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Teknillisen korkeakoulun teräsrakennetekniikan laboratorion julkaisuja 32

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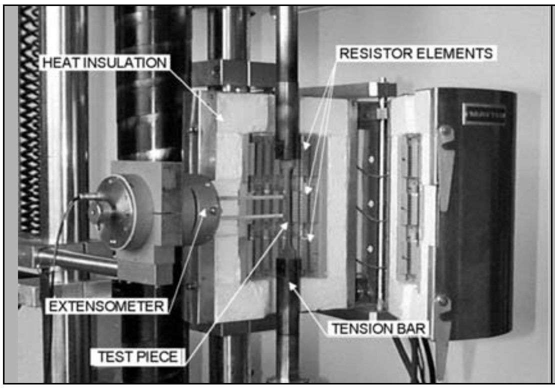
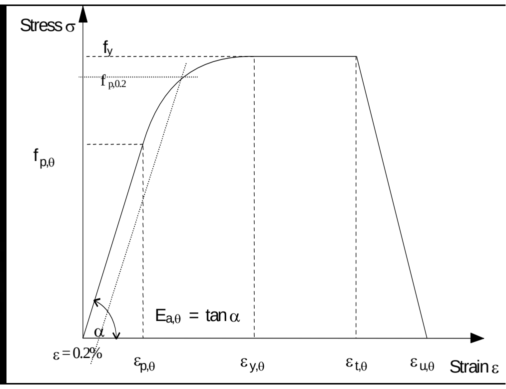
MECHANICAL PROPERTIES OF STRUCTURAL STEELS AT HIGH TEMPERATURES AND AFTER COOLING DOWN

Jyri Outinen





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MECHANICAL PROPERTIES OF STRUCTURAL STEELS AT HIGH TEMPERATURES AND AFTER COOLING DOWN

Doctoral Dissertation

Jyri Outinen

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Civil and Environmental Engineering for public examination and debate in Auditorium R1 at Helsinki University of Technology (Espoo, Finland) on the 20th of April, 2007, at 12 noon.

Helsinki University of Technology
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PREFACE

This PhD research was carried out in the Laboratory of Steel Structures, Department of Civil and Environmental Engineering, at Helsinki University of Technology, Finnish Constructional Steelwork Association and finally Rautaruukki Corporation, starting from 2002. The testing program started already in 1993.

The work has been financially supported by the following institutions and foundations: Suomen kulttuurirahasto, Tekniikan edistämissäätiö and Rakennusalan jatkokoulutusrahasto. Co-operation with universities and companies, Helsinki University of technology and VTT the Technical Research Centre of Finland, Rautaruukki Oyj and Outokumpu Oyj among others, provided the possibility to carry out the experimental testing along the work. Their support is gratefully acknowledged.

I would like to thank my supervisor, Prof D.Sc.(Tech.) Pentti Mäkeläinen, head of the Laboratory of Steel Structures at HUT, for his support and encouragement. Also the whole personnel of the Laboratory of Steel Structures and the staff at the Testing Hall of the HUT Department of Civil and Environmental Engineering are greatly acknowledged.

The pre-examiners of my thesis, Dr. Yong Wang from the University of Manchester and Dr. Mario Fontana from ETH Zürich are greatly acknowledged. I am thankful for Dr. František Wald from Chech Technical University in Prague for agreeing to act as opponent during the defense of the thesis.

Also the staff in Finnish Constructional Steelwork Association and Ruukki Construction is greatly acknowledged providing a warm and supporting atmosphere to finalize the work.

Warm thanks go to my parents and both of my brothers for strong support and encouragement. Thanks Pete, somewhere over the rainbow.

Finally I would like to thank the most important people of life, my wife Maija and children Verneri, Onni and Martta for their patience, impatience and loving along the process.

Jyri Outinen
Tuusula, 28.2.2007

ABSTRACT

Behaviour of mechanical properties of different steel grades at elevated temperatures need 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. Extensive experimental research has been carried out 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.

In this thesis a collection of test results of the behaviour of mechanical properties of different steel grades at elevated temperatures is presented with analysis of the test results. The tests have been carried out at Helsinki University of Technology during the past about 12 years. The aim of these tests has been to evaluate the accuracy of existing design values for the mechanical properties of structural steel and to support other different 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 (EN1993-1-2) for structural fire design of steel structures, which is already the officially accepted standard in the EU countries and certainly will be largely in use in the near future. The results are quite well adopted and referred in other different research projects. The main aim of this research was to provide results to other researchers and design engineers in the field of structural fire engineering to improve structural fire safety in the future.

ABSTRACT (in Finnish)

Teräsrakenteiden paloteknisessä mitoituksessa tarvitaan yksityiskohtaista tietoa materiaalien käyttäytymisestä korkeissa lämpötiloissa. Rakennusten paloturvallisuuden kannalta on olennaista, että tulipalon aiheuttaman lämpötilan nousun aiheuttamat muutokset materiaalien ja rakenteiden kestävyyteen tunnetaan sekä palonaikaisen kestävyyden että korjausrakentamisen kannalta myös tulipalon jälkeisen tilanteen osalta. Kokeellinen materiaalitutkimus on varmin tapa arvioida näitä ominaisuuksia.

Teknillisen korkeakoulun Teräsrakennetekniikan laboratoriossa on vuosina 1993–2006 tehty laajaa kokeellista tutkimusta erilaisten rakenneterästen ja ruostumattomien terästen ominaisuuksien selvittämiseksi palolämpötiloissa. Kokeelliset tutkimukset on tehty käyttäen ns. transienttikoemenetelmää, jossa materiaalin käyttäytyminen vastaa hyvin rakennemateriaalin käyttäytymistä tulipalotilanteessa. Lisäksi on tutkittu myös teräksen jäännöslujuutta jäähtymisen jälkeen, jotta voitaisiin arvioida kantavien teräsrakenteiden kestävyyttä myös tulipalon jälkeen.

Tässä väitöskirjatutkimuksessa tuotetaan kootusti perustavaa tietoa rakenneteräksen käyttäytymisestä korkeissa lämpötiloissa. Tavoitteena on ollut suunnittelussa ja myös palo-onnettomuuksien arvioinnissa käytettävän perustietämyksen lisääminen, jotta luottamusta rakenteelliseen paloturvallisuuteen voitaisiin parantaa.

CONTENTS

This dissertation consists of an overview on the research of mechanical properties of structural steels at elevated temperatures and after cooling down, and the following publications:

A Outinen J., Kesti J., Mäkeläinen P.
Fire design models for structural steel S355 based upon transient state tensile test results, Journal of Constructional Steel Research Vol.42, No. 3, pp. 161-169, Elsevier Science Ltd, 2/1997.

B Mäkeläinen P., Outinen J., Kesti J.
Fire design models for structural steel S420M based upon transient state tensile test results, Journal of Constructional Steel Research, Vol. 48, No.1, pp. 47-57, Elsevier Science Ltd, 8/1998.

C Mäkeläinen P., Outinen J.
Mechanical Properties of an Austenitic Stainless Steel at Elevated Temperatures, Journal of Constructional Steel Research Vol.46, Nos. 1-3, pp. 455, Elsevier Science Ltd, 2/1998. Full paper published in the proceedings of Second World Conference on Steel Construction, San Sebastián, Spain, 1998.

D Outinen J., Kaitila O., Mäkeläinen P.
A Study for the Development of the Design of Steel Structures in Fire Conditions, 1st International Workshop of Structures in Fire, Proceedings pp. 267-281, Copenhagen, Denmark, 2000.

E Outinen J., Mäkeläinen P.
Effect of High Temperature on Mechanical Properties of Cold-Formed Structural Steel. Ninth International Symposium and Euroconference on Tubular Structures, Düsseldorf, Germany. Proceedings book: Tubular Structures IX, Edited by: Puthli., R., Herion, S., A. A. Balkema, pp.439-444, The Netherlands 2001.

F Outinen, J., Mäkeläinen, P.
High-Temperature Strength of Structural Steel and Residual Strength After Cooling Down, Proceedings of the International Colloquium on Stability and Ductility of Steel Structures, Budapest, Hungary, Ed. M. Ivanyi, Budapest University of Technology and Economics, pp. 751-760, 2002.

G Outinen J., Mäkeläinen P.
Mechanical properties of structural steel at elevated temperatures and after cooling down, Fire and materials, An International Journal, Vol. 28, No.2-4, pp.237-251, John Wiley& Sons, 2004.

H Outinen J.
Mechanical properties of structural steels at elevated temperatures and after cooling down, Fire and Materials 2007, Delegates handbook, pp.125-126, (full article in included CD), Interscience Communications Limited, 2007.

Author’s Contribution

The research results on the mechanical properties of structural steels at elevated temperatures and after cooling down are presented in the articles in more details. The presented results have been published at the first time by the author.

The research work and preparation of the manuscripts in all papers were carried out alone by Jyri Outinen. The other authors in articles A-G, Professor Pentti Mäkeläinen and D.Sc. Jyrki Kesti and D.Sc. Olli Kaitila have acted as the supervisors of the research projects.

1. INTRODUCTION

The behaviour of mechanical properties of different structural steel grades at elevated temperatures should be well known to understand the behaviour of steel and composite structures at fire. Quite commonly, simplified material models are used to estimate e.g. 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 used steel material obtained by testing. The tests have to be carried out so that the results can be used to evaluate the behaviour of the structure, e.g. the temperature rate should be about the same that is used in the modeling assumptions.

In this thesis the author's test results, together with existing material models and the suggested models are presented in the most suitable format to be used in different kinds of structural analyses, where these steel grades are used.

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. The main test results, the models based on these tests and the analysis are presented in this thesis.

In this thesis, the ambient and high-temperature test results of structural steel grades S355, S420M, S460M, S350GD+Z and S355J2H and additionally the test results of austenitic stainless steel grade EN 1.4301 (AISI 304) are presented with a description of the testing facilities and comparisons with existing design codes and standards.

Additionally some tests at ambient temperature were also carried out for structural steel materials taken from samples that had been tested at elevated temperatures. This was to find out the residual strength of the material after fire. These test results are also presented in this thesis. Some other research results related to the after-fire characteristics of steel structures are also discussed in this thesis.

2. BACKGROUND TO THE RESEARCH

Steel structures are designed using the rules given in different design codes. Almost every country has its own design rules for steel structures. Formerly the European designers used the rules of their own country, but nowadays the designers can also use Eurocodes, which is a common design code for all EU countries. The still valid ENV versions of Eurocodes are used with additional rules given in the national application documents (NAD) of each country. The existing and forthcoming Eurocodes, EN standards are going to be taken into use in each country with the National Annexes.

Also the structural fire design of load-bearing structures is carried out using these design rules. The mechanical properties of structural steel are given as functions of temperature. These material models are used in structural calculations. A large variety of this kind of models for the behaviour of steel can be found from the national design codes of European countries and now it is time to move forward and to take into use the uniform European standards.

The material models are generated on the basis of test results from a large amount of tensile tests with different steel grades. The aim in developing these models has been to create safe models to be used when designing steel structures of common steel grades. The steel industry is developing new steel materials all the time and is naturally testing widely their products. Continuing independent academic research is still needed to get the information necessary in design.

The materials presented in this thesis represent a cross-section of commonly used structural steel grades in normal construction. The high strength steel grades are going to be more widely used and also the stainless steel will play an important role in the construction business in Europe in the near future. The Eurocode material model (EN 1993-1-2) covers now the studied materials and give the designers new opportunities to design structures more innovatively and with more accuracy.

In the future the high-strength steels with yield strength over 500N/mm^2 should be studied. These steel grades will be added to the scope of Eurocode 3 and it is necessary to prove the adequacy of these steels to Eurocode material model at elevated temperatures. There seems not to be too much information about this at least in the field of building construction. The high-strength steel grades have been used more in e.g. construction of machinery.

3. EXPERIMENTAL RESEARCH PROGRAM

3.1 Testing device

The tensile testing equipment consists of a loading device, a heating oven and the measuring and controlling devices connected to a computer. Special software, manufactured by a German company Zwick GmbH was used to run the tests and to collect the measured data and also to perform preliminary analysis of the results. This software was able to run the different kind of tensile tests that were carried out during this research. The testing device that was used in the high-temperature tensile tests had been 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 maximum load of loading device is 250 kN.

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 also from the test specimen using a temperature-detecting element that was fastened to the specimen during the heating. The small size of the oven has the benefit that the temperature differences inside the oven are relatively small and the heating is well controlled. The maximum length of a specimen tested in the oven is about 220 mm. The diameter of the oven is about 300 mm. The accuracy of the temperature detecting elements is ±3 °C. Thhe maximum temperature of the oven is 1200 °C.

The strain was measured using a special high-temperature strain gauge. The device itself is situated outside the oven so that the temperature cannot affect the device. The tips of the ceramic strain measuring rods of the strain measuring device are placed against the measuring points in the test specimen. The rods are made of material that is very little affected by the temperatures used in these tests and the whole device is calibrated with each test series t ensure the accuracy of the results.

The data from the tests, i.e. load, strain, time and the temperatures are recorded with an appropriate time interval from each test. MS Excel program was then used to study and analyze the results.

The high-temperature testing device is illustrated in Figure 1.

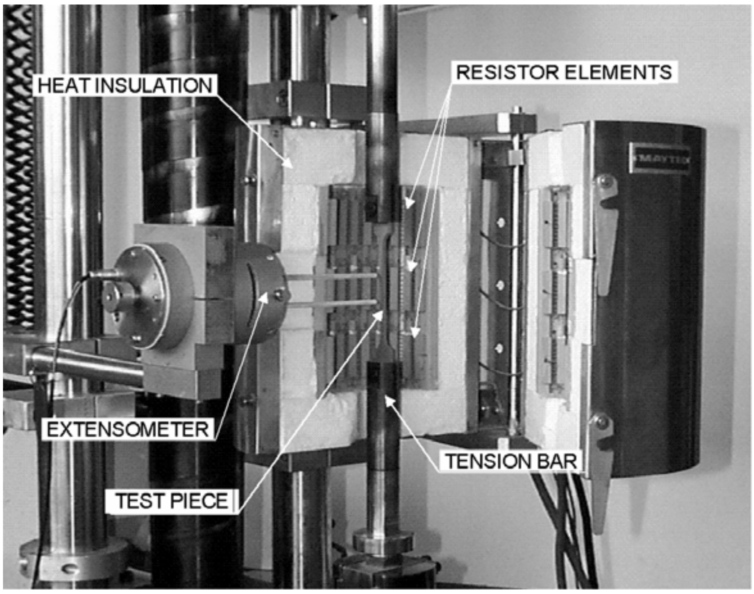


Figure 1: High-temperature tensile testing device.

3.2 Test pieces

The tensile test specimens were in accordance with the European standard EN 10 002-5 (1992). Strain was measured from the middle of the test piece. The gauge length was 25 mm (50 mm, S350GD+Z).

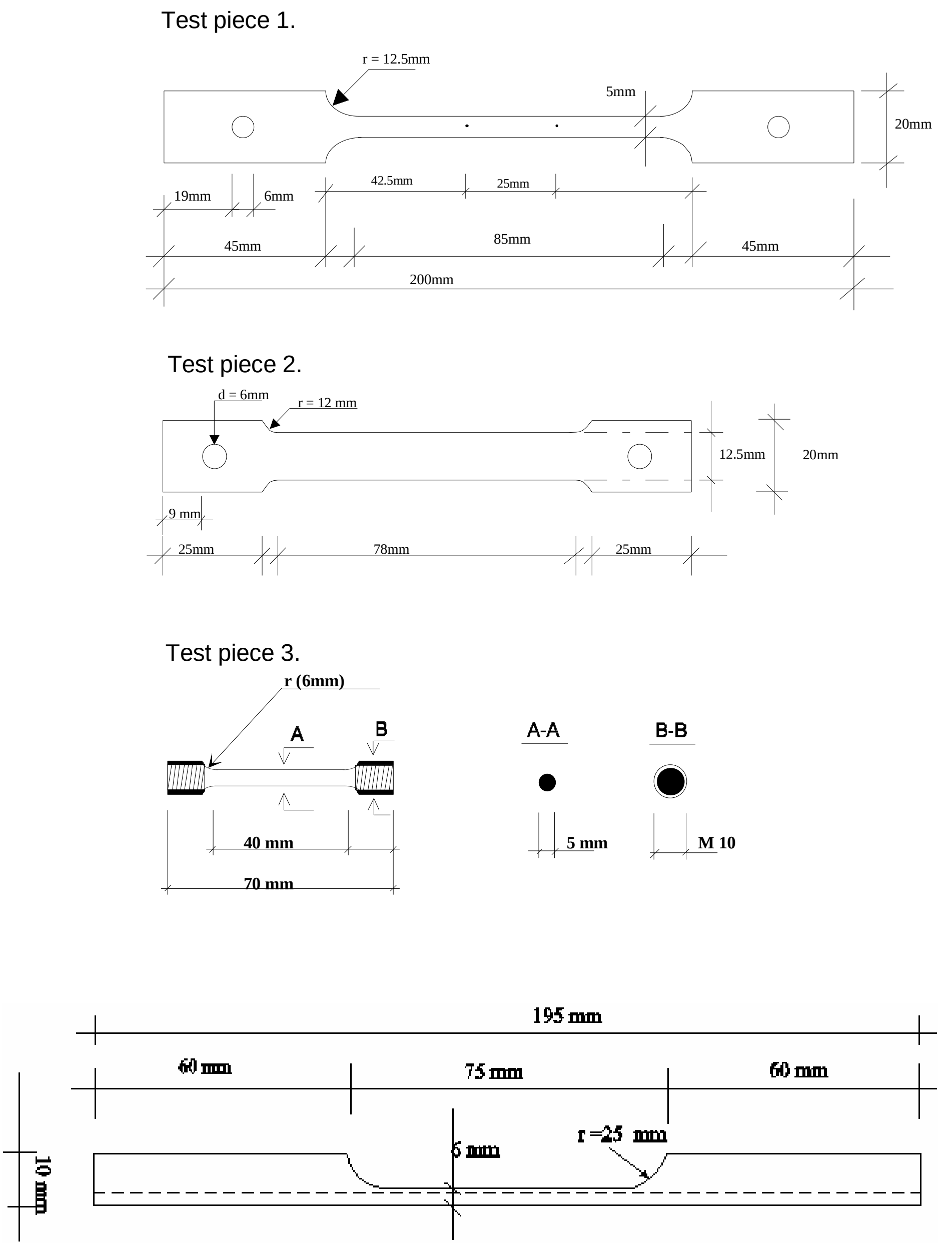
The test pieces for base materials were cut out from virgin steel plates. The nominal plate thickness for S350GD+Z was 2 mm, for S355 (base material) it was 3 mm, for high-strength steel S460 it was 20 mm. The test pieces were cut out longitudinally in the rolling direction. For the cold-formed square hollow sections (structural steel S355J2H) the thickness was 3 mm and test pieces were taken from the middle of the face opposite to the welded seam and also from the corners of the section.

The test pieces for structural steel S355J2H were cut out longitudinally from the middle face opposite to the weld seam of square hollow sections 50x50x3, 80x80x3 and 100x100x3. The test specimens are illustrated in Figure 2 and Table 1.

Test piece types 1 and 4 are used for structural steel S355J2H (SHS-tubes) and S355 (base material). Test piece type 2 is used for structural steel S350GD+Z. Test piece 3 is used for structural steel grades S355 and S460M (base material).

The main dimensions of the tests pieces are given in Table 1 in the next page. The thickness and the width of the measured zone varied for different materials depending on the thickness of the plate, from which the specimens were taken from.

The pieces were cut out with laser-cutting. High-pressure water cutting was also tried, but with this method the surface quality of the specimens wasn’t in the required level.



Test piece 4 (corner part from different sized RHS tubes (manufacturer Rautaruukki).

Figure 2: The high-temperature tensile test specimens.

TABLE 1
DIMENSIONS OF THE HIGH-TEMPERATURE TENSILE TEST SPECIMENS

		Test piece 1. (S355J2H)	**Test piece 2. (S350GD+Z)**	**Test piece 3. (S460M)**
Total length	L_t	200 mm	142 mm	70 mm
Parallel length	L_c	85 mm	78 mm	40 mm
Original gauge length	L_0	25 mm	50 mm	25 mm
Diameter	d			5 ±0.040 mm
Thickness	t	4.00 ± 0.02 mm	1.94 ± 0.02 mm	
Width	b	5.00 ± 0.04 mm	12.50 ± 0.03 mm	

Details of the test piece taken from hollow sections are given in appendix E.

3.3 Testing program

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 a lot simpler 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 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. Two kinds of methods were used to have a proper comparison of the test results obtained with different kind of test methods.

3.4 Transient state tensile 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 as shown in Figure 3.

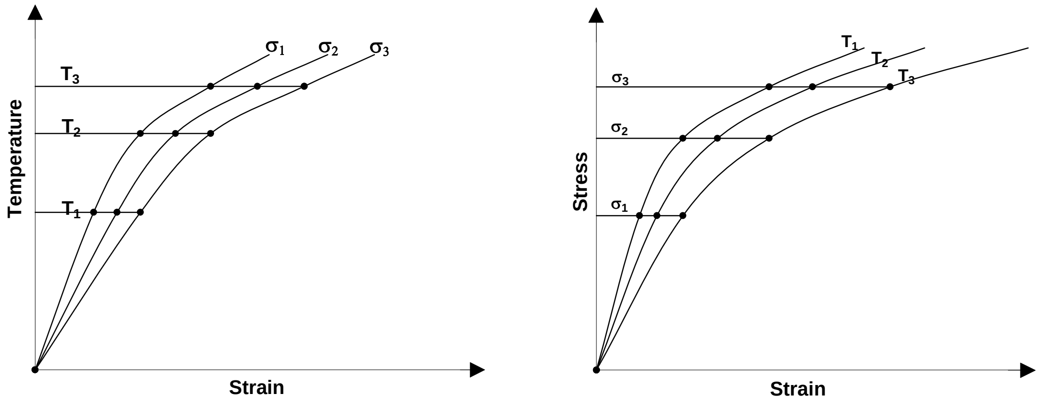


Figure 3: Converting the stress-strain curves from the transient state test results.

The mechanical material properties i.e. elasticity modulus and yield strength, can be determined from the stress-strain curves. This is illustrated in Figure 4. The strain value of $\varepsilon_{y,\theta}$ stands for 2 % total strain. There has been a lot of discussions on the strain limit that the yield strength should be based on. Naturally the designer has to decide within certain limits the allowed strain case by case.

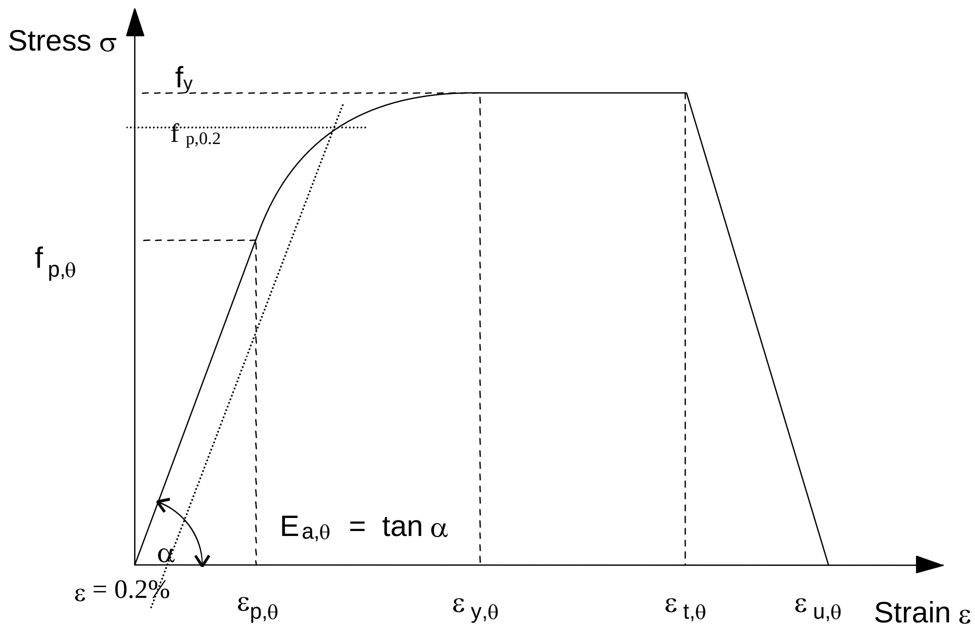


Figure 4: Stress-strain relationship for steel at elevated temperatures.

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. The creep effect gets bigger, when the heating rate gets slower. Temperature was measured accurately from the test specimen during the heating.

3.5 Steady state tensile 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. The strain rate has a significant effect on the test results and therefore the limits have been set in the testing standard. Unfortunately a large amount of research is constantly published without the information of the strain rate.

4. Tested materials

4.1 Austenitic stainless steel EN 1.4301

The studied stainless steel grade was austenitic stainless steel EN 1.4301 named. It was manufactured by Avesta Polarit Oyj (Now Outokumpu Stainless Oy). Two test series were carried out for this material; one for the base material and one for strongly cold-formed material. The test specimens for the base material were cut out from a cold-rolled steel sheet longitudinally in the rolling direction. The test specimens for the cold-formed material were taken from 4x40x40 RHS-profiles. These RHS-tubes were manufactured by Stalatube Oy.

The mechanical properties of stainless steel EN 1.4301 were determined with four tensile tests for both materials at room temperature. The increase in strength caused by cold-forming can be clearly seen from the test results shown in figure 5. The yield strength of the cold-formed material is about double that of the base material. The amount of cold-forming affects the behavior of the material. The average values of the measured properties are given in Table 2.

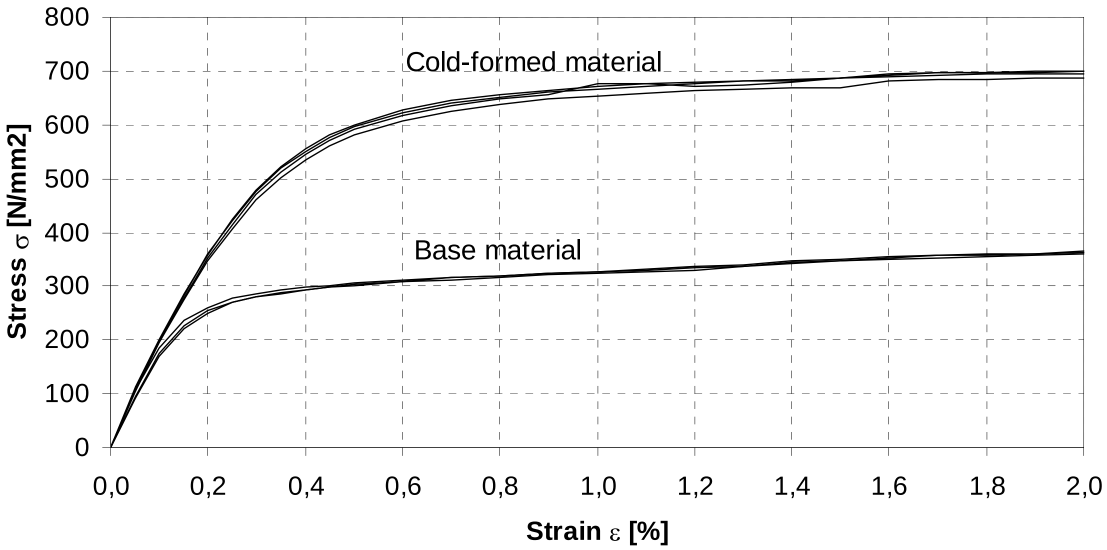


Figure 5: Stress-strain curves of stainless steel EN 1.4301 at room temperature.

TABLE 2

MECHANICAL PROPERTIES OF EN 1.4301 AT ROOM TEMPERATURE

Measured property	**symbol**	**unit**	**base material**	**cold-formed material**
Modulus of elasticity	E	N/mm^2	177844	197980
Yield stress	$R_{p0.2}$	N/mm^2	291	592
Yield stress	$R_{p1.0}$	N/mm^2	333	676
Yield stress	$R_{t1.0}$	N/mm^2	326	667
Yield stress	$R_{t2.0}$	N/mm^2	363	695
Ultimate stress	R_m	N/mm^2	640	736
Percentage elongation after fracture	A_{25}	%	53	27.4

The chemical compositions of the studied materials taken from the manufacturer's inspection certificates are given in Table 3.

TABLE 3

CHEMICAL COMPOSITION OF EN 1.4301

	C	Si	Mn	P	S	Cr	Ni	N
Base material (%)	0.027	0.420	1.560	0.031	0.001	18.30	8.500	
Cold-formed (%)	0.037	0.410	1.520	0.026	0.001	18.30	8.500	0.071

4.2 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 4 mm, longitudinally in the 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.

Four tensile tests were carried out to determine the mechanical properties of structural steel S355 at room temperature. The test results are shown in Table 4 and in Figure 6.

TABLE 4

MECHANICAL PROPERTIES OF STRUCTURAL STEEL S355 AT ROOM TEMPERATURE

	Test results	SFS-EN 10025	Inspection certificate
Modulus of elasticity [N/mm^2]	202 590	-	-
Yield strength R_{eH} [N/mm^2]	386	355	472
Yield strength $R_{p0.2}$ [N/mm^2]	385	-	-
Yield strength $R_{t2.0}$ (f_y) [N/mm^2]	397	-	-
Ultimate strength R_m (f_u) [N/mm^2]	506	490-630	546
Elongation at fracture A [%]	24	20	28

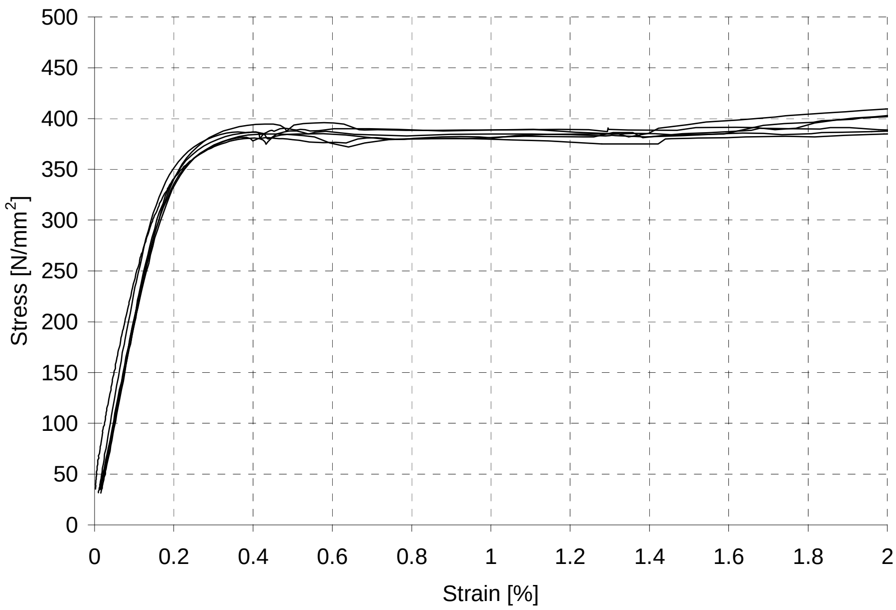


Figure 6: Stress-strain curves of structural steel S355 at room temperature.

4.3 Structural steel S420M

The test material used in this research was hot-rolled structural steel S420M manufactured by Rautaruukki Oyj. Test pieces were cut out longitudinally in the rolling direction. Steel material is in accordance with the requirements of the European standard SFS-EN 10 113-3 /7/ for structural steel S420M.

Five tensile tests were carried out at room temperature to determine the mechanical properties of the test material at room temperature. The results from the transient and steady state tests were compared with these results. The stress-strain curves were used to determine the tensile properties for each test specimen. Test results are shown in Table 5.

TABLE 5
MECHANICAL PROPERTIES OF THE TEST MATERIAL S420M AT ROOM TEMPERATURE

	E (N/mm^2)	$R_{p0.2}$ (N/mm^2)	$R_{t0.5}$ (N/mm^2)	$R_{t1.0}$ (N/mm^2)	$R_{t2.0}$ (N/mm^2)	R_m (N/mm^2)
Test 1.	211978.7	435	436	438	455	543
Test 2.	234941.2	445	448	449	460	553
Test 3.	192026.0	410	413	424	446	549
Test 4.	172000	428	431	437	461	551
Test 5.	214744.2	433	435	437	462	548
Average	205 138	430.2	432.6	437	456.8	548.8
Standard deviation	23965.37	12.87	12.66	8.86	6.61	3.77

Test results from the tensile tests are compared in Table 6 with reported test values from the inspection certificate and the minimum values given by the manufacturer.

TABLE 6
TEST RESULTS, REPORTED TEST VALUE OF INSPECTION CERTIFICATE AND THE MINIMUM VALUES GIVEN BY THE MANUFACTURER

	Measured property	Reported test value / 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

The chemical composition of the test material including a comparison with the maximum values given in standard EN10113-3 (1993) is presented in Table 7.

TABLE 7
CHEMICAL COMPOSITION OF THE STEEL MATERIAL S420M

Elementary substance		Cast analysis (%)	Maximum value (%)
Carbon	C	0.120	0.160
Silicon	Si	0.290	0.500
Manganese	Mn	1.410	1.700
Phosphorus	P	0.012	0.035
Sulphur	S	0.009	0.030
Aluminium	Al	0.033	minimum 0.020
Niobium	Nb	0.040	0.050
Vanadium	V	0.007	0.120
Titanium	Ti	0.003	0.050
Nickel	Ni	0.030	0.300
Molybdenum	Mo	0.003	0.200

4.4 Structural steel S460M

The tests for structural high-strength steel S460M were carried out using test specimens that were made from 20 mm thick steel plate. The pieces were cut out longitudinally in the rolling direction. The material fills the requirements given in standard SFS-EN 10113(1993) for structural steel S460M. The test pieces were in accordance with the testing standard SFS-EN 10002-5 (1992).

Three tests were carried out at room temperature. The test results showed that the mechanical properties were in accordance with the requirements given in standard SFS-EN 10113. It must be noted that the yield strength requirement is 440 N/mm^2 for 16…40 mm thick plates. The tensile test results are illustrated in Table 8 and in Figure 7.

TABLE 8
MECHANICAL PROPERTIES OF STRUCTURAL STEEL S460M AT ROOM TEMPERATURE

	Test results	SFS-EN 10113
Elasticity modulus [N/mm^2]	209 000	-
Yield strength R_{eH} [N/mm^2]	475	440
Yield strength $R_{p0.2}$ [N/mm^2]	451	-
Yield strength $R_{t2.0}$ (f_y) [N/mm^2]	445	-
Ultimate strength R_m (f_u) [N/mm^2]	563	530..720
Elongation at fracture [%]	23	17

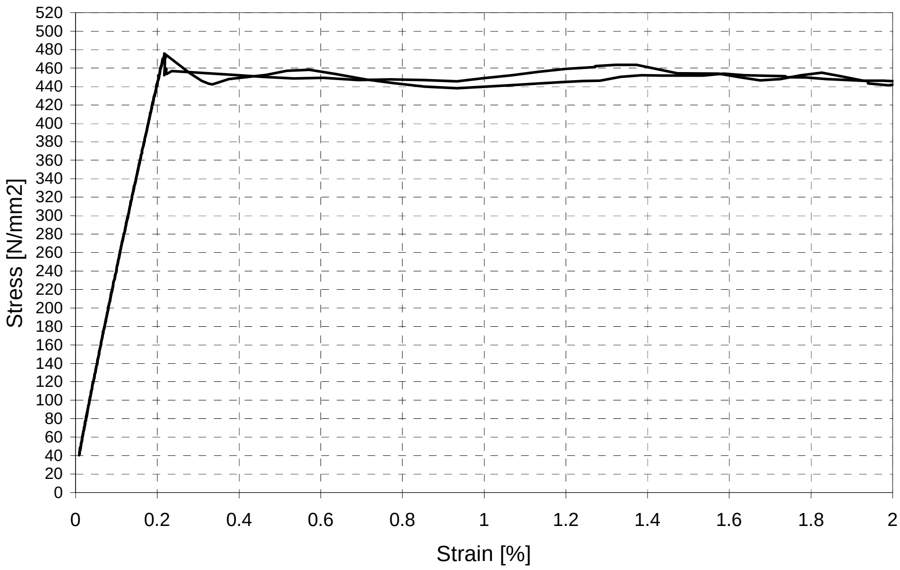


Figure 7: Stress-strain curves from tensile tests at temperature 20 °C for structural steel S460M.

4.5 Structural steel S350GD+Z

The studied material was cold-rolled hot dip zinc coated structural steel S350GD+Z (Z35) manufactured by Rautaruukki Oyj. The high-temperature test pieces were cut out from a cold-formed steel sheet with nominal thickness of 2 mm, longitudinally in the rolling direction. Steel material was in accordance with the requirements of the European standard SFS-EN 10 147 (1992).

Mechanical properties for structural steel S350GD+Z at ambient temperature were determined from three (3) tests with test pieces taken both longitudinally and transversally to rolling direction. The test results are illustrated in Table 9 and Figure 8.

TABLE 9

MECHANICAL PROPERTIES OF STRUCTURAL SHEET STEEL S350GD+Z AT ROOM TEMPERATURE

	Longitudinally to rolling direction	Transversally to rolling direction	Values given by manufacturer (transversal)	SFS-EN 10147
Modulus of elasticity [N/mm^2]	208 360	205 980		
Yield strength R_{p02} [N/mm^2]	368	402	389	-
Yield strength f_y ($R_{t2.0}$) [N/mm^2]	402	426	-	350
Ultimate strength f_u [N/mm^2]	470	480	485	420
Elongation at fracture A [%]	24	22	30 (A80)	16 (A80)

Chemical composition of the test material including a comparison with the maximum values given by the manufacturer is presented in Table 10.

TABLE 10

CHEMICAL COMPOSITION OF THE STEEL MATERIAL S350GD+Z

Elementary substance		Measured value (%)	Maximum value (%)
Carbon	C	0.08	0.20
Manganese	Mn	0.99	1.50
Sulphur	S	0.013	0.05
Phosphorus	P	0.012	0.05

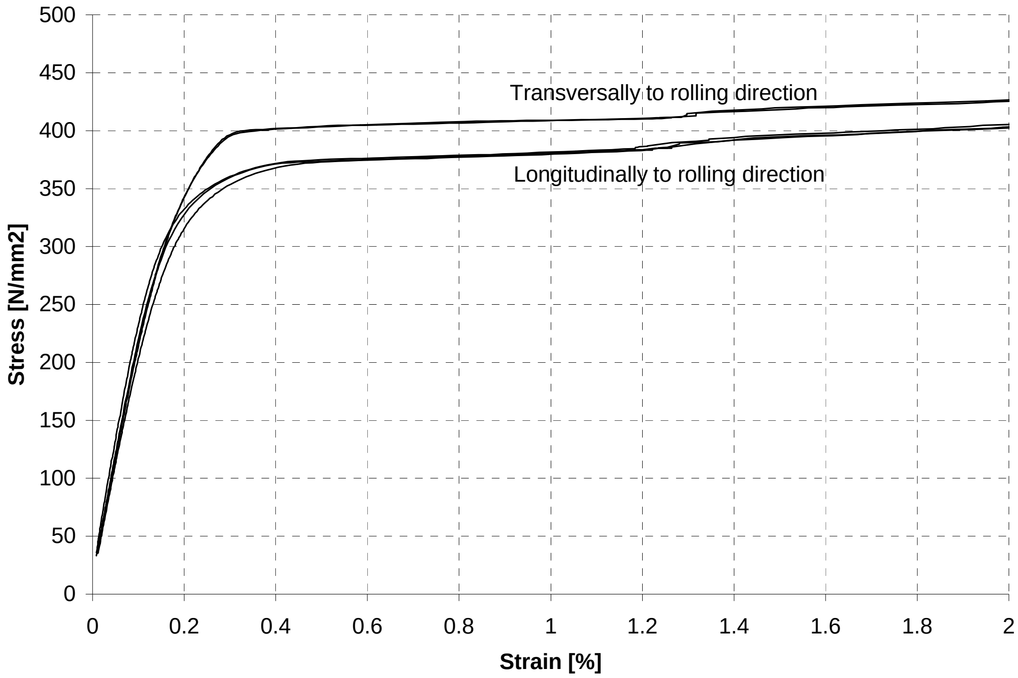


Figure 8: Stress-strain curves for structural steel S350GD+Z at room temperature.

4.6. Structural steel S355J2H

Normal tensile tests according to standard SFS-EN 10002-1 were carried out for the cold-formed material. The test results for yield strength are illustrated in Table 11 and in Figure 9. It can be seen from the test results that the increased strength caused by cold-forming is significant for all the studied hollow sections. The tensile test results at room temperature for the specimens taken from the corner part of SHS 50x50x3 are illustrated in Figure 10. The average yield strength f_y for these specimens was 601 N/mm^2.

TABLE 11
TENSILE TEST RESULTS FOR STRUCTURAL STEEL S355J2H AT ROOM TEMPERATURE. TEST PIECES TAKEN FROM SHS 50X50X3, 80X80X3 AND 100X100X3.

	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

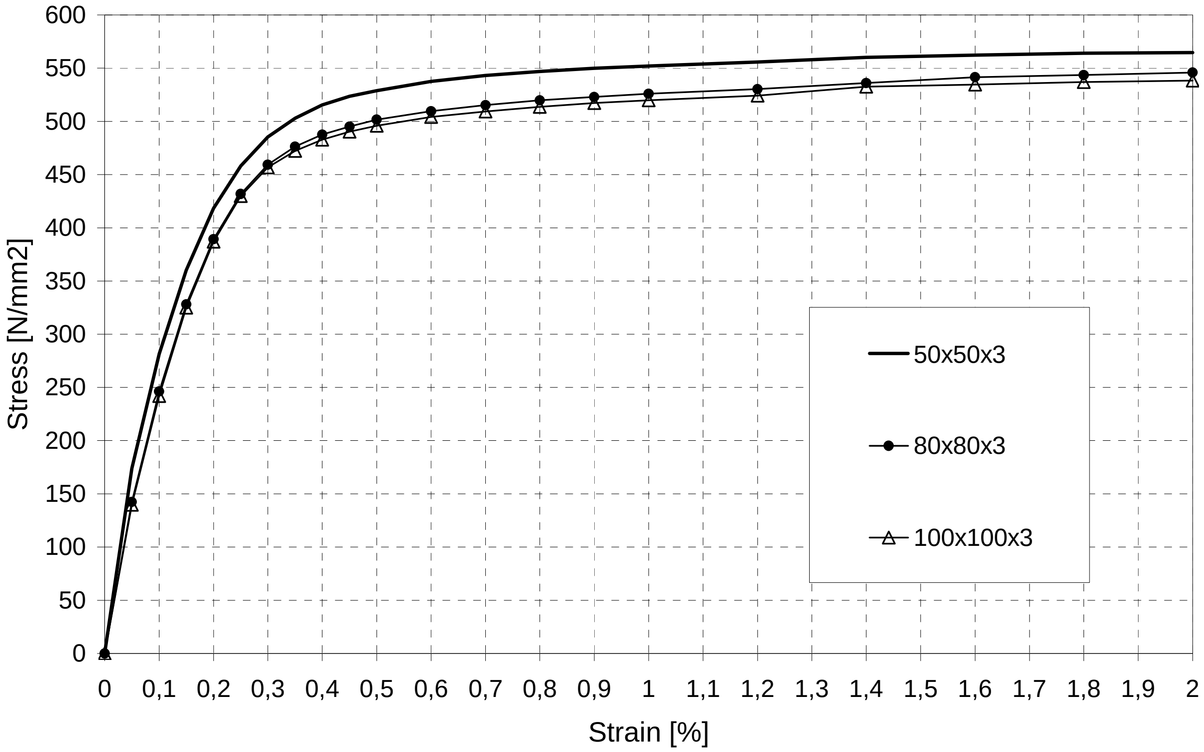


Figure 9: Tensile test results at room temperature for structural steel S355J2H. Test pieces taken from SHS 50x50x3, 80x80x3 and 100x100x3.

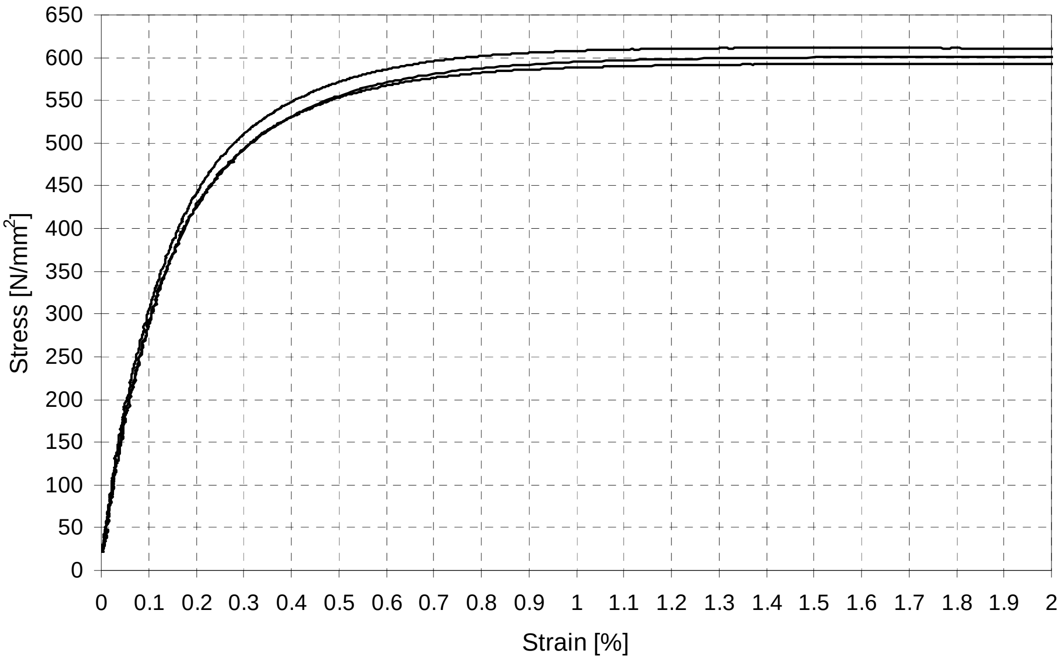


Figure 10: Tensile test results at room temperature for structural steel S355J2H. Test pieces taken from the corner part of SHS 50x50x3.

5. High-temperature tests

5.1 Transient state tests

Transient state tests give a more realistic basis to the material models than the steady state tests. The situation in the test is more like the real situation in a steel structure in fire situation. The stress in the material is almost constant while the temperature rises. This has been the main reason to carry out the more difficult and time consuming tests.

5.1.1 Temperature-strain measurements

In the transient state tensile tests the specimen is under a constant tensile load while the temperature rises. The test procedure is presented in Chapter 3.3. Transient state tensile tests were carried out with two identical tests at each load level. Deviation between the tests was very little. Some test results are presented in Figure 11 to demonstrate this small deviation. The heating rate in the transient state tests was normally 10°C min^{-1}. Also different heating rates were studied. These are reported in details in the annexes. The transient state test results were converted into stress-strain curves at temperatures 100°C - 900°C.

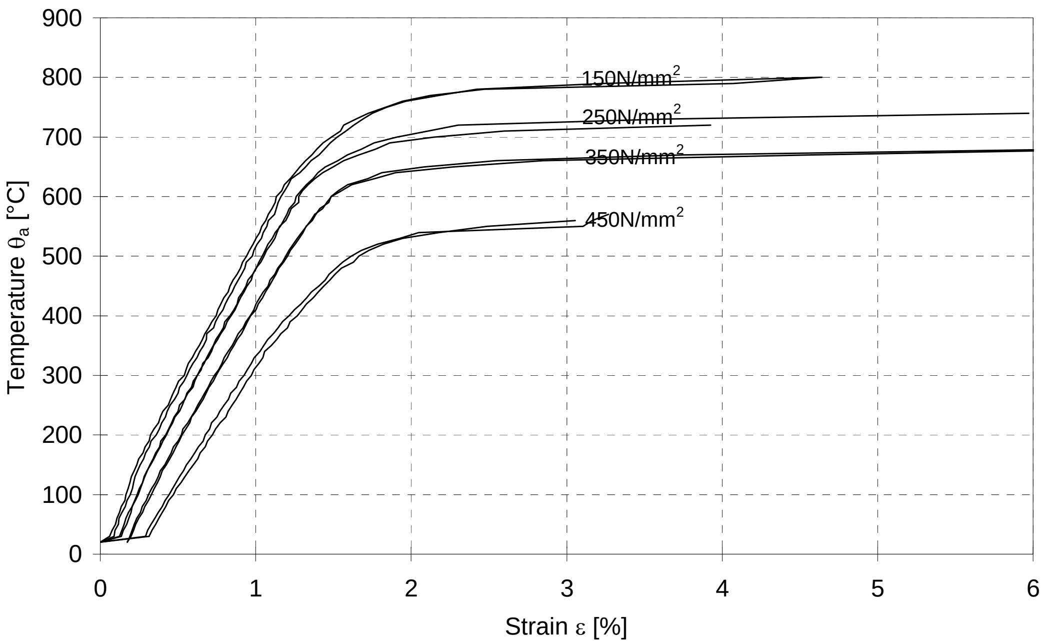


Figure 11: Temperature-strain curves from the transient state tests of austenitic stainless steel EN 1.4301 (App. C).

The thermal strain of the studied materials was determined with transient state tests at stress level of 3 N/mm^2, which was the lowest stress level tested. There was no significant difference between the test results and those in literature, e.g. with stainless steel, Peckner (1977).

5.1.2 Mechanical properties

Mechanical properties, e.g. modulus of elasticity and yield strength of different steel grades were determined from the stress-strain curves which were converted from the transient state test results (from temperature-strain curves at different load levels) as shown in figure 3. The modulus of elasticity was determined as an initial slope of the stress-strain curves. The values were compared to those given in literature. An example of the comparison is shown in Figure 12.

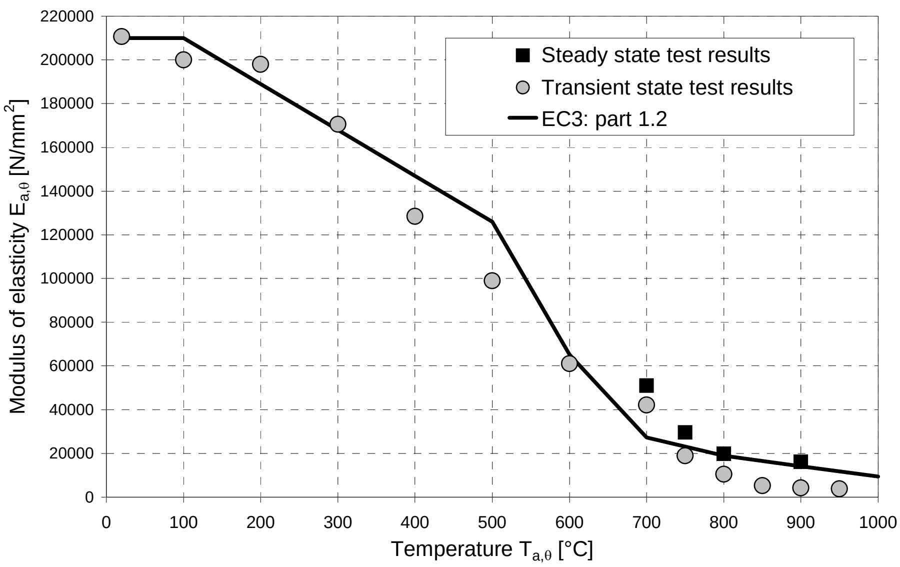


Figure 12: Modulus of elasticity of structural steel S355 at elevated temperatures (App. A).

5.1.3 Effect of heating rate on test results

In the transient state tests the heating rate affects the strain rate so that with higher heating rate the strain rate is also higher. In testing standards the heating rate is limited to 10...50 °C min^{-1}. This was adopted in this research and an example of the results is given in Figure 13 for structural steel S355J2H (App.E).

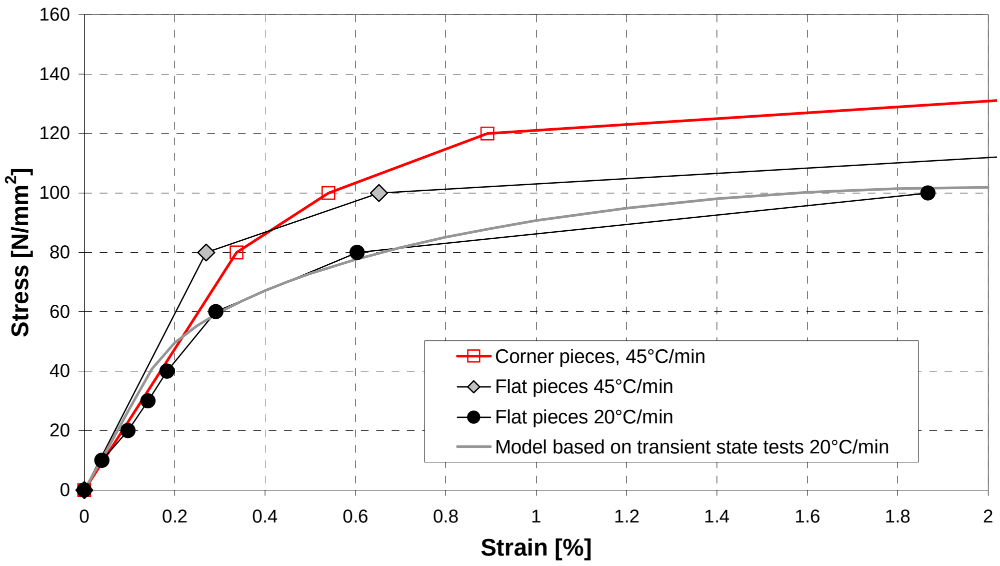


Figure 13: Stress-strain curves of structural steel S355J2H. Test results with different specimens and different heating rates at temperature 700 °C.

As seen in Figure 13, the effect is clear and the phenomena should always be taken into account when carrying out material tests. This should always be reported, when presenting results to materials. These results are discussed more thoroughly in the Appendix E, G and H.

5.2 Steady state tests

The steady state tests are a lot faster and easier to carry out than the transient state tests. Even though there are also certain problems with the testing practice, accurate results can be obtained with this method. In the steady-state tests, the test specimen was heated up to a specific temperature and after that a tensile test is carried out. In the steady state tests, stress and strain values with time are recorded.

5.2.1 Test results at elevated temperatures

In the steady state tests the results come as stress-strain values with time. From the stress-strain curves the mechanical material properties can easily 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. These rates are also limited in the testing standards.

5.2.2 Effect of strain rate on test results

The strain rate has a significant effect on the test results and therefore the limits have been set in the testing standard. Unfortunately a large amount of research is constantly published without the information of the strain rate. In this research the effect was studied. An example of this effect is illustrated in Figure 14 for structural steel S460M.

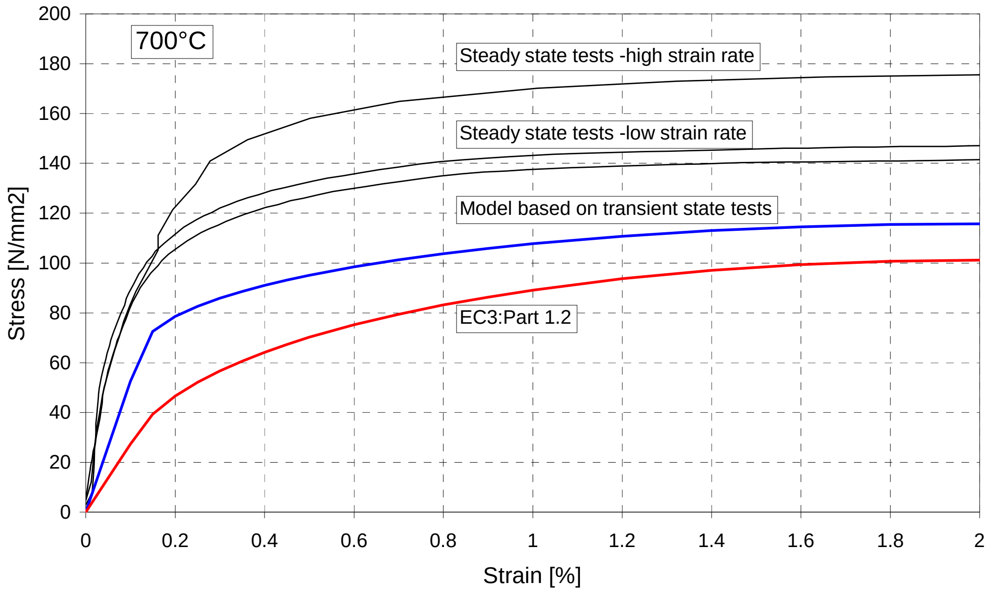


Figure 14: Effect of strain rate on test results of structural steel S460.

As seen in the figure the effect for this material is very big. In this research it was noted that the strain rate affects more the carbon steels than the stainless steels. This is also discussed further in the appendices D, G and H.

6. Residual strength of steel after heating

The strength of structural steel decreases when the temperature rises. The residual strength of steel after cooling down depends on the original properties of the steel grade, the reached temperature, loading situation, degree of deformation etc. A benefit of steel structures is that the strength of structural steel seems to recover quite well after cooling down.

6.1 Background

There is limited amount of experimental data available concerning the residual strength of structural steel after fire or after being at high temperatures. A while ago British Steel (now Corus) published a book concerning the subject by Kirby et al. (1986). This book reports test results of ordinary structural steel grades used in the UK at that time. In addition the strength of reinforcing and prestressing steels at high temperatures is reported. Some advice is also given to evaluate whether a certain steel structure is still usable after fire. A common conclusion from the results is that if the steel structures are not distorted in fire, the strength of steel will probably still be adequate, but e.g. the connections, surface coating etc. have to be checked thoroughly. A rough limit is drawn to about 600 °C after which permanent loss of strength seems to take place.

In British Standard 5950: Part 8 (1990), in appendix c there is also advice about the re-use of steel after fire. According to this, hot finished steels and cast steel can be re-used after fire if the distortions remain within the tolerances for straightness and shape. For cold finished steels that remain within tolerance, it is said that they can be assumed to have 90 % of the original strength after a fire.

It seems that no other design codes of steel structures give advice about the re-use of steel structures after fire, though it would be beneficial for the authorities when estimating fire damage and repair of steel structures after fire.

6.2 Test results

The residual strength of two steel grades was studied experimentally in this research. The steel grades were S355J2H, which is a steel grade used in hollow steel sections and S350GD+Z, which is a commonly used hot-dip galvanized, cold-finished steel used in thin-gauge steel structures. The nominal yield strength for S355J2H is 355N/mm^2, but the actual, measured yield strength was significantly higher. The nominal yield strength of S350GD+Z is 350N/mm^2 and the measured value was quite near the nominal value. There is a lack of information of the residual strength of other structural steels. This could be an interesting research topic which would serve the possibility of re-using e.g. structures after fire.

6.2.1 Test results of S355J2H

A tensile test series was carried out to determine the yield strength of this steel grade used in high-temperature stub column tests. The specimens were taken out from SHS 50x50x3 tubes after they had been tested at elevated temperatures (maximum temperature was 710 °C). The average yield strength of the material before high-temperature tests was 529 N/mm^2 and the nominal yield strength 355 N/mm^2. The test results are illustrated in Figure 15.

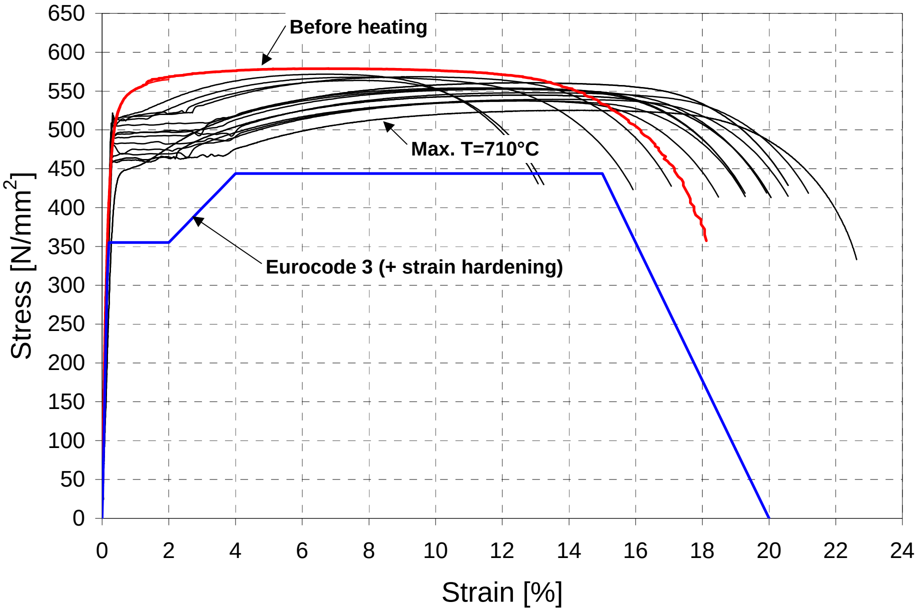


Figure 15: Tensile test results of structural steel S355J2H.

The test results are compared with Eurocode 3: Part 1.2. material model for structural steels at elevated temperatures and with the test results for the unheated material.

It can be seen from the previous figure, that the material strength is quite well preserved. It has to be noted that the columns were tested up to collapse and the residual strength of the material is still over its nominal value. From these results we came to the same conclusion as the research by Kirby et.al. (1986), i.e. if the distortions of a steel structure are within the tolerance limits, the strength of the material is still adequate. A safer approach could be to recommend to use 90% of the nominal yield strength.

6.2.2 Test results of S350GD+Z

For cold-finished structural steel S350GD+Z tensile tests were also carried out at ambient temperature for material taken from members that had been tested at elevated temperatures. This was to find out the remaining strength of the material after fire. It has to be noted that the material has reached temperatures up to 950 °C in the compression tests. The compression tests were carried in a research project of VTT, the Technical Research Centre of Finland.

The temperature histories from the compression tests are illustrated in Figure 16. The tensile test specimens were taken from compression members 24, 27 and 30. The specimens were taken from thin-gauge steel wall studs from the middle of the hotter flange, i.e. from the side, where the gas burner was situated during the test. The wall studs were part of a wall structure, where the gypsum board provided the fire protection and the support against buckling of the compression members.

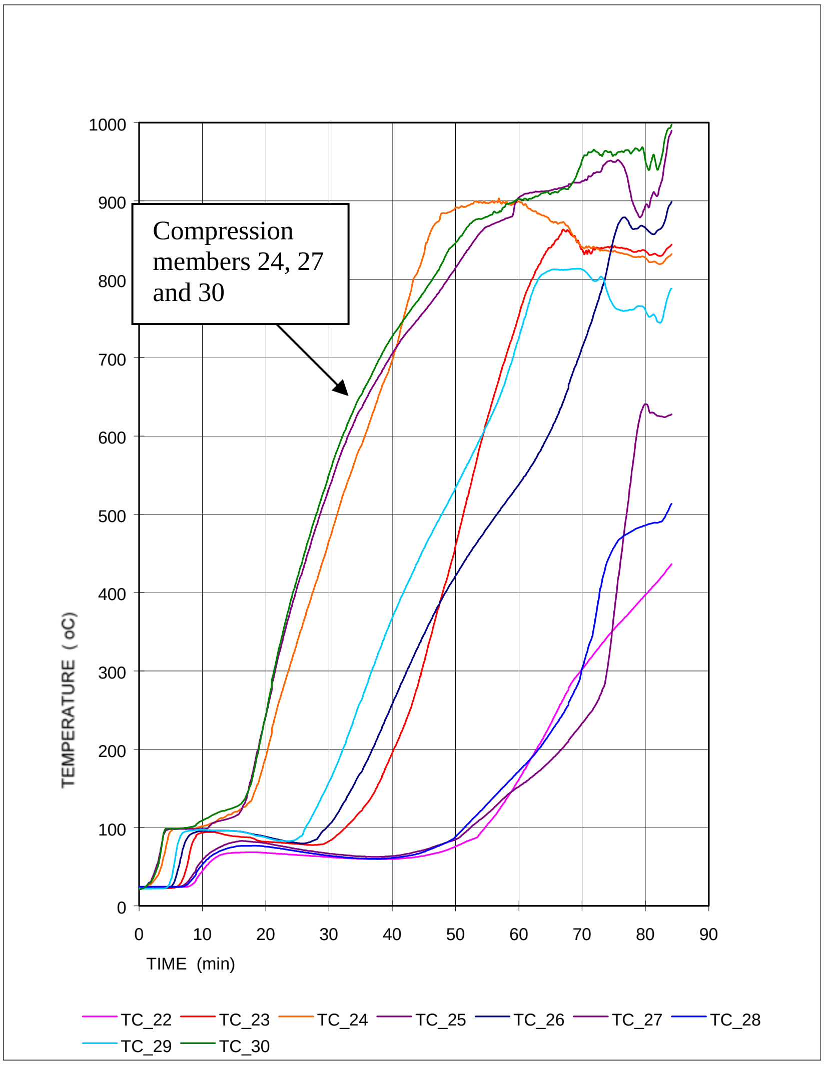


Figure 16: Temperature histories of the compression test specimens, from which the tensile test specimens were taken after cooling down.

In Figure 17 the tensile test results are compared with the test results for unheated material. It can be seen that the yield strength has decreased almost back to the nominal yield strength level of the material. This supports the advice given in BS5950 (1990), that for cold finished steel the strength can be assumed to be 90 % of the original strength if the distortions are within the shape and straightness tolerances of the structure.

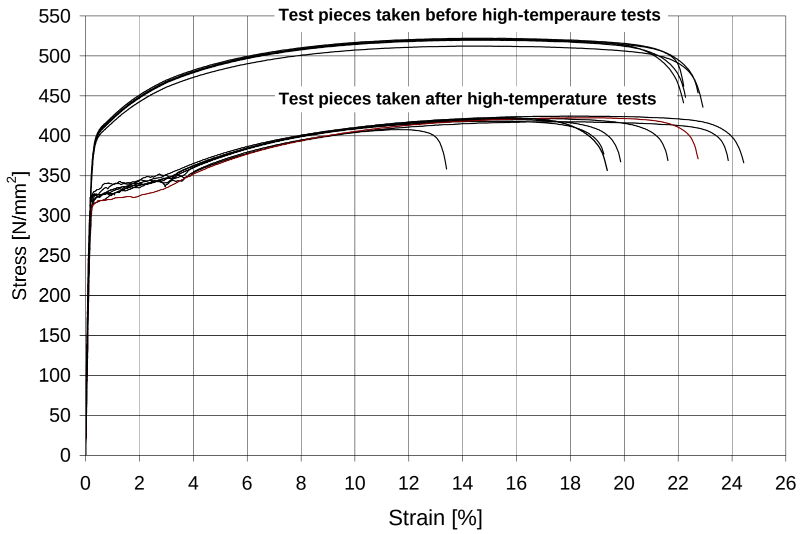


Figure 17: Tensile test results for structural steel S350GD+Z. Test pieces taken before and after high-temperature compression tests.

The thin-gauge steel members that were in the compression tests were quite distorted after the tests and so the structure wouldn't be re-usable after such damage. Despite this, the mechanical properties of the steel material were preserved at almost at 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.

The hot-dip zinc coating is normally done with zinc bath that is at about 450 °C. It has to be noted, that the zinc coating melts at high temperatures (419.6 °C) and on-site repair of this kind of damage is normally not worthwhile. The thickness of the coating can be measured easily on-site using portable measuring device and therefore the evaluation of the possibility to re-use the fire affected thin-gauge steel structure is quite simple. If the zinc coating is not affected, the evaluators know that also the strength of steel has not changed and therefore the structure is still usable.

The thin-gauge steel wall studs are normally protected by the wall sheeting (e.g. gypsum), that provides protection against the temperature and also support to the slender columns against buckling. In steel-concrete composite slabs the strength of steel sheeting is quite often neglected in fire situation and it is also protected by counter ceiling.

7. CONCLUSIONS

An overview of the test results for structural steels S355, S420, S460, S350GD+Z, S355J2H and austenitic stainless steel EN 1.4031 (AISI 304) were given in this paper. The high temperature test results have been published in a way to provide the data in a suitable 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 the Appendices.

Structural steel grades S355, S420 and S460 (App. A, B, H) seemed to follow well the predicted behaviour and there were not too much difference from the Eurocode 3 model.

The behaviour of structural steel S350GD+Z (App F, G, H) 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 evaluating the remaining strength of steel structures after fire.

The behaviour of steel S355J2H (App. E) 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 (App. C) behaved very well and the results are quite promising for 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 stainless steel EN 1.4301 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.

The research was carried out by using transient state tensile test method. Steady state test method was also used to study the difference between the test results from different kind of test methods. The mechanical properties i.e. thermal elongation, elasticity modulus and yield strength of the studied material were determined from the test results. The test results from the transient state tests were first converted to stress-strain curves. The properties were determined at temperatures up to 900 °C.

The test results of EN 1.4301 (AISI 304) from the transient state tests and steady state tests seem to support the steady state test results carried out earlier. The results are also very near the values given in the literature. This is very promising concerning the constructional fire design of austenitic stainless steels. One of the main objectives of a former project concerning the fire resistance of stainless steel structures was to study the possibility to use austenitic stainless steel in load-bearing structures up to 30 minutes fire resistance time without fire protection. This possibility seems to be very realistic on the basis of the transient state test results.

A large number of tests were carried out during these projects. However, the materials cover a very little part of the materials used in steel structures. There is still a huge lack of information about the high-temperature properties concerning especially the high-strength steel grades and stainless steels. All these materials should be studied very carefully in the near future to have realistic basis for the structural fire design using these new materials.

A summary table of the studied steel grades is given in Table 12 in the next page.

TABLE 13

Summary of the studied steel grades and the results

Steel grade	Appendix	Test method	Output	Comment
S355	A, G, H	Transient state 10°C/min.	σ-ε values 20°C-700°C E, f_y	EC 3 model Ramberg-Osgood model
S420M	B, G, H	Transient state 10°C/min. Steady state	σ-ε values 20°C-700°C E, f_y	EC 3 model Ramberg-Osgood mod
S460	D, G, H	Transient state 10°C/min. Steady state 700°C -900°C	σ-ε values 20°C-900°C E, f_y	EC 3 model Different strain rates is steady state tests
S355J2H	E, F	Transient state Steady state up to 900°C	σ-ε values 20°C-900°C E, f_y Residual strength	Different heating rates Different hollow sections Effect of cold-forming
S350GD+Z	F, G, H	Transient state Steady state up to 900°C	σ-ε values 20°C-900°C E, f_y Residual strength	EC 3 model (ENV 1993-1-2 values of E suggested to be used. Values of f_y based on tests)
EN 1.4301 base material	C, H	Transient state Steady state up to 900°C	σ-ε values 20°C-900°C E, f_y	EC 3 model , $R_{p0.2}$; f_y, E
EN 1.4301 Cold-formend	C, H	Transient state Steady state up to 900°C	σ-ε values 20°C-900°C E, f_y	EC 3 model , $R_{p0.2}$; f_y, E

REFERENCES

Ala-Outinen T., Fire resistance of austenitic stainless steels Polarit 725 (EN 1.4301) and Polarit 761 (EN 1.4571), VTT Research notes 1760, Technical Research Centre of Finland, Espoo 1996.

European Committee for Standardisation (CEN), Eurocode 3: Design of steel structures, Part 1.2: Structural fire design, Brussels 1993.

European Convention for Constructional Steelwork (ECCS), European Recommendations for the Fire Safety of Steel Structures, Elsevier Scientific Publishing Company, Amsterdam 1983.

Olawale A.O., Plank R.J., The collapse analysis of steel columns in fire using a finite strip method, International Journal for Numerical Methods in Engineering, Vol. 26 2755-2764, 1988.

Mäkeläinen P., Miller K., Mechanical properties of cold-formed galvanized sheet steel at elevated temperatures. Research Report ECCS-TC-3/1983/15 (SF) April 1983.

Mäkeläinen P., Miller K., Mechanical Properties of Cold-Rolled Hot-Dip Zinc Coated Sheet Steel Z32 at Elevated Temperatures, Helsinki University of Technology, Division of Structural Engineering, Publication 58, Espoo 1983, 31 pages.

Outinen, J., Mäkeläinen, P. Transient state tensile test results of structural steel S355 (RAEX 37-52) at elevated temperatures. Rakenteiden Mekaniikka, 1995. Vol. 28, nro 1, pp. 3-18.

Outinen, J. & Mäkeläinen, P., Transient state tensile test results of structural steels S235, S355 and S350GD+Z at elevated temperatures. Espoo 1995, TKK/Rakennetekniikan laitosjulkaisu 129. 38s.

Outinen, J., Kesti, J. & Mäkeläinen, P., Ohutlevyrakenneteräksen S350GD+Z ja rakenneteräksen S355 palotekniset materiaalimallit. Rakenteiden Mekaniikka, 1995. Vol. 28, nro 4, pp. 3-28

Outinen, J. & Mäkeläinen, P., Transient State Tensile Test Results of Structural Steel S355 (RHS) at elevated temperatures, Helsinki University of Technology, Laboratory of Steel Structures, TeRT-95-11, Espoo 1995

Outinen J., Kesti J., Mäkeläinen P., Behaviour of high-strength structural steel S420M at elevated temperatures, Rakenteiden Mekaniikka, 1996. Vol. 29, nro 3-4, s. 103-114.

Outinen, J. & Mäkeläinen, P., Rakenneterästen S355, S420M ja ohutlevyrakenneteräksen S350GD+Z palotekniset materiaalimallit. Espoo 1996, Teknillinen korkeakoulu/ Rakennetekniikan laitosjulkaisu 131. 16 s + 20 s. liitt.

Outinen, J. & Mäkeläinen, P., Behaviour of structural steels at elevated temperatures, 5th International Colloquium on Stability and Ductility of Steel Structures, Nagoya, Japan, 1997.

Outinen J., Kesti J., Mäkeläinen P., Fire design models for structural steel S355 based upon transient state tensile test results, Journal of Constructional Steel Research Vol.42, No. 3, pp. 161-169, Elsevier Science Ltd, 2/1997.

Mäkeläinen P., Outinen J., Kesti J., Fire design models for structural steel S420M based upon transient state tensile test results, Journal of Constructional Steel Research, Vol. 48, No.1, pp.

47-57, Elsevier Science Ltd, 8/1998.

Outinen J., Mäkeläinen P., Mechanical Properties of Austenitic Stainless Steel Polarit 725 (EN 1.403) at Elevated Temperatures, Teknillinen korkeakoulu, Teräsrakennetekniikka, Julkaisu/Report 1, Espoo 1997.

Mäkeläinen P., Outinen J., Results of the High-Temperature Tests on Structural Steels S235, S355, S350GD+Z and S420M, Teknillinen korkeakoulu, Teräsrakennetekniikka, Julkaisu/Report 2, Espoo 1998.

Mäkeläinen P., Outinen J., Mechanical Properties of an Austenitic Stainless Steel at Elevated Temperatures, Second World Conference on Steel Construction, San Sebastián, Spain, 1998.

Mäkeläinen P., Outinen J., Behaviour of an Austenitic Stainless Steel at Fire Temperatures, Nordic Steel Construction Conference 98, Bergen, Proceedings in Vol.2, pp. 743-750, Norway, 1998.

Mäkeläinen P., Outinen J., Mechanical Properties of an Austenitic Stainless Steel at Elevated Temperatures, Journal of Constructional Steel Research Vol.46, Nos. 1-3, pp. 455, Elsevier Science Ltd, 2/1998.

Pecner D., Bernstein I.M., Handbook of Stainless Steels, McGraw-Hill 1977.

Rakentamismääräyskokoelma, ohjeet B6, Ohutlevyrakenteet and B7, Teräsrakenteet (Finnish Codes of Building Regulations, Codes B6 and B7, Cold-formed Steel Structures and Steel Structures), Helsinki 1989, Helsinki 1987.

Rakentamismääräyskokoelma, ohjeet B7, Teräsrakenteet (Finnish Codes of Building Regulations, Code B7, Steel Structures), Helsinki 1987.

Ramberg W., Osgood W.R., Description of stress-strain curves by three parameters, NACA Technical Note No. 902, 1943.

Standard EN 10 002-2: Metallic materials. Tensile testing. Part 2: Verification on the load cell of tensile testing machine, Brussels 1992.

Standard EN 10 002-4: Metallic materials. Tensile testing. Part 4: Verification of extensometers used in uniaxial testing, Brussels 1992.

Standard SFS-EN 10 002-5: Metallic materials. Tensile testing. Part 5: Method of testing at elevated temperature (in Finnish), Helsinki 1992.

Standard SFS-EN 10 113-3: Hot rolled products in weldable fine grade structural steels. Delivery conditions for thermomechanical rolled steels. (in Finnish), Helsinki 1993.

Standard SFS-EN 10 025: Hot-rolled products of non-alloy structural steel (in Finnish), Helsinki 1993.

Standard SFS-EN 10 147: Continuously hot-dip zinc coated structural steel sheet and strip. Technical delivery conditions. (in Finnish), Helsinki 1992.

APPENDICES

A Outinen J., Kesti J., Mäkeläinen P.
Fire design models for structural steel S355 based upon transient state tensile test results, Journal of Constructional Steel Research Vol.42, No. 3, pp. 161-169, Elsevier Science Ltd, 2/1997.

B Mäkeläinen P., Outinen J., Kesti J.
Fire design models for structural steel S420M based upon transient state tensile test results, Journal of Constructional Steel Research, Vol. 48, No.1, pp. 47-57, Elsevier Science Ltd, 8/1998.

C Mäkeläinen P., Outinen J.
Mechanical Properties of an Austenitic Stainless Steel at Elevated Temperatures, Journal of Constructional Steel Research Vol.46, Nos. 1-3, pp. 455, Elsevier Science Ltd, 2/1998. Full paper published in the proceedings of Second World Conference on Steel Construction, San Sebastián, Spain, 1998.

D Outinen J., Kaitila O., Mäkeläinen P.
A Study for the Development of the Design of Steel Structures in Fire Conditions, 1st International Workshop of Structures in Fire, Proceedings pp. 267-281, Copenhagen, Denmark, 2000.

E Outinen J., Mäkeläinen P.
Effect of High Temperature on Mechanical Properties of Cold-Formed Structural Steel. Ninth International Symposium and Euroconference on Tubular Structures, Düsseldorf, Germany. Proceedings book: Tubular Structures IX, Edited by: Puthli., R., Herion, S., A. A. Balkema, pp.439-444, Netherlands 2001.

F Outinen J., Mäkeläinen P.
High-Temperature Strength of Structural Steel and Residual Strength After Cooling Down, Proceedings of the International Colloquium on Stability and Ductility of Steel Structures, Budapest, Hungary, Ed. M. Ivanyi, Budapest University of Technology and Economics, pp. 751-760, 2002.

G Outinen J., Mäkeläinen P.
Mechanical properties of structural steel at elevated temperatures and after cooling down, Fire and materials, An International Journal, Vol. 28, No.2-4, pp.237-251, John Wiley& Sons, 2004.

H Outinen J.
Mechanical properties of structural steels at elevated temperatures and after cooling down, Fire and Materials Conference, San Francisco, USA, Proceedings, pp. Interscience Communications Limited, UK, 2006. (to be published in February 2006).

HELSINKI UNIVERSITY OF TECHNOLOGY LABORATORY OF STEEL STRUCTURES PUBLICATIONS

TKK-TER-17 Kaitila, O., Kesti, J., Mäkeläinen, P.
Rosette-Joints and Steel Trusses, Research Report and Design Recommendations, 2001.

TKK-TER-18 Ma, Z.
Fire Safety Design of Composite Slim Floor Structures, 2000.

TKK-TER-19 Kesti, J.
Local and Distortional buckling of Perforated Steel Wall Studs, 2000.

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Behaviour of a Semi-Continuous Beam-Column Connection for Composite Slim Floors, 2000.

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