Stainless steel in fire (SSIF)
CONTRACT N° RFS-CR-04048

WP 3 Members with Class 4 cross-sections in fire

Task 3.1 Fire tests on RHS sections

1 EXECUTIVE SUMMARY

The aim of this work package was to provide design rules for structural members with Class 4 cross-sections in fire. A series of tests have been performed for rectangular hollow sections and the fire tests have been systematically modelled with the help of advanced non-linear finite element analysis packages. Stainless steel material models from either earlier ECSC research projects or WP4 of the current research project have been adopted. In the analyses both geometrical and material non-linearity has been included. The temperature distributions measured in the tests have been taken into account. From the results of the fire tests and numerical analyses, design rules for practical use have been developed for structural members with Class 4 cross-sections.

2 CONTENTS

3 INTRODUCTION

The local capacity of the member is dependent on the resistances of the constituent elements that make up the cross-section. Elements may be susceptible to local buckling, which reduce their effectiveness to carry load. In normal temperature design, local buckling is taken into account by the use of effective widths. In addition to the cross-sectional resistance, consideration should be given to overall buckling of members. There is little fire test data or guidance on thin steel sections, which by their very nature may fail by local buckling. The common technical interest of the project is that light structures fabricated by cold forming technology or by welding can be very economical in many cases.

4 OBJECTIVES

The aim of this work package was to provide design rules for structural members with Class 4 cross-sections in fire. A simple fire design rules for practical use for structural members with Class 4 cross-sections have been delivered.

5 EXPERIMENTAL WORK

The main goal of the test series was to provide design rules for steel structures in case of fire when the structure fails by local buckling.

A series of tests have been performed for rectangular hollow sections. The calculation of a thin steel section at normal temperature is based on the effective cross-section. The effective cross-section depends on the dimensions of the plate, on the load, on the material yield strength and on the modulus of elasticity.

Due to the small length of test specimens (modified slenderness is $\leq$ 0,2), global flexural buckling does not occur. The concentric compression tests were performed for two different cross-sections. The cross-sections of hollow sections were RHS 200x200x5 and RHS 150x150x3. The profiles were manufactured by Stalatube, and the profiles from which the specimens were cut were taken from normal production and manufactured by a cold roll-forming process.

5.1 Material properties at normal temperature

Material properties at normal temperature were determined with tensile tests according to EN-10 002-1 (1990). Tests were performed for both types of cross-section. Four tensile tests for both types of cross-section were carried out. The test pieces were taken from the web face and the flange face not including the welded seam (Figure 1). By flange face were meant the one opposite to the welded seam and by web face the one beside it. All tensile tests have two repeats. The stress-strain curves and material properties obtained from the coupon tests are documented in Appendix 1 and the material properties are given in Table 1. Appendix 1 gives also the steel mill certificates according to EN 10 204-3-1B.

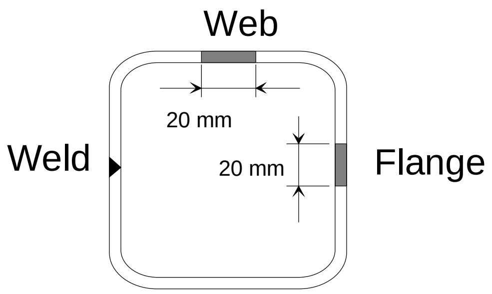

Figure 1. Location of test pieces taken from the cross-section

Table 1. Summary of tensile tests results.

m = mean value $s=\sqrt{\frac{1}{n-1}\Sigma(x_i-\bar{x})^2}$ *standard deviation*

Cross-section	Specimen	Yield strength $R_{p0.2}$ [MPa] (0.2 % strain)		Tensile strength R_m [MPa]		Elongation [%]	
		m	s	m	s	m	s
RHS 150x150x3	Flange face	397	16.26	666	5.66	49.8	0.35
RHS 150x150x3	Web face	329	14.85	641	2.83	53.5	0
RHS 200x200x5	Flange face	341	52	629	13.43	56.3	3.18
RHS 200x200x5	Web face	286	2.12	616	2.12	58.0	0.71

The measured strength values of the flange of both cross-sections are higher than the nominal values of yield strength according to the steel mill certificates.

Imperfections in the longitudinal direction and the flatness of faces of all specimens were measured. Appendix 2 gives the details. The differences in dimensions and the deviations in straightness were small on the basis of the measurements.

5.2 Tests at normal temperature

The specimens of RHS sections were tested at normal temperature with the same load equipment as at elevated temperatures. The tests were repeated two times for one cross-section. The specimen types and test arrangement are shown in Figure 2.

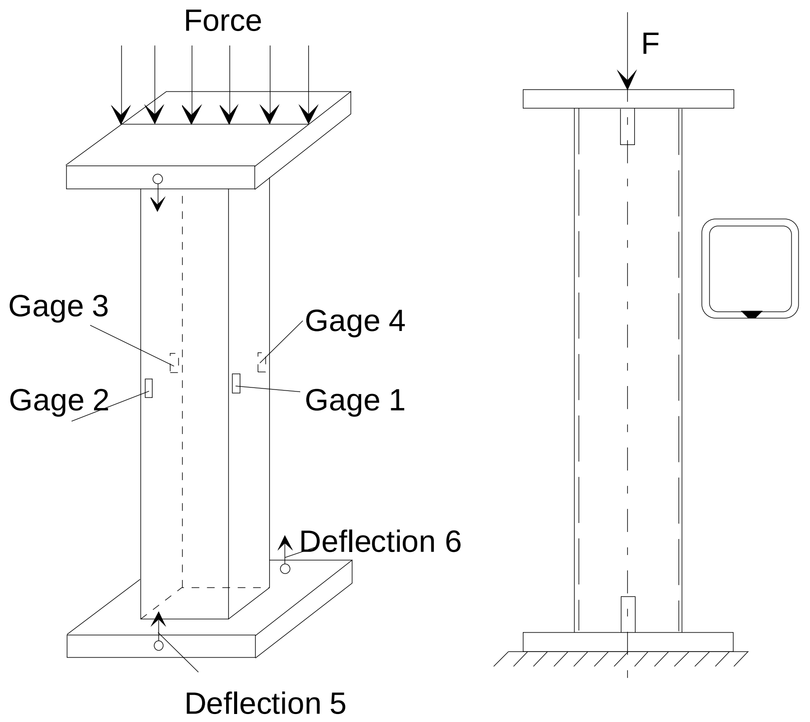

Figure 2. Specimen types and test arrangement.

Table 2. Test results at normal temperature.

Test name	Profile	Length [mm]	Load [kN]
A13	RHS 200x200x5	900	1129
A16	RHS 200x200x5	900	1118
B13	RHS 150x150x3	900	398
B16	RHS 150x150x3	900	393

In the tests the stress was measured at mid-length with four strain gauges. The displacement from the front and back side was also measured. Appendix 3 shows the measured force-displacement curves and photographs of specimens tested at normal temperature.

The loss of load-bearing capacity at normal temperature occurred very suddenly as a result of local buckling in the middle of the column.

5.3 Tests at elevated temperatures

A total of 6 tests were performed at the VTT for columns of Class 4 cross-section. The columns were rectangular hollow sections with the same cross-sectional dimensions (RHS 200x200x5 and RHS 150x150x3) as at normal temperature tests. The length (with end plates) of the columns was 900 mm. The columns were tested using one set of support conditions (fixed ends) with concentric compression load. The material was EN 1.4301.

The RHS cross-sections were tested at 3 different load levels. The specimens of RHS sections were also tested at normal temperature with the same load equipment as at elevated temperatures (Chapter 3).

During the tests the axial load was kept constant and the furnace temperature was controlled to rise subsequently by 10°C/min (Figure 3). This rate was chosen to give a slow steel temperature rise in the failure phase of the columns. The furnace temperature was not controlled according to standard the EN 1363-1: 1999 (ISO 834-1) standard fire curve as this would have given too high a temperature rise for unprotected steel columns, making measurements of failure temperature imprecise. Unprotected columns were studied as measurements were easy to conduct. The details of tests are summarised in Table 3.

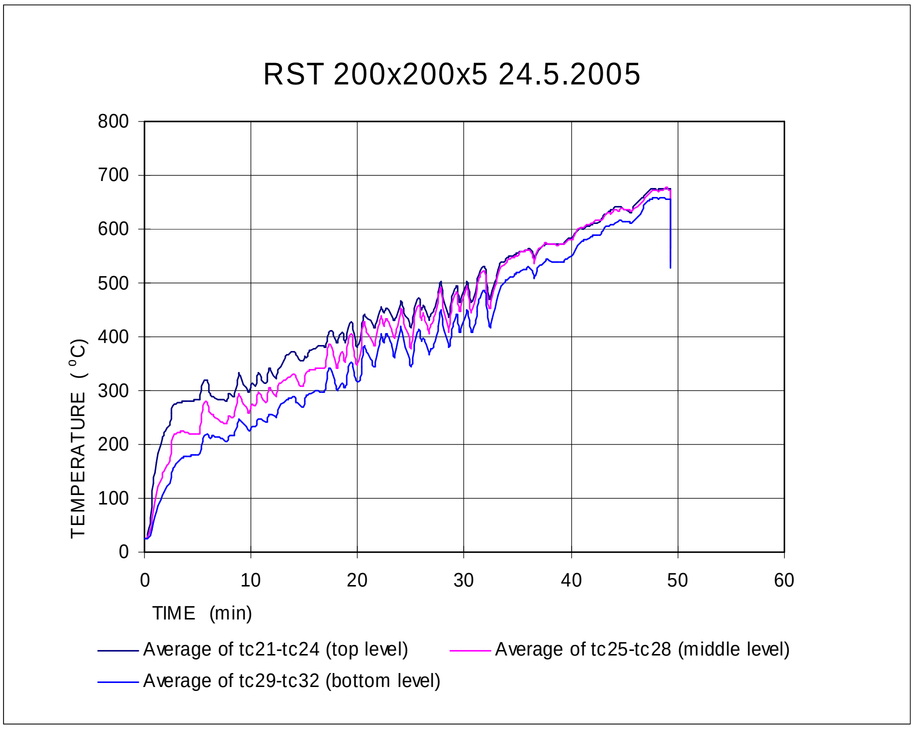

Figure 3. Furnace gas temperature as a function of time. Test for column A11.

Table 3. Summary of tests for rectangular hollow sections RHS 200x200x5 and RHS 150x100x3.

Column id	Profile	Length [mm]	Material	Load [kN]	Load level	Test date
A11	RHS 200x200x5	900	EN 1.4301	694	0,62	24.5.2005
A12	RHS 200x200x5	900	EN 1.4301	567	0,5	19.5.2005
A15	RHS 200x200x5	900	EN 1.4301	463	0,41	7.6.2005
B15	RHS 150x150x3	900	EN 1.4301	248	0,63	10.5.2005
B11	RHS 150x150x3	900	EN 1.4301	203	0,51	9.5.2005
B14	RHS 150x150x3	900	EN 1.4301	165	0,42	12.5.2005

5.3.1 Test set-up

The columns were tested using one set of support conditions and in the vertical position. The steel columns were heated in a model furnace specially built for testing loaded columns and beams. The test furnace is designed to simulate conditions to which a member might be exposed during a fire, i.e. temperatures, structural loads, and heat transfer. It comprises a furnace chamber located within a steel framework.

The internal dimensions of the furnace chamber are: width 1500 mm, height 1300 mm and depth 1500 mm. The interior faces of the chamber are lined with fire resistant bricks. Inside are four oil burners, arranged on the two walls of the furnace containing two burners each.

Loading was applied by a hydraulic jack of capacity 2 MN located outside and above the furnace chamber (see Figure 4). A steel unit with circulating water was placed between the column and the loading jack. Sideways support of the steel unit was achieved by the furnace roof element.

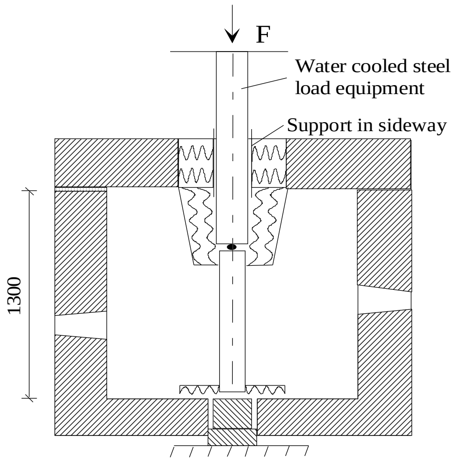

Figure 4. Test set-up in furnace tests.

Axial deformation of the test specimen were determined by measuring the displacement of the top of the water-cooled steel unit using transducers. The load was controlled and measured using pressure transducers.

The temperatures of each column were measured at three cross-sections using a total of 12 chromel-alumel thermocouples (K-Type) 2 x 0.5 mm. Furnace gas temperatures 100 mm from the columns were measured with 12 sheated chromel-alumel thermocouples (K-Type) with diameter of 3.0 mm, also at three cross-sections. The location and numbering of thermocouples of a specimen is shown in Figure 5. The temperatures measured by furnace thermocouples were averaged automatically, and the average used for controlling the furnace temperature.

Temperature readings were taken at each thermocouple at intervals of 10 s. Deformations were measured and recorded automatically at intervals of 10 s. Observations were made of the general behaviour of the column specimen during the course of the tests and photographs and videofilm were taken.

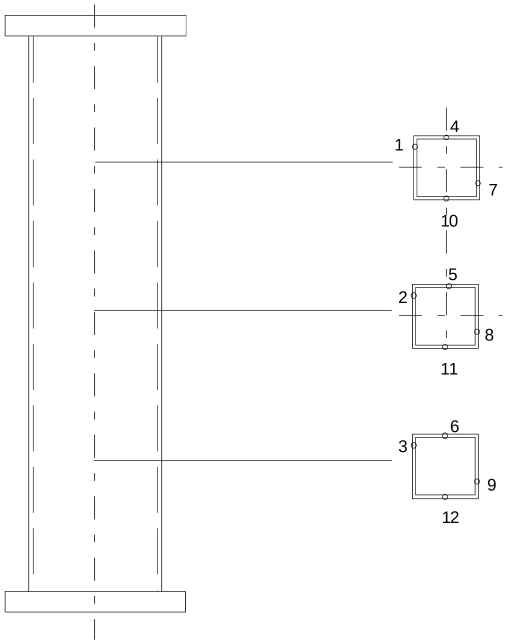

Figure 5. Column specimen details, and location and number of thermocouples.

Figure 6. Furnace test set-up.

6 RESULTS

In Table 4 are shown the reduction factors for strength and stiffness of material EN 1.4301 at elevated temperatures in accordance with EN 1993-1-2 (2005).

Table 4. Reduction factors for strength and stiffness at elevated temperatures for stainless steel EN 1.4301 (AISI 304).

Steel temperature [°C]	Reduction factor (relative to f_y) for proof strength $k_{0.2p,\theta} = f_{0.2p,\theta}/f_y$	Reduction factor (relative to E_a) for the slope of the linear elastic range $k_{E,\theta} = E_{a,\theta}/E_a$
20	1,00	1,00
100	0,82	0,96
200	0,68	0,92
300	0,64	0,88
400	0,60	0,84
500	0,54	0,80
600	0,49	0,76
700	0,40	0,71
800	0,27	0,63
900	0,14	0,45
1000	0,06	0,20
1100	0,03	0,10

6.1 Calculation according to Eurocodes

The formulae determining the effective width at normal temperature are expressed in prEN 1993-1-4 (2005). The effective cross section area and the effective section modulus are based on the material properties at 20 °C according to EN 1993-1-2 (2005). Cross-sectional properties are calculated from nominal dimensions including material thickness and corner radius. The strength of the material is taken as the mean value measured from tensile tests of webs and flanges (Table 1). The yield strength of steel at normal temperature is determined as the proof strain of 0.2% and has been determined by tensile testing. In the normal temperature the modulus of elasticity used is 200 kN/mm^2. In the calculations the Poisson's ratio for steel has been taken as 0.3 and is assumed to be independent of temperature.

6.2 Test results

Appendix 4 shows the measured temperatures at three levels during fire tests, the expansion of a test specimen and the photographs after fire tests.

In Figure 7 the load-bearing capacities for the cross-section RHS 200x200x5 have been calculated as described in Section 6. The load-bearing capacity is calculated according to Equation 1 (blue line).

$$N_{b,Rd} = A_{eff} \cdot k_{0,2\,proof,\theta} \cdot f_y \qquad (1)$$

The load bearing capacity marked with red line is calculated according to Equation 2:

$$N_{b,Rd} = k_{0,2proof,\theta} \cdot N_{bR,measured} \quad (2)$$

where $N_{bR,measured}$ is the mean value of load-bearing resistances at normal temperature.

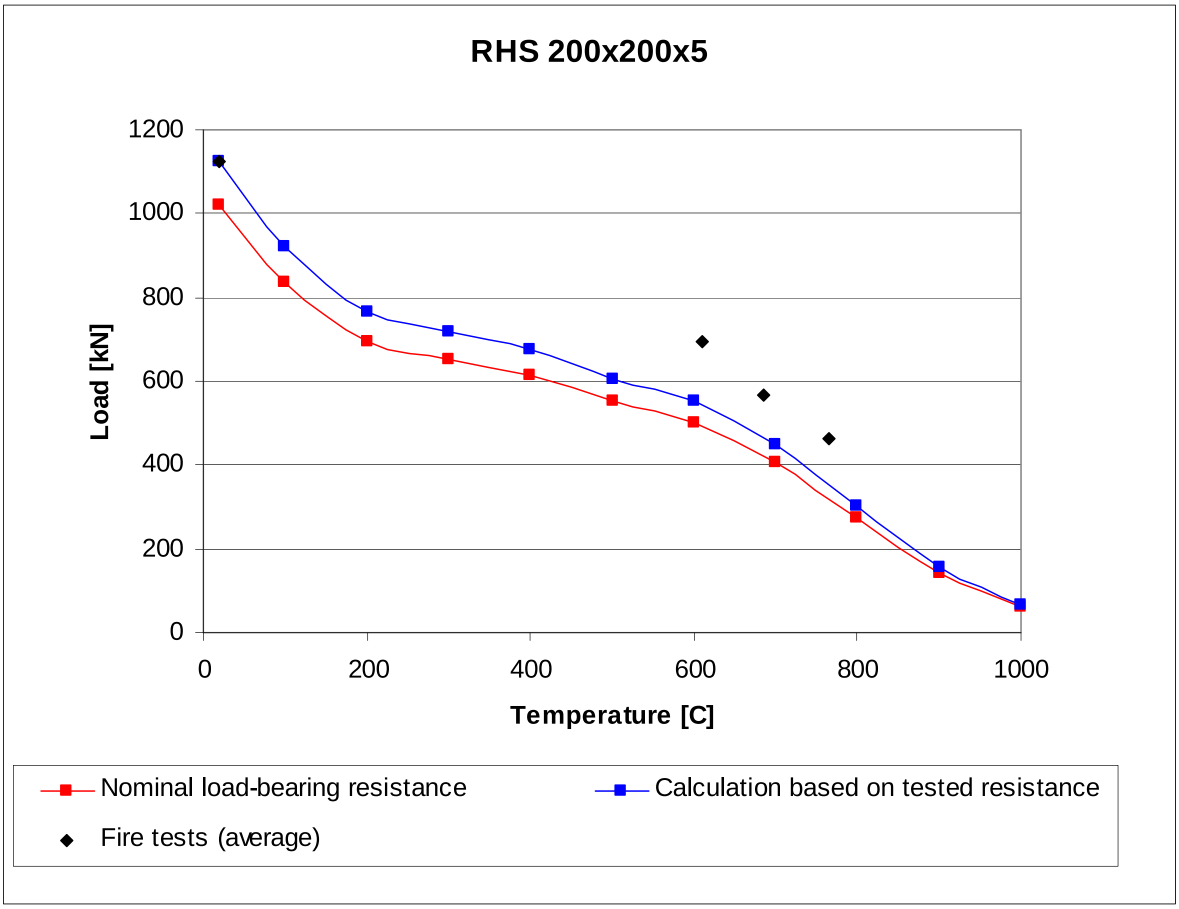

Figure 7. Measured temperatures compared with calculated results. Concentrically compressed column RHS 200x200x5.

The column loses its load-bearing capacity the moment a buckle appears. The end temperature is the maximum temperature at the level (upper, middle or lower) where a buckle appears (see Appendix 4). The calculation and test results are shown in Figure 8 for the cross-section RHS 150x100x3.

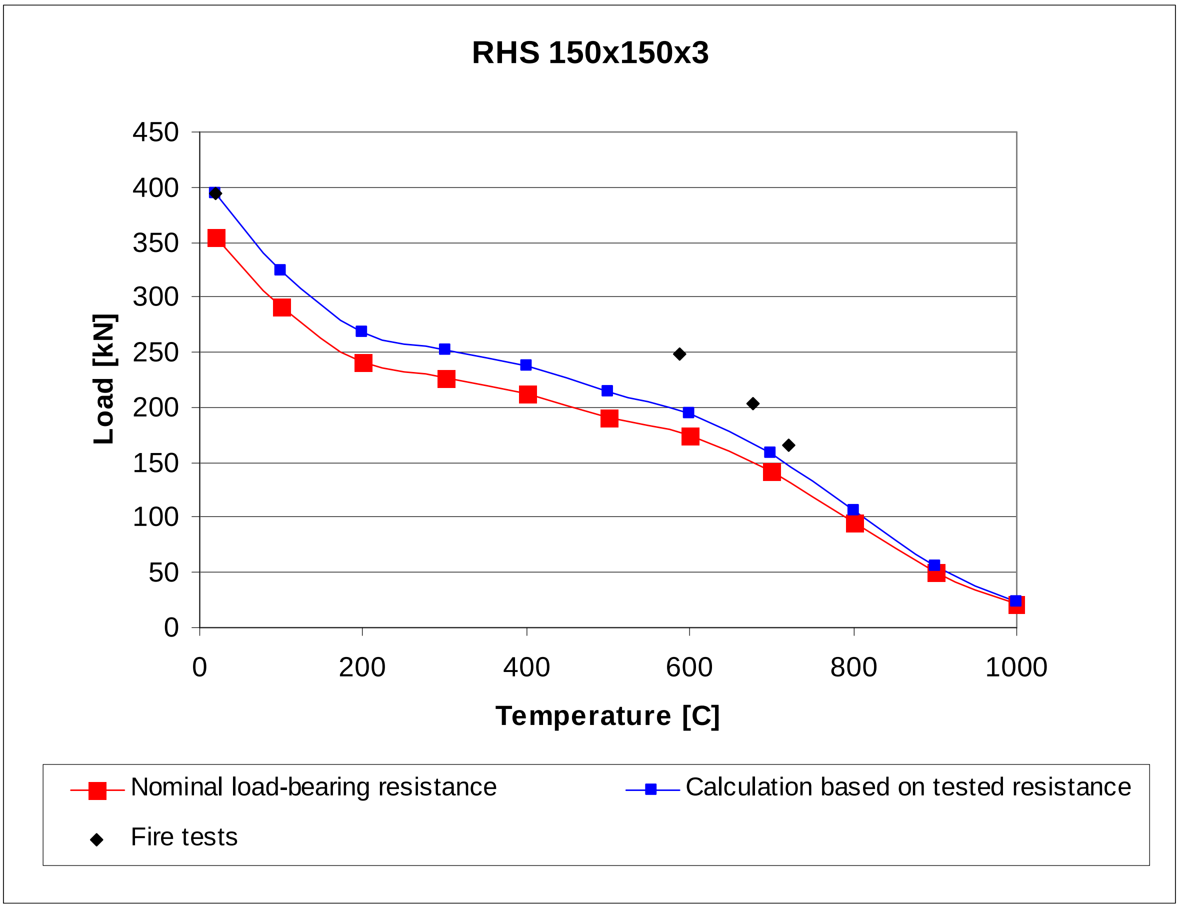

Figure 8. Measured temperatures compared with calculated results. Concentrically compressed column RHS 150x150x3.

7 NUMERICAL ANALYSIS

The fire tests have been systematically modelled with the help of advanced non-linear finite element analysis packages by SBI.

8 DEVELOPMENT OF DESIGN GUIDANCE

From the results of the fire tests and numerical analyses, design rules for practical use heve been developed for structural members with Class 4 cross-sections by SBI.

9 CONCLUSIONS

The concentric compression tests were performed for two cross-sections of Class 4 (RHS 200x200x5 and RHS 150x150x3). In the tests the specimens were so short that global flexural buckling did not occur. Therefore the column loses its load-bearing capacity soon after the buckle appears. The fire tests were transient-state tests and the specimens were unprotected. In addition to the fire tests the specimens were tested at normal temperature.

The yield strength of steel at normal temperature was determined by tensile tests at a proof strain of 0.2%. The effective width at normal temperature is determined according to prEN

1993-1-4-(2005). The load-bearing capacities of members are calculated according to Eurocode. Comparing the fire test results with the resistance calculated according to the present calculation methods shows that if the effective cross section area is based on the material properties at 20 °C, and the yield strength is reduced to the corresponding temperature, the predicted resistance is on the safe side.

10 RECOMMENDATIONS FOR FURTHER WORK

The respective test series should be carried out for other stainless steel material types and for other *b/t* relationships.

11 REFERENCES

EN 1363-1: 1999 *Fire resistance tests - Part 1: General requirements*, CEN European Committee for Standardization, Brussels, Belgium, 1999.

prEN 1993-1-4. 2005. Eurocode 3: Design of steel structures, Part 1.4: General rules, Supplementary rules for stainless steels. Brussels: European Committee for Standardization (CEN). 36 p.

EN 1993-1-2. 2005. Eurocode 3: Design of steel structures, Part 1.2: Structural fire design. Brussels: European Committee for Standardization (CEN). 76 p.

APPENDIX 1: STRESS-STRAIN CURVES AT NORMAL TEMPERATURE AND STEEL MILL CERTIFICATES

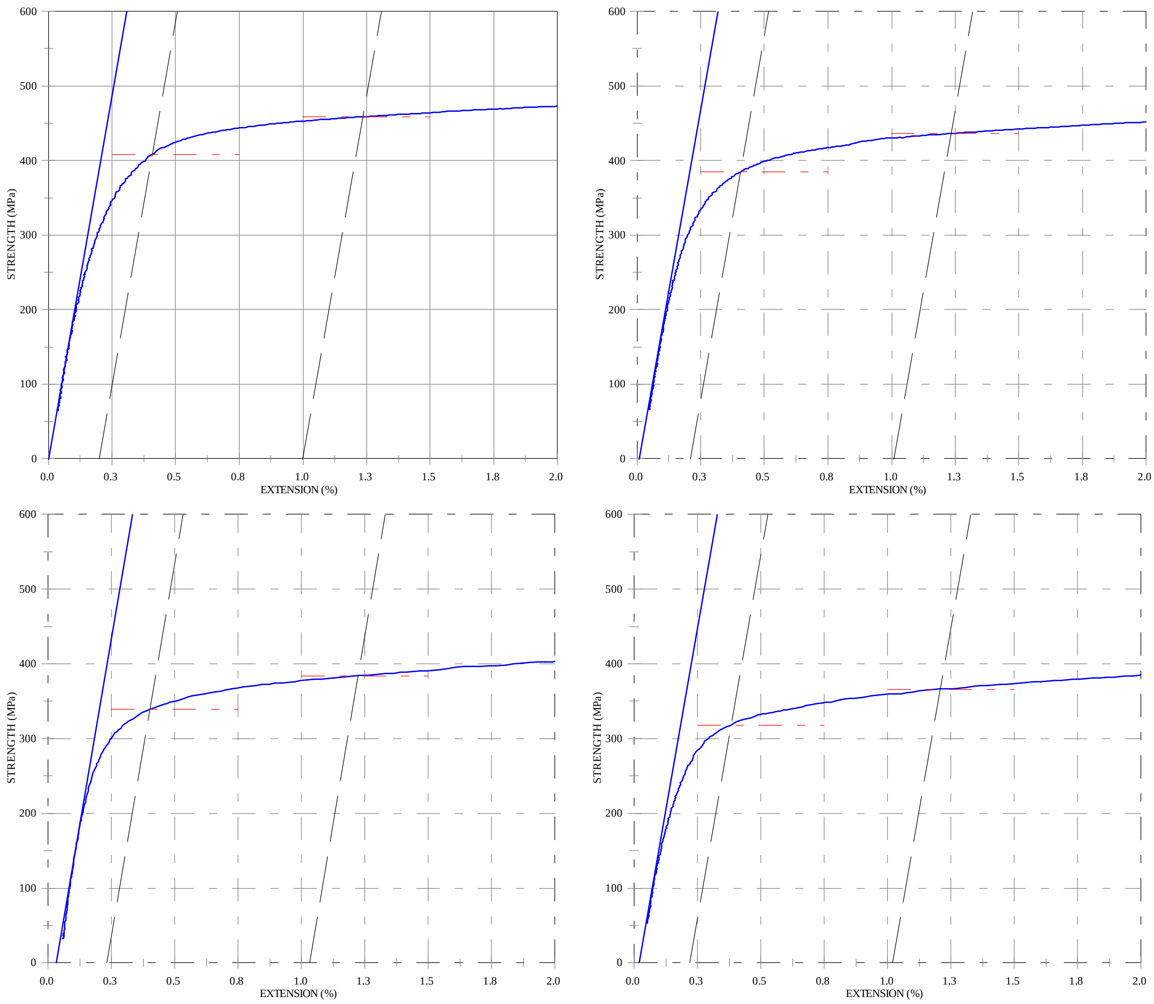

Figure 1. Stress-strain curves of RHS 150x150x3 (material EN 1.4301) at normal temperature.

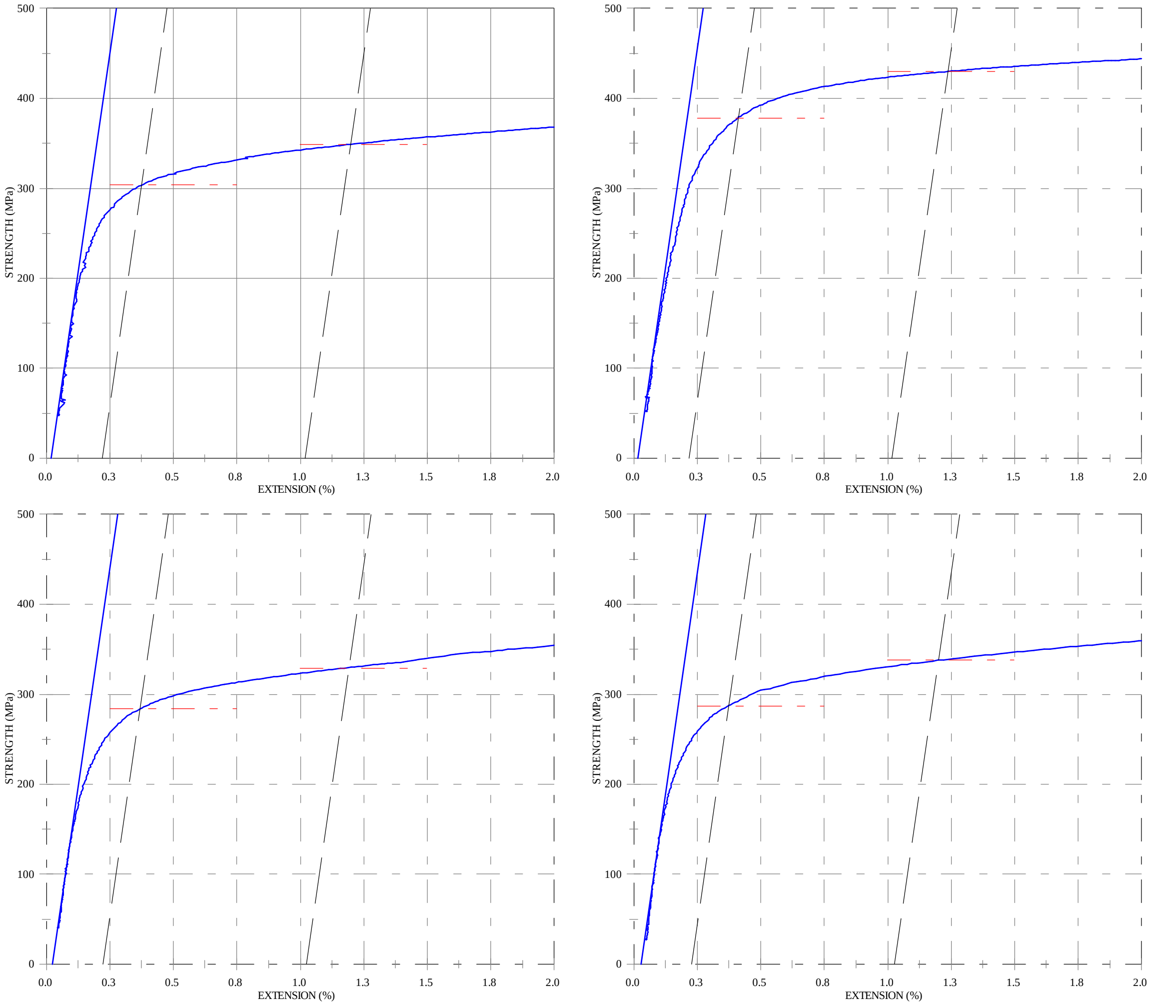

Figure 2. Stress-strain curves of RHS 200x200x5 (material EN 1.4301) at normal temperature.

AINESTODISTUS 1/1

Päiväys 11.05.2005

EN 10204 3.1.B

TILAUSNUMERONNE

VIITE

Stalatube Oy
Taivalkatu 7
15170 LAHTI

TOIMITUSTIEDOT

RUOSTUMATTOMIA TERÄSPUTKIA

Määrä/m	Tuote	Pintakäsittely
6 m	200x200x5 mm	unpolished

Sulatusnro	Laatu
457672	EN 1.4301

KEMIALLINEN ANALYYSI(terästehtaan todistuksen mukaisesti)

C %	Si %	Mn %	P %	S %	Cr %	Ni %	Mo %
0,050	0,470	1,710	0,028	0,001	18,300	8,200	0,000

Ti %	Nb %	Cu %	N %	Others %	Al %	Ca %	Mg %
0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000

TESTITULOKSET (Raina)

Näyte	MYÖTÖ-LUJUUS Rp0.2 N/mm2	1% VENYMÄ-RAJA Rp1.0 N/mm2	MURTO-LUJUUS Rm N/mm2	VENYMÄ A5 %	KOVUUS A50 %
Testi 1	289	341	624	54	168
Testi 2	288	337	618	55	175

Korroosiotesti DIN 50914 hyväksyttävä

100 % pyörrevirtatarkastus SEP 1914

STALATUBE OY

Lahti
11.05.2005

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AINESTODISTUS

1/1

Päiväys 11.05.2005
EN 10204 3.1.B

TILAUSNUMERONNE
VIITE

TOIMITUSTIEDOT

RUOSTUMATTOMIA TERÄSPUTKIA

Määrä/m	Tuote	Pintakäsittely
6 m	150x150x3 mm	unpolished

Sulatusnro	Laatu
E50277006	EN 1.4301

KEMIALLINEN ANALYYSI(terästehtaan todistuksen mukaisesti)

C %	Si %	Mn %	P %	S %	Cr %	Ni %	Mo %
0,042	0,350	1,500	0,027	0,007	18,200	8,100	0,000

Ti %	Nb %	Cu %	N %	Others %	Al %	Ca %	Mg %
0,000	0,000	0,000	0,049	0,000	0,000	0,000	0,000

TESTITULOKSET (Raina)

Näyte	MYÖTÖ-LUJUUS Rp0.2 N/mm2	1% VENYMÄ-RAJA Rp1.0 N/mm2	MURTO-LUJUUS Rm N/mm2	VENYMÄ A5 %	KOVUUS A50 %
Testi 1	331	372	641	49	183
Testi 2	341	390	648	46	0

Korroosiotesti DIN 50914 hyväksyttävä

100 % pyörrevirtatarkastus SEP 1914

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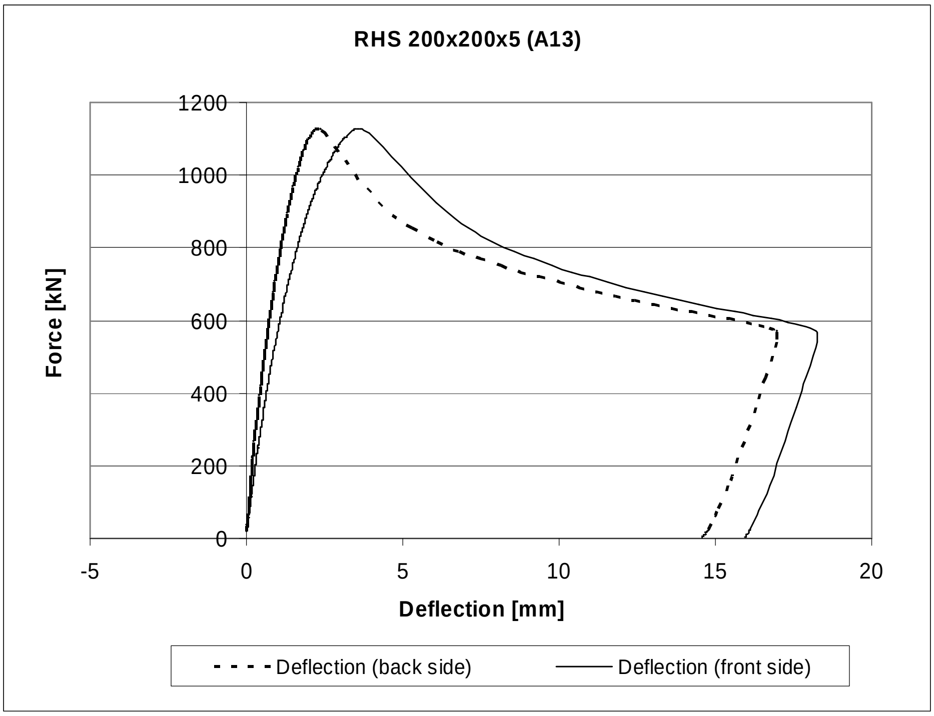
APPENDIX 2: THE DIMENSIONS OF SPECIMENS

Specimen	Length of specimen	Depth of web	Depth of flange	Length of circle	Longtudinal straightness				Cross-section straightness			
	[mm]	[mm]	[mm]	[mm]	Side 1 [mm]	Side 2 [mm]	Side 3 [mm]	Side 4 [mm]	Side 1 [mm]	Side 2 [mm]	Side 3 [mm]	Side 4 [mm]
RHS 200x200x5												
A11	839	199,89	199,95	777	-0,3	-0,02	-0,41	0,18	-0,41	-0,24	-0,25	-0,28
A12	839	199,91	200,17	777	-0,35	0,3	-0,13	0,08	-0,43	-0,22	-0,46	-0,41
A13	839	199,82	199,95	777	-0,41	0,31	-0,4	0,31	-0,13	-0,27	-0,08	-0,12
A14	839	200,05	199,83	777	-0,38	0,34	-0,27	0,29	-0,37	-0,32	-0,3	-0,1
A15	839	199,97	199,92	778	-0,28	0,23	-0,28	0,37	-0,46	-0,41	-0,35	-0,25
A16	839	199,9	200,05	777	-0,15	0,44	-0,11	0,25	-0,31	-0,1	-0,29	-0,09
	Mean value **839,00**	Mean value **199,92**	Mean value **199,98**	Mean value **777,17**			Max **0,44**	Min **-0,41**			Max **-0,08**	Min **-0,46**
RHS 150x150x3												
B11	840,5	149,81	150,6	588	-0,2	0,49	0,4	0,28	-0,43	-0,04	-0,22	-0,32
B12	839	149,7	150,4	589	-0,84	0,38	-0,53	0,29	-0,65	-0,05	-0,48	-0,45
B13	839	150	150,7	589	-0,7	0,69	-0,16	0,73	-0,51	-0,2	-0,25	0,13
B14	838,5	150,1	150,72	589	-0,71	0,62	-0,15	-0,41	-0,66	-0,47	-0,6	-0,25
B15	839	149,69	150,45	588	-0,94	-0,62	-0,4	-0,01	-0,71	-0,15	-0,56	-0,31
B16	839	149,83	150,46	588	-0,4	-0,45	-0,51	-0,06	-0,6	-0,27	-0,32	-0,41
	Mean value **839,17**	Mean value **149,86**	Mean value **150,56**	Mean value **588,50**			Max **0,73**	Min **-0,94**			Max **0,13**	Min **-0,71**

APPENDIX 3: LOAD DISPLACEMENT CURVES AT NORMAL TEMPERATURE AND PHOTOGRAPHS OF COMPRESSED TESTS



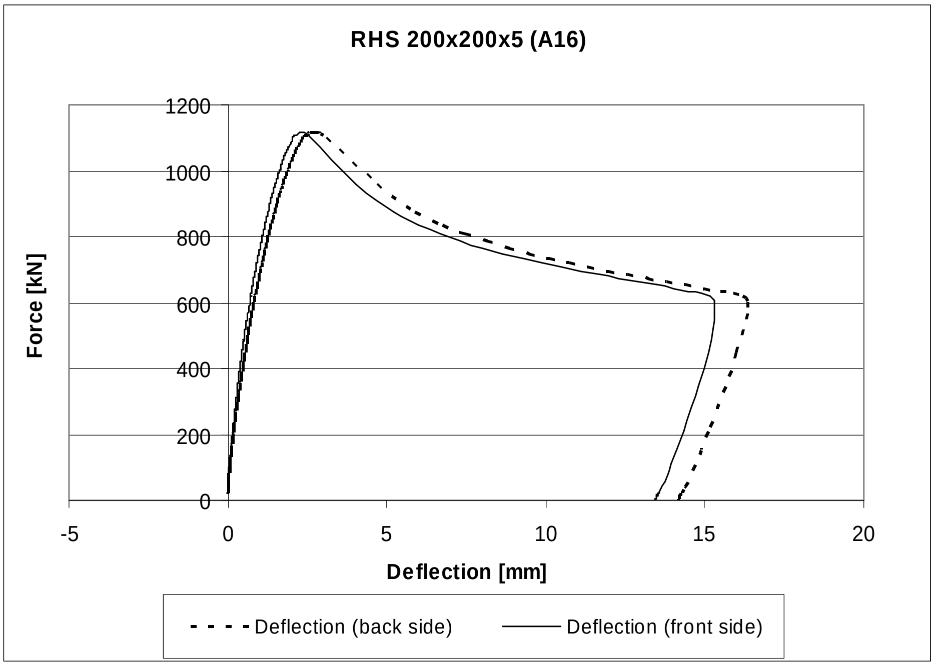
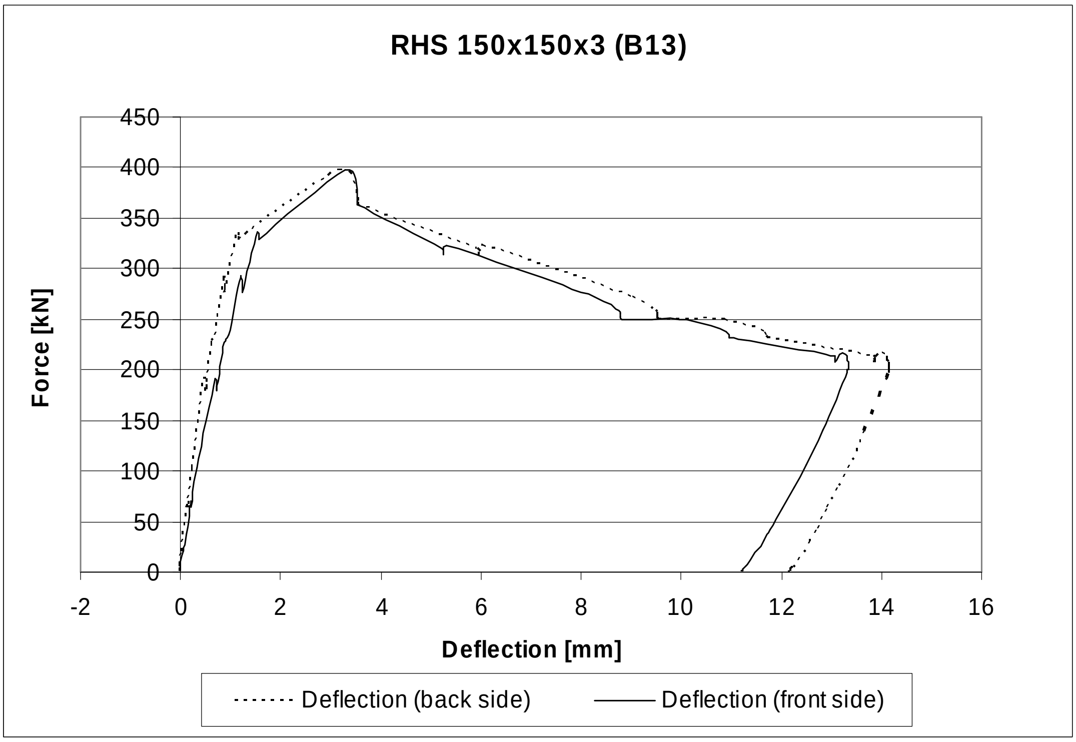


Figure 1. Load-displacement curves for RHS 200x200x5 under concentric compression. Displacement shortening in the longitudinal direction measured from the front and back sides.



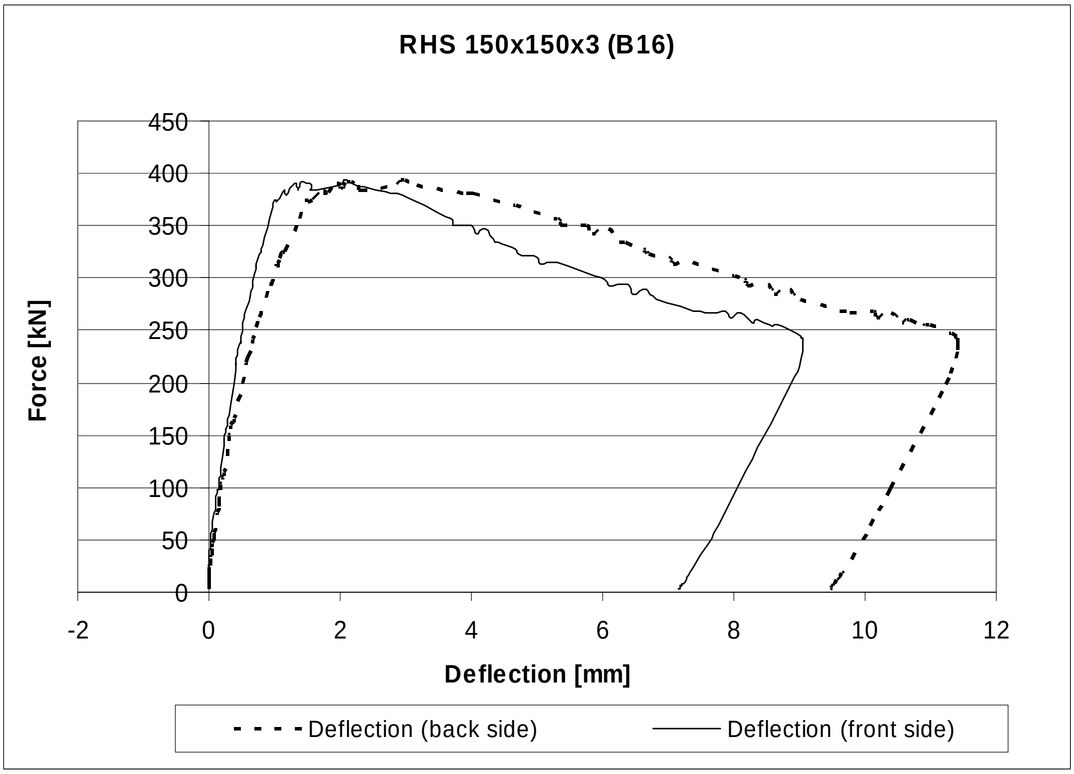


Figure 2. Load-displacement curves for RHS 150x150x3 under concentric compression. Displacement shortening in the longitudinal direction measured from the front and back sides.

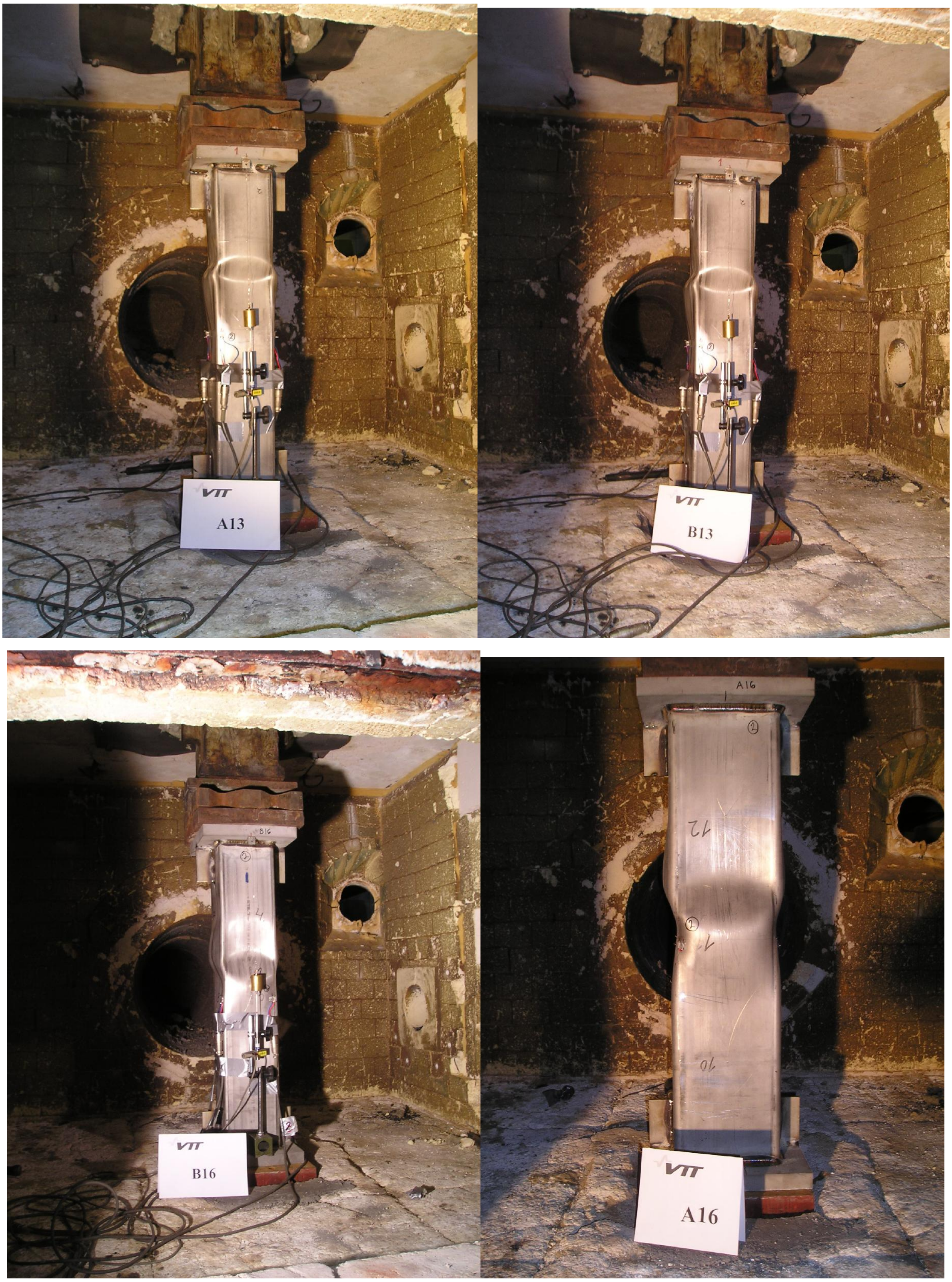


Figure 3. Photographs of concentrically compressed tests at normal temperature.

APPENDIX 4: MEASURED TEMPERATURES AND DEFORMATIONS DURING FIRE

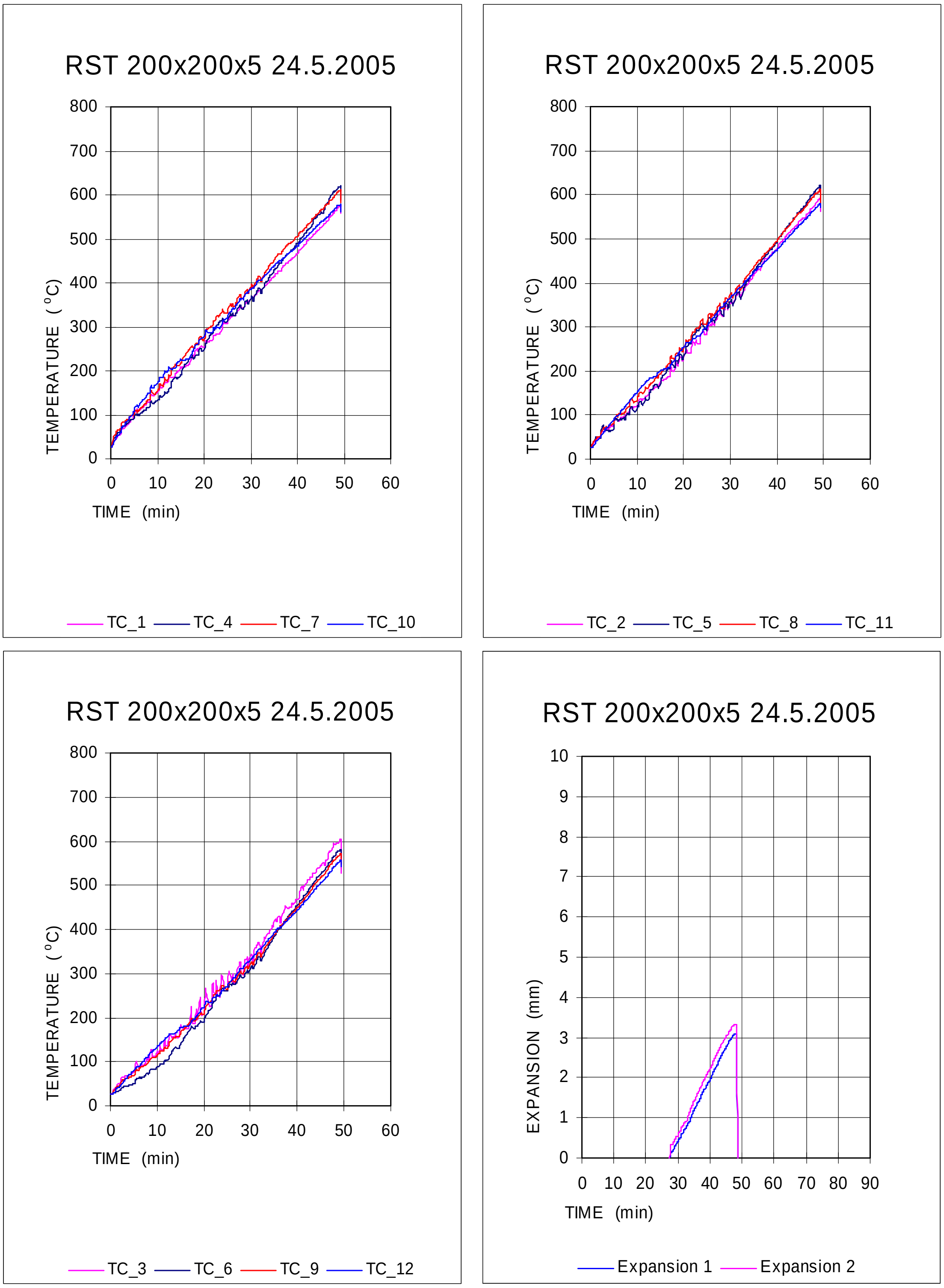


Figure 1. Measured temperatures during fire tests and the expansion of the test specimen A11. Maximum measured temperature 609 °C in the upper part of the column when buckle consisted. Remark: The measurement of expansion failed in the beginning of the test. Load is 694 kN.

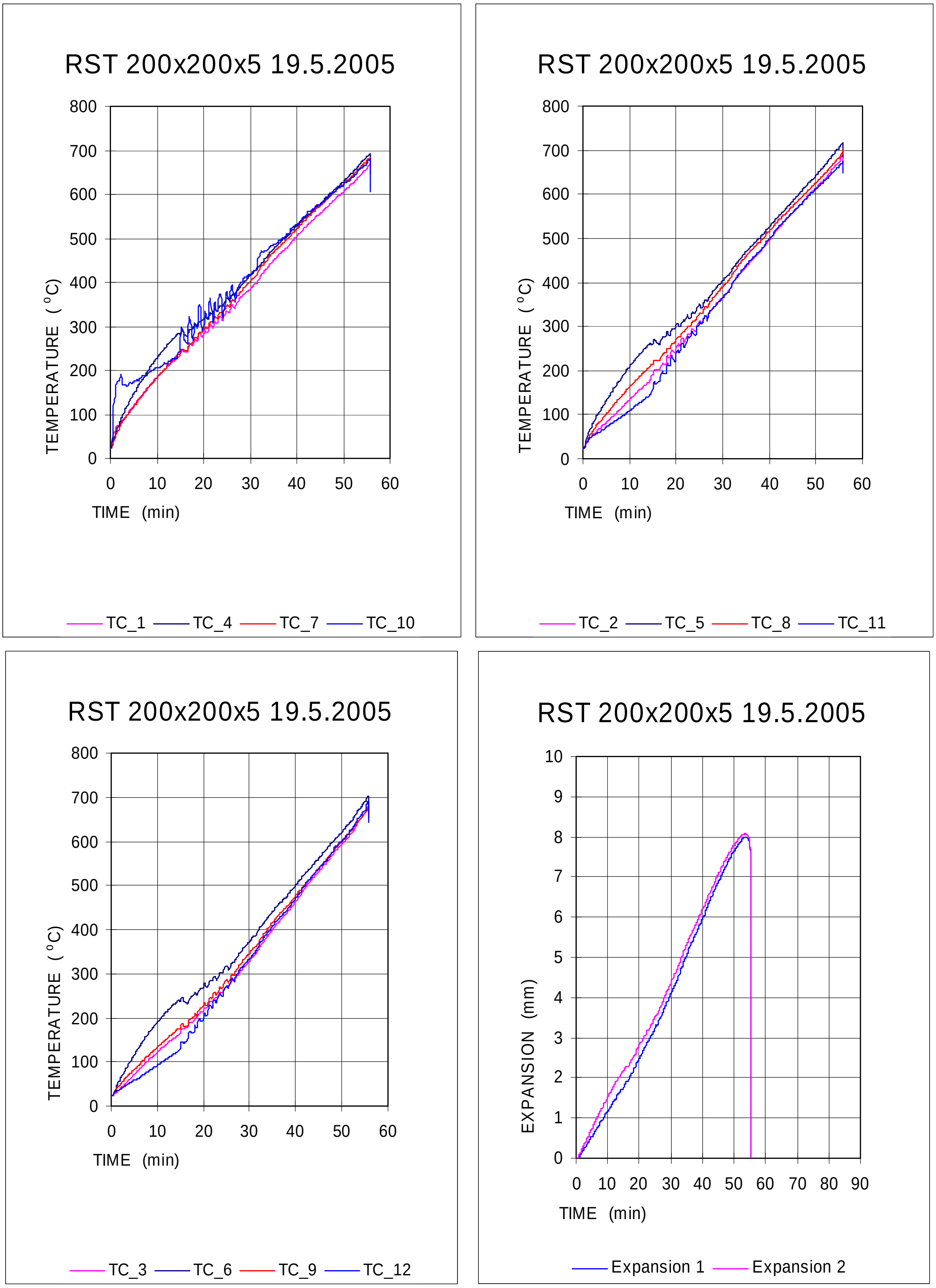


Figure 2. Measured temperatures during fire tests and the expansion of the test specimen A12. Maximum measured temperature 685 ℃ in the middle of the column when buckle consisted. Load is 567 kN.

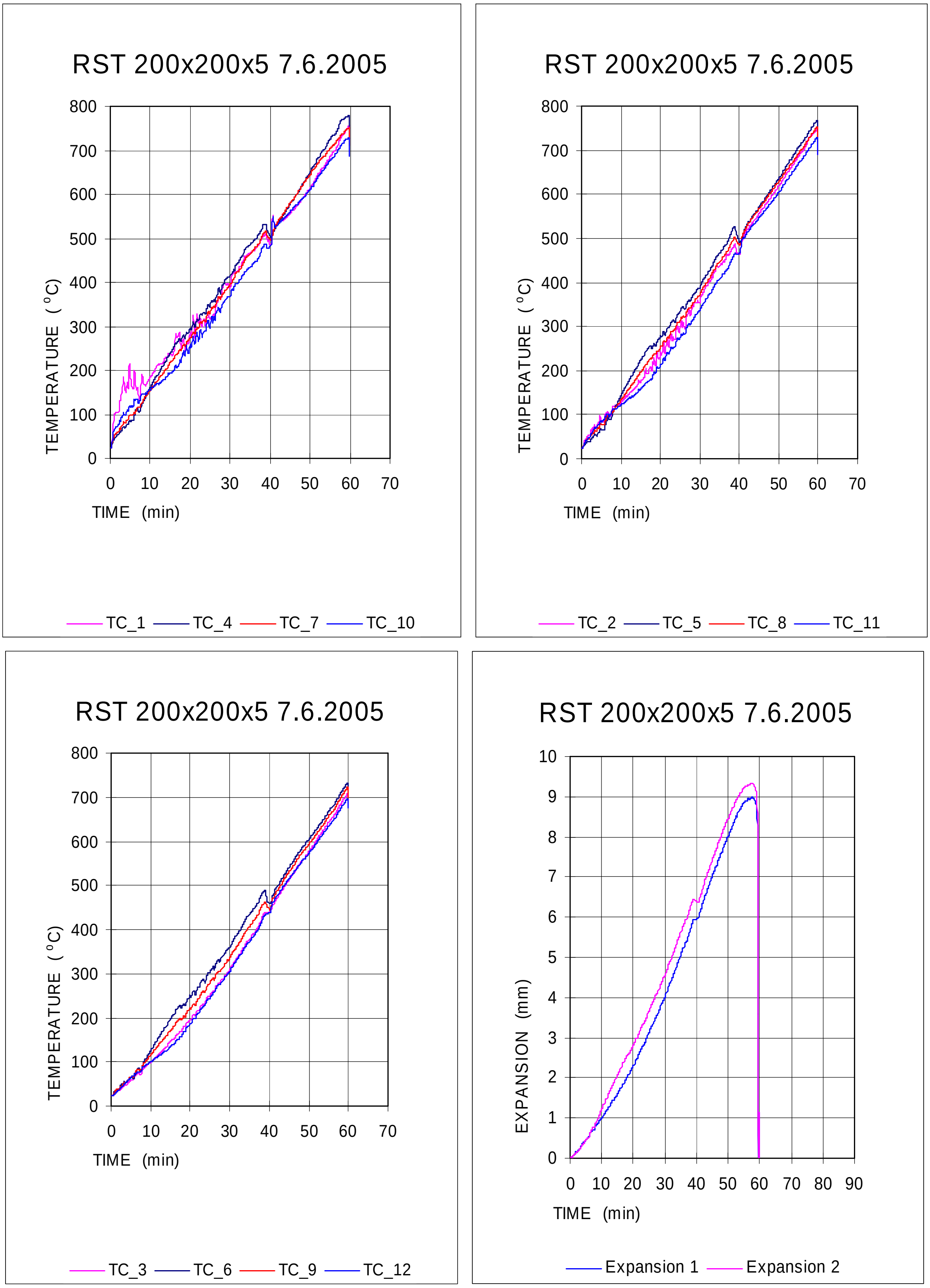


Figure 3. Measured temperatures during fire tests and the expansion of the test specimen A15. Maximum measured temperature 764 °C in the upper part of the column when buckle consisted. Load is 463 kN.

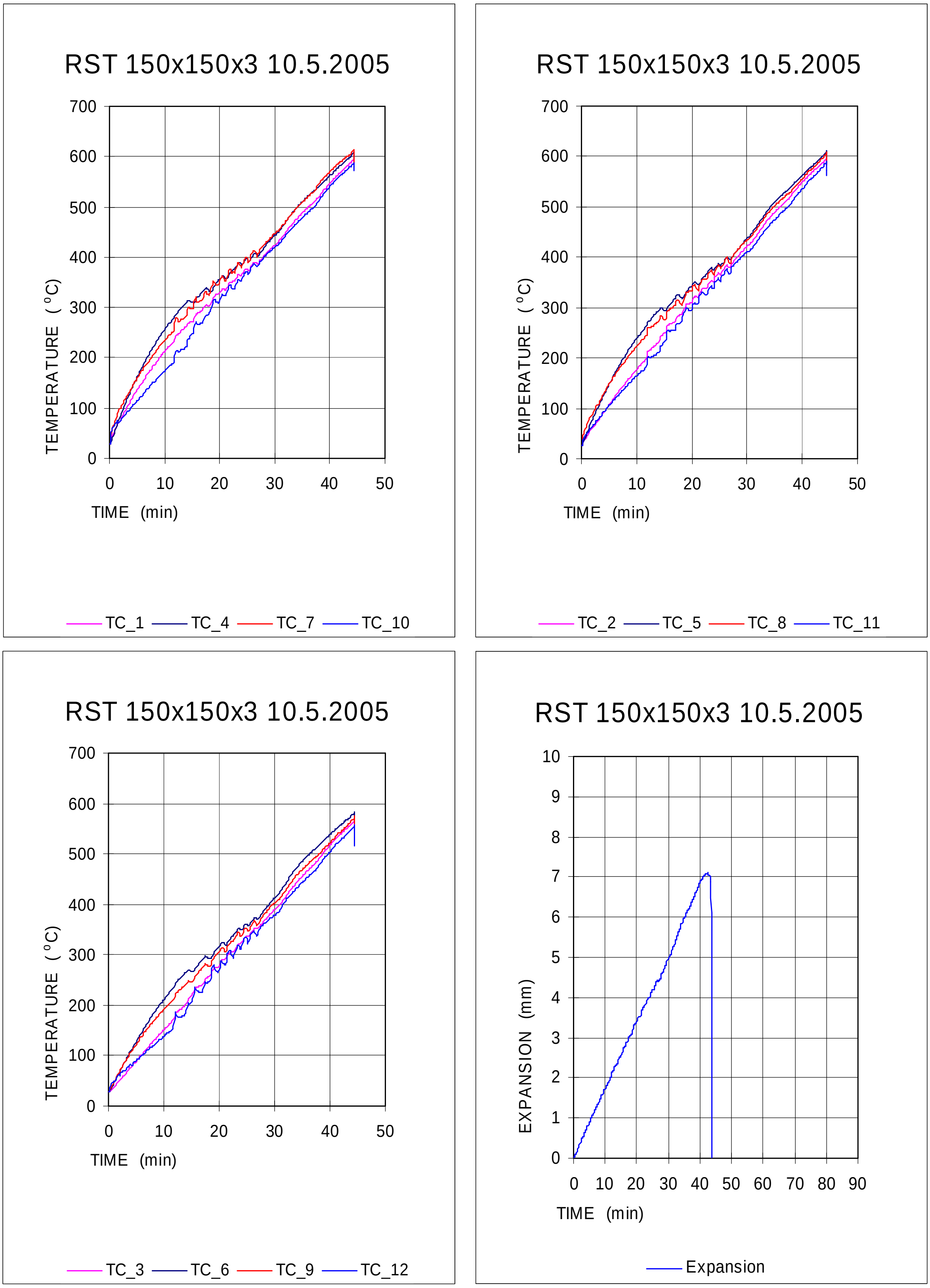


Figure 4. Measured temperatures during fire tests and the expansion of the test specimen B15. Maximum measured temperature 588 °C in the middle of the column when buckle consisted. Remark: The measurement of expansion only with one sensor. Load is 248 kN.

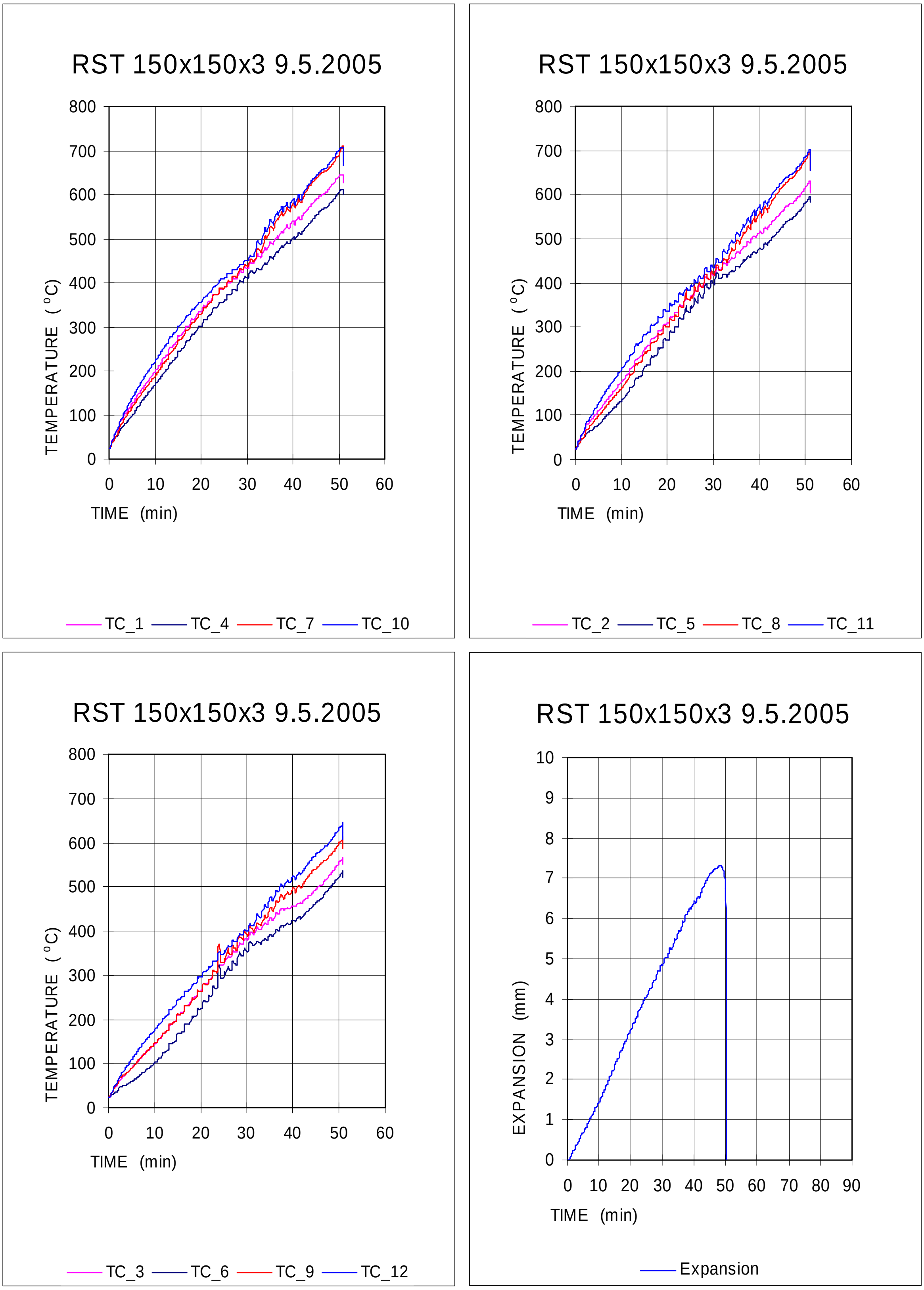


Figure 5. Measured temperatures during fire tests and the expansion of the test specimen B11. Maximum measured temperature 676 °C in the upper part of the column when buckle consisted. Remark: The measurement of expansion only with one sensor. Load is 203 kN.

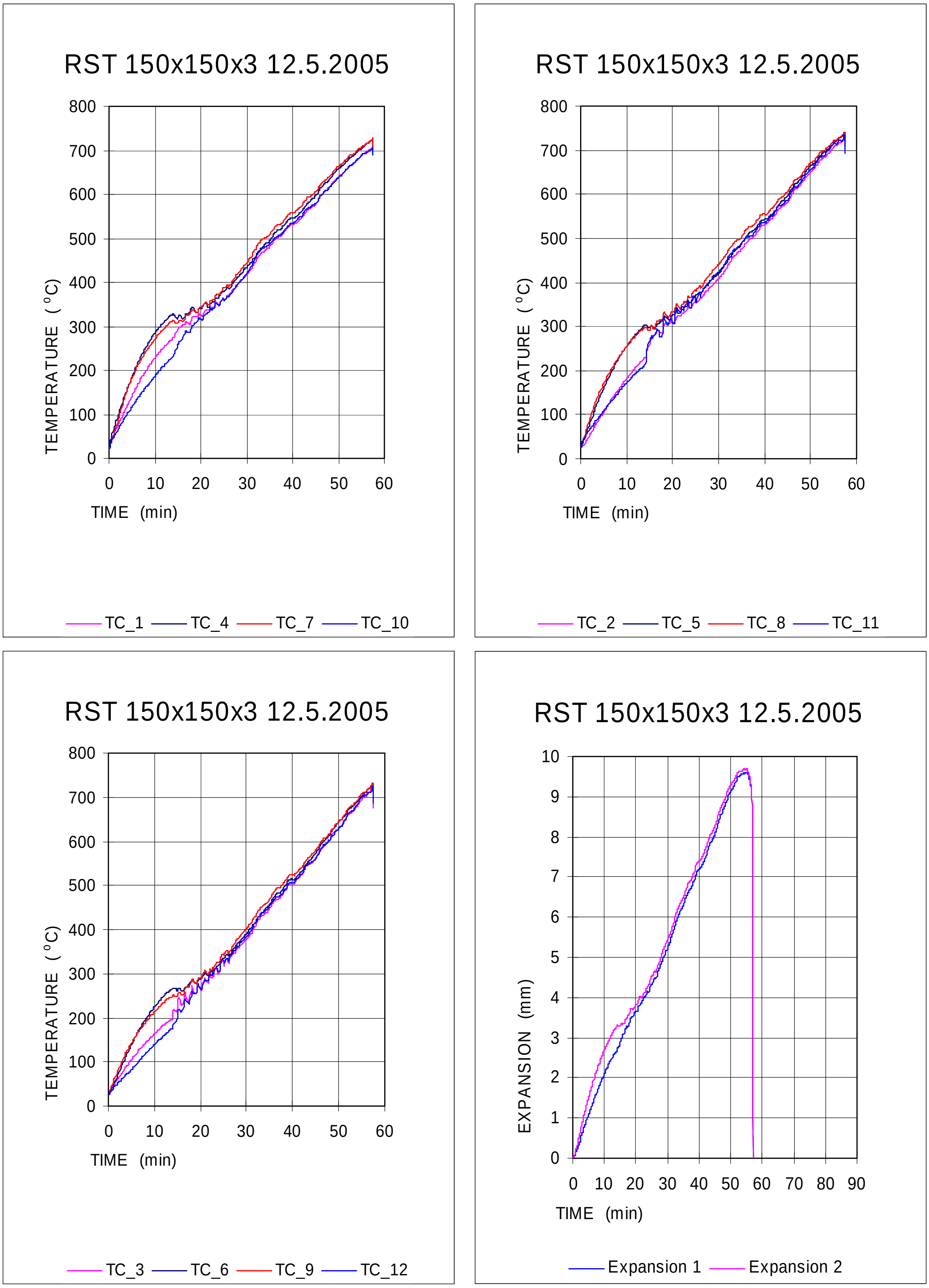


Figure 6. Measured temperatures during fire tests and the expansion of the test specimen B14. Maximum measured temperature 720 °C in the middle of the column when buckle consisted. Load is 165 kN.

Figure 7. Photographs of concentrically compressed RHS 200x200x5 after fire tests.

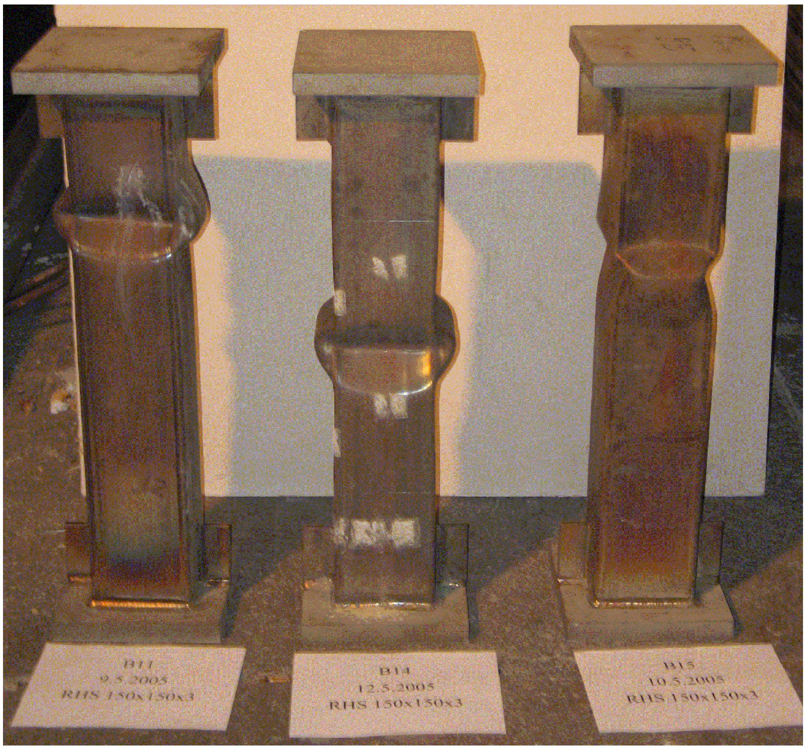


Figure 8. Photographs of concentrically compressed RHS 150x150x3 after fire tests.