Appendix H

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MECHANICAL PROPERTIES OF STRUCTURAL STEEL AT ELEVATED TEMPERATURES AND AFTER COOLING DOWN

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ABSTRACT

In this paper a collection of test results of the behaviour of mechanical properties of different steel grades at elevated temperatures is presented. The tests have been carried out at Helsinki University of Technology during the past about 10 years. The aim of these tests have been to evaluate the accuracy of existing design values for the mechanical properties of structural steel and to support different other research projects aimed at studying the behaviour of steel or composite structures in fire. The results are presented with a comparison to the European design standard for structural fire design of steel structures EN 1993-1-2[1], which is already officially accepted standard in the EU countries and certainly will be largely in use in the near future.

INTRODUCTION

The behaviour of mechanical properties of different steel grades at elevated temperatures needs to be well known to understand the behaviour of steel and composite structures in fire. Quite commonly simplified material models are used to estimate the structural fire resistance of steel structures. In more advanced methods, for example in finite element or finite strip analyses, it is important to use accurate material data to obtain reliable results.

To study thoroughly the behaviour of certain steel structure at elevated temperatures, one should use the material data of the steel obtained by testing. The tests have to be carried out so that the results can be used to evaluate the behaviour of the structure, i.e. the temperature rate should be about the same that is used in the modelling assumptions.

Extensive experimental research has been carried out since 1994 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 [3-5]. The tests were carried out using European testing standards. It is also essential to use standardized testing procedures to get camparable results with other studies.

Main test results of the high-temperature testing research are presented in this paper. The tests were carried out for carbon steel grades S355, S460M, S355J2H and S350GD+Z, and also for stainless steel EN 1.4301 (AISI 304). Test results are presented here with a short description of the testing facilities and comparison with common design standards.

Some tests were also carried out for structural steel material cooled to ambient temperature after testing at high temperature. This was to find out the remaining strength of the material after fire. Some of these test results are also presented in this paper.

TEST METHODS

Two types of test methods are commonly used in the small-scale tensile tests of steel at high temperatures; transient-state and steady-state test methods. The steady state tests are easier to carry out than the transient state tests and therefore that method is more commonly used than the transient state method. However, the transient state method seems to give more realistic test results especially for low-carbon structural steel and that is why it is used in this research project as the main test method. A series of steady state tests were also carried out in this project.

Transient-state test method

In transient-state tests, the test specimen is under a constant load and under a constant rate of temperature rise. Temperature and strain are measured during the test. As a result, a temperature-strain curve is recorded during the test. Thermal elongation is subtracted from the total strain. The results are then converted into stress-strain curves. The mechanical material properties i.e. elasticity modulus and yield strength, can be determined from the stress-strain curves.

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}. Some tests were also carried out using heating rates 10°C min^{-1} and 30°C min^{-1}. In addition some tests were carried out with a high heating rate close to the ISO-curve to compare the real behaviour of the material with this heating rate. Temperature was measured accurately from the test specimen during the heating.

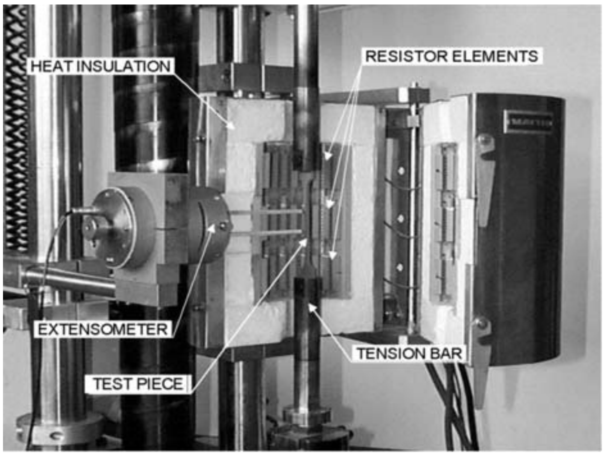
Steady-state test method

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.

TESTING DEVICE

The tensile testing machine used in the tests is verified in accordance with the standard EN 10 002-2 [2]. The extensometer is in accordance with the standard EN 10 002-4 [2]. The testing device is illustrated in Figure 1.

Figure 1: High-temperature tensile testing device



The oven in which the test specimen is fixed 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 temperature-detecting element that was fastened to the specimen during the heating.

STUDIED MATERIALS

Structural steel 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.

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.

Structural steel 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.

Structural steel 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.

Stainless steel EN 1.4301 (AISI 304)

Two similar test series were carried out. One series for the base material and the other for strongly cold-formed material. Increase of strength caused by cold-forming is significant for the studied material and one main objective of this research was to study the remainder of the increased strength at elevated temperatures. In the first series, the test pieces were cut out from a rectangular hollow section 40x40x4mm and in the second series the test pieces were cut out from a virgin sheet of a cold rolled stainles steel sheet.

TEST RESULTS

Test results of 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 Figures 2 and 3.

Figure 2: Yield strength of structural steel S355 at temperatures 20°C - 950°C

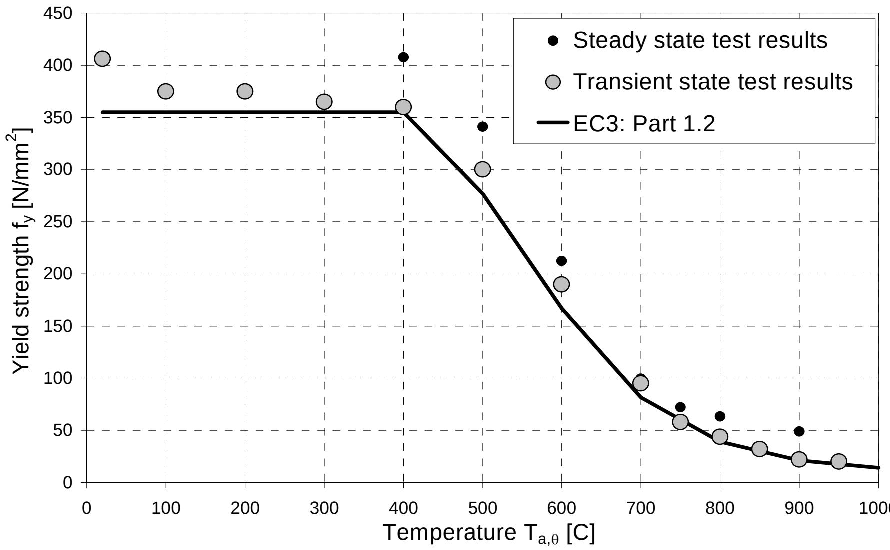
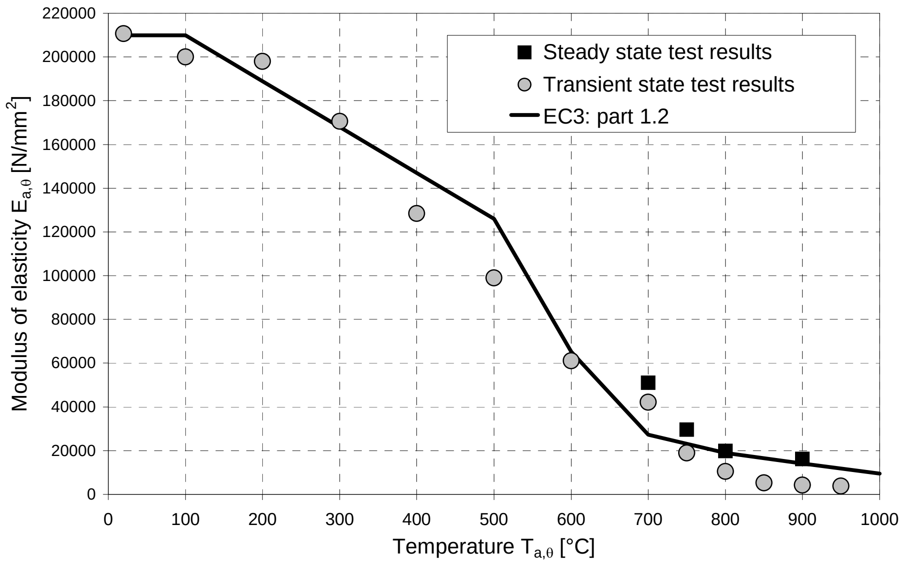


Figure 3: Modulus of elasticity of structural steel S355 at temperatures 20°C - 950°C



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.

The behaviour of structural steel S355 analyzed on the basis of transient state test results seems 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.

Test results of structural steel S460

A series with 60 test specimen was carried out to study the behaviour of the mechanical properties of structural high-strength steel S460 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 to 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 4 and 5.

Figure 4: Yield strength of structural steel S460M at high temperatures

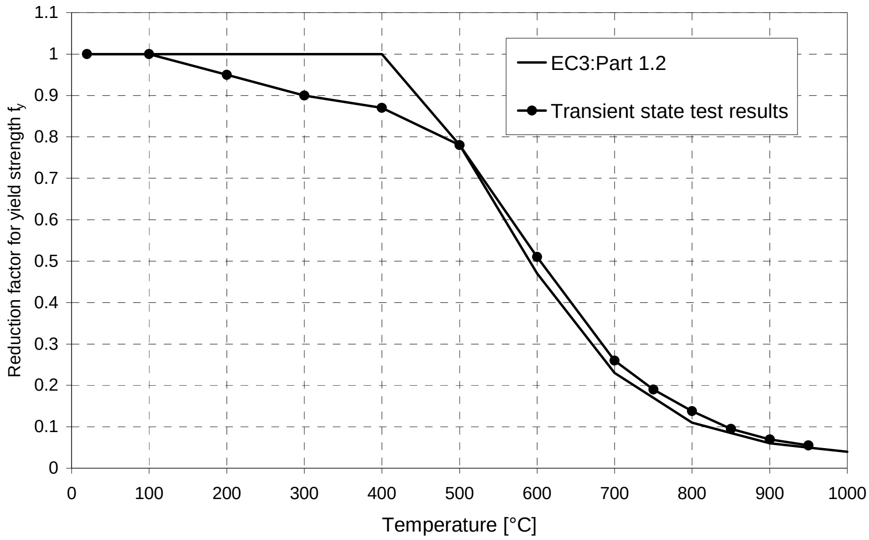
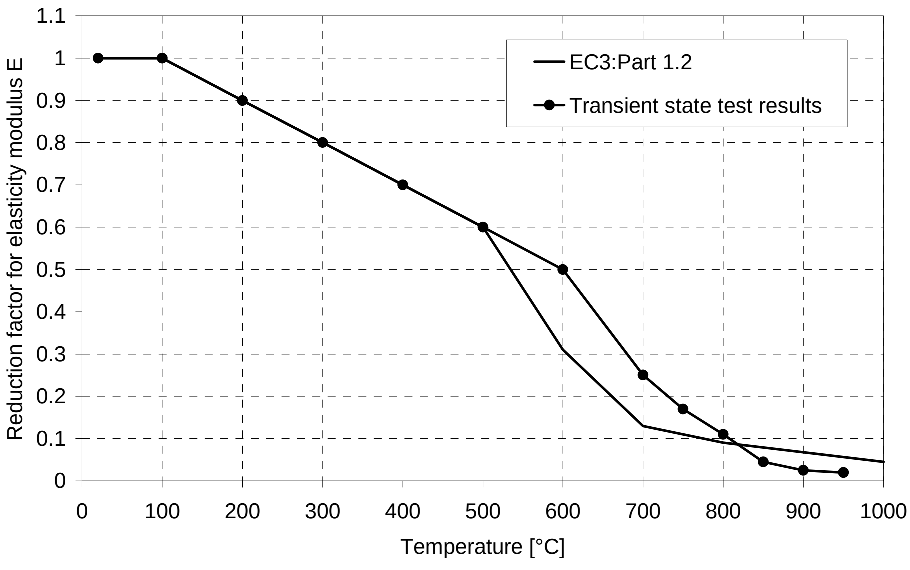
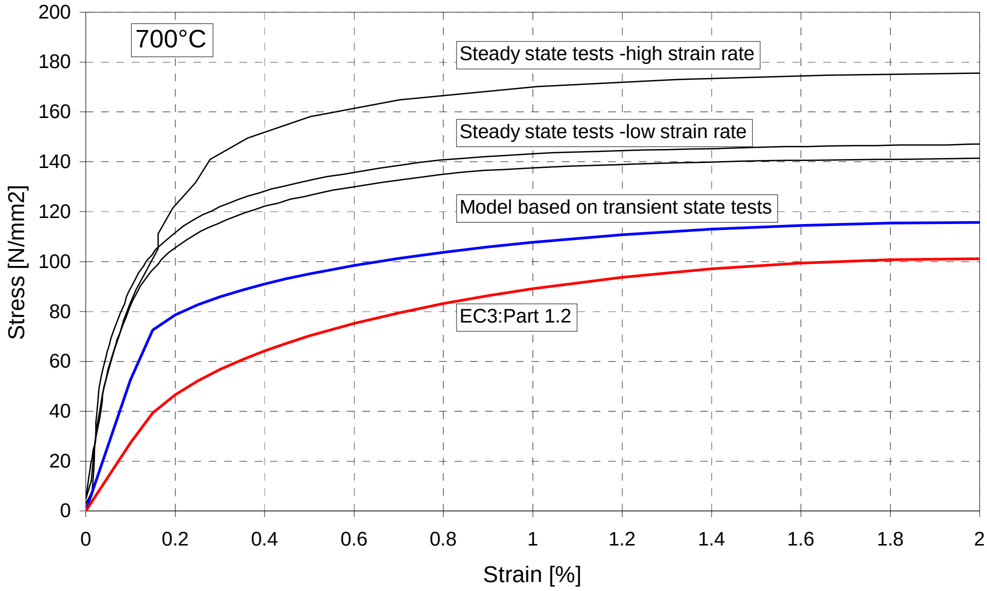


Figure 5: Modulus of elasticity of structural steel S460M at high temperatures



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 8 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 Figure 6.

Figure 6: Steady state test results of structural steel S460M at temperature 700°C compared with the transient state tests and Eurocode 3: Part 1.2



On the basis of these results it seems that the material model of Eurocode 3 is on the safe side and it can well be used in the structural design. The great difference between the results with different strain rates clearly shows that it is of high importance to indicate the strain rate when presenting test results from this kind of tests. Otherwise the comparability of the results from different sources cannot be ensured.

Structural steel S355J2H

Tensile tests at room temperature according standard SFS-EN 10002-1 were carried out for the cold-formed material. The test results for yield strength are illustrated in Table 1. It can be seen from the test results that the increased strength caused by cold-forming is significant for all studied hollow sections. The nominal yield strength for the material is 355N/mm^2. Additional tensile tests at room temperature were carried out for the specimens taken from the corner part of SHS 50x50x3. The average yield strength f_y for these specimens was 601 N/mm^2.

Table 1: Tensile test results for structural steel S355J2H at room temperature.
Test pieces from the face of SHS cross-sections.

	Yield strength f_y [N/mm^2]	Yield strength $R_{p0.2}$ [N/mm^2]	Yield strength $R_{t0.5}$ [N/mm^2]
50x50x3	566	520	526
80x80x3	544	495	502
100x100x3	539	490	497

A test series of over 100 tensile tests was conducted for the material taken from SHS-tubes 50x50x3, 80x80x3 and 100x100x3. The heating rate in the tests was 20°C/minute. Some tests were also carried out with a heating rate of 10°C/minute and 30°C/minute. A small test series was also carried out with a heating rate of 45°C/minute.

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. A small test series with test specimen taken from the corner parts of the SHS-tube 50x50x3 was also carried out as an addition to the original project plan. The test results have been fitted into the EC3: Part 1.2 material model using the calculation parameters determined from the transient state tests.

From the test results it was clearly seen that with a heating rate of 20°C/minute the increased strength caused by cold forming starts to vanish at temperatures 600°C-700°C. For test specimen with higher heating rates the increased strength seems to remain to higher temperatures. The test results at temperatures 20°C – 1000°C are illustrated in Tables 2, 3 and 4.

Table 2: Mechanical properties of structural steel S355J2H at elevated temperatures. Test pieces from SHS 50x50x3

Temp. [°C]	Modulus of Elasticity E [N/mm^2]	Proportional limit f_p [N/mm^2]	Yield strength f_y [N/mm^2]	Yield strength $R_{p0.2}$ [N/mm^2]	Yield strength $R_{t0.5}$ [N/mm^2]
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	4.528	22.64	10	11

Table 3: Mechanical properties of structural steel S355J2H at elevated temperatures. Test pieces from SHS 80x80x3

Temp [°C]	Modulus of Elasticity E [N/mm^2]	Proportional limit f_p [N/mm^2]	Yield strength f_y [N/mm^2]	Yield strength $R_{p0.2}$ [N/mm^2]	Yield strength $R_{t0.5}$ [N/mm^2]
20	210000	462,4	544	500	525
100	210000	462,4	544	500	505,4882
200	189000	424,32	527,68	473	478,1146
300	168000	353,6	516,8	432	438,4486
400	147000	299,2	462,4	379	384,3109
500	126000	163,2	353,6	255	270,426
600	65100	65,28	174,08	117	128,1229
700	27300	38,08	97,92	67	70,38595
750	23100	27,2	65,28	44	48,80605
800	18900	8,16	35,36	21	24,87326
850	16537,5	7,344	29,92	16	22,46505
900	14175	6,528	16,32	11	12,67555
950	11812,5	5,44	13,6		

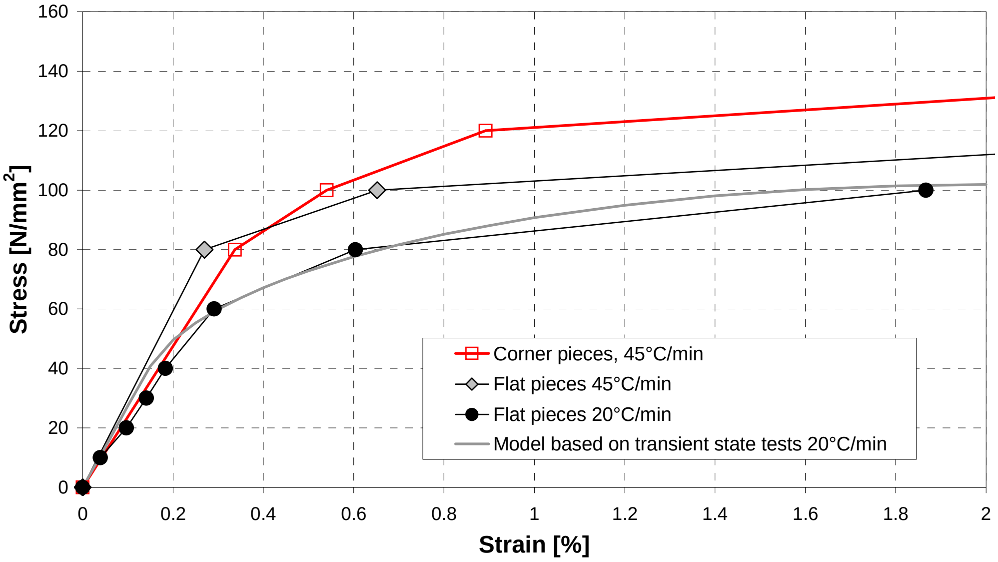
Table 4: Mechanical properties of structural steel S355J2H at elevated temperatures.
Test pieces from SHS 100x100x3

Temp [°C]	Modulus of Elasticity E [N/mm^2]	Proportional limit f_p [N/mm^2]	Yield strength f_y [N/mm^2]	Yield strength $R_{p0.2}$ [N/mm^2]	Yield strength $R_{t0.5}$ [N/mm^2]
20	210000	458,15	539	496	500,9744
100	210000	458,15	539	496	500,9744
200	189000	420,42	522,83	469	473,8989
300	168000	350,35	512,05	427	434,6986
400	147000	296,45	458,15	373	381,0532
500	126000	161,7	350,35	252	268,1464
600	65100	64,68	172,48	117	127,0427
700	27300	37,73	86,24	53	64,46188
750	23100	26,95	59,29	38	45,50802
800	18900	18,865	40,425	23	25,24635
850	16537,5	10,78	29,645	17	22,26879
900	14175	6,468	16,17	11	12,56227

The test results with heating rates of 10°C/minute and 20°C/minute don't differ from each other, but the heating rate 30°C/min seemed to give higher test results. This led to the decision to carry out additional tests with a higher heating rate. Also the behaviour of the corner parts of the profile was studied.

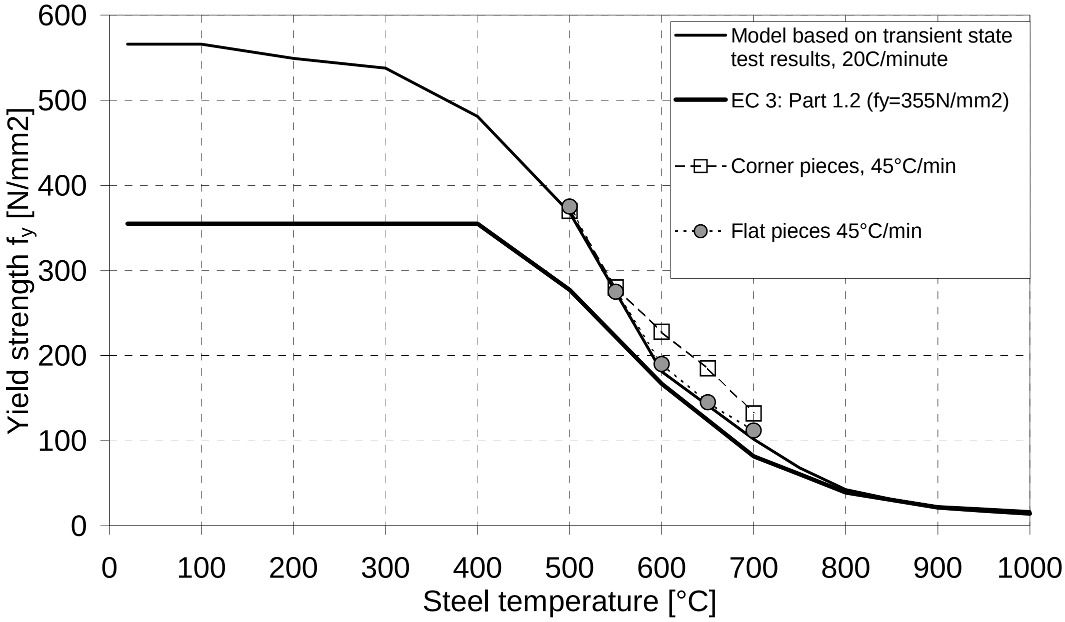
Three small test series were carried out. One with corner specimens with a heating rate 20°C/minute, one with corner specimen with a heating rate 45°C/minute and one with flat specimen with a heating rate 45°C/minute. The test results at temperature 700°C are illustrated in Figure 7.

Figure 7: Stress-strain curves of structural steel S355J2H. Test results with different specimens and different heating rates at temperature 700°C



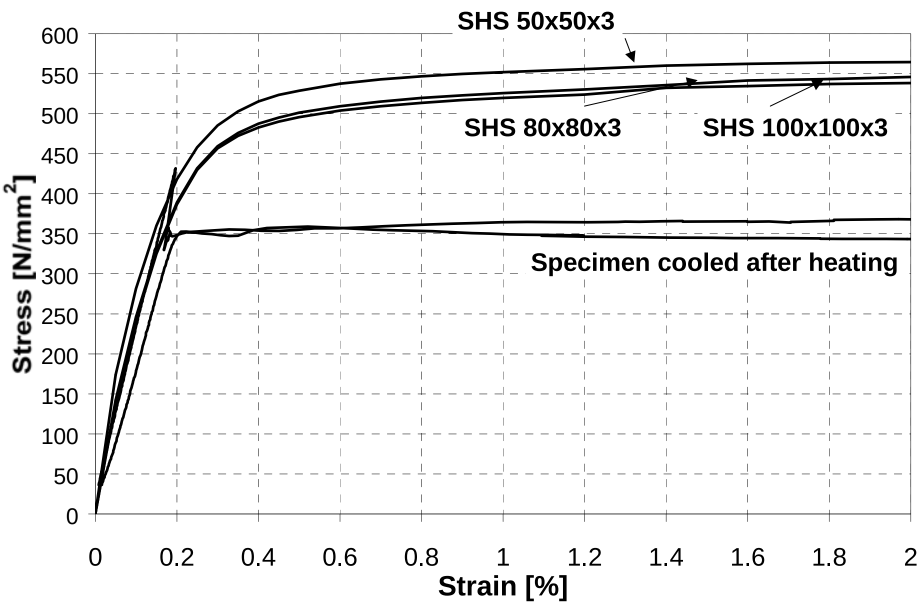
For the specimens taken from the face of the square hollow section the difference between the test results with heating rates of 20°C/minute and 45°C/minute is not as big as was assumed before. Also the difference between the test results with flat specimens and corner specimens with a heating rate of 20°C/minute was not very big. The test results for the corner pieces are significantly higher with a heating rate of 45°C/minute. In Figure 8 the yield strength f_y determined from these test results is illustrated at temperatures from room temperature up to 700°C.

Figure 8: Yield strength f_y of structural steel S355J2H. Test results with different specimens and different heating rates at temperatures 20-700°C



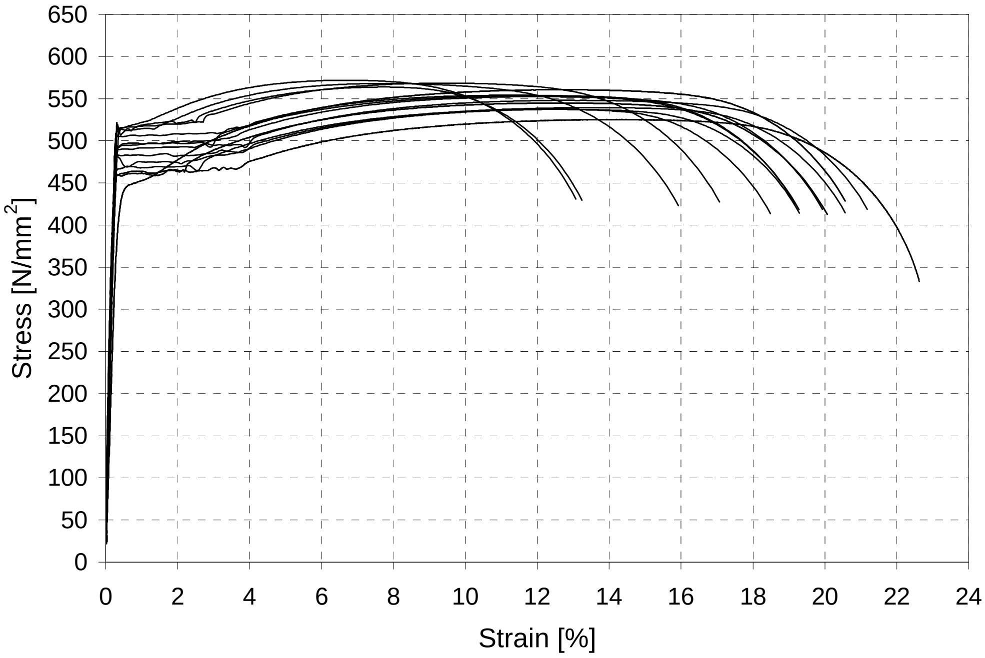
Some tests for structural steel S355J2H were carried out at room temperature with test specimens that had been heated unloaded up to temperature 950°C and cooled down to ambient temperature. The mechanical properties of the material seemed to return back to the nominal values of structural steel S355. In Figure 9 the test results of these tests are compared with the normal room temperature test results.

Figure 9: Comparison between the tensile test results of heated and non-heated test specimen on structural steel S355J2H at room temperature.



In addition a small tensile test series was carried out to determine the yield strength of the material used in high-temperature stub column tests. The maximum temperatures in these tests were from 300°C to 700°C. The specimens were taken out from SHS 50x50x3 tubes after they had been tested at elevated temperatures. The average yield strength of the material before high-temperature tests was 529N/mm^2 and the nominal yield strength 355N/mm^2. The test results are illustrated in Figure 10.

Figure 10: Tensile test results at ambient temperature for structural steel S355J2H. Test coupons taken from SHS 50x50x3 tubes after high-temperature stub column tests.



Structural sheet steel S350 GD+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 of 60 tests that were 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 the Finnish national norm concerning the material models used in structural fire design of unprotected steel members. The test results were fitted to ENV1993-1-2 material model and the results are illustrated in Table 5.

In Figure 11 the experimentally determined yield strength f_y is compared with ENV1993-1-2 material model. In the Eurocode, the nominal yield strength is assumed to be constant until 400°C, but in the real behaviour of the studied steel it starts to decrease earlier.

Ambient temperature tests were also carried out for material taken from members that have been tested at elevated temperatures. This was to find out the remaining strength of the material after fire. In Figure 12 the tensile test results are compared with the test results for unheated material.

Table 5: Reduction factors for mechanical properties of structural steel S350GD+Z at temperatures 20°C-1000°C. Values based on transient state test results

Steel Temp. θ_a [°C]	Reduction factor for the slope of the linear elastic range $k_{E,\theta} = E_{a,\theta}/E_a$	Reduction factor for proportional limit $k_{p,\theta} = f_{p,\theta}/f_y$	Reduction factor for satisfying deformation criteria **(informative only)** $k_{x,\theta} = f_{x,\theta}/f_y$	Reduction factor for yield strength $k_{p0,2,,\theta} = f_{p0,2,\theta}/f_y$	Reduction factor for yield strength $k_{y,\theta} = f_{y,\theta}/f_y$
20	1.000	1.000	1.000	1.000	1.000
100	1.000	0.970	0.970	1.000	0.970
200	0.900	0.807	0.910	0.863	0.932
300	0.800	0.613	0.854	0.743	0.895
400	0.700	0.420	0.790	0.623	0.857
500	0.600	0.360	0.580	0.483	0.619
600	0.310	0.180	0.348	0.271	0.381
700	0.130	0.075	0.132	0.106	0.143
800	0.090	0.000	0.089	0.077	0.105
900	0.068	0.000	0.057	0.031	0.067
950	0.056	0.000	0.055	0.023	0.048
1000	0.045	0.000	0.025	0.014	0.029

Figure 11: The reduction factor for effective yield strength $f_{y,\theta}$ of structural steel S350GD+Z determined from test results compared with the values given in Eurocode 3: Part 1.2

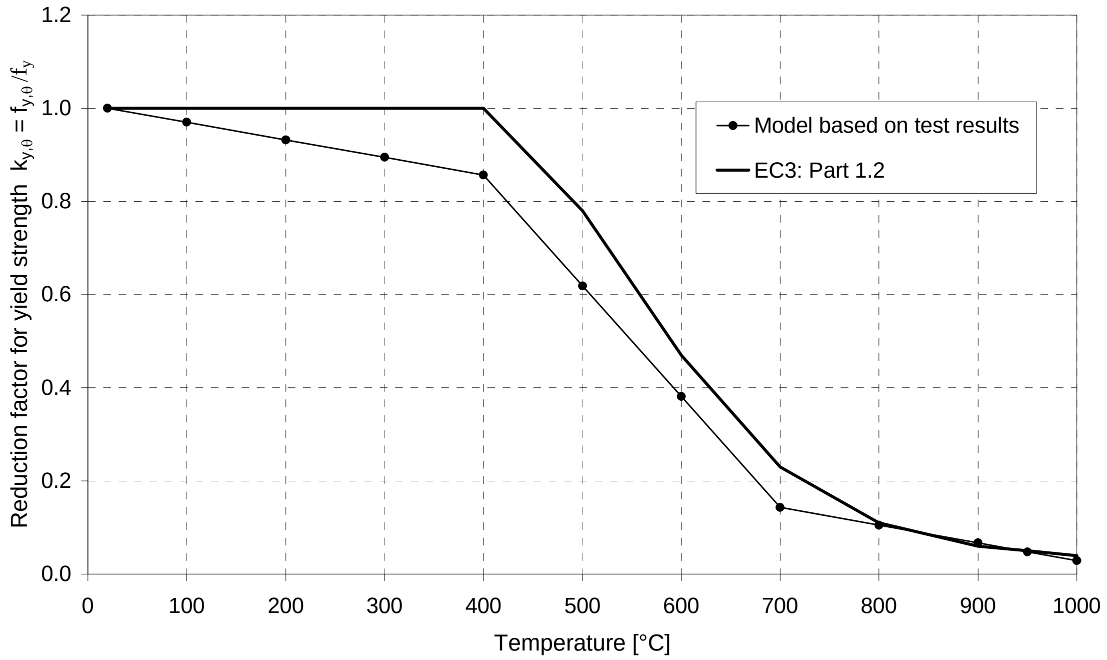
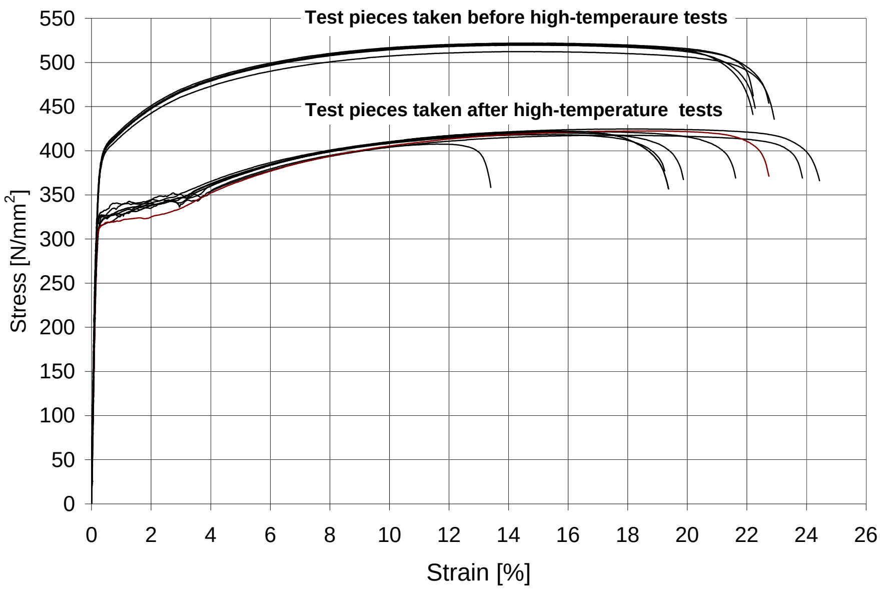


Figure 12: Tensile test results for structural steel S350GD+Z. Test pieces taken before and after high-temperature compression tests



From Figure 12 it can be seen that the increased yield strength of the material due cold-forming has decreased back to the nominal yield strength level of the material. It has to be noted that the material has reached temperatures up to 950°C in the compression tests.

The members that were in the compression tests were quite distorted after the tests. Despite this, the mechanical properties of the steel material were preserved in the nominal strength level of the material. This kind of phenomenon should be taken into account when considering the load bearing capacity of steel structures that have been in fire and are otherwise still usable, i.e. not too badly distorted.

Stainless steel EN 1.4301 (AISI 304)

Mechanical properties of the studied stainless steel were determined with four tensile tests for both cold-formed and base material at ambient temperature [5] .The increase of strength caused by cold-forming can be clearly seen from the test results. Yield strength of the cold-formed material was about double compared to that of the base material. In Table 2, $R_{p0.2}$ is the yield strength based on 0.2% non-proportional strain and $R_{t2.0}$ is the yield strength based on 2 % total strain. The average values of the measured properties are given in Table 6.

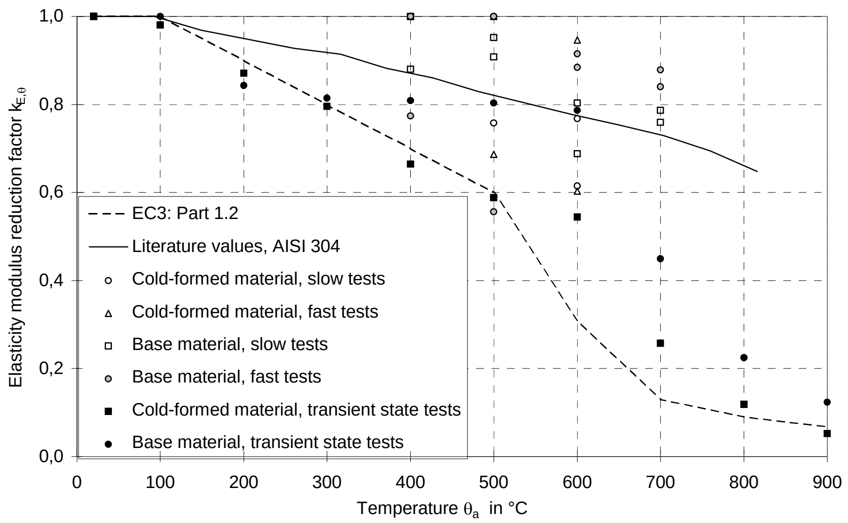
Table 6: Mechanical properties of stainless steel EN 1.4301 at room temperature

Measured property	Unit	Base material	Cold-formed material
Modulus of elasticity	N/mm^2	177844	197980
Yield stress (0.2 % non-proportional strain)	N/mm^2	291	592
Yield stress (2.0 % total strain)	N/mm^2	363	695
Ultimate stress	N/mm^2	640	736
Percentage elongation after fracture	%	53	27.4

The modulus of elasticity of stainless steel EN 1.4301 was determined from the stress-strain curves which were converted from the transient state test results. The modulus of elasticity was also determined from the steady state test results.
The modulus of elasticity was determined as an initial slope of the stress-strain curves. It is difficult to determine the exact value for the modulus of elasticity at elevated temperatures because the stress-strain curves of stainless steels do not have any exact proportional limit, especially at elevated temperatures. The

deviation of the test results from different kind of tests is very large. Comparison between the transient state and steady state test results and the values given in the literature are presented in Figure 13.

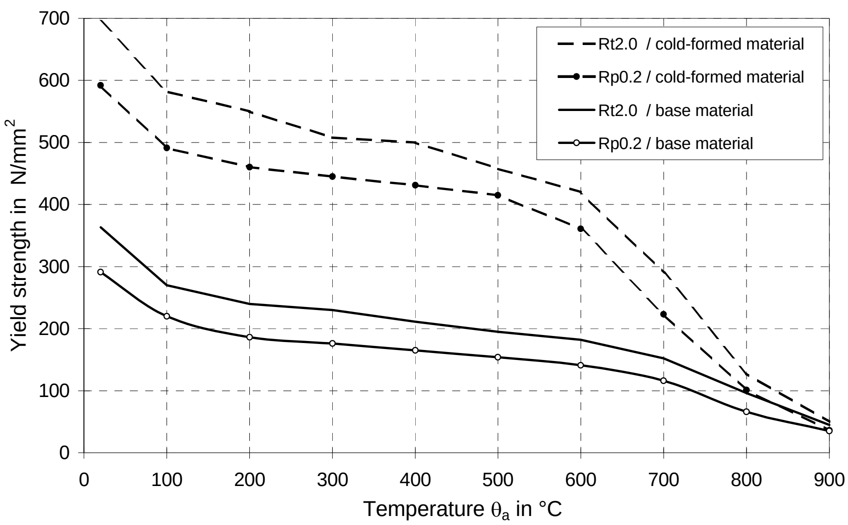
Figure 13: Temperature dependence of modulus of elasticity for stainless steel EN 1.4301



The yield strength of stainless steels is usually given as based upon 0.2% non-proportional strain. In Eurocode 3 the yield strength is given as based upon 2% total strain. Yield strength was determined from the stress-strain curves based on the transient state test results.

The cold-forming process causes a significant strength increase in a metallic material. The yield strength of the base material of EN 1.4301 was only about half of that of the cold-formed material at room temperature. The remaining of this difference at elevated temperatures can be clearly seen from the test results. The difference seems to remain about the same as at room temperature up to 600°C. The test results for both materials are presented in Fig.14.

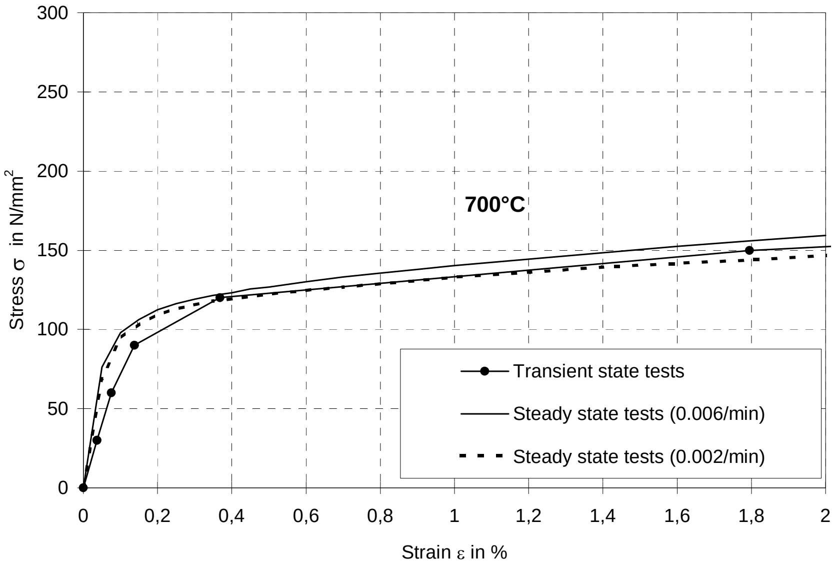
Figure 14: Temperature dependence of yield stresses of stainless steel EN 1.4301



The nominal yield strength at room temperature for the base material is 230N/mm^2 and for cold-formed material 350N/mm^2. The measured yield strength values for EN 1.4301 at elevated temperatures seem to stay at a high level compared to their nominal values. The yield strength of the cold-formed material at temperature 600°C is still above the nominal value.

The steady state tests for stainless steel EN 1.4301 were carried out as displacement-controlled with two different strain rates 0,002min^{-1} and 0,006min^{-1}. Steady state tests were carried out for cold-formed material at temperatures 400°C, 500°C and 600°C and for base material at temperatures 400°C, 500°C, 600°C and 700°C. Difference between the stress-strain curves from transient state and steady state tests was very little at the studied temperature range. Figure 15 shows clearly the uniformity of the results obtained from different tests. The difference is bigger for low carbon steels[3].

Figure 15: Stress-strain curves for base material of stainless steel EN 1.4301 at temperature 700°C



CONCLUSIONS

An overview of the test results for structural steels S355, S460, S350GD+Z , S355J2H and austenitic stainless steel EN 1.4031 and AISI 304 were given in this paper. The high temperature test results were fitted to the 'Eurocode 3 model' to provide the data in a useful form to be used in finite element modeling of steel structures. The aim of this research is mainly to get accurate information of the behaviour of the studied steel grades and to provide useful information for other researchers.The test data is presented more accurately in Refs. 3-5.

Structural steel grades S355 and S460 seemed to follow well the predictet behaviour and threre were not too much difference from the Eurocode 3 model.

The behaviour of structural steel S350GD+Z differed from the EC3 model and a new suggestion was made on the basis of the high-temperature tests. The mechanical properties after heating seemed to be near the nominal values of the material, which is good, when thinking of the remaining strength of steel structures after fire.

The behaviour of steel S355J2H seemed also 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. The strength after high-temperature tests returned to the nominal value.

Austenitic stainless steel behaved very well and the results are quite promising in the view of fire design. Values of the yield strength reduction factor of the base material were slightly above those values given in the literature for the whole temperature range.

The yield strength reduction factor of the cold-formed material is clearly higher than that given in the literature for AISI 304 until the temperature exceeds about 670°C. When the yield strength values of the studied materials at elevated temperatures are scaled to their nominal values at room temperature, the difference between the test results and the yield stress reduction factor for structural steels given in Eurocode 3 is significant. The measured yield strength values for cold-formed material, for example, are still above the nominal values when the temperature exceeds 600°C.

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