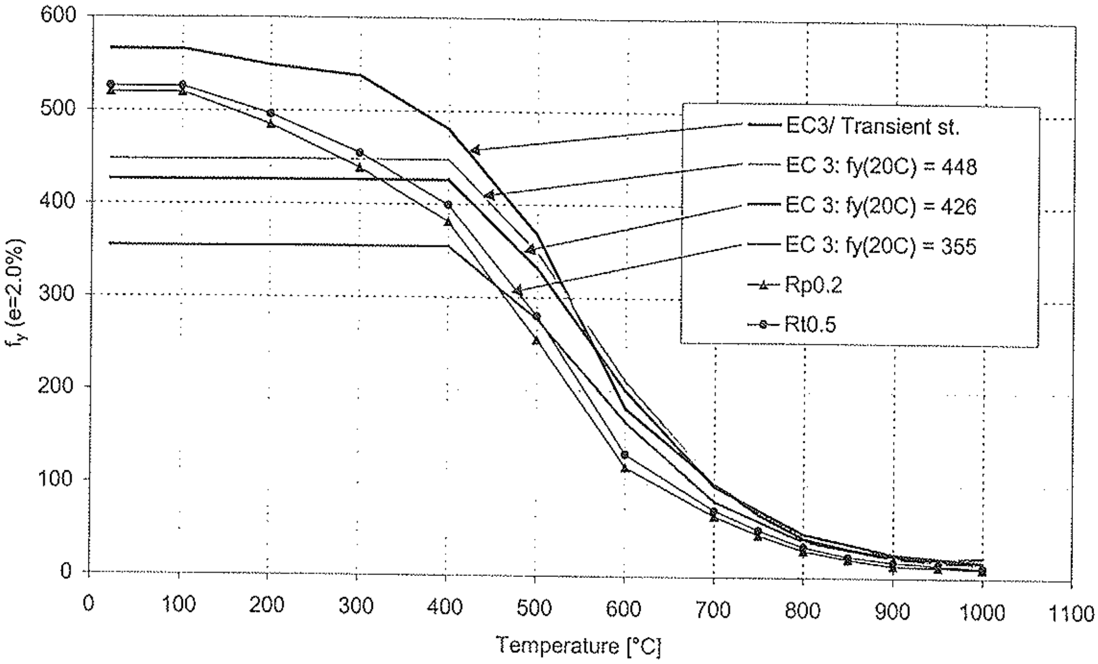

Figure 14: Yield strength of structural steel S355J2H at temperatures 20°C - 950°C (Test pieces taken from SHS 50x50x3)

TABLE 3

MECHANICAL PROPERTIES OF STRUCTURAL STEEL S355J2H AT ELEVATED TEMPERATURES

TEST PIECES TAKEN FROM SHS 50X50X3

Temperature	Modulus of Elasticity E	Proportional limit f_p	Yield strength f_y	Yield strength $R_{p0.2}$	Yield strength $R_{t0.5}$
20	210000	481.1	566	520	526
100	210000	481.1	566	520	526
200	189000	441.48	549.02	485	496
300	168000	367.9	537.7	439	455
400	147000	311.3	481.1	381	399
500	126000	169.8	367.9	255	280
600	65100	67.92	181.12	118	132
700	27300	39.62	101.88	66	72
750	23100	28.3	67.92	46	51
800	18900	19.81	42.45	29	33
850	16537.5	11.32	31.13	20	23
900	14175	6.792	22.64	13	17
950	11812.5	5.66	19.81	12	14
1000	9450	14.15	22.64	10	11

Transient state tests at stress level 100N/mm2 were carried out with three different heating rates; 10°C, 20°C and 30°C/min. The test results fom these tests are illustrated in the next figure.

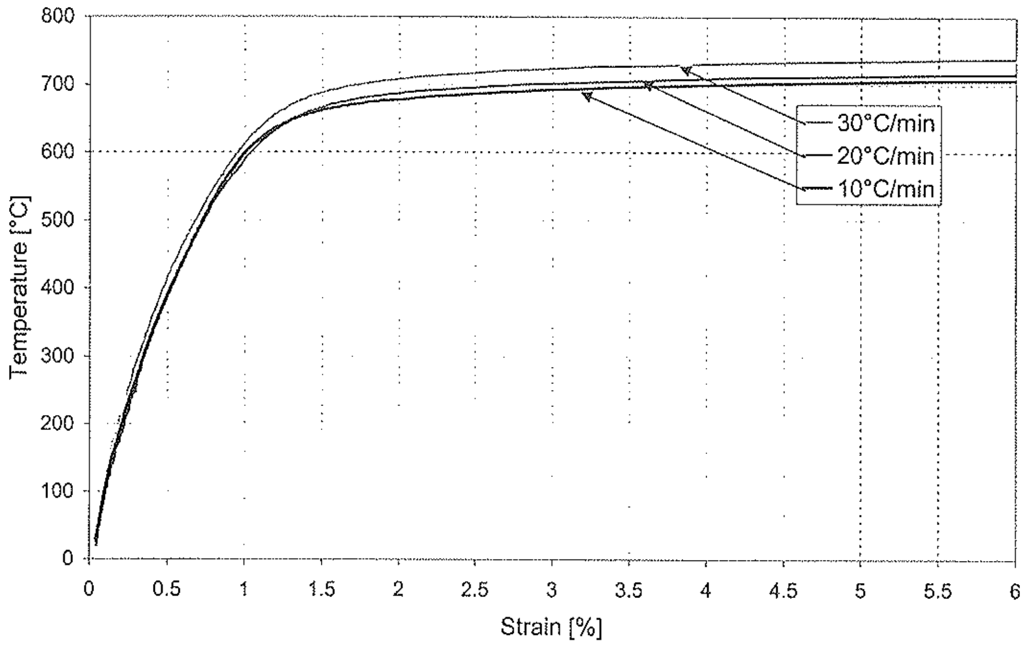

Figure 15: Temperature-strain curves of structural steel S355J2H at stress level $100 N/mm^2$ with heating rates 10°C, 20°C and 30°C/min. Test pieces taken from SHS 50x50x3.

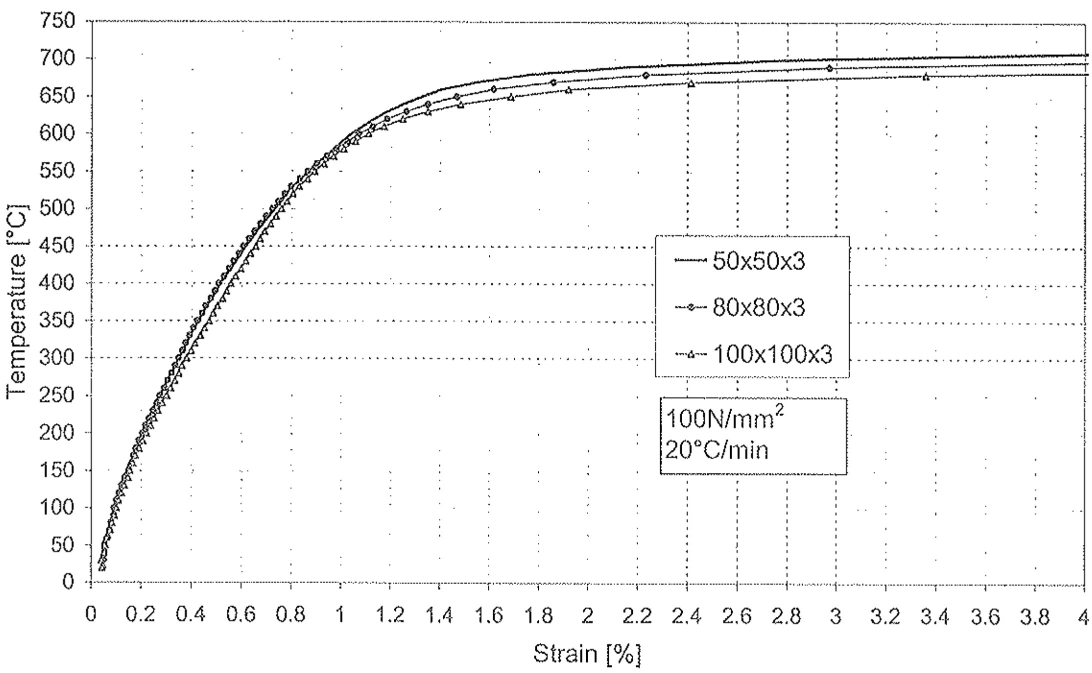

Figure 16: Temperature-strain curves of structural steel S355J2H at stress level $100 N/mm^2$. Test pieces taken from SHS 50x50x3, 80x80x3 and 100x100x3.

CONCLUSIONS

An overview of the test results for structural steels S350, S355, S460 and S355J2H is given in this paper. It has to be noted that the test results are going to checked and analyzed moro thoroughly by the end of his project. Also more tests are going to be carried out.
The test results show clear differences in the behaviour of these steel grades at elevated temperatures. For structural sheet steel S350GD+Z a new proposal for the behaviour of the yield strength was given. For structural steel grades S355 and S460 the material model given in EC3 seems to be quite good.
The behaviour of the mechanical properties of cold-formed steel seemed to be very promising. The increase of strength due to cold-forming seemed to remain quite well at elevated temperatures. This should naturally be taken into account when estimating the behaviour of cold-formed steel structures. More tests concerning the strength of the studied material after heating and the high-temperature behaviour of the corner parts of the square hollow sections are going to be carried out.

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