# Stainless steel in fire (SSIF)

## CONTRACT N° RFS-CR-04048

## WP 1 Fire resistant structures and products

### Task 1.1: The applications of stainless steel in demanding constructions

### Task 1.2: Structural solutions for load-bearing structures meeting R30 or R60 requirements

### Task 1.3: Structural solutions for fire separating structures meeting EI30 or EI60 requirements

### Task 1.4 Experimental tests in fire situation

## EXECUTIVE SUMMARY

The main objective of the work package was to develop new stainless steel products without passive or active fire protection that can achieve 30 or 60 minutes fire resistance in a standard fire or in a natural fire. The developed products should include both load-bearing structures and fire separating members. The special cross-sections (tubes within each others with fire protection and column exposed to fire from one sides) have potential in building. Also corrugated core sandwich panels may be used as load bearing and separating structures. For that kind of structures it is very important that the insulation work is performed carefully. On the basis of the calculations and tests carried out, the structures where no insulation is used have problems to meet the requirements 30 or 60 min standard fire.

# CONTENTS

# 1 INTRODUCTION

The fire resistance of structures is dependent on the thermal behaviour of the structure and the strength properties of the material. The dimensions of the cross section and the thermal properties of the material have an influence on the behaviour at elevated temperatures. When products meeting the requirement of 60 minutes fire resistance are developed, the challenge is not only obtaining better material properties, but also devising innovative solutions, which limit the temperature rise as much as possible. According to existing knowledge, it is considered quite likely that austenitic stainless steels can be used in load-bearing structures without fire protection when the parametric or local fire is adopted or the fire resistance time is 30 minutes or less according to the standard fire-temperature curve.

# 2 OBJECTIVES

The main objective was to generate structural solutions where it is possible to use stainless steel structural members in buildings without fire protection, both considering the ‘standard’ fire and lower, more realistic fire loads. The new developed products include load-bearing structures and fire separating members.

# 3 SELECTION OF TEST SPECIMENS

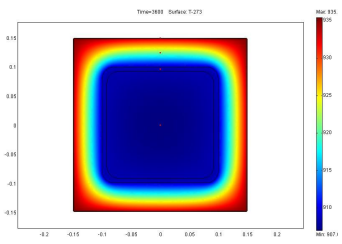
## 3.1 Structural solutions for load-bearing structures meeting R30 or R60 requirements

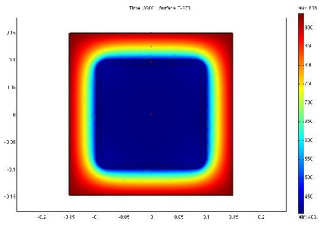
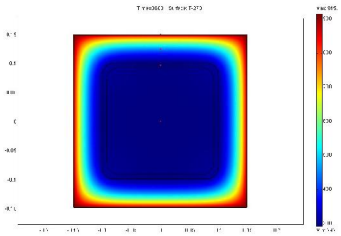
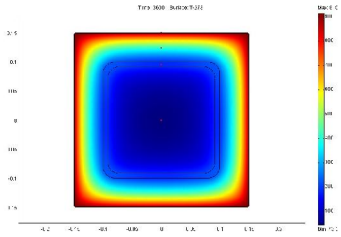
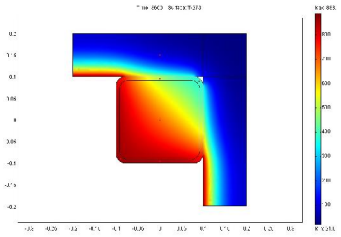
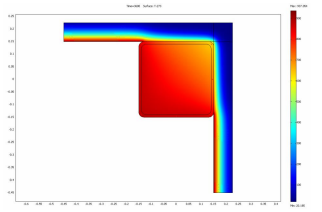
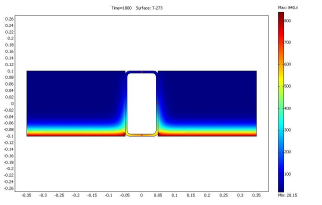
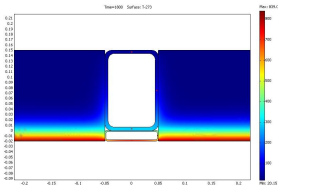
The temperature development has been computed for the different test specimens (Table 1). The calculated temperatures are used when load-bearing capacity is estimated. The thermal action follows the EN 1363-1: 1999 (ISO 834-1) standard fire curve. In Table 1 are shown the calculated cross-sections.

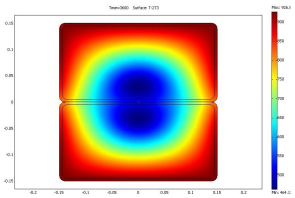
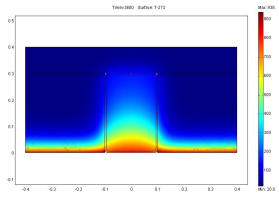
The calculations present preliminary modelling results of the test setup. The modelling has been done using COMSOL Multiphysics 3.2, which is a finite element based numerical analysis program.

The general modelling assumptions are shown in Appendix 1. The heat transfer from the fire to the exposed surfaces, and from the back surface of the wall element to the ambient, is assumed to happen through radiation and convection.

*Table 1. The computed cross-sections.*

| Specimen | | Cross-sections | Materials |
|---|---|---|---|
| 1. Tubes within each others without fire protection |  | RHS 300x300x1.5 & RHS 200x200x8 | EN 1.4301 |

| | | | |
|---|---|---|---|
| 2. Tubes within each others, space between profiles insulated with mineral wool (space inside inner profile empty) |  | RHS 300x300x1.5 & RHS 200x200x8 | EN 1.4301 & mineral wool 30 kg/m3 |
| 3. Tubes within each others, space between profiles filled with concrete (space inside inner profile empty) |  | RHS 300x300x1.5 & RHS 200x200x8 | EN 1.4301 & concrete (moisture 3% ) |
| 4. Tubes within each others, all cavities filled with concrete |  | RHS 300x300x1.5 & RHS 200x200x8 | EN 1.4301 & concrete (moisture 3% ) |
| 5. Column section in corner, concrete walls |  | RHS 200x200x8<br><br>Concrete wall thickness 100 mm | EN 1.4301 & concrete (moisture 3% ) |
| 6. Column section in corner, SIPOREX walls |  | RHS 300x300x10<br><br>SIPOREX wall thickness 150 mm | EN 1.4301 & SIPOREX |
| 7. Column exposed to fire from one sides |  | RHS 200x100x6 | EN 1.4301 & SIPOREX |
| 8. Column of two parts exposed to fire from one sides |  | RHS 150x100x6 & RHS 20x100x2<br><br>SIPOREX wall thickness 150 mm | EN 1.4301 & SIPOREX |

| | | | |
|---|---|---|---|
| 9. Two profiles side by side filled with mineral wool |  | RHS 300x150x5 | EN 1.4301<br><br>mineral wool 30 kg/m$^3$ |
| 10. Beam section in floor, surrounded by concrete |  | RHS 300x200x8<br><br>Concrete slab 100 mm | EN 1.4301 & concrete (moisture 3% ) |

The temperature distributions of cross-sections (Table 1) are shown in Appendix 2.

On the basis of calculations the applications for fire tests were chosen. The final dimension and the insulation material of four test specimen have been chosen. In the work concerning the selection of the load bearing structures, VTT has had co-operation with Finnish tube producer Stalatube. In Table 2 is shown the chosen cross-sections for the applications.

*Table 2. Load bearing structures for fire tests.*

| Test | Material | Date | Furnace | Profiles |
|---|---|---|---|---|
| 1. Tubes within each others with fire protection (injected mineral wool) | EN 1.4301 | 26.9.2005 | Cubic-furnace | RHS 300x300x10 & RHS 200x200x8 |
| 2. Column section in corner, SIPOREX walls | EN 1.4301 | 13.10.2005 | Cubic-furnace | RHS 300x300x10<br><br>SIPOREX wall (thickness 150 mm) |
| 3. Column exposed to fire from one sides | EN 1.4301 | 8.8.2006 | Cubic-furnace | RHS 200x100x6 |
| 4. Column of two parts exposed to fire from one sides | EN 1.4301 | 14.8.2006 | Cubic-furnace | RHS 150x100x6 & RHS 20x100x2 |

The possibility to use the material LDX2101 (1.4162) has also been considered. On the basis of further studies the mechanical properties of LDX2101 (1.4162) decrease at elevated temperatures quite strongly and therefore LDX2101 (1.4162) has been excluded.

In the first test program draft of load-bearing structures a full scale test was planned. The structure were planned to be a beam fabricated of rectangular hollow sections. During the design of the structure, a conclusion was drawn that it is not reasonably to carry out that kind of test. A structure which could have an application in practical was not found, because there

were too many problems concerning the fastenings to slabs. The conclusion was to replace (completely) the full scale test with unloaded small-scale tests. These tests, although unloaded, will yield relevant information on suitable load-bearing solutions for stainless steel structures.

### 3.2 Structural solutions for fire separating structures meeting EI30 or EI60 requirements

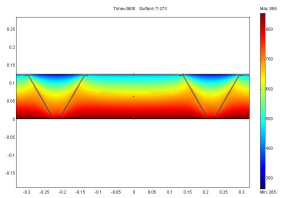
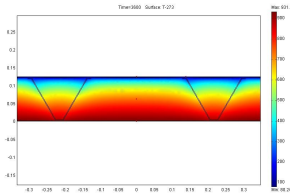
The low emissivity of stainless steel is utilised in the development of separating structures. The problems due heat expansion are eliminated by structural solutions. Wall structures which meet load-bearing and separating requirements were also considered. The aim was to meet a fire resistance of 30 to 60 minutes in the case of standard fire exposure.

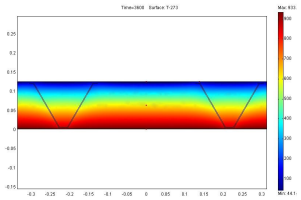
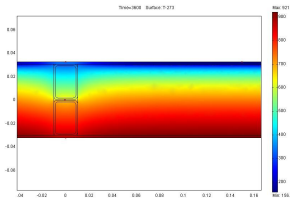
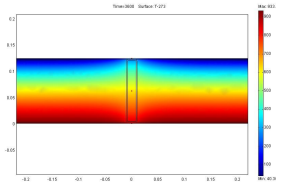
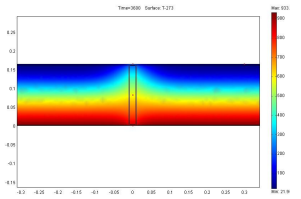
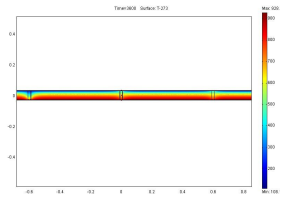
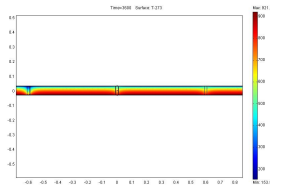
The temperature development calculations have been carried out. The calculations present preliminary modelling results of the test setup. The modelling has been done using COMSOL Multiphysics 3.2, which is a finite element based numerical analysis program. The thermal action follows the EN 1363-1: 1999 (ISO 834-1) standard fire curve.

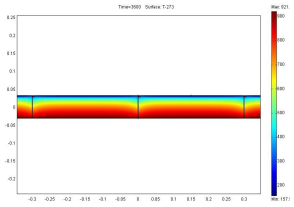
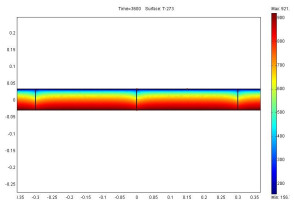
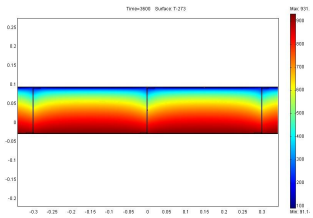
The calculations of temperature development carried out for separating structures (wall structures and floor structures) are shown in Table 3.

The general modelling assumptions are shown in Appendix 1. The heat transfer from the fire to the exposed surfaces, and from the back surface of the wall element to the ambient, is assumed to happen through radiation and convection.

*Table 3. Computed separating structures.*

| Specimen | | Cross-sections | Materials |
|---|---|---|---|
| 1. Corrugated core sandwich panel without fire protection (floor structure)<br>Case 1 |  | Steel profiles:<br>V-profile:<br>$h$ = 120 mm, $t$ =1.5 mm, Exposed side plate:<br>$t$ = 1.5 mm<br>Unexposed side plate:<br>$t$ =3.0 mm | EN 1.4301 |
| 2. Corrugated core sandwich panel with fire protection (floor structure)<br>Case 2 |  | Steel profiles:<br>V-profile:<br>$h$ = 120 mm, $t$ =1.5 mm, Exposed side plate:<br>$t$ = 1.5 mm<br>Unexposed side plate:<br>$t$ =3.0 mm | EN 1.4301 & mineral wool 30 kg/m$^3$ |

| | | | |
|---|---|---|---|
| 3. Corrugated core sandwich panel with fire protection (floor structure)<br>Case 3 |  | Steel profiles:<br>V-profile:<br>*h* = 120 mm, *t* =1.5 mm,<br>Exposed side plate:<br>*t* = 1.5 mm<br>Unexposed side plate:<br>*t* =3.0 mm | EN 1.4301 & mineral wool 140 kg/m$^3$ |
| 4. Sandwich panel where a web consists of two rectangular hollow sections, fire protection (wall structure)<br>Case 4 |  | Steel profiles:<br>2 x RHS 30x20x1.2<br>Bottom plate: 2.0 mm<br>Top plate: 2.0 mm | EN 1.4301 & mineral wool 140 kg/m$^3$<br>1 mm strip of insulation between RHS-profiles |
| 5. Sandwich panel where a web consists of one rectangular hollow section, fire protection (wall structure)<br>Case 5 |  | Steel profile:<br>RHS 120x20x1.5<br>Exposed side plate: 2.0 mm<br>Unexposed side plate: 2.0 mm | EN 1.4301 & mineral wool 140 kg/m$^3$ |
| 6. Sandwich panel where a web consists of one rectangular hollow section, fire protection (wall structure)<br>Case 6 |  | Steel profile:<br>RHS 160x20x1.5<br>Exposed side plate: 2.0 mm<br>Unexposed side plate: 2.0 mm | EN 1.4301 & mineral wool 140 kg/m$^3$ |
| 7. Sandwich panel where a web consists of one rectangular hollow section, fire protection (wall structure)<br>Case 7 |  | Steel profile:<br>RHS 60x20x1.5<br>Bottom plate: 2.0 mm<br>Top plate: 2.0 mm | EN 1.4301 & mineral wool 140 kg/m$^3$ |
| 8. Sandwich panel where a web consists of one rectangular hollow section, fire protection (wall structure)<br>Case 8 |  | Steel profile:<br>RHS 60x20x1.5<br>Bottom plate: 2.0 mm<br>Top plate: 2.0 mm | EN 1.4301 & mineral wool 30 kg/m$^3$ |

| | | | |
|---|---|---|---|
| 9. Sandwich panel where a web consists of one Z-profile, fire protection (wall structure)<br>Case 9 |  | Steel profile:<br>Z 60x5x2 c/c 300 mm<br>Bottom plate: 2.0 mm<br>Top plate: 2.0 mm | EN 1.4301 & mineral wool 30 kg/m$^3$ |
| 10. Sandwich panel where a web consists of one Z-profile, fire protection (wall structure)<br>Case 10 |  | Steel profile:<br>Z 60x5x1 c/c 300 mm<br>Bottom plate: 2.0 mm<br>Top plate: 2.0 mm | EN 1.4301 & mineral wool 30 kg/m$^3$ |
| 11. Sandwich panel where a web consists of one Z-profile, fire protection (wall structure)<br>Case 11 |  | Steel profile:<br>Z 120x20x2 c/c 300 mm<br>Bottom plate: 2.0 mm<br>Top plate: 2.0 mm | EN 1.4301 & mineral wool 30 kg/m$^3$ |

The temperature distributions of structures (Table 3) are shown in Appendix 3.

For separating structures, the failure criteria are a temperature rise on the unexposed side of 140°C average or 180°C (at any point).

On the basis of computed temperatures it can be seen, that the Case 1 do not fulfil the requirement of 30 or 60 minute in standard fire. If density of mineral wool will be more than 30 kg/m$^3$, the requirements of average temperature requirement and maximum temperature will be fulfilled at 60 minutes with a floor structure according to Case 2.

Even if the thickness of wall structure will be 164 mm, the maximum temperature requirement not fulfilled at 60 minutes in Cases 5 and 6. The conclusion was that the requirement of 30 minute will be realistic for wall structure.

The structures which have been chosen as floor structure are corrugated core sandwich panels. The construction is designed together with Finnish company Kenno Tech Ltd, who will fabricate the specimens. For wall structure the Case 9 was chosen, but the thickness of Z-profile was 1.5 mm.

The fire separating specimens are grade 1.4301. In Table 4 is shown the test program of the fire separating structures. The dimensions of the third small scale test specimen and the full-scale specimen were decided after the first cubic furnace tests. The specimen in the full-scale test was loaded during the fire test.

A new type of laser-welded stainless steel sandwich panel has been developed by Kenno Tech Ltd. The sandwich panel consists of two stainless steel sheets as cover plates and V-profiles comprising the web of the section. The voids are filled with mineral wool to improve the thermal behaviour

*Table 4. Fire separating structures.*

| | | | | |
|---|---|---|---|---|
| 1. Floor structure, corrugated core sandwich panel with fire protection (mineral wool) | EN 1.4301 & mineral wool | 7.9.2005 | Cubic-furnace | The dimensions of the specimen about 1.25 m x 1.25 m |
| 2. Wall structure, Z-profiles, with fire protection (mineral wool) | EN 1.4301 & mineral wool | 18.8.2005 | Cubic-furnace | The dimensions of the specimen about 1.25 m x 1.25 m |
| 3. Wall structure, Z-profiles, with fire protection (mineral wool) | EN 1.4301 & mineral wool | 13.10.2005 | Cubic-furnace | The dimensions of the specimen about 1.25 m x 1.25 m |
| 4. Floor structure, corrugated core sandwich panels, load bearing structure | EN 1.4301 | 15.11.2005 | Horizontal -furnace | The max. dimensions about 5 x 3 meters |

# 4 EXPERIMENTAL WORK

### 4.1.1 Load-bearing structures

Based on chapter 3, load-bearing structures have been chosen for the test programme. Fire resistance tests have been performed to develop and verify the calculation method for determine the temperature development of the structures exposed to fire. Four different types of structures have been tested.

#### 4.1.1.1 Test set-up

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 specimens were unloaded in the fire tests.

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. 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. Observations were made of the general behaviour of the column specimen during the course of the tests and photographs and video film were taken.

#### 4.1.1.2 Test specimens

Based on chapter 3, load-bearing structures had been chosen for the test programme. Fire resistance tests have been performed to develop and verify the calculation method for determine the temperature development of the structures exposed to fire. Two different types of structures have been tested in 2005 and the rest of tests have been carried out during August 2006. The specimens were unloaded in the fire tests.

*Table 1. The load-bearing tests.*

| Test | Material | Date | Furnace | Profiles |
|---|---|---|---|---|
| 1. Tubes within each others with fire protection (injected mineral wool) | EN 1.4301 | 26.9.2005 | Cubic-furnace | RHS 300x300x10 & RHS 200x200x8 |
| 2. Column section in corner, SIPOREX walls | EN 1.4301 | 13.10.2005 | Cubic-furnace | RHS 300x300x10<br>SIPOREX wall (thickness 150 mm) |
| 3. Column exposed to fire from one sides | EN 1.4301 | 8.8.2006 | Cubic-furnace | RHS 200x100x6 |
| 4. Column of two parts exposed to fire from one sides | EN 1.4301 | 14.8.2006 | Cubic-furnace | RHS 150x100x6 & RHS 20x100x2 |

**<u>Tubes within each others with fire protection</u>**

Mineral wool was injected between tubes. The density of wool was 75 kg/m$^3$. The dimensions as well location and numbering of thermocouples of a specimen is shown in Appendix 4. In Figure 1 is shown some photographs of test specimens.

*Figure 1. Tubes within each others with fire protection.*

**Column section in corner**

The tube was installed in the corner of siporex walls. The location and numbering of thermocouples of a specimen is shown in Appendix 5. In Figure 2 is shown a photograph of the fire test.

*Figure 2. The column in the corner.*

**Column exposed to fire from one sides**

The tube was installed inside the siporex wall. The location and numbering of thermocouples of a specimen is shown in Appendix 6. In Figure 3 is shown a photograph of the fire test.

*Figure 3. RHS 200x100x6 column exposed to fire from one side.*

**Column of two parts exposed to fire from one sides**

The tube was installed inside the siporex wall. The location and numbering of thermocouples of a specimen is shown in Appendix 7. In Figure 4 is shown a photograph of the fire test.

*Figure 4. Column of two parts exposed to fire from one sides*

### 4.1.2 Fire separating structures:

The Finnish company Kenno Tech Ltd. has fabricated corrugated core sandwich panels with fire protection of mineral wool. The fire separating specimens are grade 1.4301. The specimens in the cubic furnace tests were unloaded. The dimensions of the specimen for the third cubic furnace test and for the full-scale specimen was decided after two cubic furnace tests. The specimen in the full-scale test was loaded during the fire test.

#### 4.1.2.1 Test set-up

**Small scale tests**

The wall and floor elements were tested in the VTT Fire Research testing laboratory's cubic furnace. The elements' horizontal dimensions were approximately 1250 mm × 1250 mm. The total thickness of the wall element was 64 mm and the total thickness of the floor element was 124.5 mm. The elements were installed onto the top opening of the furnace so that their bottom surfaces were exposed to heating and the top surface was open to the testing hall.

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. Observations were made of the general behaviour of

the column specimen during the course of the tests and photographs and video film were taken. In Figure 5 is shown of test arrangements.

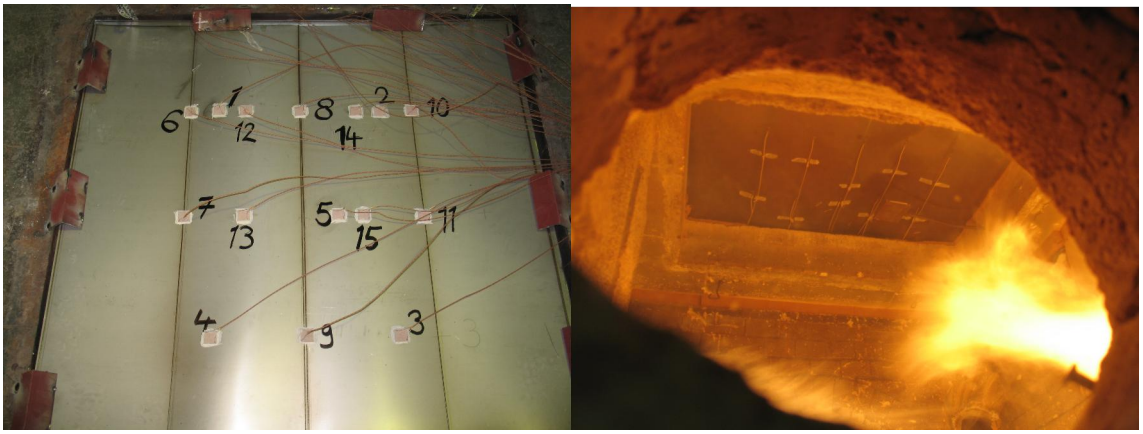



*Figure 5. Photographs of fire test 13.10.2005.*

**Full scale test**

An insulated floor construction was same as the floor structure in a small scale test. The width of the full panel was 1504 mm, length 5405 mm and thickness 125 mm. The total width of the ceiling was 3015 mm. The test specimen was loaded under the test. The variable action at normal temperature is 250 kg/m$^2$ and in the fire situation 50% of that. The elements were installed onto the top opening of the furnace so that their bottom surfaces were exposed to heating and the top surface was open to the testing hall.

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. Observations were made of the general behaviour of the column specimen during the course of the tests and photographs and video film were taken. In Figure 5 is shown of test arrangements.

The fabrication of a panel is presented in Figure 6 and in Figure 7 is shown of test arrangements of large scale fire test.

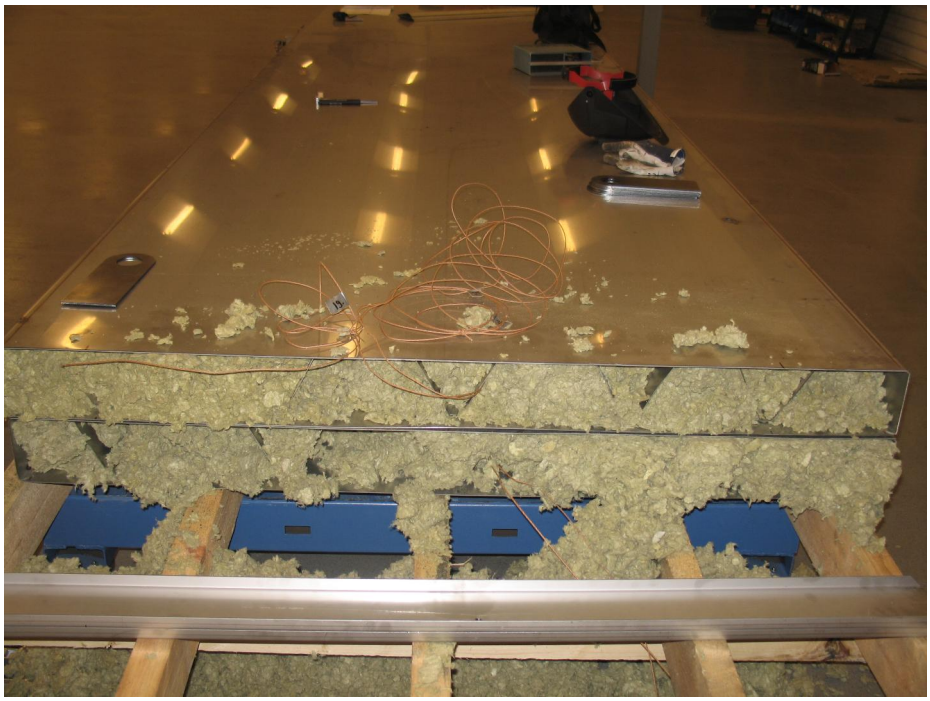


*Figure 6. The fabrication of a panel at keno Tech Ltd.*

*Figure 7. Photographs of large scale fire test 15.11.2005.*

#### 4.1.2.2 Test specimens, small scale tests

**<u>Wall structures</u>**

The wall element consisted of a stainless steel Z 60×15×1.5-section core and 2 mm thick stainless steel top and bottom plates connected by welding to the flanges of Z-section. The c/c-distance of the Z-profiles was approximately 300 mm. The spaces between the Z-profiles and the plates were filled with blowing mineral wool with an approximate density of 75 kg/m$^3$. The dimensions as well location and numbering of thermocouples of a specimen is shown in Appendix 8.

Due to problems in the preparation of one test specimen (test 18.8.2005), only one of the three interior Z-profiles was welded onto the top and bottom plates. The other two were only welded onto the top plate (on the unexposed side). This meant that there was probably a

small air gap between the exposed side plate and the flanges of two of the interior Z-profiles, and probably between the plate and the mineral wool. In the other test specimen, the top flange of the properly welded Z-profile (test 13.10.2005).

The cross-sections of the wall and floor test specimens are shown in Appendices 8 and 9, respectively.

**Floor structures**

The core of the floor element consisted of V-shaped steel profiles with wall thickness 2 mm and height 120 mm. A 1.5 mm thick stainless steel plate was welded onto the lower flanges of the V-profiles on the exposed side and a 3.0 mm thick stainless steel plate onto the top flanges on the unexposed side. The spaces between the core elements were filled with blowing mineral wool with an estimated density of 75 kg/m$^3$. However, a calculation based on the actual weight of the test specimen and the volume of the insulation material showed that the actual density was approximately 115 kg/m$^3$. The cross-section of the test specimen as well the listing of thermocouples used in the test and their locations are shown in Appendix 9.

#### 4.1.2.3 Test specimens, large scale tests

An insulated floor construction was same as the floor structure in a small scale test. The width of the full panel was 1504 mm, length 5405 mm and thickness 125 mm. The total width of the ceiling was 3015 mm. The test specimen was loaded under the test. The elements were installed onto the top opening of the furnace so that their bottom surfaces were exposed to heating and the top surface was open to the testing hall.

The chipboard on the top was 11mm thick and reached to the distance of 150 mm from the side edge of the test specimen. The hat profile under the joint between the two panels was 20 mm deep, about 136 mm broad totally and 100 mm broad on the top and made of 1.0 mm thick stainless steel sheet.

The joint between panels was covered with the hat profile below and with a stripe of chipboard above in 11 November. The hat profile was fixed to the lower plate with screws Ø4.2mm*12.5 mm c/c 100 mm. The chipboard stripe on the joint was fastened by a staggered space of about 500mm with countersunk self-drilling steel screws Ø2,2mm*25,5 mm by drilling first holes with a separate drill bit. Around the long edges of the specimen 50 mm thick mineral wool Paroc Wired Mat 100 was bent 100 mm onto the top face and 100 mm under the lower surface. The mat was pressed through two rows of 80 mm long Ø3 mm protruding steel wires which were welded in one end to the edge steel profile of the specimen c/c about 300mm, and Ø39 mm washers were stroked on the other end of steel wire down to the mineral wool surface. The specimen was surrounded by 200 mm broad, 250 mm high and 600 mm long aerated concrete blocks. The gap between the blocks and the edges of the specimen was tightened with one layer of 50 mm thick Paroc FPS 14 mineral wool on the sides and two layers at the ends.

Measured weight of the chipboard was 7.7 kg/m$^2$ and the density measured as an average of 3 samples was 707 kg/m$^3$. In Appendix 10 is shown the construction of the full scale test specimen

## 4.2 Results

### 4.2.1 Load-bearing structures

The measured temperatures are shown in Appendices 11 - 14. In Figure 8 is studied the effect of the emissivity. Temperatures are calculated with the emissivity of 0,2 and 0,4 and compared with test results of the column in the corner.

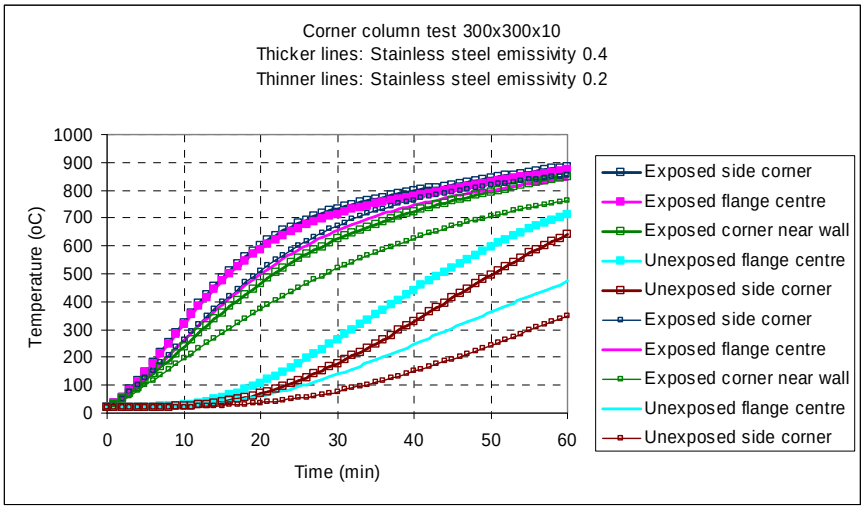



*Figure 8. The effect of emissivity.*

Below are compared calculated temperatures with measured ones. The values are calculated with the emissivity of 0,2 and 0,4. On the basis of calculations it can bee seen that the correlation of the calculated values and the measured values is good when emissivity 0,2 is used.

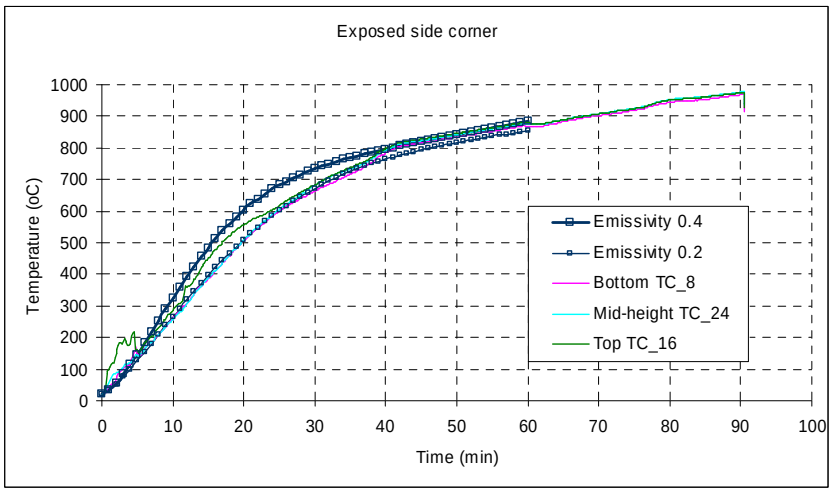



*Figure 9. Column exposed to fire from two sides. Test results compared with computed values, exposed side corner.*

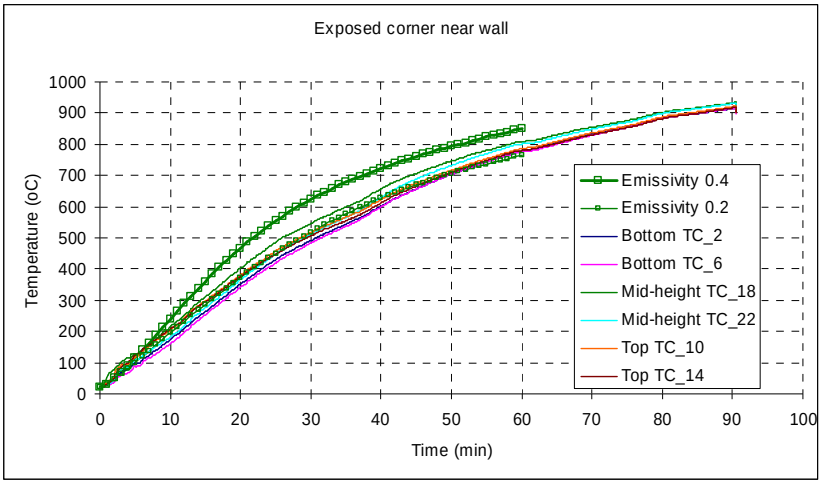



*Figure 10. Column exposed to fire from two sides. Test results compared with computed values, exposed corner near wall.*

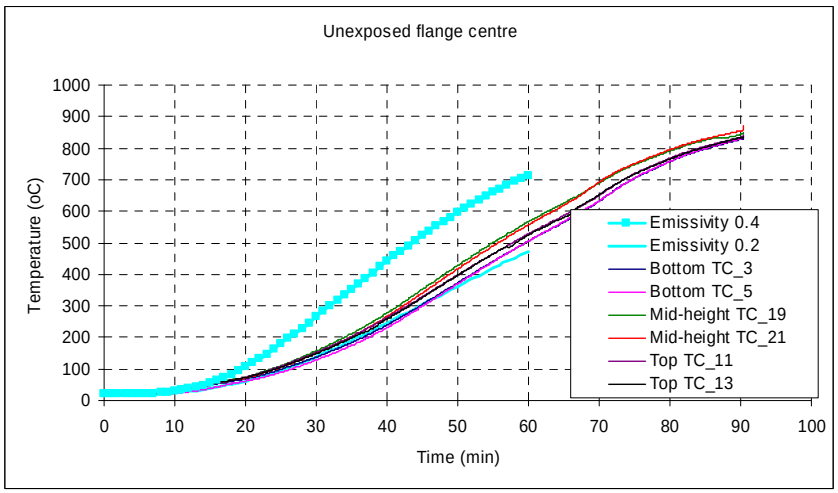



*Figure 11. Column exposed to fire from two sides. Test results compared with computed values, unexposed flange centre.*

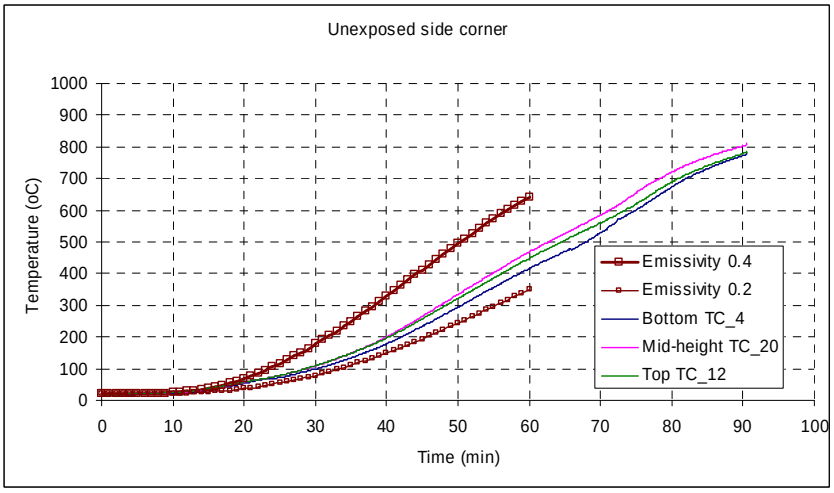



*Figure 12. Column exposed to fire from two sides. Test results compared with computed values, unexposed side corner.*

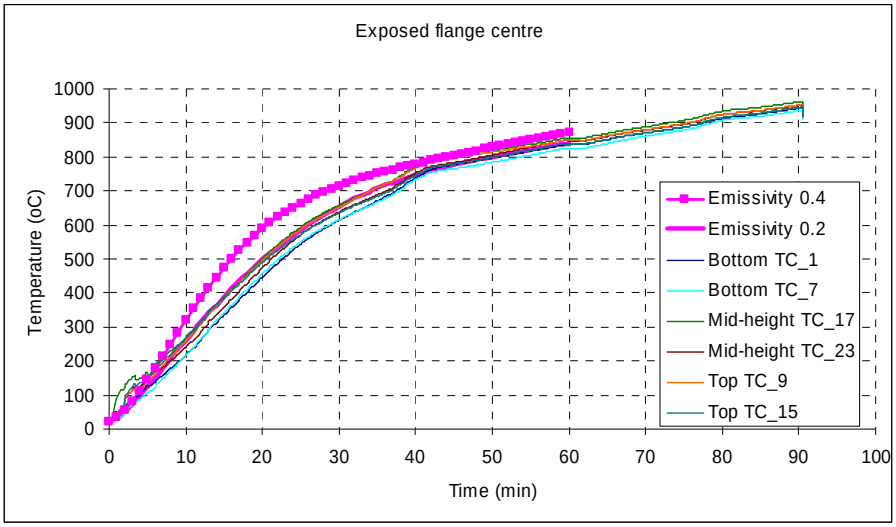



*Figure 13. Column exposed to fire from two sides. Test results compared with computed values, exposed flange centre.*

#### 4.2.1.1 Conclusions

**Tubes within each others with fire protection**

The temperature at mid height of furnace was 973°C (mean value) after 60 minutes in standard fire. In the middle of the outer tube (RHS 300x300x10) the mean value of measured temperatures was 925°C and in the middle of the inner tube (RHS 200x200x8) the mean value of measured temperatures was 414 °C. This means that the inner tube has about 60% left of its capacity according to EN 1993-1-2.

**Column section in the corner**

The temperature differences between exposed and unexposed sides are remarkable. The maximum temperature in the exposed corner (mid height of the column) is 878°C and in the unexposed corner (mid height of the column) 466°C after 60 minutes standard fire. To utilise the low temperatures, the connection between the column and wall should be ensured.

**Column exposed to fire from one side**

The temperature differences between exposed and unexposed sides are remarkable. The maximum temperature in the exposed side (mid height of the column) was 806°C and in the unexposed side (mid height of the column) 299°C after 60 minutes standard fire. This means that in calculations temperature distribution should be taken in to account.

**Column of two parts exposed to fire from one side**

The temperature differences between exposed and unexposed sides are remarkable .The maximum temperature in the exposed side (mid height of the column) is 871°C, between two parts (measured from RHS 100x150x6) 583°C and in the unexposed side (mid height of the column) 95°C after 60 minutes standard fire. In calculations temperature distribution should

be taken in to account. The structure is quite demanding to construct when considering the construction process.

### 4.2.2 Fire separating structures:

The sandwich panel system has been tested in small and a large scale fire tests to investigate the thermal and load bearing behaviour of the element exposed to fire. Furthermore, numerical models have been established and calibrated based on the fire tests.

The tests were carried out in the VTT Fire Research testing laboratory. Four fire separating structures have been tested; three of them were small scale tests and one a full scale test. The small scale tests were unloaded and the aim of tests was to determine the temperature rise in a specimen.

#### 4.2.2.1 Wall structures, small scale tests

The measured temperatures of tests carried out 18.8.2005 and 13.10.2005 are shown in Appendices 15 and 16, respectively. Before testing, preliminary modelling was carried out in order to have a prediction of the test specimen behaviour. The results of these preliminary models are given in Figures 14 and 15.

The lower set of measured temperatures in Figure 14 corresponds to the top flanges of those Z-profiles that were not welded onto the bottom steel plate. The higher set of measurements (TC22-TC23) corresponds to the top flange of the properly welded Z-profile. It can be noted that the differences between these two sets of measured curves are considerable. The measured curves at the top flange of the properly welded Z-profile are the ones that are of interest to us here.

Until about time 25 minutes, the measured curves (TC22-TC23) are between the two calculated curves. However, after this, the measured temperatures continue to increase faster than the calculated temperatures.

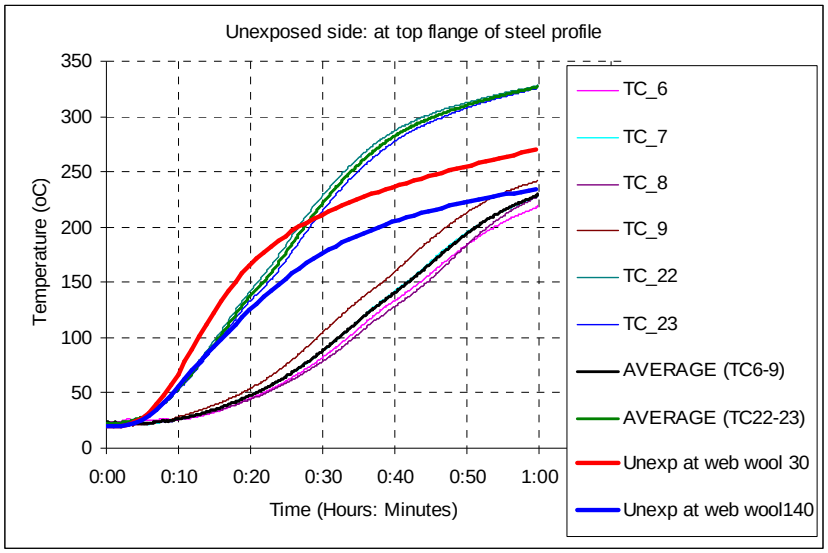



*Figure 14. Measured and calculated temperatures at the unexposed side flange of the Z-profile according to preliminary FE-models created before testing.*

Figure 15 shows the temperatures at the unexposed side between the webs of the Z-profiles. It can be seen again that the correlation between the calculated and the measured temperatures is not very good, although the absolute temperature differences at these low temperature levels are not so large.

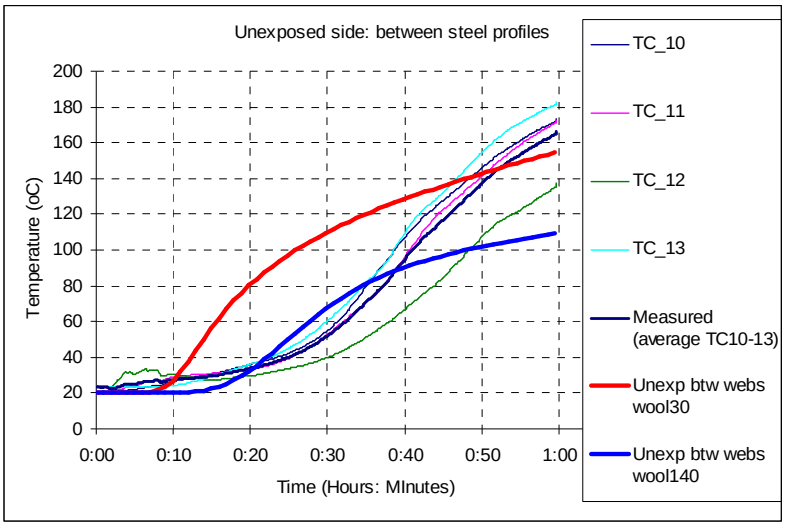



*Figure 15. Measured and calculated temperatures at the unexposed side midway between flanges of the Z-profile according to preliminary FE-models created before testing.*

As a conclusion from the above, it can be said that the initial FE-models could not predict the temperatures on the unexposed side very well. The reasons for this were examined and it was found that, by mistake, the heat convection coefficient on the top surface of the unexposed side plate had been taken as equal to $h$ = 25 W/m$^2$K, although the correct value according to EN 1991-1-2: 2002 is 4 W/m$^2$K, when radiation is accounted for separately, and 9 W/m$^2$K, when this value is assumed to include the effects of radiation. A value also commonly used in different studies is 10 W/m$^2$K. The model was calculated again using $h$ = 4 W/m$^2$K and $h$ = 10 W/m$^2$K, respectively, and the results are shown in Figures 16 and 17 for *wool30* and *wool140*.

It can be seen from Figures 16 and 17 that the reduction of the value of the heat transfer coefficient has a relatively large influence on the temperatures. Less heat is transferred away from unexposed side when the coefficient is smaller, so the temperatures are increased. It appears from Figures 16 and 17 that the value $h$ = 10 W/m$^2$K already gives temperatures that are on the safe side compared to the test results. Using $h$ = 4 W/m$^2$K and $\rho_{wool}$ = 30 kg/m$^3$ leads to strongly overestimated temperatures, when radiation heat transfer is also modelled on the unexposed face, as it is in these models.

The best correlation at the top flange of the Z-profile is obtained using $h$ = 4 W/m$^2$K and $\rho_{wool}$ = 140 kg/m$^3$. Between the webs, the best correlation is obtained using $h$ = 10 W/m$^2$K and $\rho_{wool}$ = 140 kg/m$^3$, which leads to a slight underestimation of temperatures at the web. On the other hand, at the webs, the test curves run smoothly between the curves corresponding to $h$ = 10 W/m$^2$K (for both insulation wool thicknesses). Between the webs, all curves run higher than the test measurements.

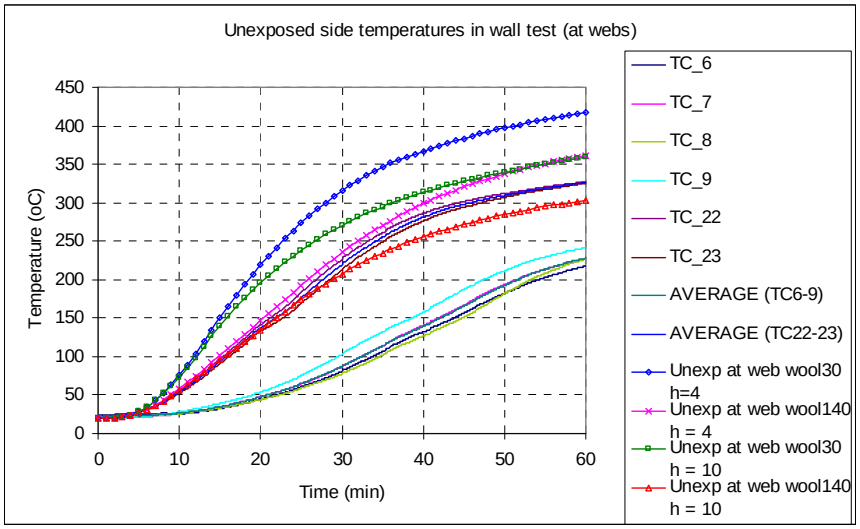



*Figure 16. Measured and calculated temperatures at the unexposed side flange of the Z-profile with convection heat transfer coefficient on unexposed side equal to 4 W/m$^2$K and 10 W/m$^2$K.*

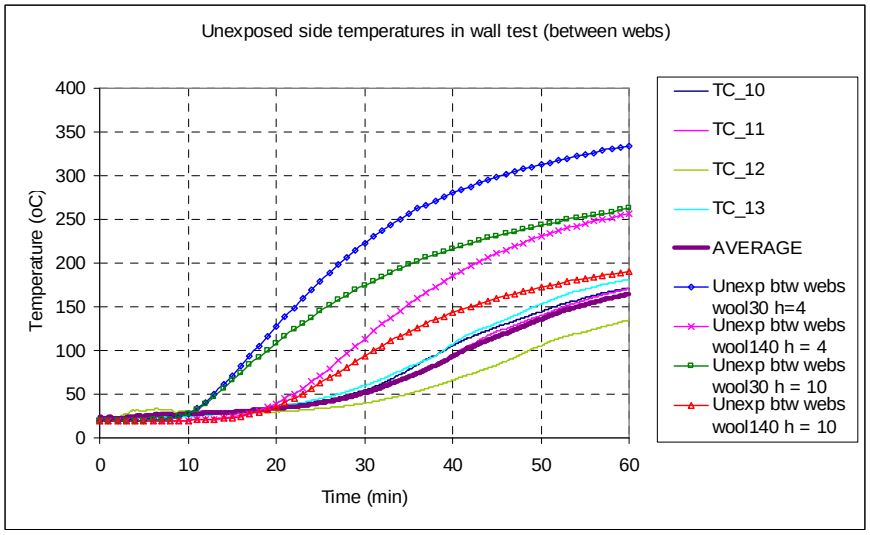



*Figure 17 Measured and calculated temperatures at the unexposed side midway between flanges of the Z profile with convection heat transfer coefficient on unexposed side equal to 4 W/m$^2$K and 10 W/m$^2$K.*

In order to improve the model further, an idea to calculate the effective thermal conductivity of the insulation material using backward calculation from the test results came up. This was done, but the thermal conductivity was only obtained up to temperature 550°C, which was the highest average temperature of the insulation in the test. If there had been measuring points within the insulation (along the insulation thickness), a more accurate estimate of the effective thermal conductivity could have been obtained. In any case, this scheme did not provide a solution to the modelling problem.

Therefore a different scheme was adopted. A 1 mm thick air gap was modelled between the bottom (exposed side) steel plate and the insulation material. As described above, due to the lack of welds at the flanges, this type of a small air gap was probably present in the actual tested structure. In fact, there is always a very small air layer between structural layers, but

usually this air layer need not be taken into account in the modelling because of its small thickness.

The model was calculated twice, using 30 kg/m$^3$ and 140 kg/m$^3$ mineral wool insulation material models, respectively, so that upper and lower bounds could be obtained for the temperatures (see chapter 2.2). Figures 18 and 19 show the temperature curves at the top flange of the Z-profile and midway between the Z-profiles, respectively, for models with and without air gaps.

The differences between the corresponding curves with or without an air gap are small at first but get larger towards the end of the test, so that the absolute temperature difference at *t* = 60 min is approximately 20-30°C. The measured unexposed side temperatures at the web fit nicely between the upper and lower bounds provided by the calculations for different wool types, whether an air gap is present or not. Between the webs, the presence of the air gap brings the calculated temperatures slightly closer to the measured curves, but they are still overestimated by the calculations.

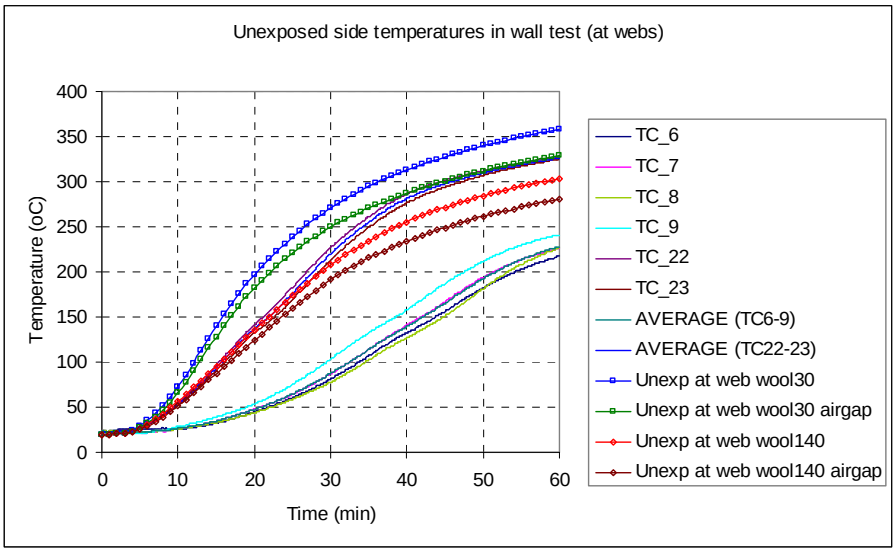



*Figure 18. Measured and calculated temperatures at the unexposed side flange of the Z-profile with h = 10 W/m$^2$K at the unexposed surface for all models, wool30 and wool140, and with or without air gap.*

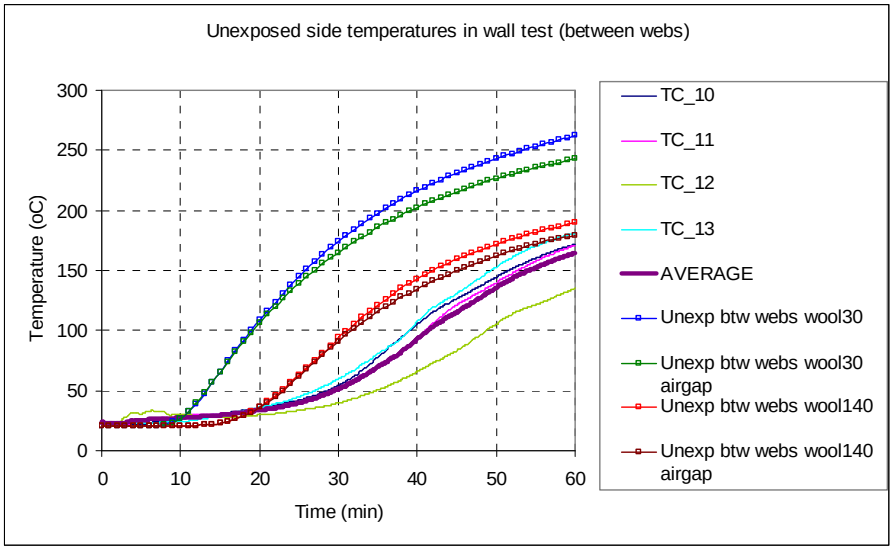



*Figure 19 Measured and calculated temperatures midway between the Z-profiles with h = 10 W/m$^2$K at the unexposed surface for all models, wool30 and wool140, and with or without air gap.*

As a conclusion from the numerical thermal analyses on the wall structure, it can be concluded that a very good estimate of the maximum temperatures on the unexposed side of the wall structure can be reached using the modelling procedure described above. The temperatures midway between the profiles are overestimated by the current procedure. This is assumed to be caused by the inaccuracy of the available mineral wool material data when applied to the blowing mineral wool used in the test. Also the fact that in the numerical model, the internal surface connections are ideal and provide full continuity between surfaces, allows the heat to be transferred more quickly through the stainless steel parts in the structure, i.e. the heat flows along the Z-profile to the unexposed side and then continues along the cover plate to the measuring point, instead of being transferred only directly through the insulation material.

#### 4.2.2.2 Floor element, small scale test

The core of the floor element consisted of V-shaped steel profiles with wall thickness 1,5 mm and height 120 mm. A 1.5 mm thick stainless steel plate was welded onto the lower flanges of the V-profiles on the exposed side and a 3.0 mm thick stainless steel plate onto the top flanges on the unexposed side. The spaces between the core elements were filled with blowing mineral wool.

The temperature rise was in a small scale test under the acceptance limit corresponding to one hour in the case of standard fire exposure. The same profile was chosen to a large scale test and preliminary calculations were made to ensure the mechanical behaviour of the structure in the case of fire.

As for the wall element, some preliminary modelling was carried out before testing in order to have a prediction of the test specimen behaviour. The results of these preliminary models are given in Figures 20 and 21.

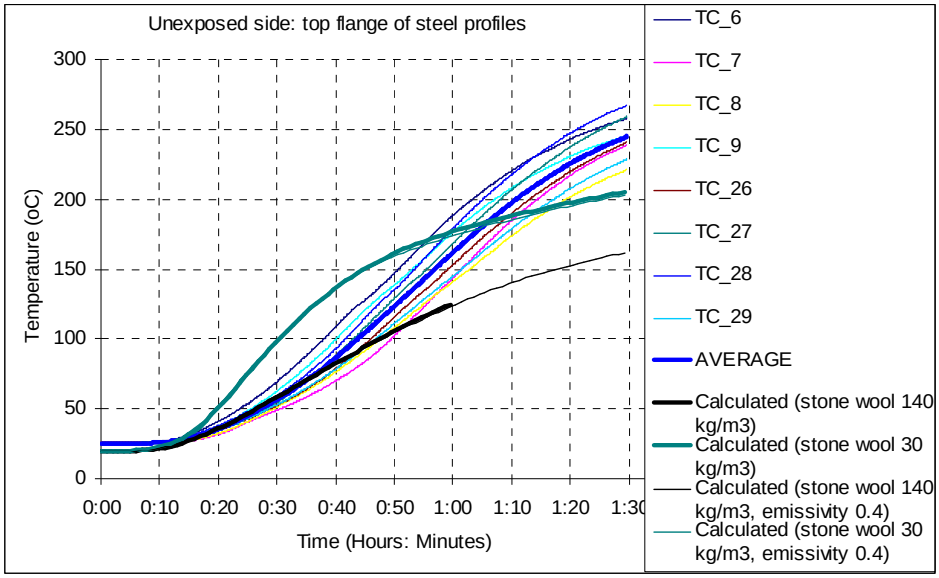



*Figure 20 . Measured and calculated temperatures at the unexposed side flange of the V-profile according to preliminary FE-models created before testing.*

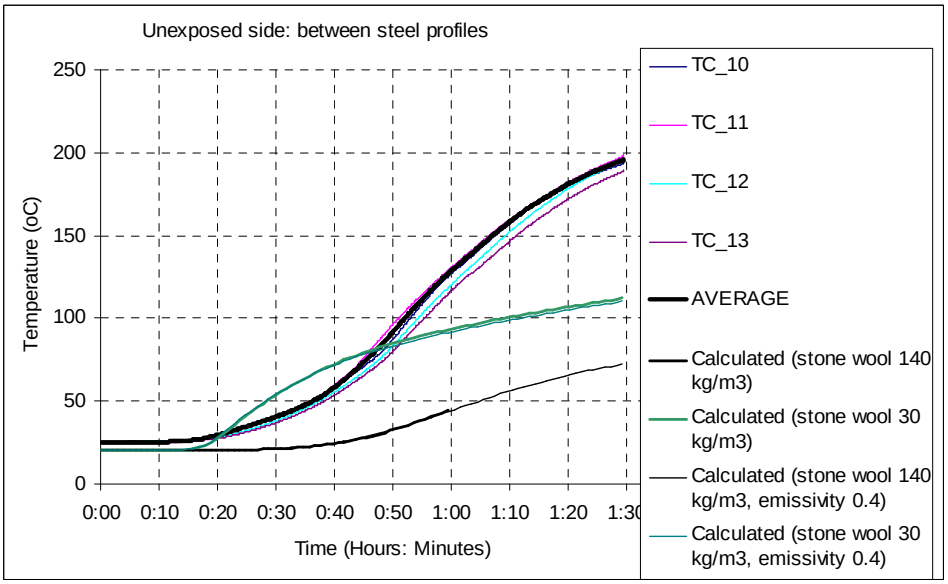



*Figure 21 Measured and calculated temperatures at the unexposed side midway between flanges of the V-profile according to preliminary FE-models created before testing.*

It can be seen that the measured temperatures increase higher than the calculated temperatures. However, as was the case for the wall model described in Chapter 5.2.2.1, by mistake the convection heat transfer coefficient was taken as equal to $h$ = 25 W/m$^2$K on the unexposed side in these preliminary models. Therefore the tests were calculated again by applying $h$ = 4 W/m$^2$K and $h$ = 10 W/m$^2$K on the unexposed surface, as was done for the wall model. The emissivity on the unexposed side was equal to 0.4 in all these calculations.

The results of the calculations with $h$ = 4 W/m$^2$K and $h$ = 10 W/m$^2$K on the unexposed side are shown in Figures 20 and 21. The temperatures at the unexposed side flange of the V-profile are reproduced very well by the models with $\rho_{wool}$ = 140 kg/m$^3$, especially when $h$ = 4 W/m$^2$K. The models with $\rho_{wool}$ = 30 kg/m$^3$ overestimate the temperatures. However, at the

measuring point midway between the V-profiles, the models with $\rho_{wool}$ = 140 kg/m$^3$ give lower temperatures than those measured in the test, while the models with $\rho_{wool}$ = 30 kg/m$^3$ give results that are on the safe side. However, it can again be noted that when $h$ = 10 W/m$^2$K, the test results run between the two curves with insulation densities $\rho_{wool}$ = 140 kg/m$^3$ and $\rho_{wool}$ = 30 kg/m$^3$, respectively.

It can be concluded that upper and lower bounds for the unexposed side temperatures can be obtained by calculating the structure using both insulation mineral wool densities and $h$ = 10 W/m$^2$K on the unexposed side. The more precise modelling of the actual test temperatures would probably require more accurate information on the thermal properties of the blowing mineral wool material.

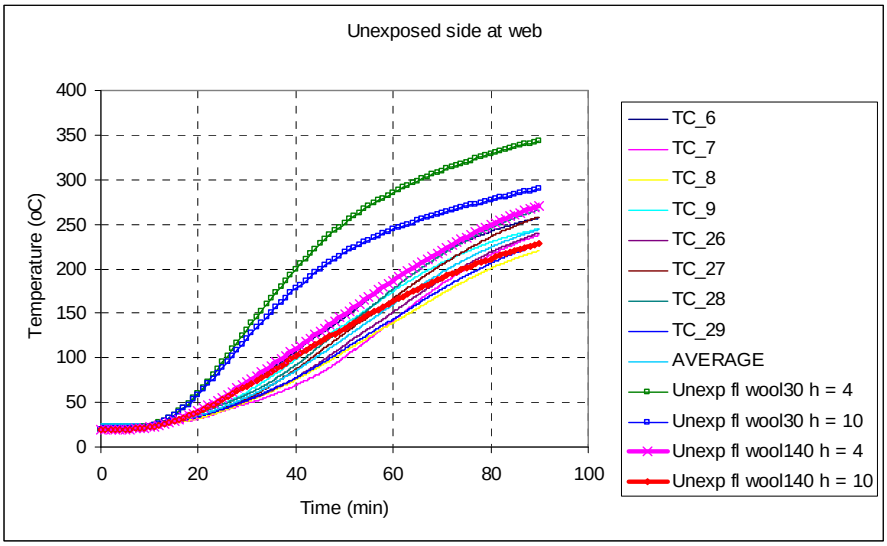



*Figure 22 Measured and calculated temperatures at the unexposed side flange of the V-profile with convection heat transfer coefficient on unexposed side equal to 4 W/m$^2$K and 10 W/m$^2$K.*

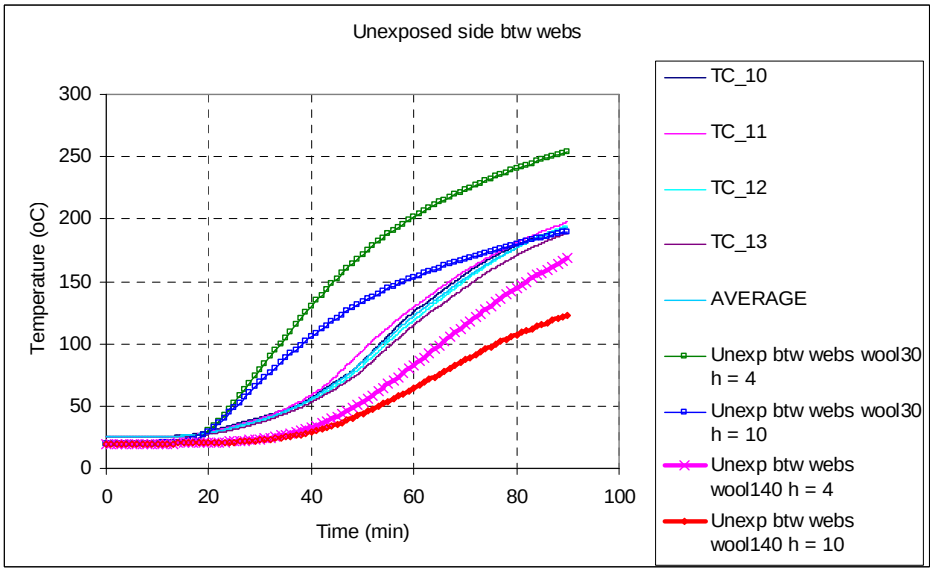



*Figure 23 Measured and calculated temperatures at the unexposed side midway between flanges of the V-profile with convection heat transfer coefficient on unexposed side equal to 4 W/m$^2$K and 10 W/m$^2$K.*

#### 4.2.2.3 Parametric modelling of wall element

In EN 1363-1: 1999, the following insulation criteria are given for separating walls:

- the average temperature on the unexposed surface of a separating element of a building construction must not exceed the initial average temperature by more than 140°C
- the temperature on the unexposed surface must not at any point exceed the initial average temperature by more than 180°C.

As can be seen by looking at the test results of the wall element test (e.g. Figures 14 and 15), these limits were breached in this test for fire resistance time $t$ = 60 min. Therefore it was decided to carry out some additional calculations for which the depth of the wall element is varied in order to meet the insulation criteria at fire resistance time $t$ = 60 min.

The same wall structure setup was kept - only the height of the Z-profile and the thickness of the insulation $d$ were increased from 60 mm to 80 mm, 100 mm and then to 120 mm in consecutive models. The results of the calculations for the unexposed side flange of the Z-section are shown in Figure 24 and for the location midway between flanges in Figure 25.

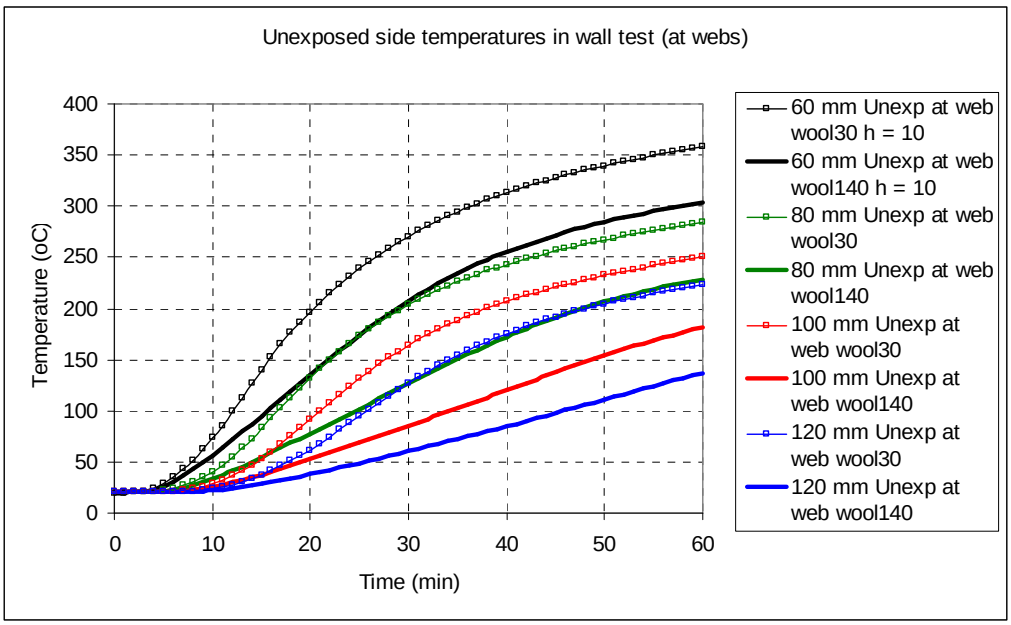



*Figure 24 Calculated temperatures at the unexposed side flange of the Z-profile with heights. 60 mm (black), 80 mm (green), 100 mm (red) and 120 mm (blue) and different insulation densities.*

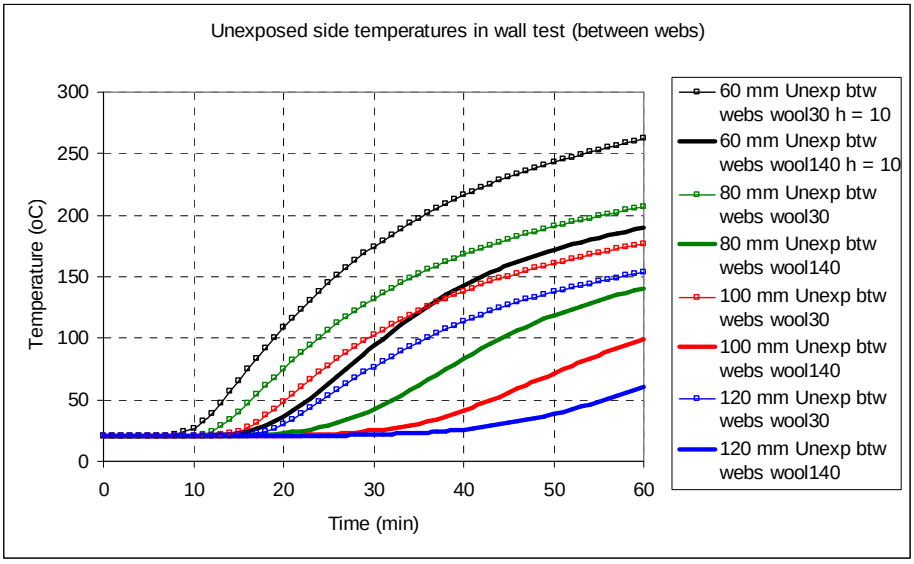



*Figure 25 Calculated temperatures at the unexposed side midway between the Z-profiles with heights 60 mm (black), 80 mm (green), 100 mm (red) and 120 mm (blue) and different insulation densities.*

It can be seen from Figures 24 and 25 how the calculated temperatures on the unexposed side of the wall structure decrease when the wall thickness is increased. As discussed in Chapters 3 and 4, the two curves corresponding to different insulation densities give calculated upper and lower bounds for the temperatures reached at the unexposed side flange of the V-profile. This is the location where the maximum temperatures on the unexposed side are reached.

For the different wall thicknesses, the calculated upper and lower bound temperatures increases at time $t$ = 60 minutes are given in Table 1. It should be noted that in Figures 24 and 25, the initial temperature is 20°C, which has been subtracted from the values in Table 5.

*Table 5. Calculated upper and lower bound temperature increases for different wall thicknesses at time t = 60 minutes.*

| Z-profile height | Upper bound (*wool30*) | Lower bound (*wool140*) | Average |
|---|---|---|---|
| 60 mm | 339°C | 283°C | 311°C |
| 80 mm | 265°C | 209°C | 237°C |
| 100 mm | 229°C | 161°C | 195°C |
| 120 mm | 203°C | 117°C | 160°C |

The actual maximum temperature increase reached in the test on the wall with 60 mm core Z-profiles was about 308°C, which is approximately the average value between the upper and lower bounds. If this “rule of thumb” is applied to the other cases, the actual temperature increase reached in a similar test for an 80 mm wall would be about 237°C and for a 100 mm wall about 195°C. Both of these values are higher than the limit of 180°C given in the

requirements. For the 120 mm wall, the average temperature increase according to the calculations would be about 160°C, which is less than the limit value of 180°C.

It can be concluded that it is quite likely that the temperature increase for a wall with thickness 120 mm will stay below the prescribed limits. For wall thickness 100 mm, it appears that the requirement may well be satisfied, but obviously this is less likely than for the 120 mm thick wall. The 80 mm thick wall does not appear to fulfil the requirements according to the present calculations.

#### 4.2.2.4 Conclusions

Finite element analyses have been carried out using FEMLAB© and COMSOL Multiphysics© in order to model the preliminary tests on a wall element (core element Z-profile height 60 mm) and on a floor element (core element V-profile height 120 mm) in the frame of the project "Structures in Fire" at VTT. The modelling was handicapped by the lack of accurate data on the thermal properties of the blowing mineral wool material used as insulation in the specimens.

The estimated density of the blowing mineral wool material was 75 kg/m$^3$, but the actual density calculated on the basis of the floor test specimen was about 115 kg/m$^3$. Material data for mineral wool slabs with densities 30 kg/m$^3$ and 140 kg/m$^3$ were available, so it was assumed that by modelling the structures twice by using each of these mineral wool slab materials, upper and lower bounds for the unexposed side temperatures could be obtained.

This proved to be a correct assumption on the basis of the modelling reported herein. Furthermore, it was noted that on the unexposed side, the heat should be assumed to be transferred by convection and radiation. A suitable value for the convection heat transfer coefficient was found to be 10 W/m$^2$K in this case and the emissivity of stainless steel was taken as equal to 0.4 on all stainless steel surfaces subject to radiation. The convection heat transfer coefficient on the exposed side was taken as equal to 25 W/m$^2$K.

Once the finite element models were validated as best as possible on the basis of the available test data, three additional parametric wall models were created, for which the thickness of the wall was varied. This was done in order to obtain an estimate of the minimum wall thickness necessary for the fulfilment of insulation requirements at fire resistance time $t$ = 60 min. On the basis of the calculations, it was found that it is likely that a wall with a core element Z-profile of height (and insulation thickness) 120 mm is sufficient for this purpose. A core element Z-profile height (and insulation thickness) equal to 100 mm may also be sufficient, but this is difficult to ascertain on the basis of the present analyses.

#### 4.2.2.5 Floor element, large scale test

In the large scale test besides the temperature rise, the mechanical properties (deformations) were measured. On the basis of calculations maximum deformation in the middle of specimen after one hour standard fire is 276 mm. Unfortunately there were some fails in blowing of mineral wool and as consequence of the fact there were some cavities. Due that, the temperature rise in certain parts of the structure was so high that the test had to be interrupted after 47 minutes standard fire (Figure 26).

The test report of the large scale fire test will be completed in March 2006.

*Figure 26. Photographs of large scale fire test.*

In figure 27 is shown the deformation in the middle of the floor element.

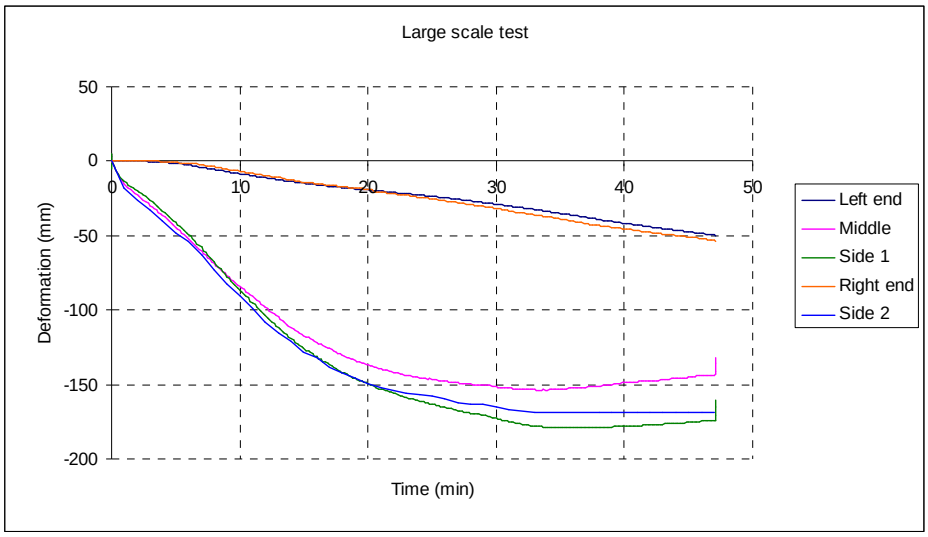



*Figure 27. the deformation in the middle of the floor element in large scale test.*

On the basis of the tests and the calculations carried out, it may be supposed that the structure can meet the requirements in one hour standard fire in the case where the insulation in the voids is perfect.

The fabrication corrugated core sandwich panel has taken more time than planned because of the thermocouple instrumentation. Due to problems in the preparation of one test specimen (test 18.8.2005), only one of the three interior Z-profiles was welded onto the top and bottom plates. The other two were only welded onto the top plate (on the unexposed side). This meant that there was probably a small air gap between the exposed side plate and the flanges of two of the interior Z-profiles, and probably between the plate and the mineral wool. In the other test specimen, the top flange of the properly welded Z-profile (test 13.10.2005).

In the large scale floor test there were some fails in blowing of mineral wool and as consequence of the fact there were some cavities. Due that, the temperature rise in certain parts of the structure was so high that the test had to be interrupted after 47 minutes standard fire.

# 5 NUMERICAL ANALYSIS

Numerical analysis has been carried out by University of Hannover.

# 6 DEVELOPMENT OF DESIGN GUIDANCE

On the basis of WP1 the design guidance will not be developed.

# 7 CONCLUSIONS

The main objective of the work package was to develop new stainless steel products without passive or active fire protection that can achieve 30 or 60 minutes fire resistance in a standard fire or in a natural fire. The developed products should include both load-bearing structures and fire separating members.

Finite element analyses have been carried out using FEMLAB© and COMSOL Multiphysics© in order to model fire tests. On the basis of calculations the tested columns and sandwich panels were chosen.

Four different kinds of columns have been tested: tubes within each others, column section in the corner and columns exposed to fire from one side from one or two parts. For tubes within each others, the inner tube (RHS 200x200x8) the mean value of measured temperatures was 414 °C. This means that the inner tube has about 60% left of its capacity according to EN 1993-1-2. For other columns the temperature differences between exposed and unexposed sides were remarkable. This means that in calculations temperature distribution should be taken in to account. The structure from two parts is quite demanding to construct when considering the construction process.

The sandwich panel system has been tested in small and a large scale fire tests to investigate the thermal and load bearing behaviour of the element exposed to fire. It can be concluded that it is quite likely that the temperature increase for a wall with thickness 120 mm will stay below the prescribed limits. For wall thickness 100 mm, it appears that the requirement may well be satisfied, but obviously this is less likely than for the 120 mm thick wall. The 80 mm thick wall does not appear to fulfil the requirements according to the present calculations.

It may be supposed that the tested large scale floor structure can meet the requirements in one hour standard fire for corrugated core sandwich panel with fire protection of mineral wool in the case where the insulation in the voids is perfect (h=120 mm). Sandwich panels (Z-profiles, with fire protection of mineral wool, the thickness of 60 mm) will not meet the requirements in 30 min standard fire (the maximum temperature is above 180 °C). On the basis of the calculations and tests carried out, the structures where no insulation is used have problems to meet the requirements 30 or 60 min standard fire.

The special cross-sections (tubes within each others with fire protection and column exposed to fire from one sides) have potential in building. Also corrugated core sandwich panels may be used as load bearing and separating structures. For that kind of structures it is very important that the insulation work is performed carefully.

# 8 RECOMMENDATIONS FOR FURTHER WORK

More full scale test should be carried out and the cots-effective of special structures should be evaluated.

**REFERENCES**

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

EN 1991-1-2: 2002 *Eurocode 1 Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire*, CEN European Committee for Standardization, Brussels, Belgium, 2002.

EN 1992-1-2:2003(E) Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design. CEN 2003.

EN 1993-1-2: 2005 *Eurocode 3: Design of steel structures - Part 1.2: General rules, Structural fire design*, CEN European Committee for Standardization, Brussels, Belgium, 2005.

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Incropera & DeWitt (2002), *Fundamentals of Heat and Mass Transfer*, Fifth Edition, John Wiley & Sons, U.S.A. 2002.

Kaitila, O., *Numerical thermal analyses of Kenno Tech wall and floor structures*, Stainless Steel in Fire, Contract N° RFS-CR-04048, WP1 Fire resistant structures and products, 29.9.2005.

# APPENDIX 1: THERMAL MATERIAL PROPERTIES AT ELEVATED TEMPERATURES AND HEAT EXPOSURE

## STAINLESS STEEL

The thermal properties of stainless steel will be taken according to EN 1993-1-2: 2005. In some calculations the emissivity is assumed to be 0.2.

## BLOWING MINERAL WOOL

The thermal properties for the blowing mineral wool used in the structure were not directly available. However, it was known that the estimated density of the mineral wool was 75 kg/m$^3$. Thermal properties were available for mineral wool slabs with densities 30 kg/m$^3$ (*wool30*) and 140 kg/m$^3$ (*wool140*), so these were used for the calculations with the expectation that they would provide at least upper and lower bound temperature curves for different points of interest in the structure. The specific heat capacities of the 30 kg/m$^3$ and 140 kg/m$^3$ mineral wool slabs were taken as 900 J/kgK and 800 J/kgK, respectively. The thermal conductivities $\lambda$ (W/mK) were modelled according to Eq. (1) for mineral wool 30 and Eq. (2) for mineral wool 140.

$$\lambda = 0.034 - 0.00016T + 1.09 \cdot 10^{-6} T^2 \qquad (1)$$

$$\lambda = 0.0341 - 0.0095(T/100) + 0.0034(T/100)^2 \qquad (2)$$

where $T$ is the insulation temperature (°C)

Furthermore air gaps were included in some models in order to obtain a more realistic model. Air properties were taken according to Incropera & DeWitt (2002). They correspond to generally available air thermal properties. The thermal conductivities of mineral wool and air are shown in Figure 1.

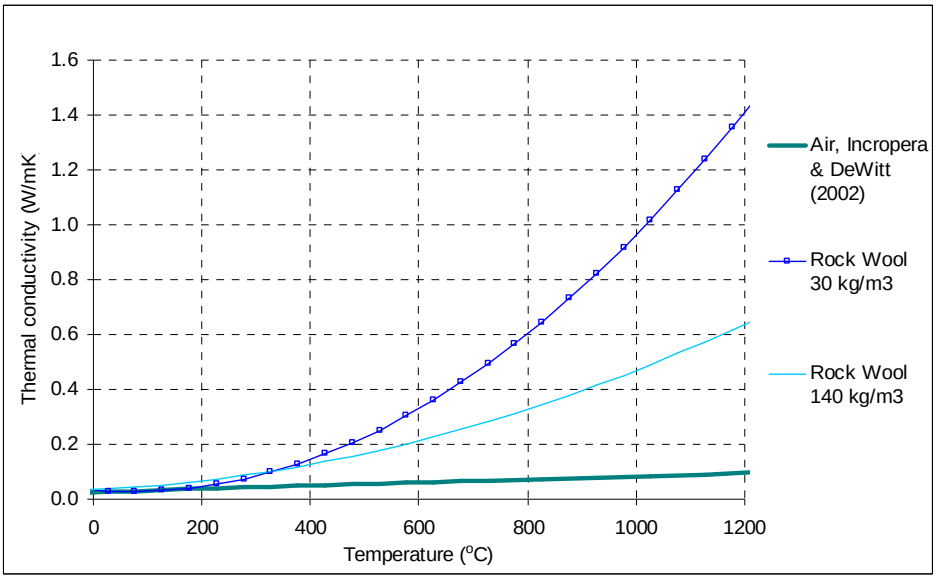



*Figure 1. Thermal conductivities of mineral wool and air as functions of temperature.*

## SIPOREX

The thermal properties of SIPOREX were taken as temperature-independent values:

- Thermal conductivity $k$ = 0.12 W/mK
- Specific heat capacity $c_p$ = 1000 J/kgK
- Emissivity $\varepsilon$ = 0.7
- Density $\rho$ = 500 kg/m$^3$

## CONCRETE

The thermal properties of concrete will be taken according to EN 1992-1-2: 2003.

## HEAT EXPOSURE

The thermal action in the furnace followed the EN 1363-1: 1999 (ISO 834-1) standard fire curve, as given in Eq. (3).

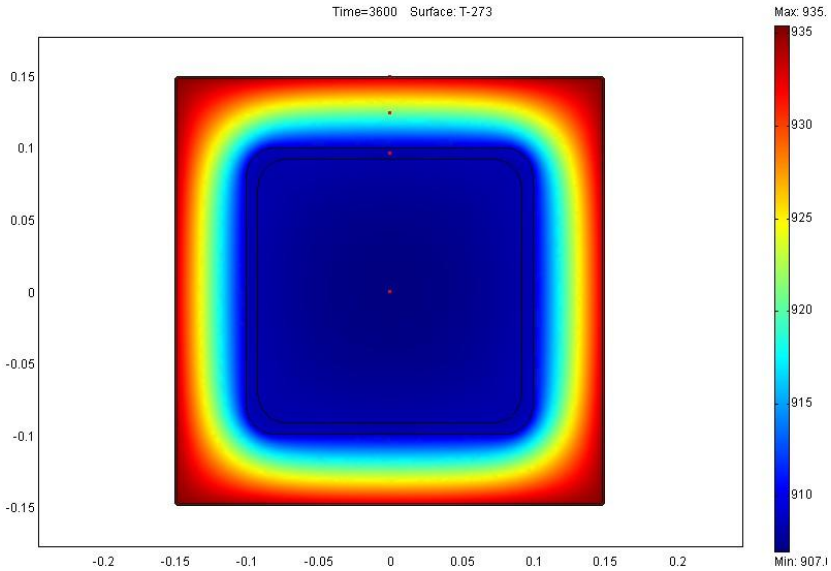
$$T = 20 + 345 \log_{10}(8t + 1) \qquad (3)$$

where $T$ is the gas temperature (°C)

$t$ is the time (min)

The heat transfer from the fire to the bottom surface of the test element, and from the top surface of the test element to the ambient, is assumed to happen through radiation and convection. The emissivity of stainless steel was taken as equal to 0.4 on all stainless steel surfaces subjected to radiation and the coefficient of convection heat transfer was taken as 25 W/m$^2$K on the fire exposed side and 9 W/m$^2$K on the unexposed side wall surfaces.

# APPENDIX 2: THE COMPUTED TEMPERATURE DISTRIBUTIONS IN CROSS-SECTIONS



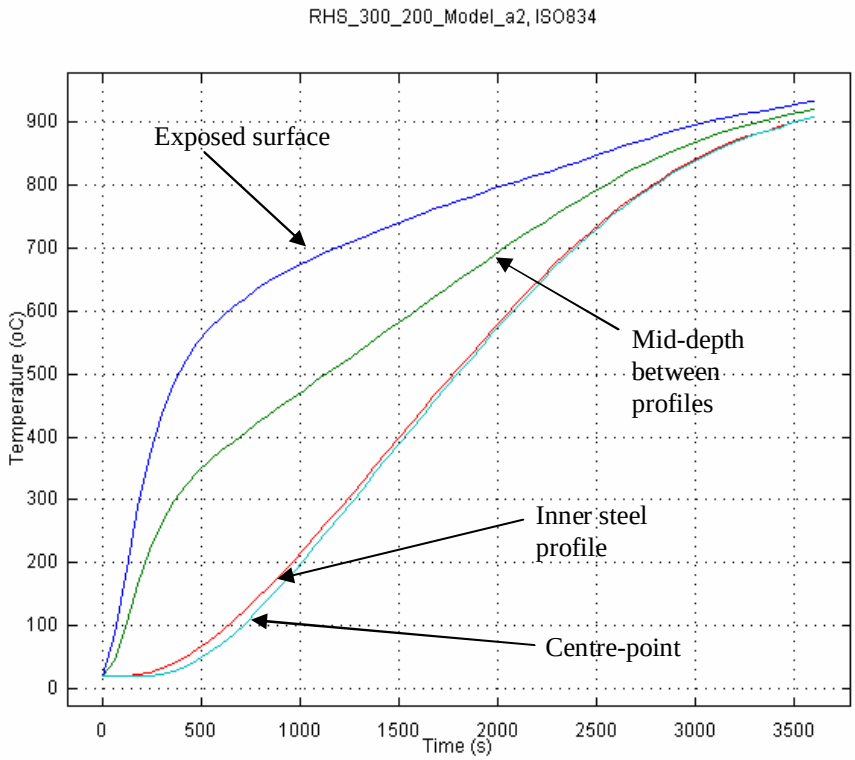




*Figure 1. Case 1: All cavities empty (air). Temperature distribution (°C) at t = 60 min. Temperatures at exposed surface (blue), mid-depth of insulation (green), inner steel profile (red) and centre-point of structure (turquoise). Data points shown with red dots in contour plot.*

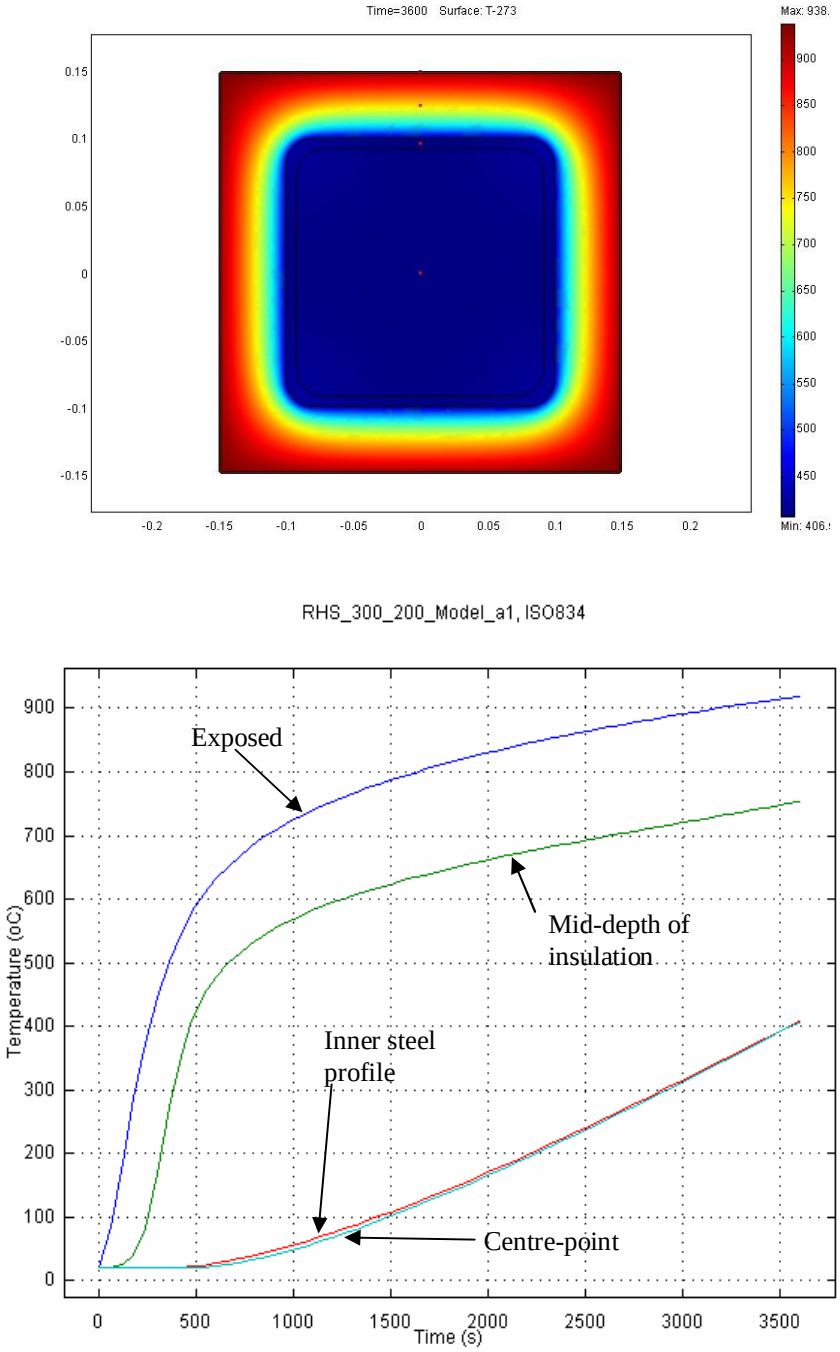
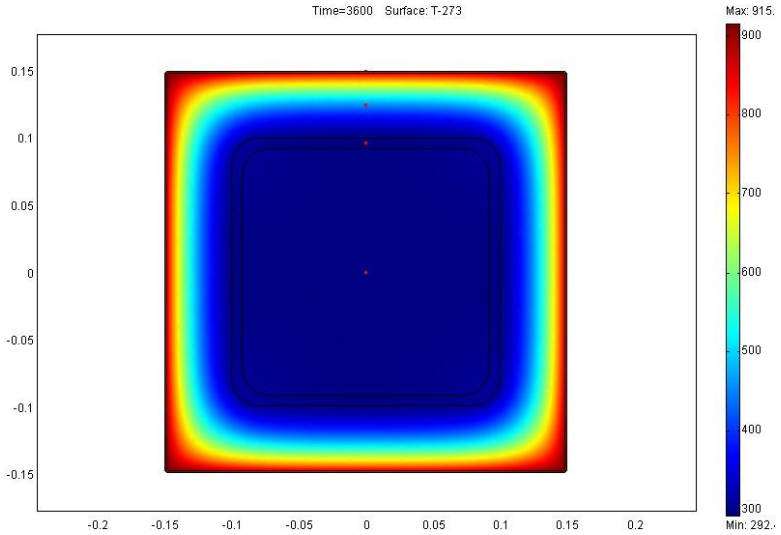



*Figure 2. Case 2: Space between profiles insulated with stone wool 30 kg/m$^3$, space inside inner profile empty. Temperature distribution (°C) at t = 60 min. Temperatures at exposed surface (blue), mid-depth of insulation (green), inner steel profile (red) and centre-point of structure (turquoise). Data points shown with red dots in contour plot.*



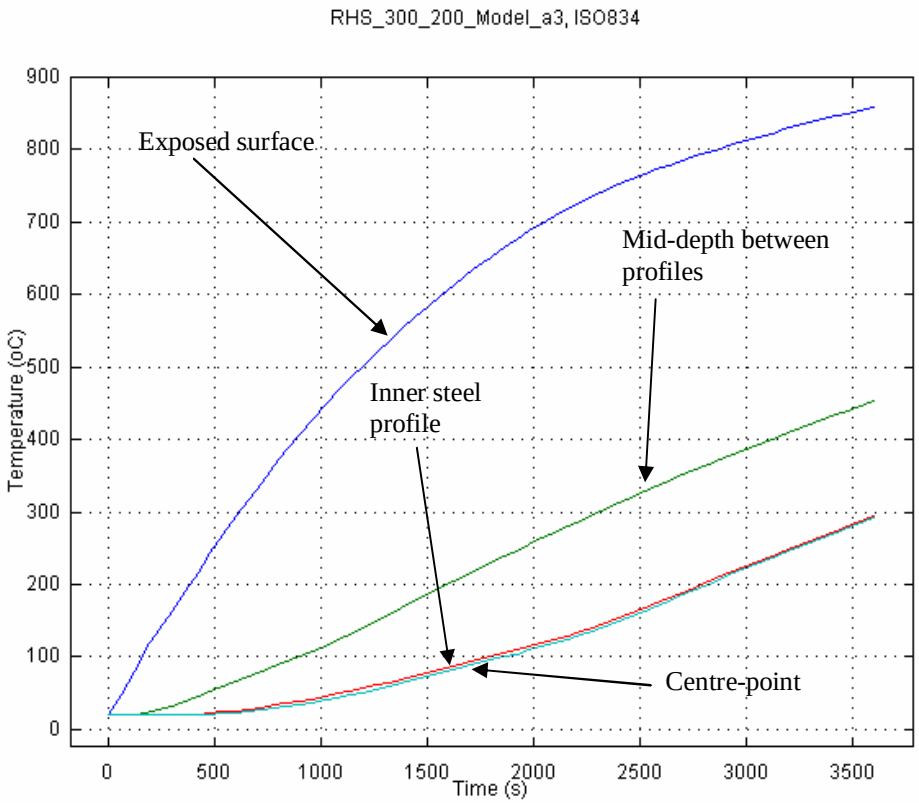




*Figure 3. Case 3: Space between profiles filled with concrete (moisture 3 %), space inside inner profile empty (air). Temperature distribution (°C) at t = 60 min. Temperatures at exposed surface (blue), mid-depth of insulation (green), inner steel profile (red) and centre-point of structure (turquoise). Data points shown with red dots in contour plot.*

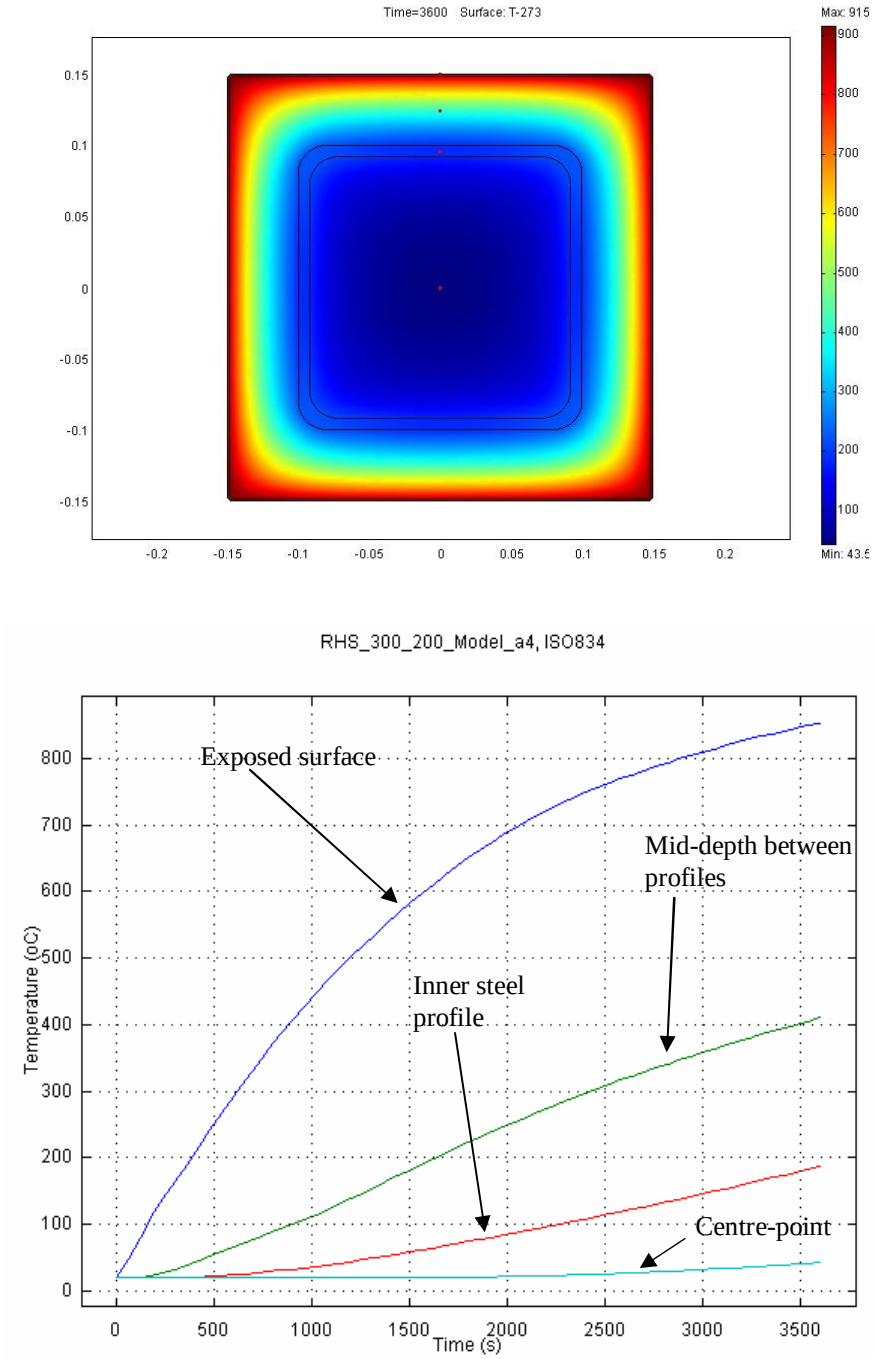
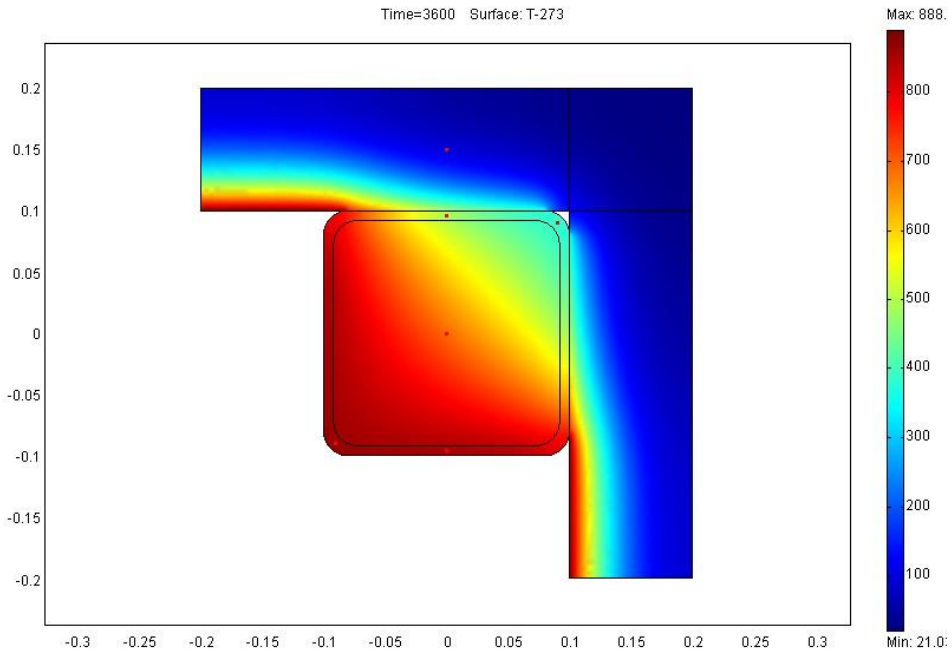



*Figure 4. Case 4: Space between profiles and space inside inner profile filled with concrete (moisture 3 %). Temperature distribution (°C) at t = 60 min. Temperatures at exposed surface (blue), mid-depth of insulation (green), inner steel profile (red) and centre-point of structure (turquoise). Data points shown with red dots in contour plot.*



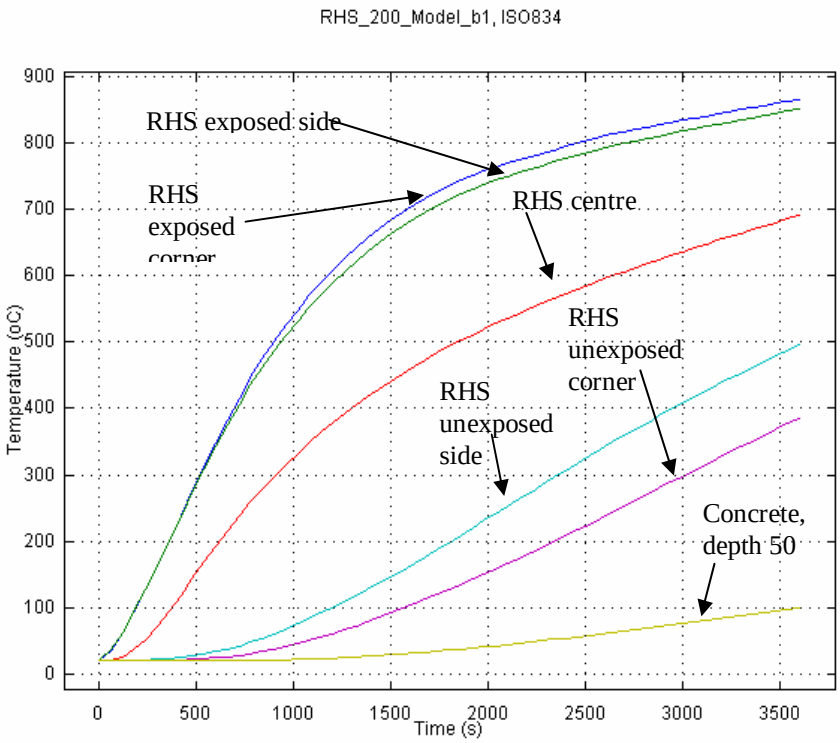
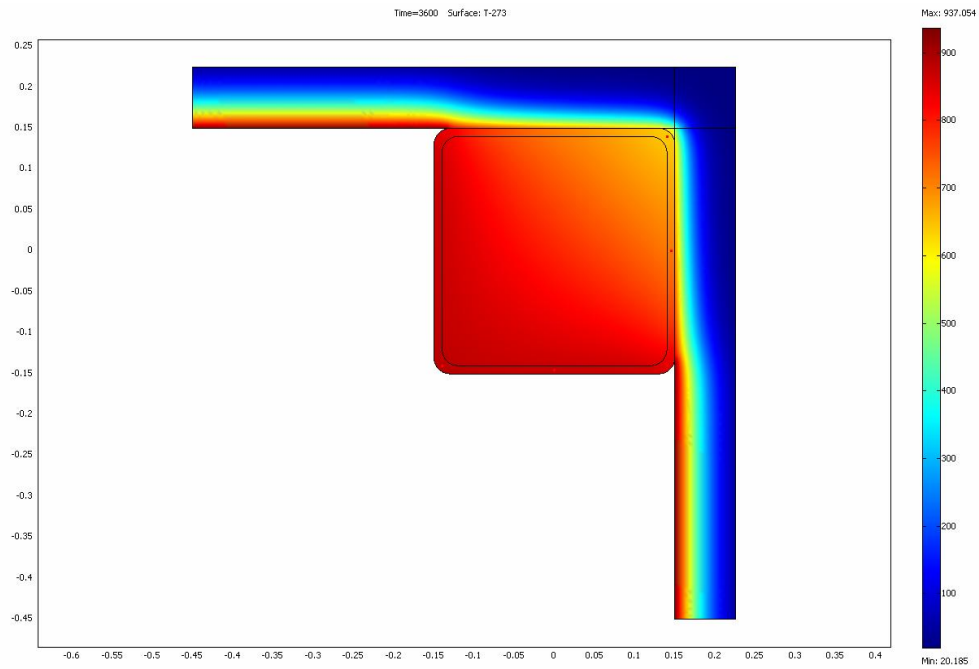




*Figure 5. Case 5. Space inside profile empty (air), concrete walls. Temperature distribution (°C) at t = 60 min.*



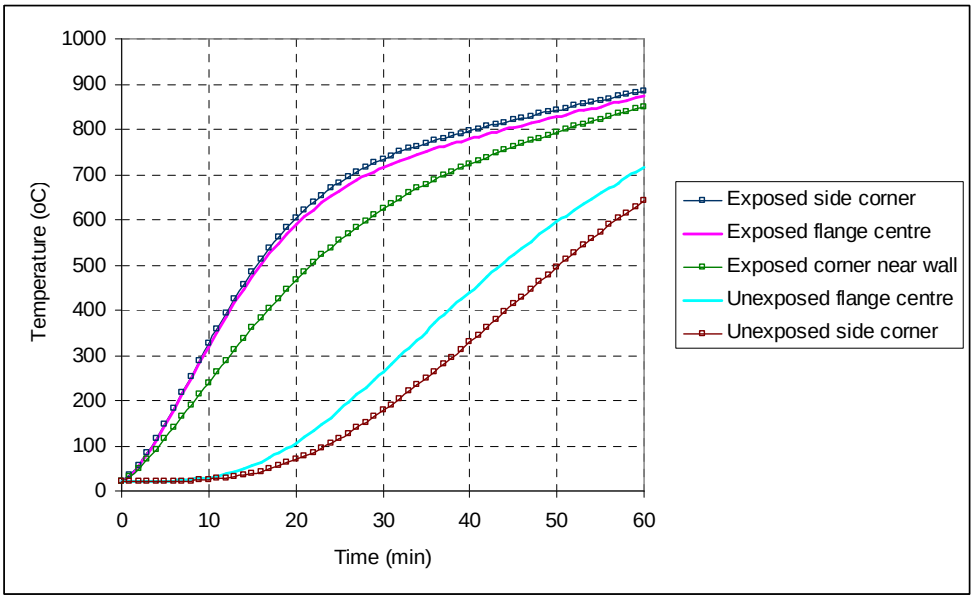
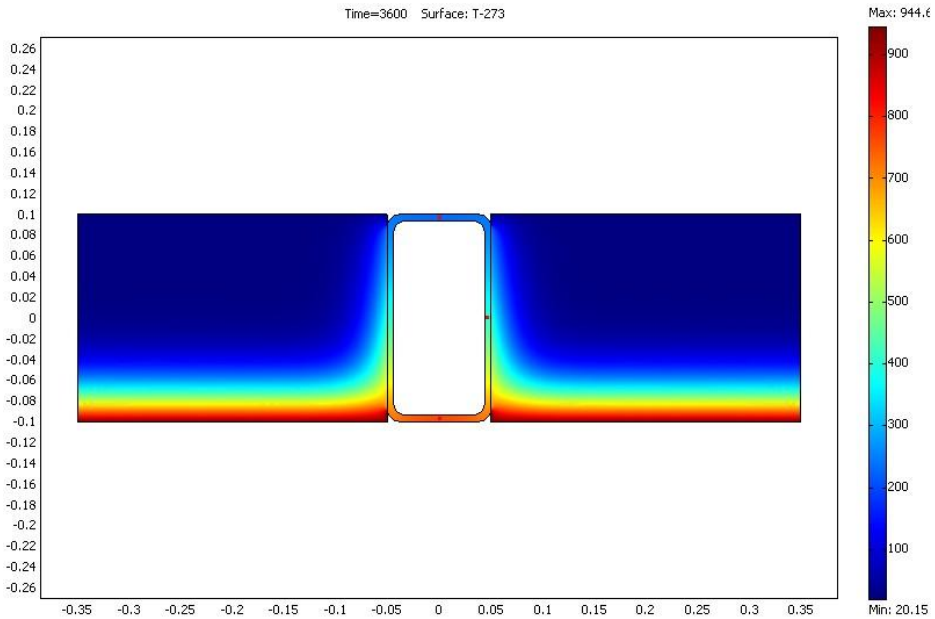




*Figure 6. Case 6: Space inside profile empty (air), SIPOREX walls of thickness 100 mm. Temperature distribution (°C) at t = 60 min.*



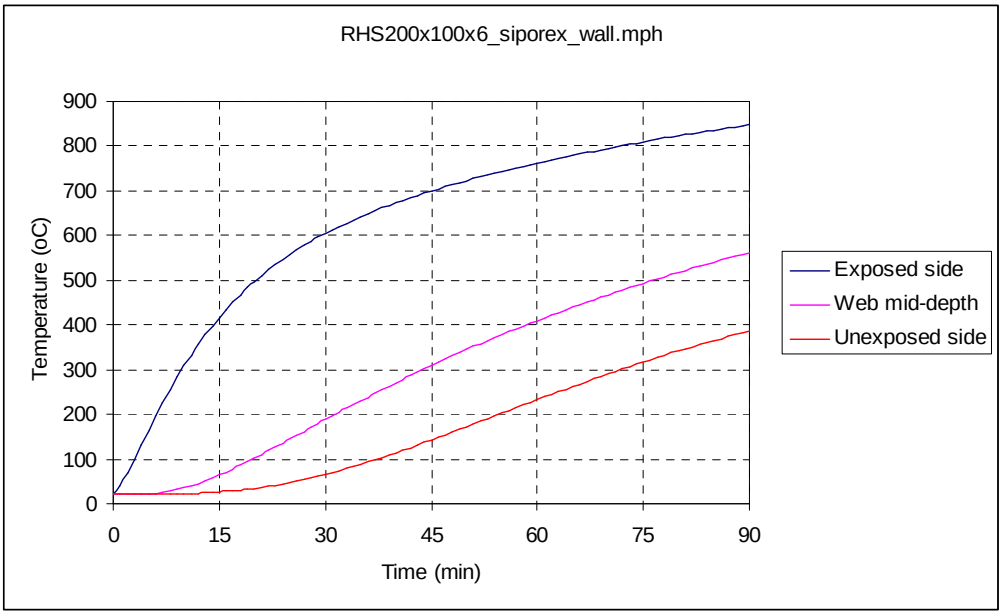
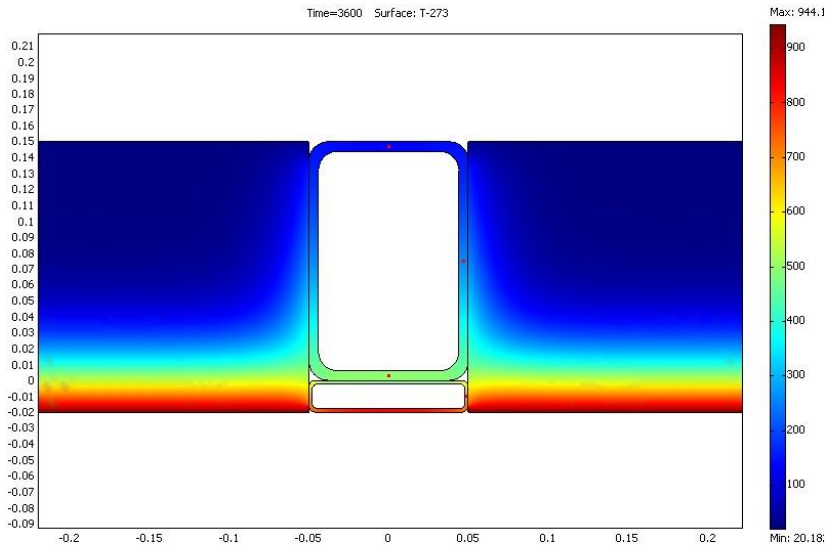




*Figure 7. Case 7: RHS 200x100x6 and siporex wall of thickness 200 mm. Space inside profile empty (air)Temperature distribution (°C) at t = 60 min.*



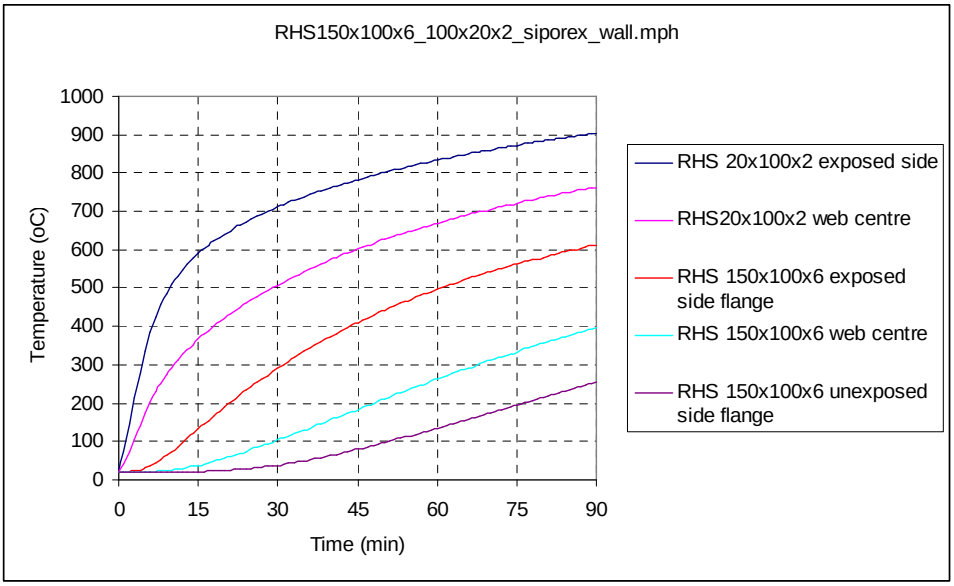
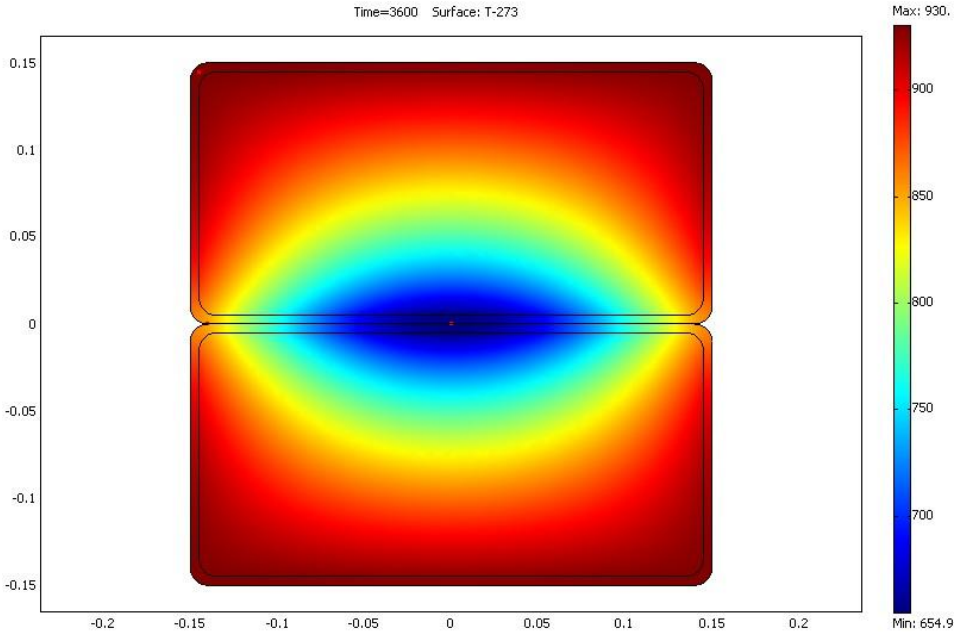




*Figure 8. Case 8: : RHS 150x100x6 & RHS 20x100x2 and siporex wall with thickness 150 mm. Space inside profile empty (air). Temperature distribution (°C) at t = 60 min.*



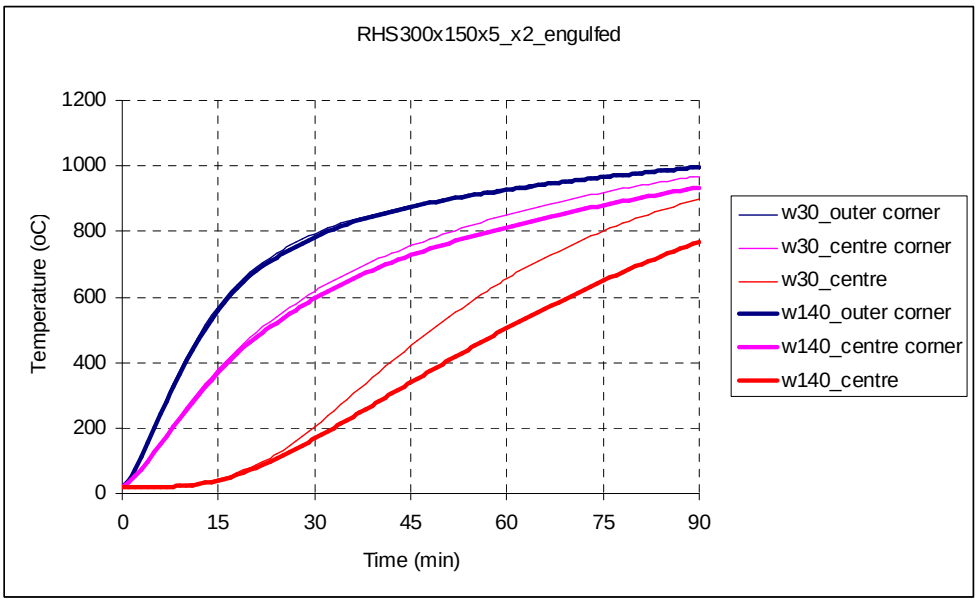
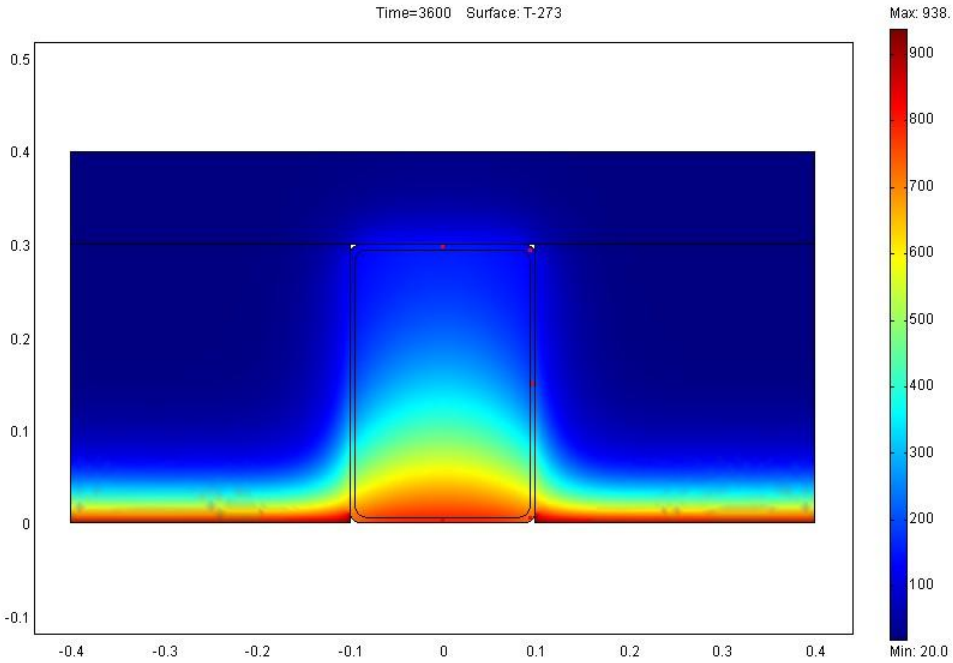




*Figure 9. Case 9: Two RHS 300x150x5 profiles side by side. Space inside profile filled with mineral wool 30 kg/m$^3$. Temperature distribution (°C) at t = 60 min.*



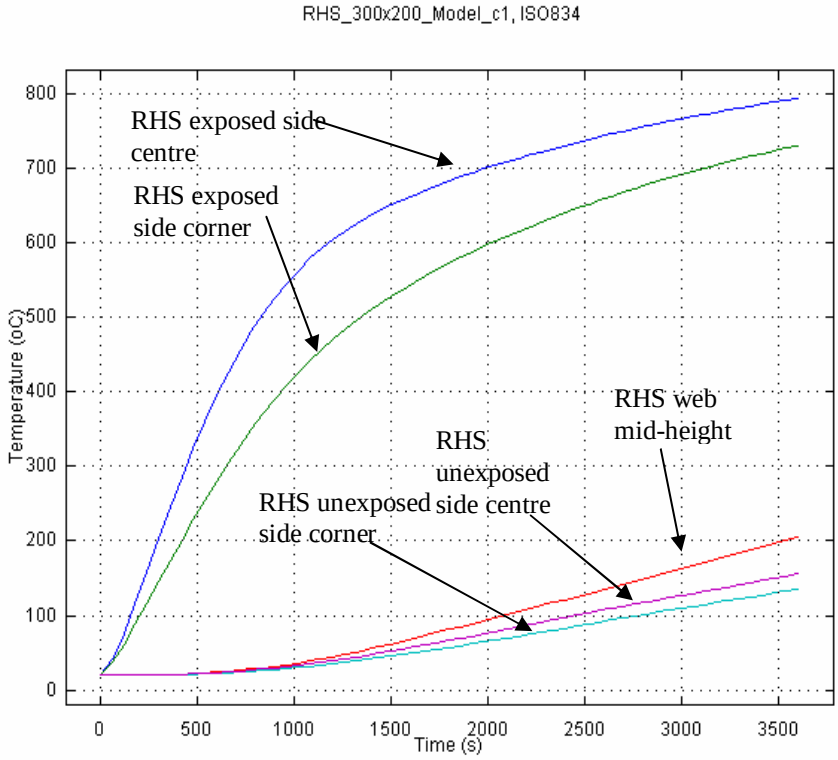
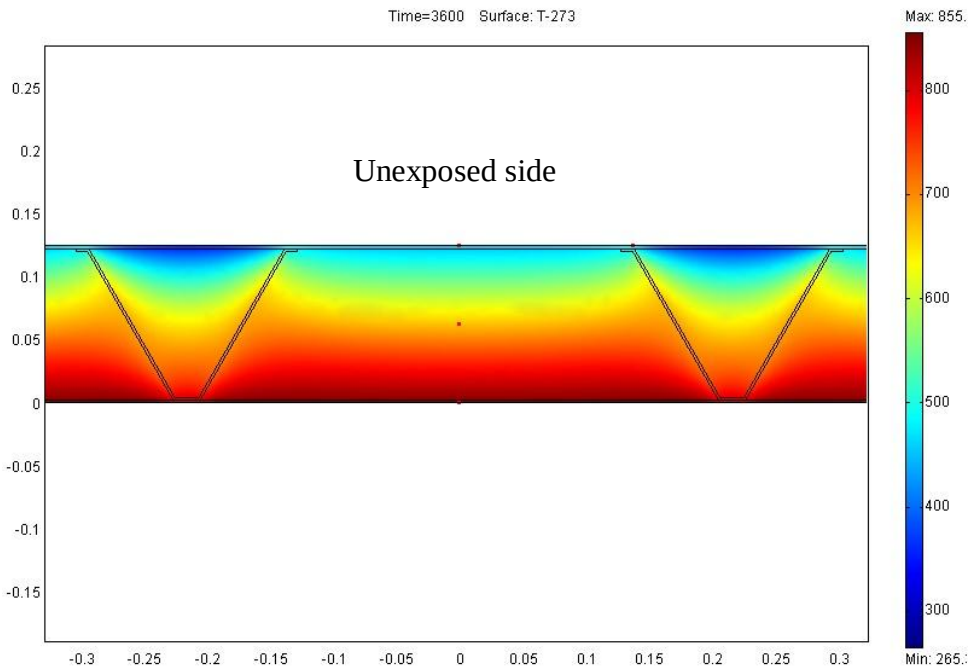




*Figure 10. Case 10: RHS 300x200x? beam section in floor, surrounded by concrete (moisture 3%). Bottom flange subjected to ISO 834 fire, other sides inside structure. Temperature distribution (°C) at t = 60 min.*

# APPENDIX 3: THE COMPUTED TEMPERATURE DISTRIBUTIONS IN SANDWICH PANELS



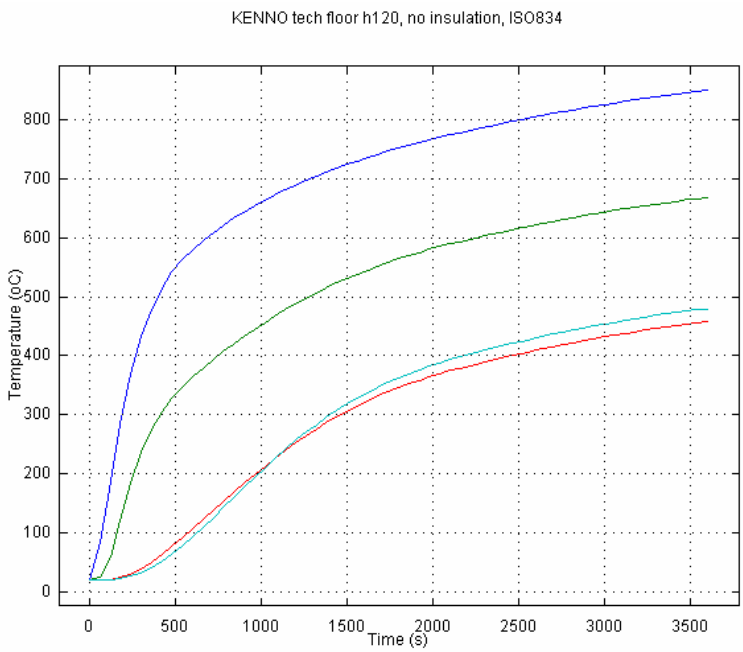
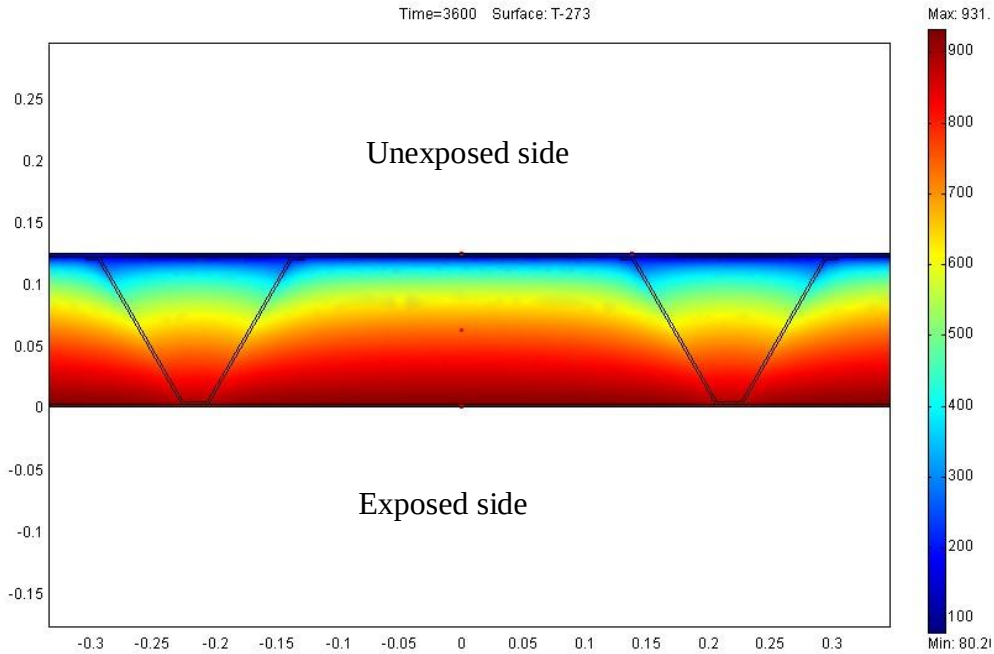




*Figure 1. Case 1: All cavities empty (air). Temperature distribution (°C) at t = 60 min. Temperatures at exposed side surface (blue), mid-depth of insulation (green) and unexposed surface (red). Temperatures at unexposed surface at the profile flange location in turquoise. Data points shown with red dots in contour plot.*



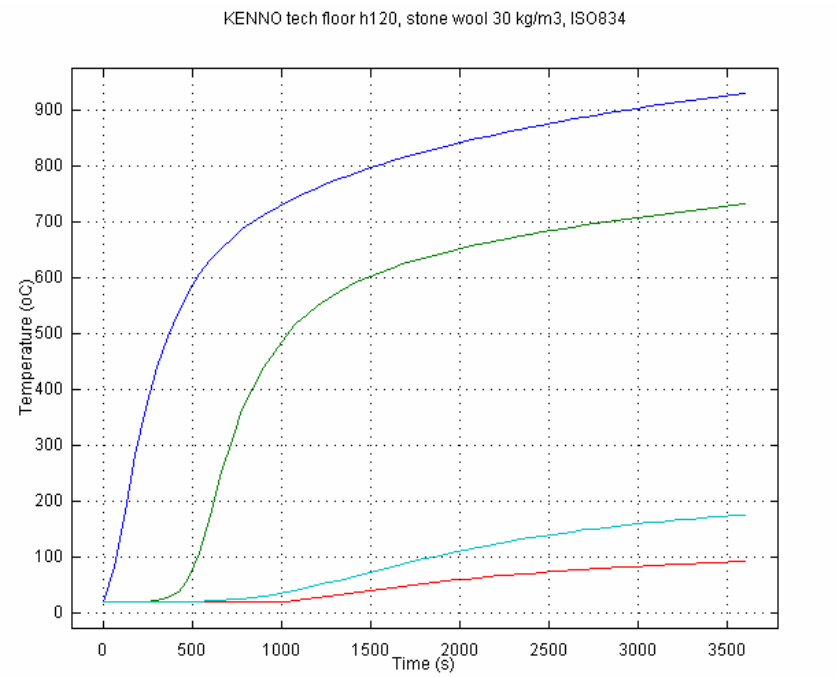
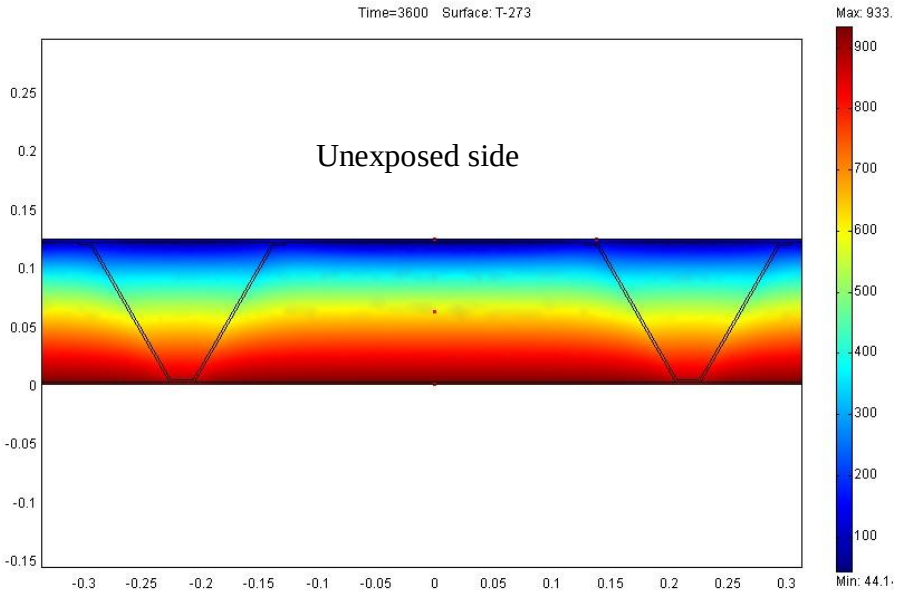




*Figure 2. Case 2: Space inside profile filled with mineral wool 30 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed surface (blue), mid-depth of insulation (green), inner steel profile (red) and at the profile flange location in turquoise. Data points shown with red dots in contour plot.*



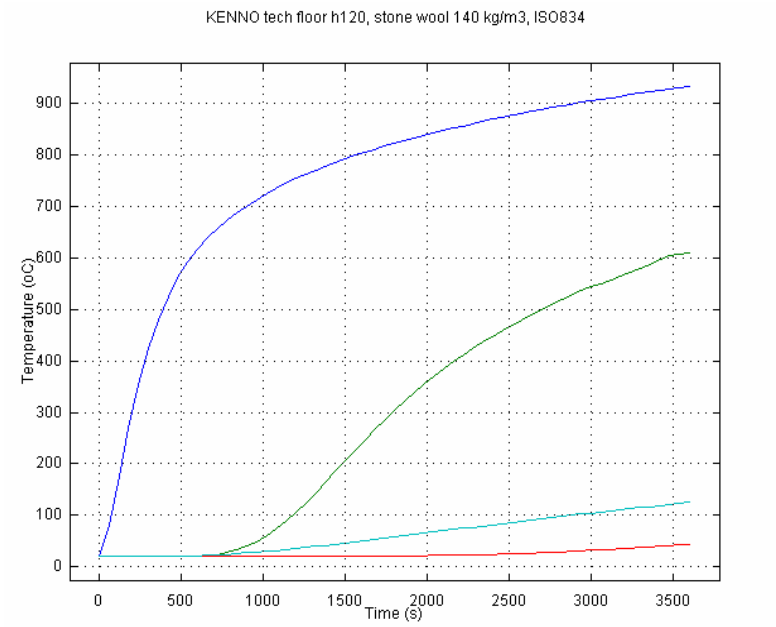
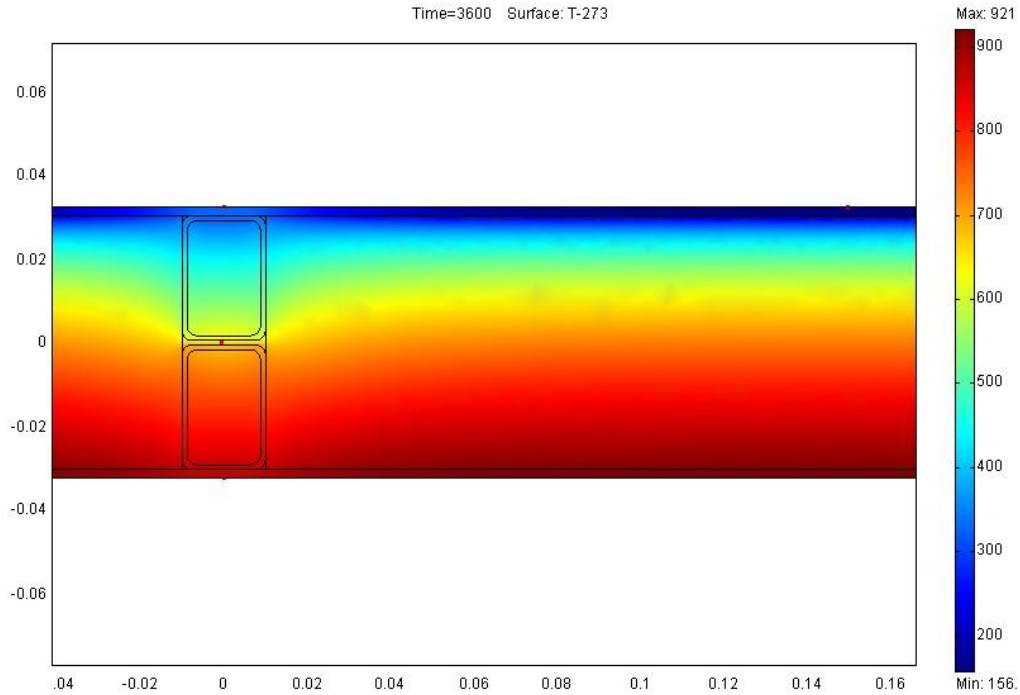




*Figure 3: Case 3. Space inside profile filled with mineral wool 140 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed surface (blue), mid-depth of insulation (green), inner steel profile (red) and at the profile flange location in turquoise. Data points shown with red dots in contour plot.*



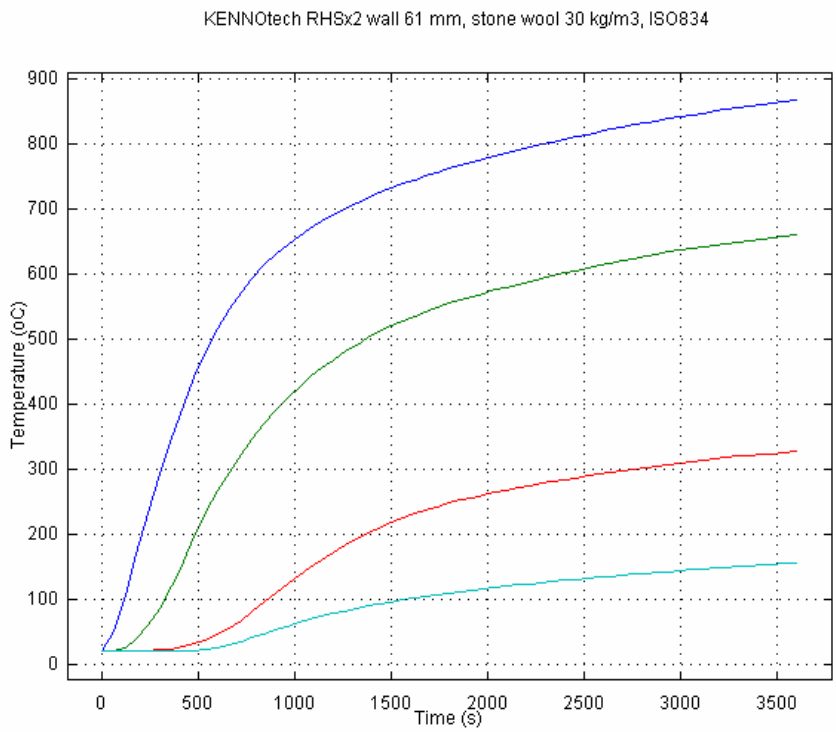
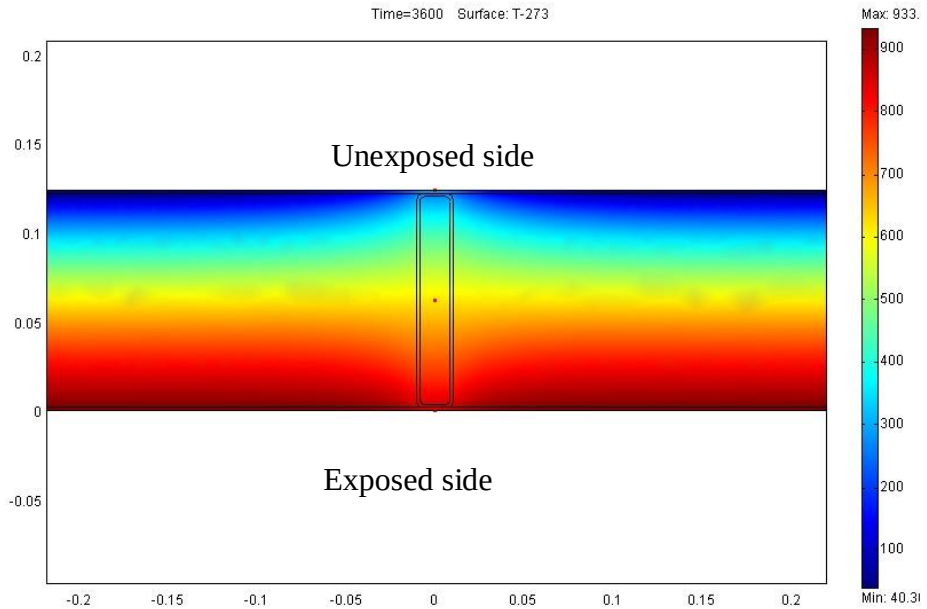




*Figure 4: Case 4. Space inside profile filled with mineral wool 30 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at Point 1: exposed side surface (blue), Point 2: mid-depth of insulation between RHS-profiles (green) and Point 3: unexposed surface (red). Temperatures at Point 4: unexposed surface between the RHS-profiles in turquoise. Data points shown with red dots in contour plot above.*



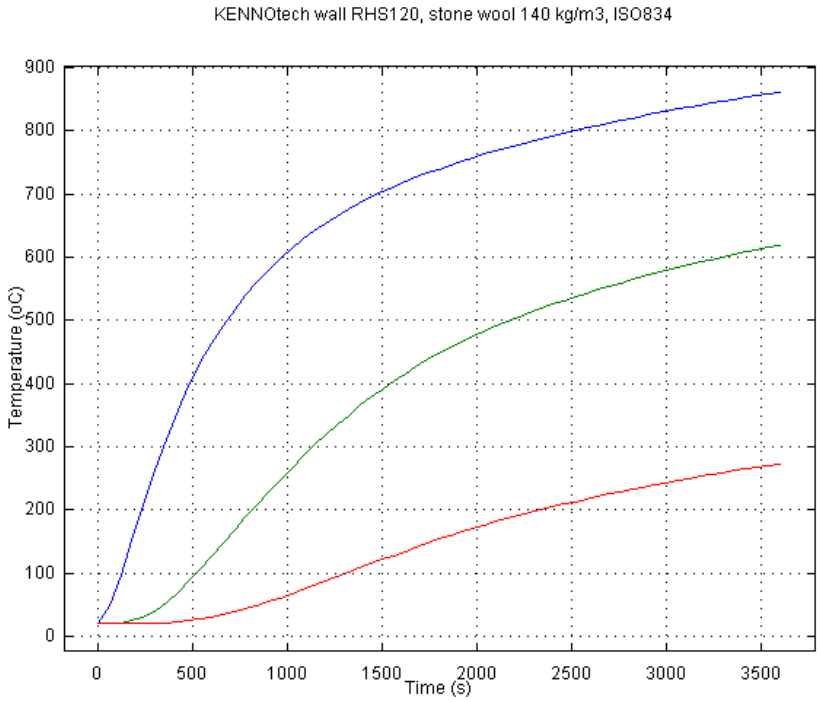
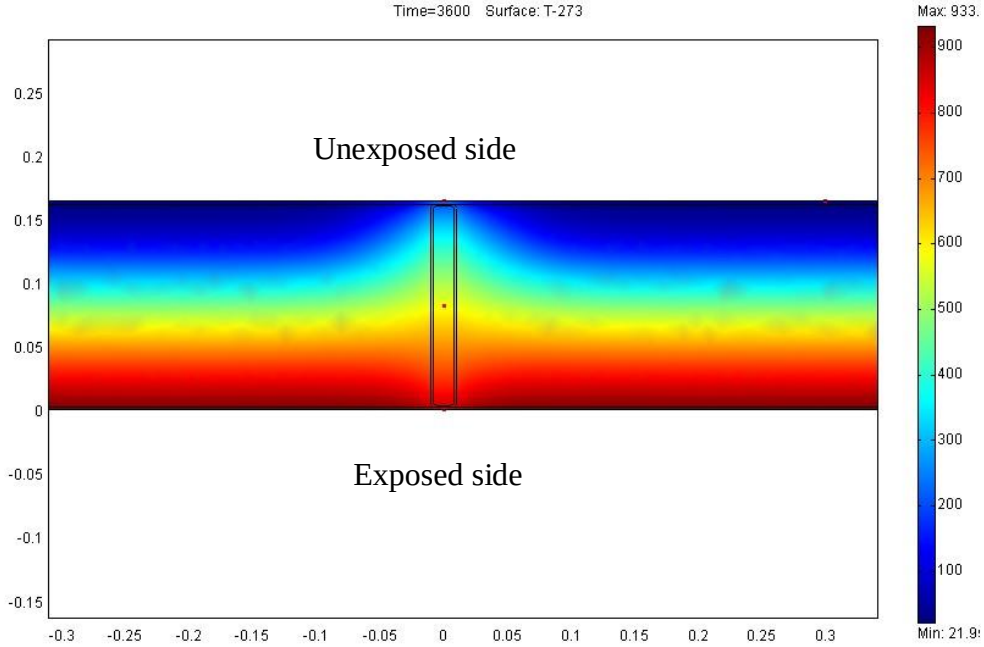




*Figure 5: Case 5. Space inside profile filled with mineral wool 140 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed side surface (blue), centre point of RHS (green) and unexposed surface (red). Data points shown with red dots in contour plot.*



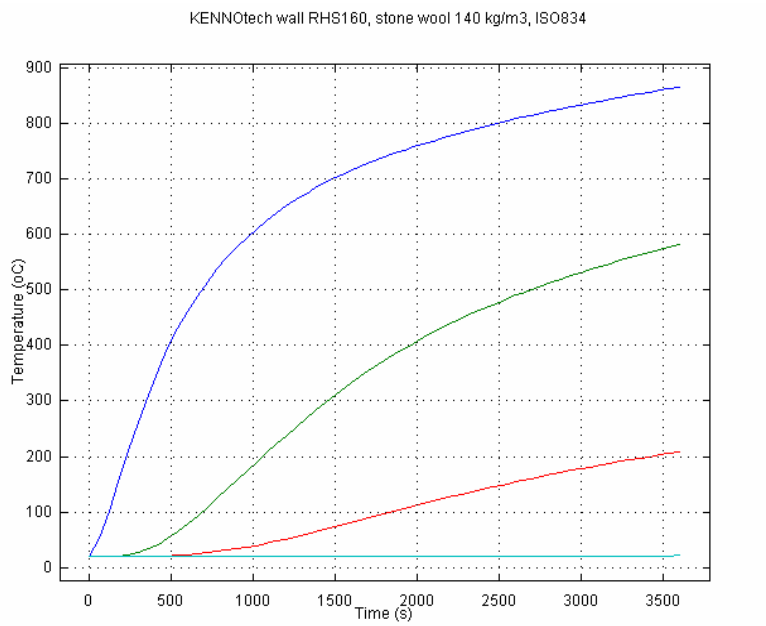
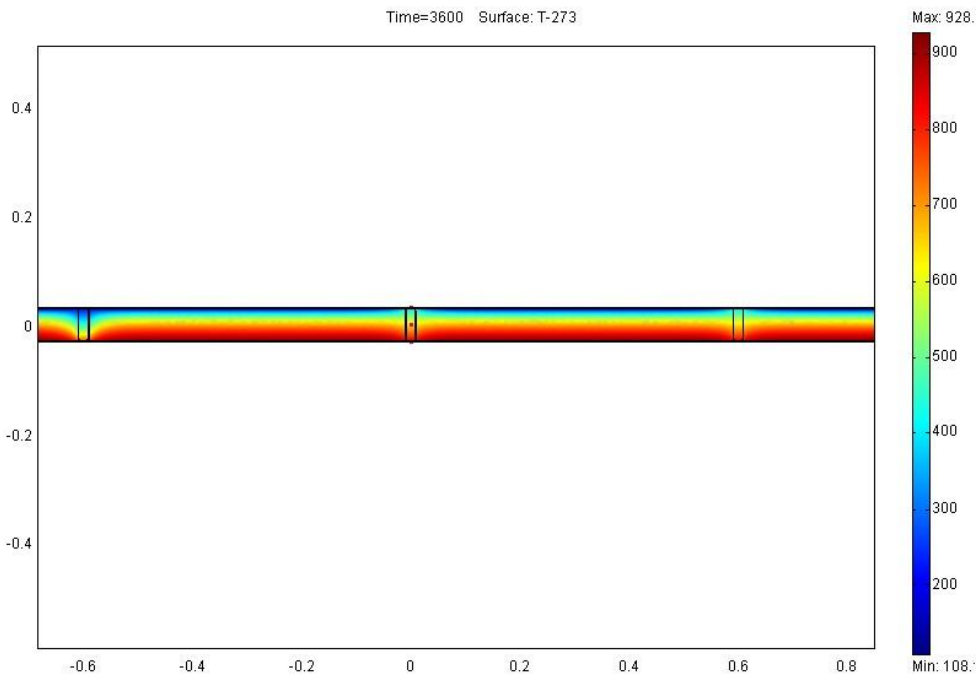




*Figure 6: Case 6. Space inside profile filled with mineral wool 140 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed side surface (blue), centre point of RHS (green) and unexposed surface (red) along axis of RHS. Lowest curve (turquoise) at unexposed surface between RHS-columns.. Data points shown with red dots in contour plot.*



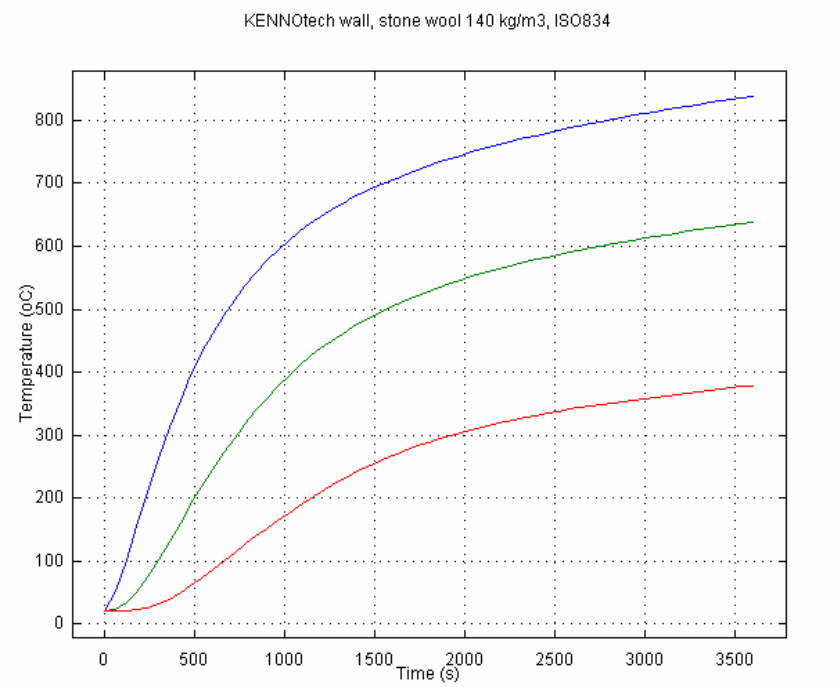
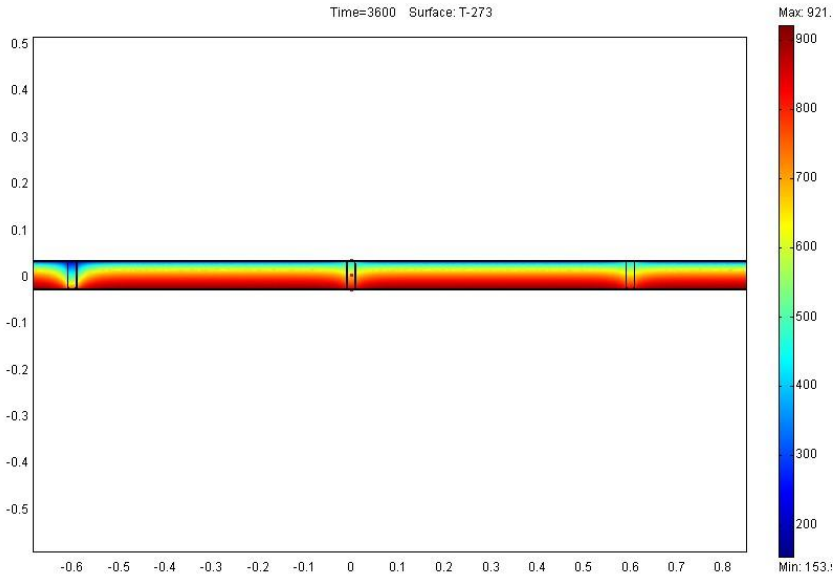




*Figure 7: Case 7. Space inside profile filled with mineral wool 140 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed side surface (blue), centre point of RHS (green) and unexposed surface (red). Data points shown with red dots in contour plot.*



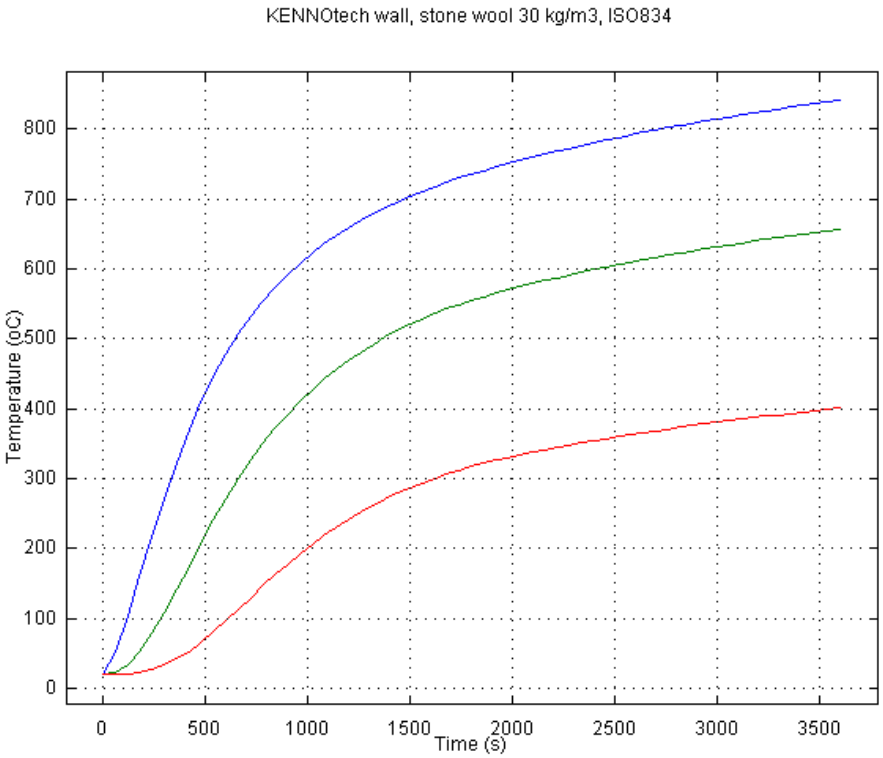
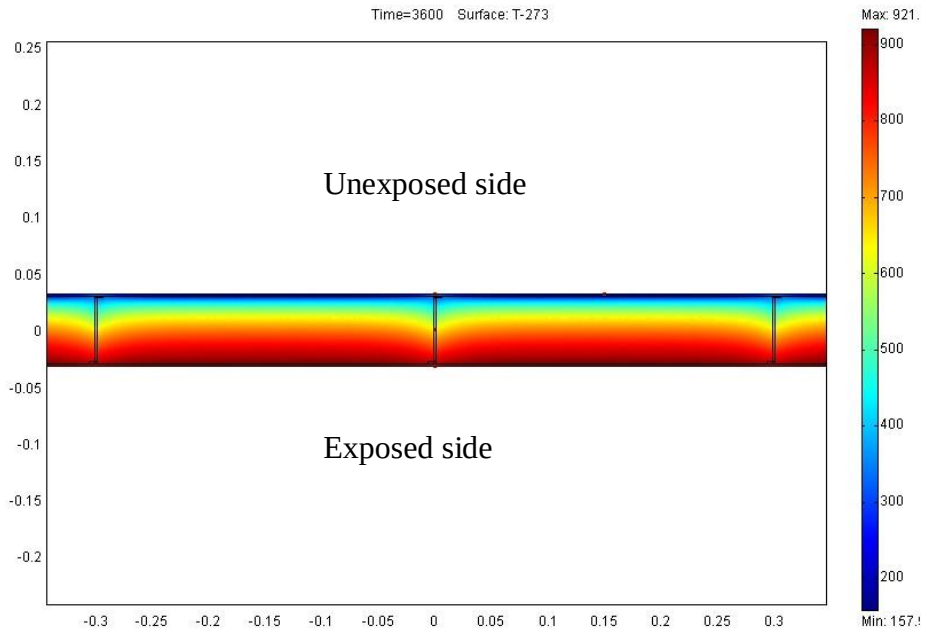




*Figure 8: Case 8. Space inside profile filled with mineral wool 30 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed side surface (blue), centre point of RHS (green) and unexposed surface (red). Data points shown with red dots in contour plot.*



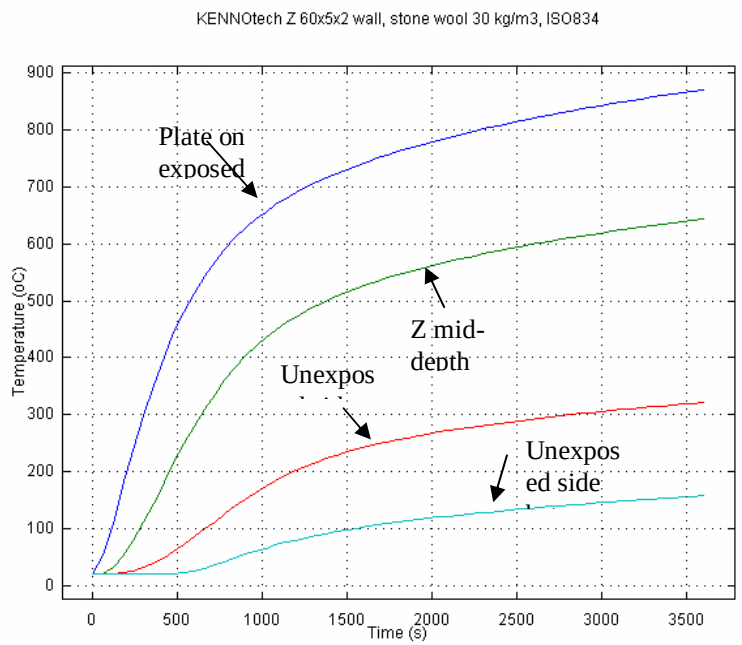
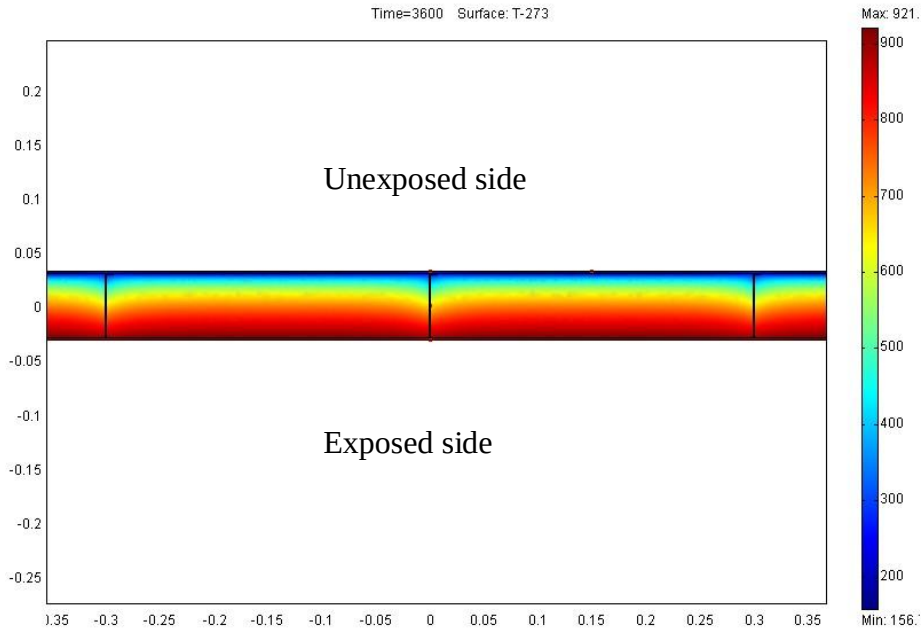




*Figure 9: Case 9. Space inside profile filled with mineral wool 30 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed side surface (blue), centre point of Z-profile 60x20x2 (green) and unexposed surface (red). Temperatures at unexposed surface between the Z-profiles in turquoise. Data points shown with red dots in contour plot.*




Kenno Tech Z-wall 60x5x1 wool30: Temperature distribution at *t* = 60 min.

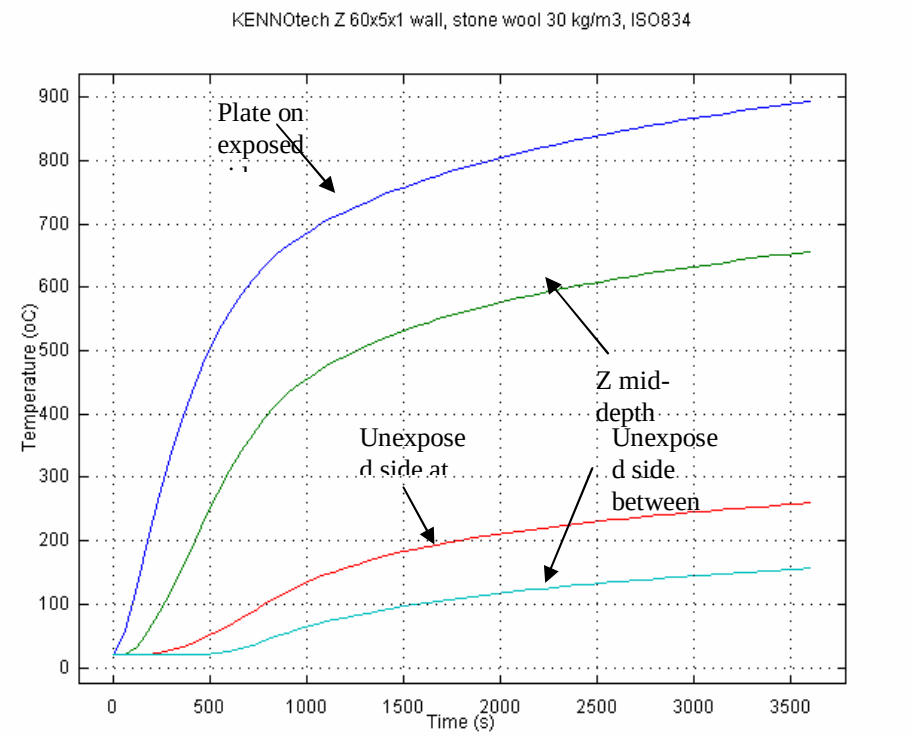
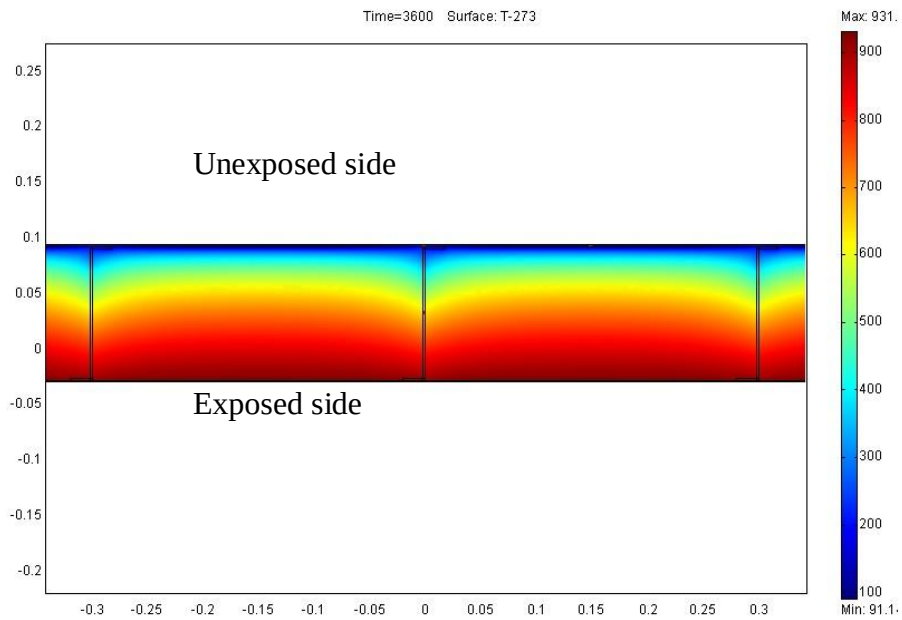



*Figure 10: Case 10. Space inside profile filled with mineral wool 30 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed side surface (blue), centre point of Z-profile 60x20x1 (green) and unexposed surface (red). Temperatures at unexposed surface between the Z-profiles in turquoise. Data points shown with red dots in contour plot.*



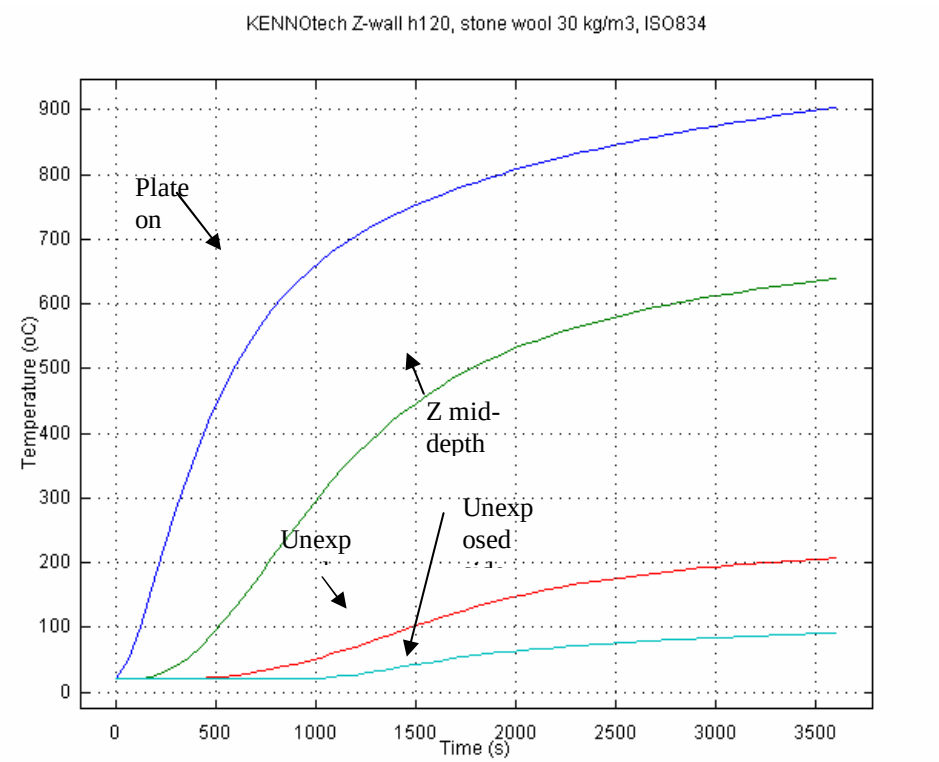
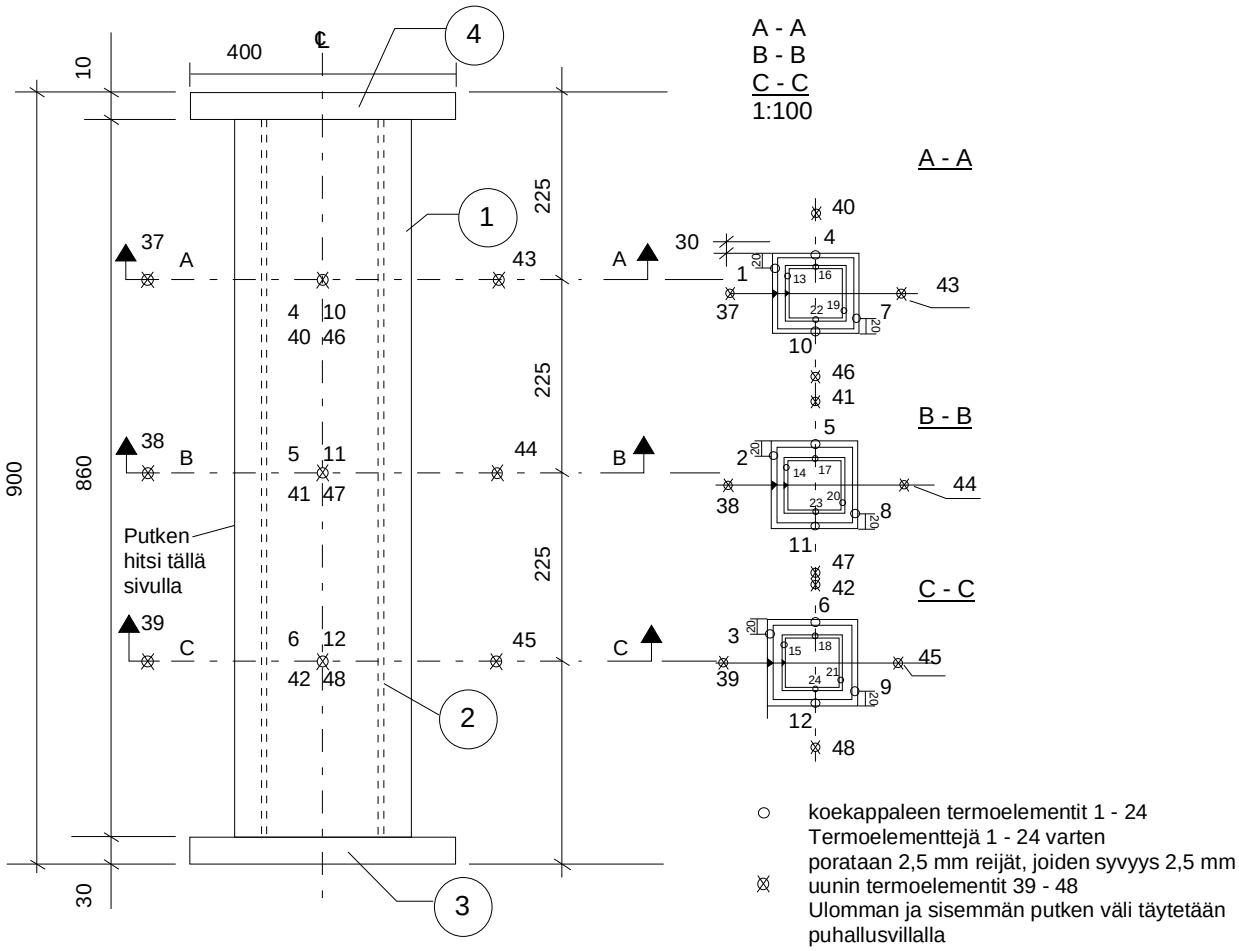




*Figure 11: Case 11. Space inside profile filled with mineral wool 30 kg/m$^3$ . Temperature distribution (°C) at t = 60 min. Temperatures at exposed side surface (blue), centre point of Z-profile 120x20x1 (green) and unexposed surface (red). Temperatures at unexposed surface between the Z-profiles in turquoise. Data points shown with red dots in contour plot.*

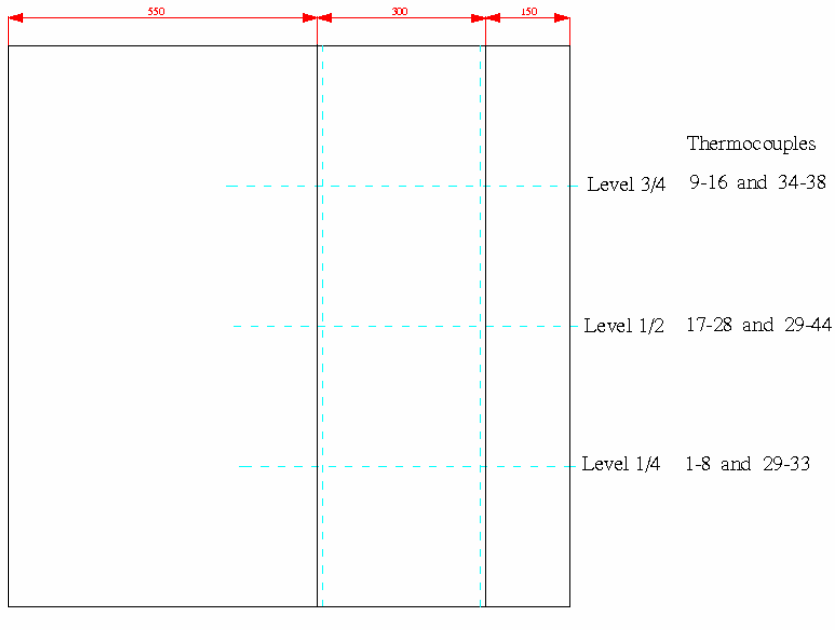
# APPENDIX 4: THE NESTED TUBES WITH FIRE PROTECTION

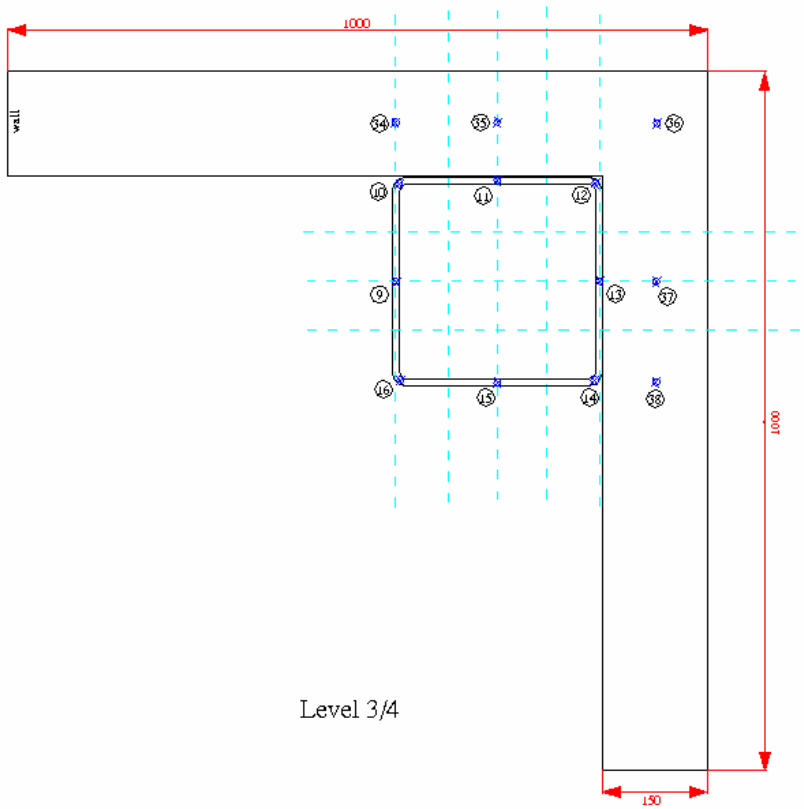


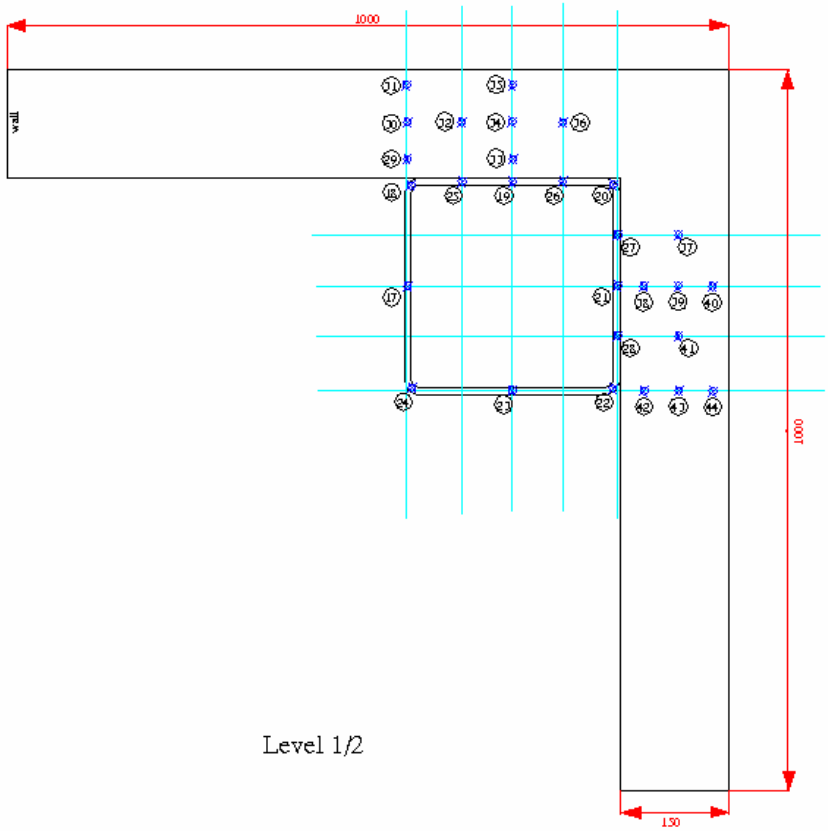

Koepilari 300 & 200/Polttokoe
Valmistetaan 1 kpl

| Osa | Nimike | Laatu | Kpl |
|---|---|---|---|
| 1 | RHS 300 x 300 x 10 | EN 1.4301 | 1 |
| 2 | RHS 200 x 200 x 10 | EN 1.4301 | 1 |
| 3 | Levy 400 x 400 x 30 | EN 1.4301 | 1 |
| 4 | Levy 400 x 400 x 10 | EN 1.4301 | 1 |

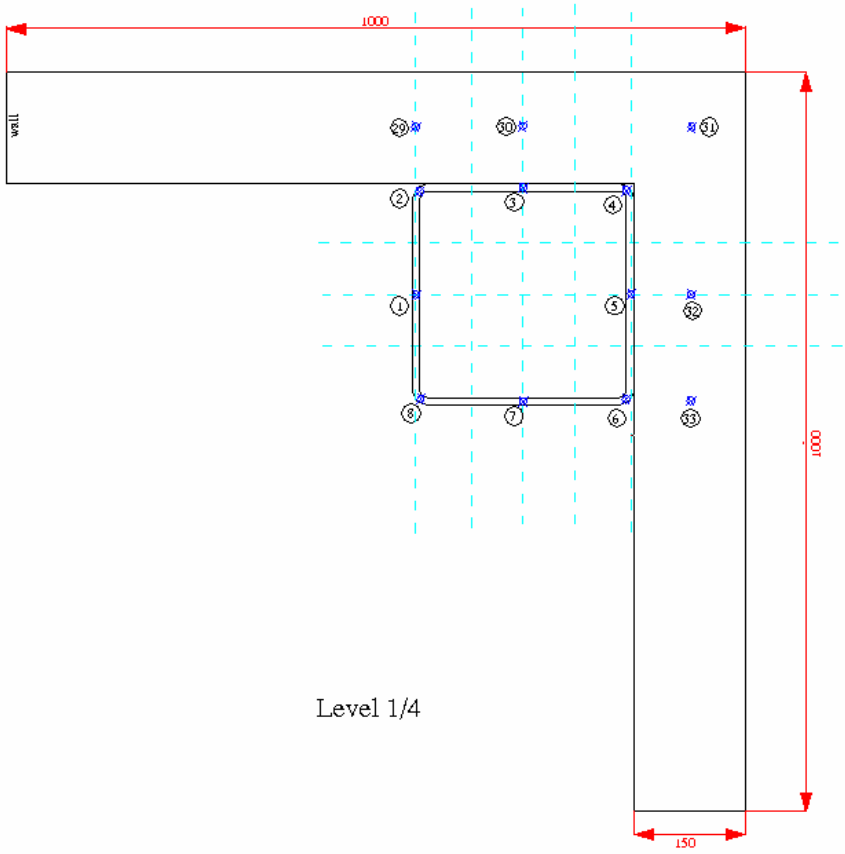
# APPENDIX 5: THE COLUMN IN THE CORNER



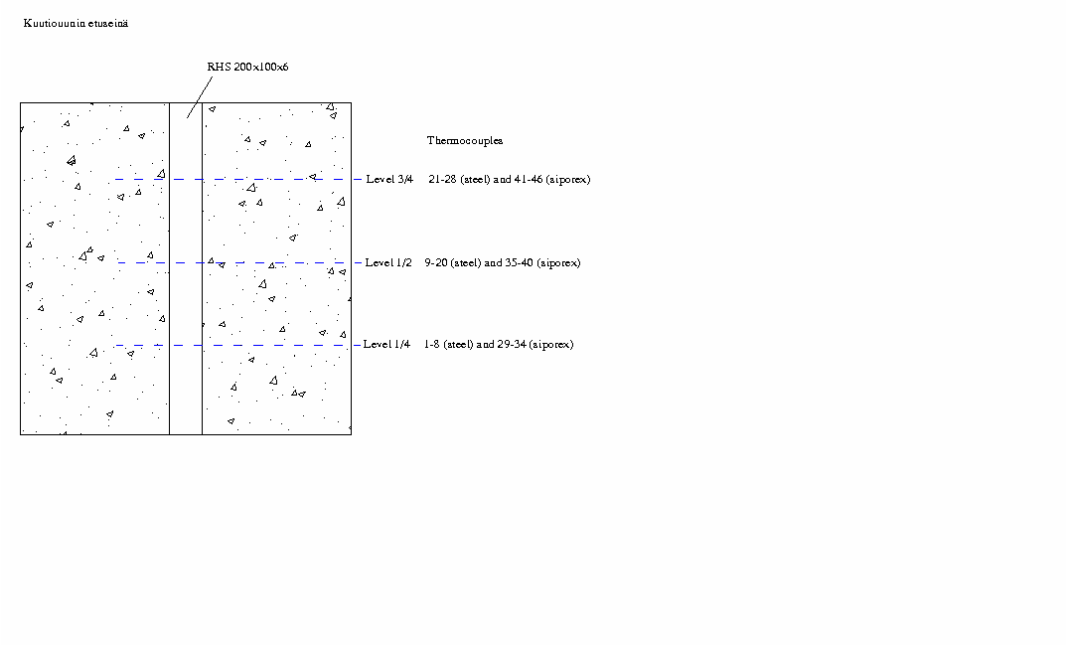


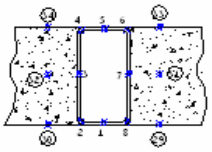

Level 1/2




Level 1/4

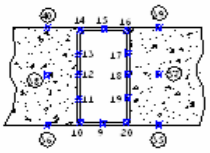
# APPENDIX 6: RHS 200x100x6 COLUMN INSIDE THE WALL



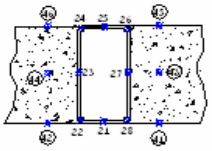
Thermocouples
1-8 (steel)
29-34 (siporex)

Level 1/4



Thermocouples
9-20 (steel)
35-40 (siporex)

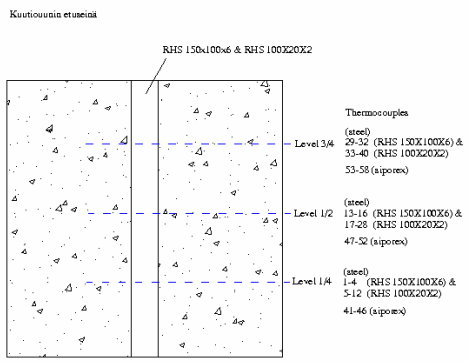
Level 1/2

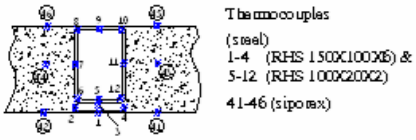


Thermocouples
21-28 (steel)
41-46 (siporex)

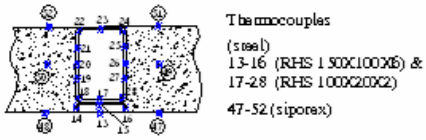
Level 3/4

# APPENDIX 7: RHS 150x100x6 AND RHS 100x20x2 COLUMN INSIDE THE WALL

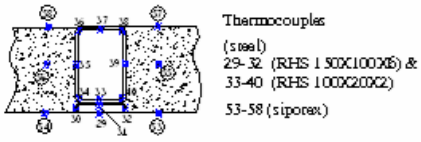



Level 1/4



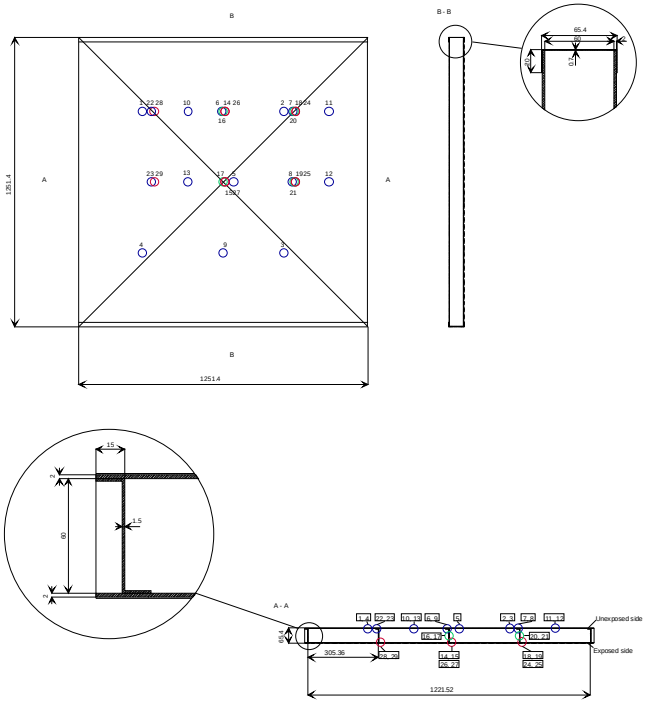

Level 1/2

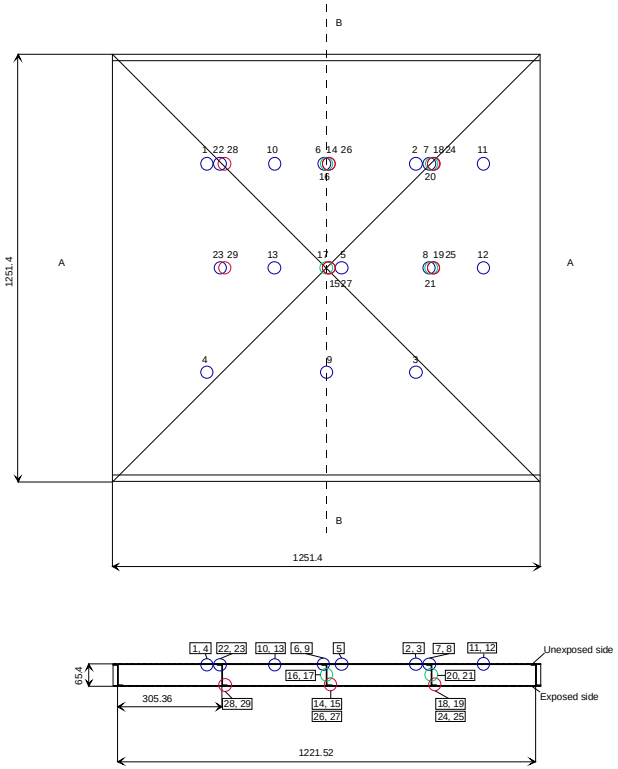



Level 3/4

# APPENDIX 8: THE WALL STRUCTURE, SMALL SCALE TEST. THE LOCATION OF MEASURING POINTS FOR TEMPERATURE

18.8.2005

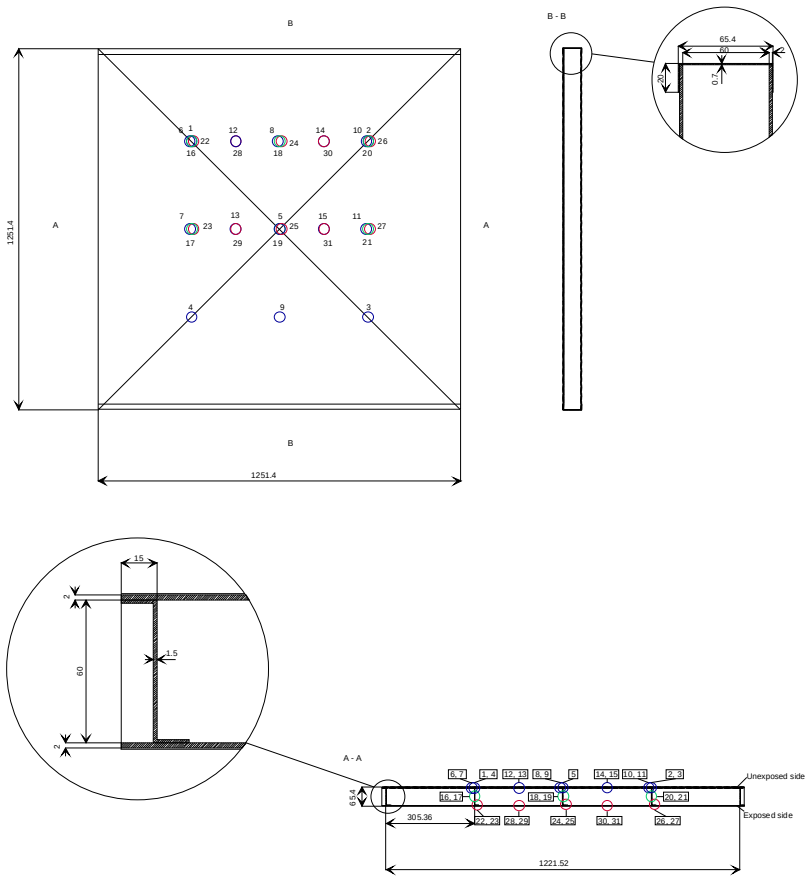


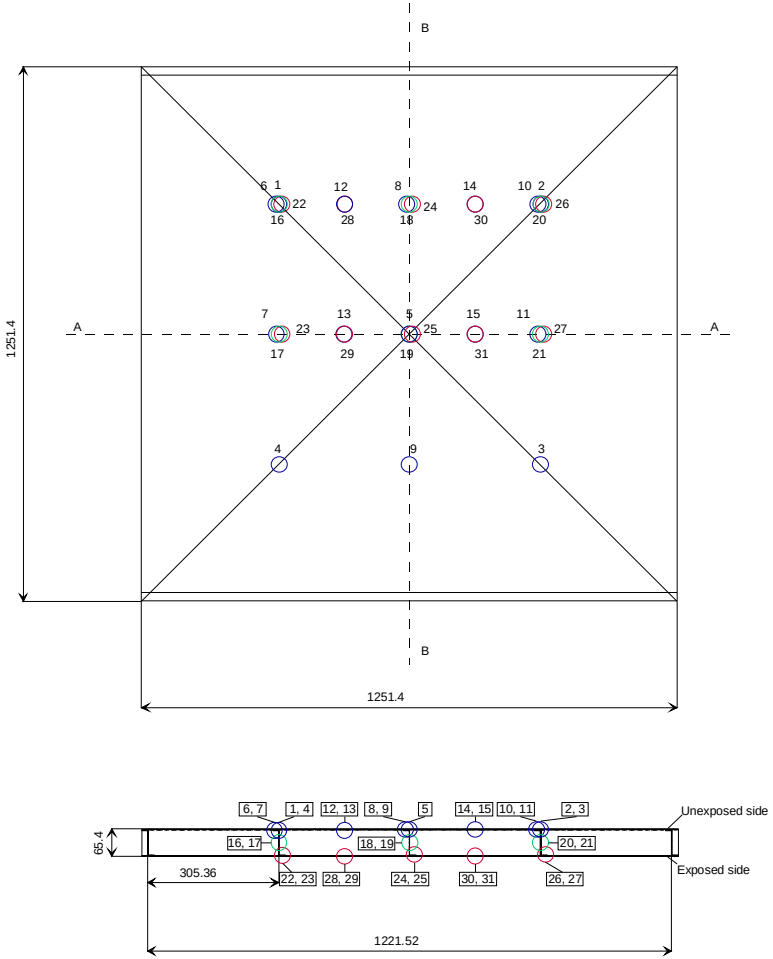




Locations of thermocouples on the specimen:

| | |
|---|---|
| 1 - 5 | on the unexposed surface of the specimen used for the average temperature rise |
| 6 - 9 | on the welded seams on the unexposed surface |
| 10 - 13 | between welded seams on the unexposed surface |
| 14 - 15 | at the flange of the profile |
| 16 - 17 | at the middle height of the web profile |
| 18 - 19 | at the flange of the profile |
| 20 - 21 | at the middle height of the web profile |
| 22 - 23 | on the welded seam on the unexposed surface |
| 24 - 29 | on the welded seam on the exposed surface |

13.10.2005

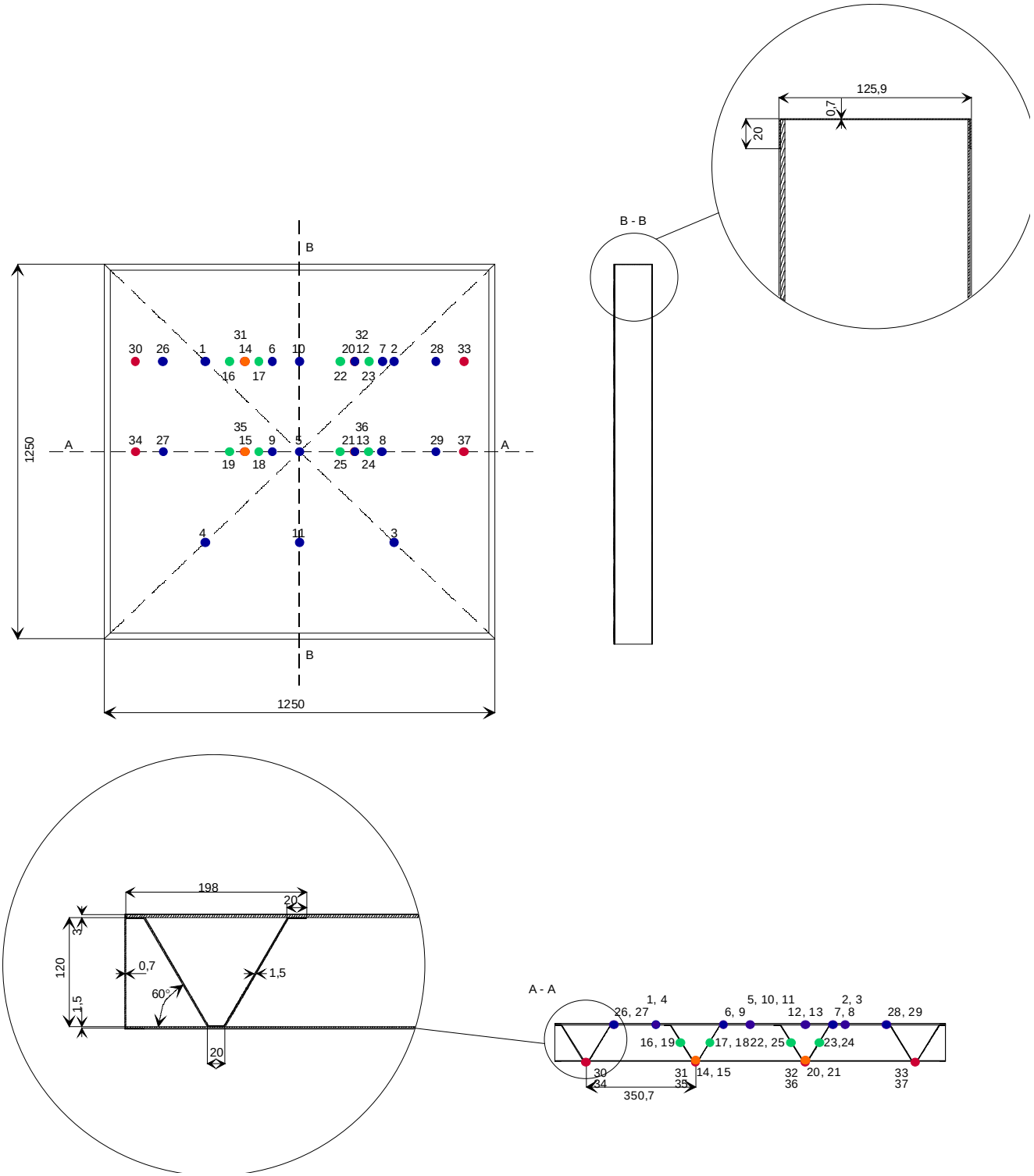


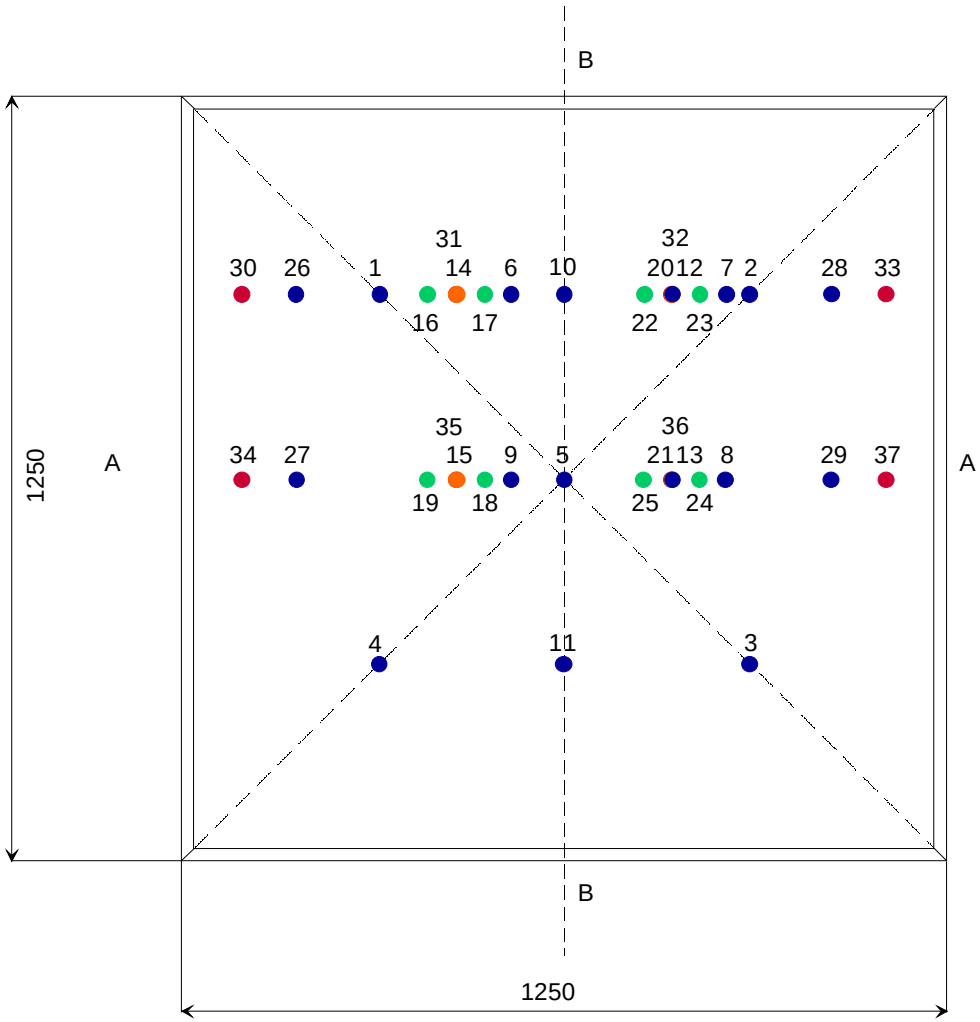



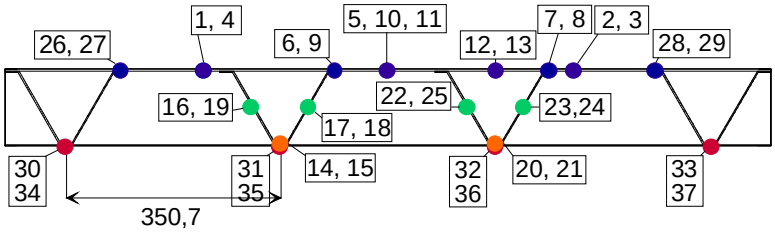

Location of thermocouples on the specimen:

| | |
|---|---|
| 1 - 5 | on the unexposed surface of the specimen used for the average temperature rise |
| 6 - 11 | on the welded seams on the unexposed surface |
| 12 - 15 | between welded seams on the unexposed surface |
| 16 - 21 | at the middle height of the web profile |
| 22 - 27 | on the welded seam on the exposed surface |
| 28 - 31 | between welded seams on the exposed surface |

# APPENDIX 9: THE FLOOR STRUCTURE, SMALL SCALE TEST. THE LOCATION OF MEASURING POINTS FOR TEMPERATURE



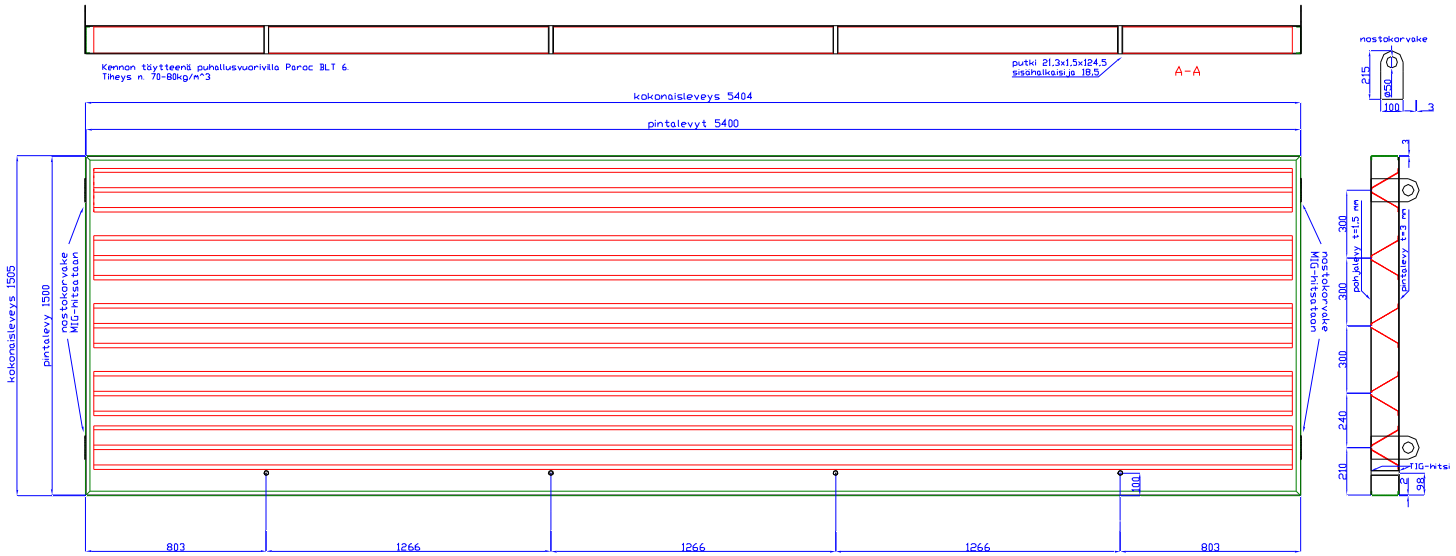


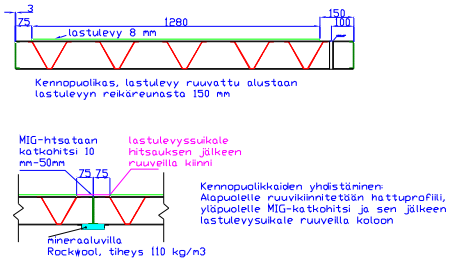




Thermocouples:

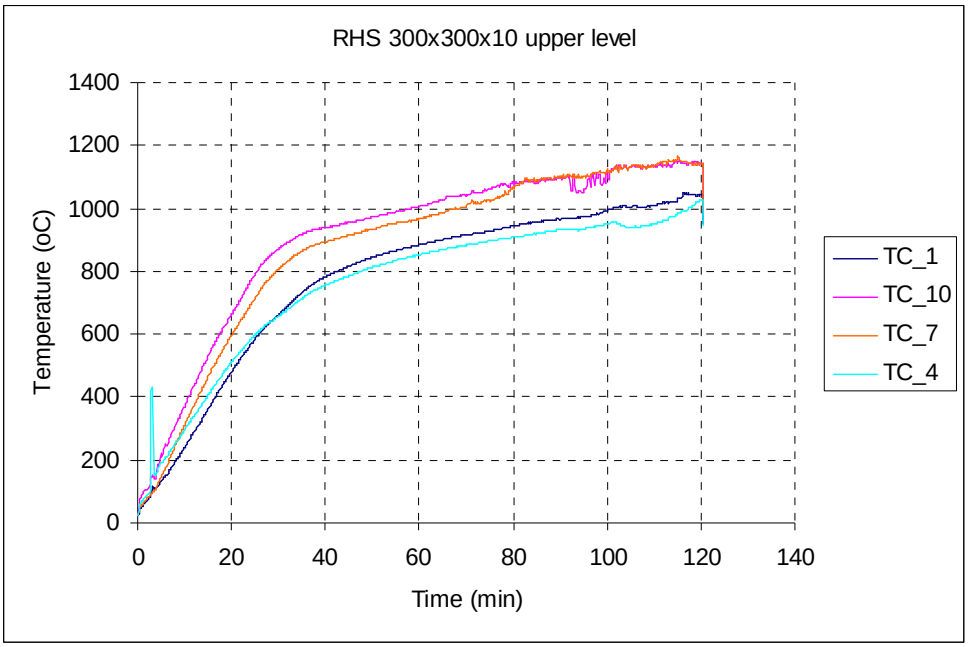
| | |
|---|---|
| 1 - 5 | standard top surface thermocouples |
| 6 - 9 | top surface at weld |
| 10 - 11 | top surface midway between webs (wide gap) |
| 12 - 13 | top surface midway between webs (narrow gap) |
| 14 - 15 | bottom flange of V-profile |
| 16 - 19 | web of V-profile |
| 20 - 21 | bottom flange of V-profile |
| 22 - 29 | top surface at welds |
| 30 - 37 | bottom surface |

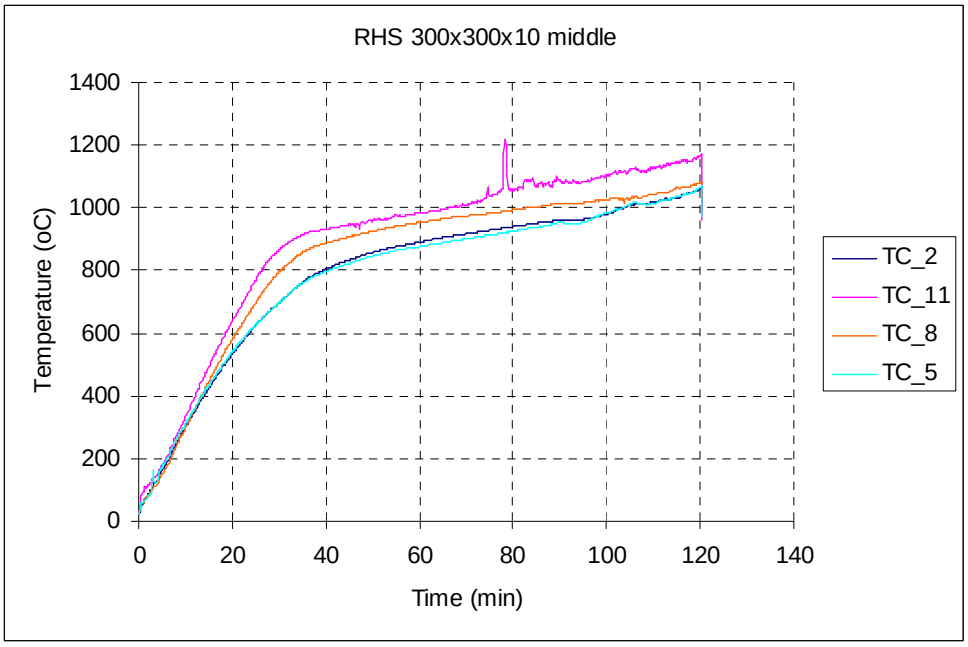
# APPENDIX 10: THE FLOOR STRUCTURE, LARGE SCALE TEST

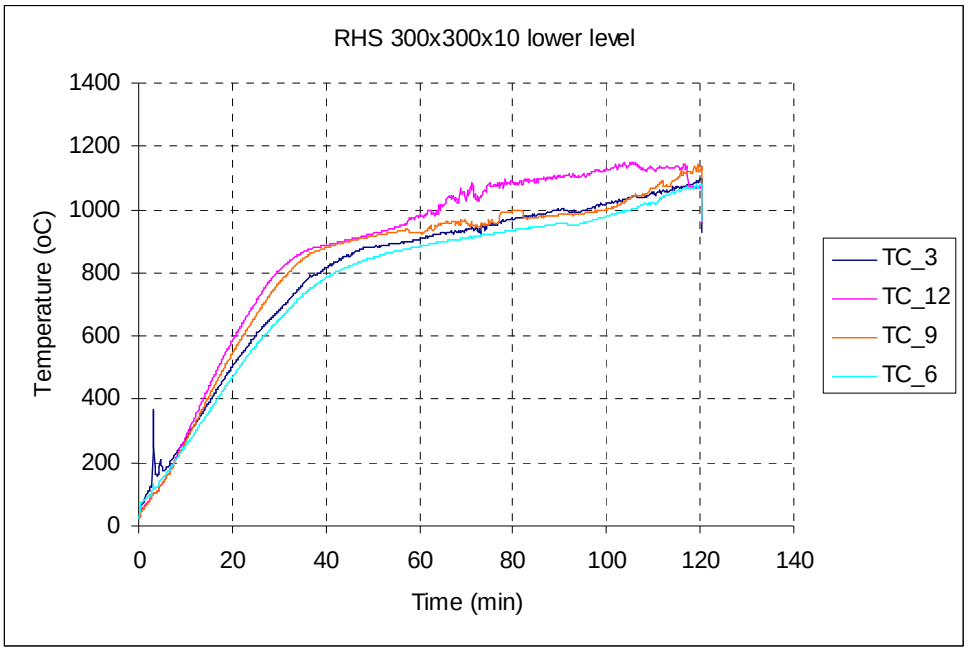


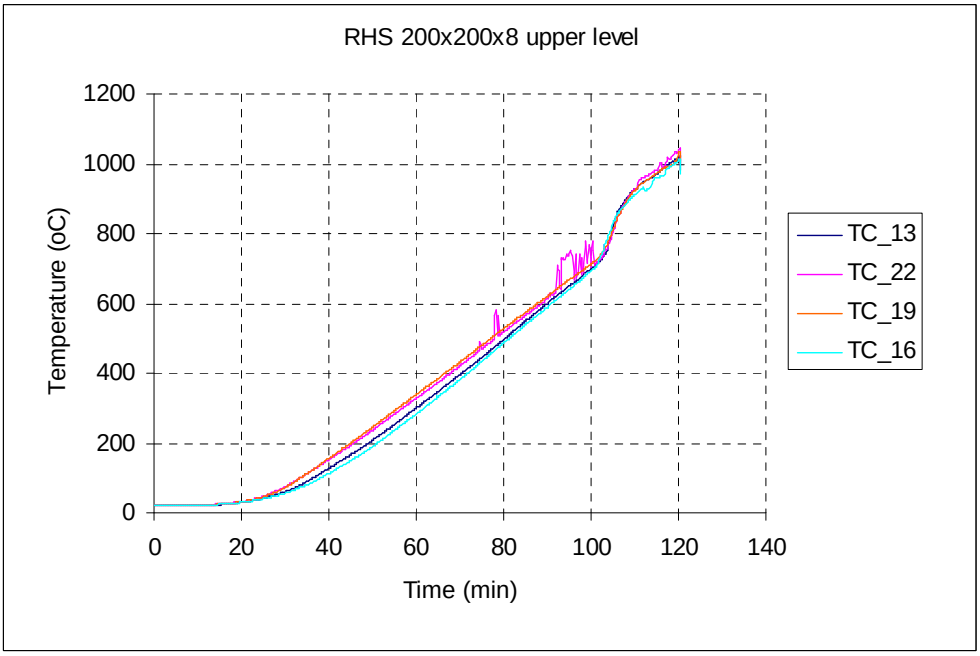



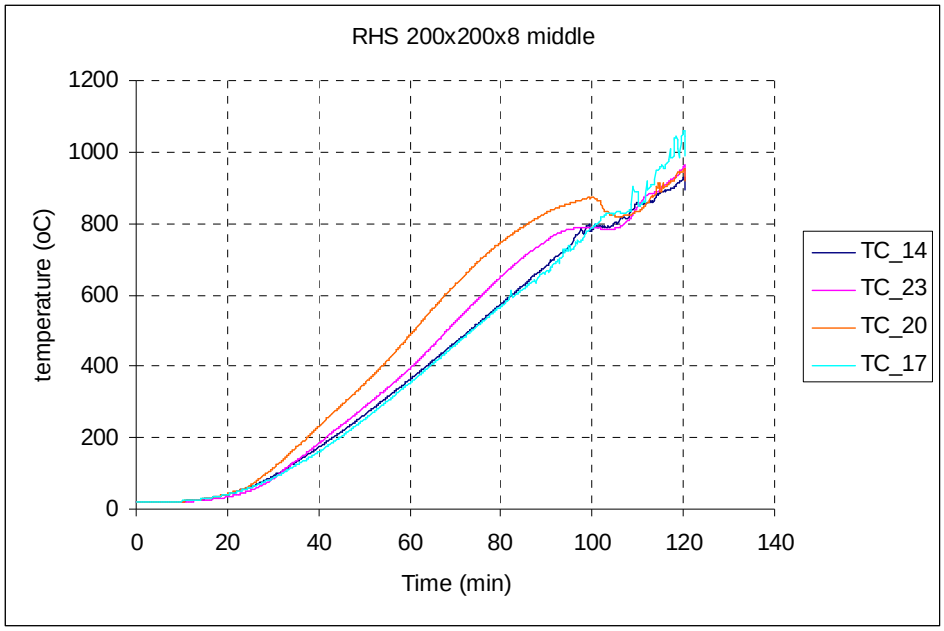
# APPENDIX 11: MEASURED TEMPERATURES OF THE COLUMN WITH NESTED TUBES

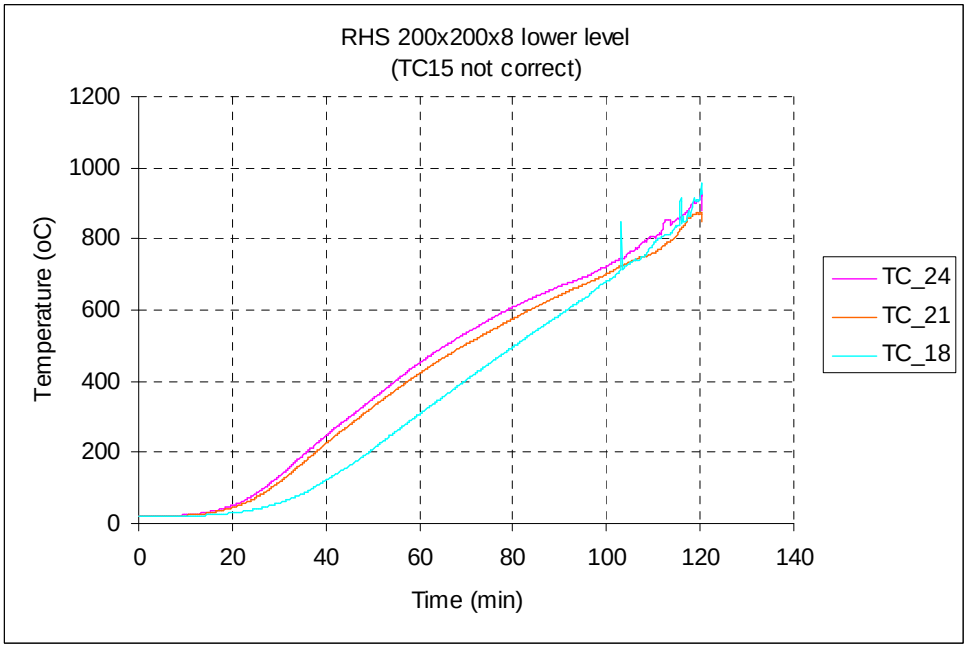


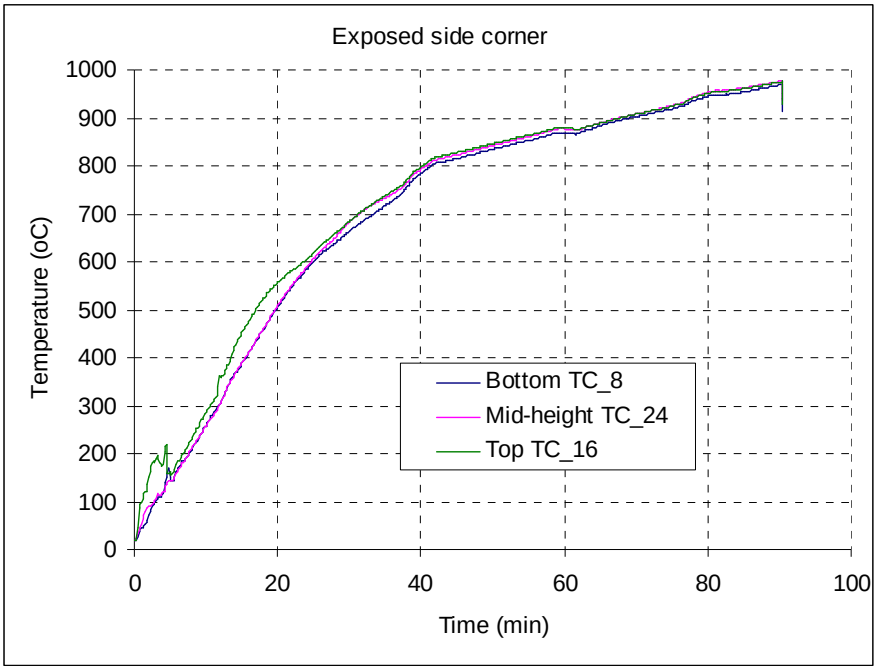

RHS 300x300x10 lower level
Temperature (oC)
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
Time (min)
TC_3
TC_12
TC_9
TC_6

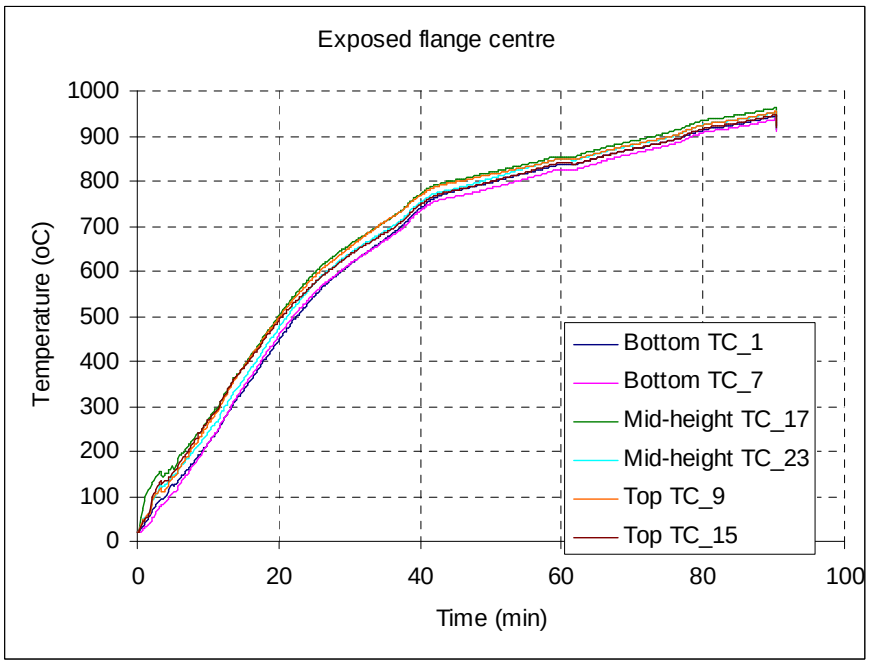

RHS 200x200x8 upper level
Temperature (oC)
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
Time (min)
TC_13
TC_22
TC_19
TC_16

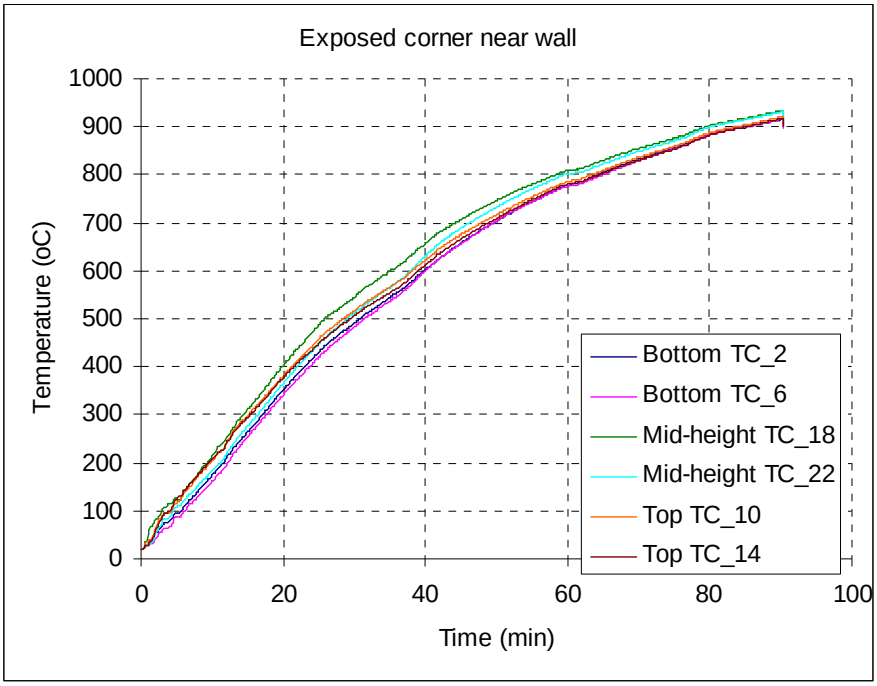

RHS 200x200x8 middle
temperature (oC)
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
Time (min)
TC_14
TC_23
TC_20
TC_17

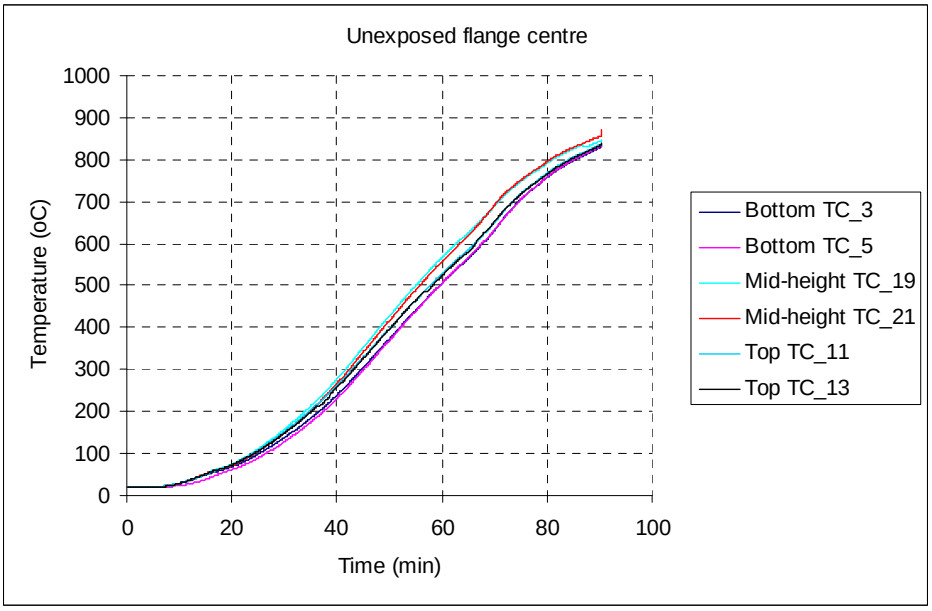

RHS 200x200x8 lower level
(TC15 not correct)
Temperature (oC)
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
Time (min)
TC_24
TC_21
TC_18

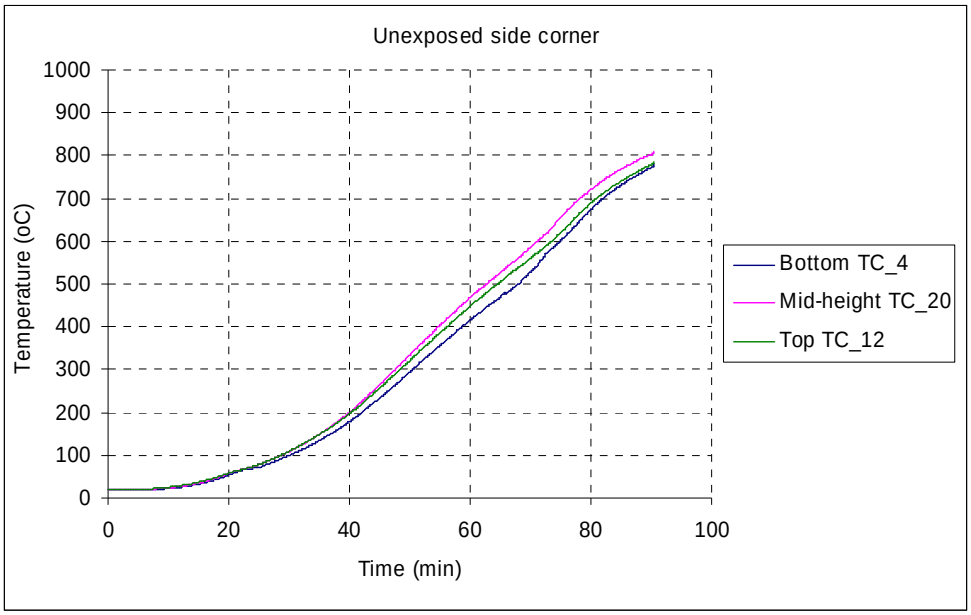
# APPENDIX 12: MEASURED TEMPERATURES OF THE COLUMN IN THE CORNER

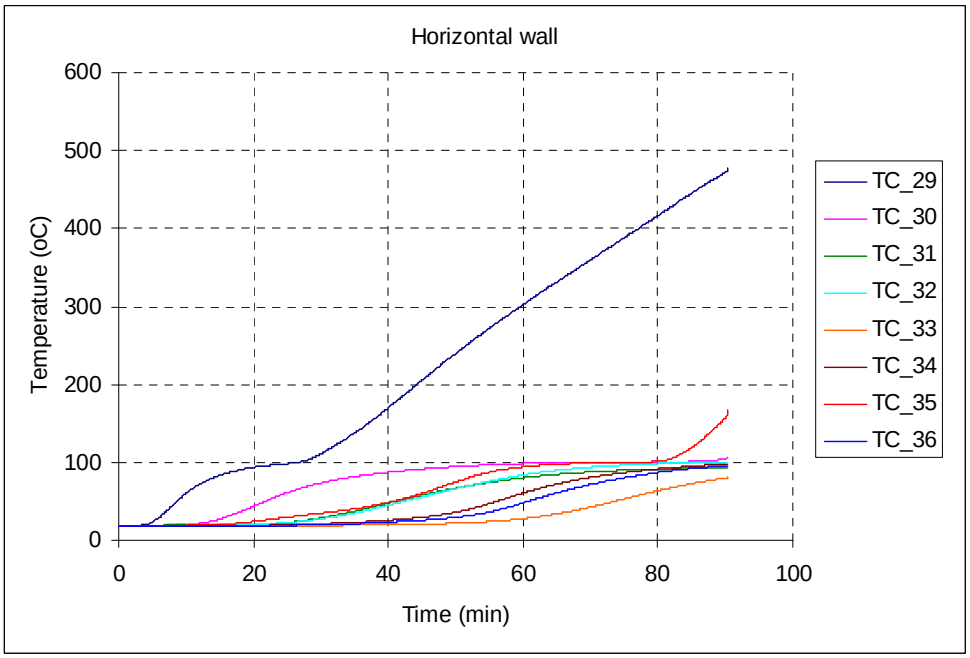


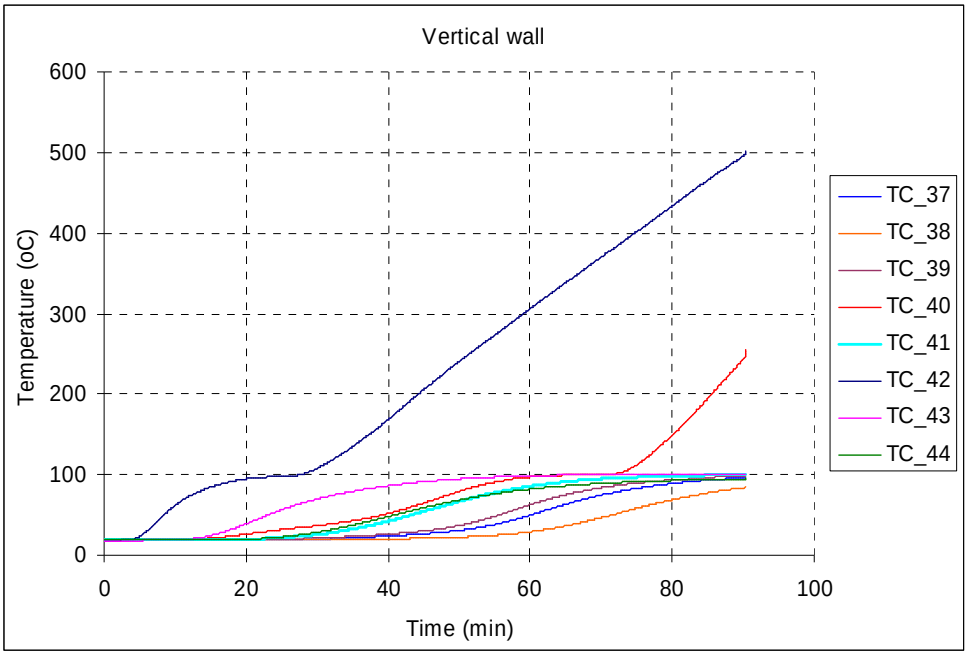




Exposed corner near wall
Temperature (oC)
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Time (min)
Bottom TC_2
Bottom TC_6
Mid-height TC_18
Mid-height TC_22
Top TC_10
Top TC_14

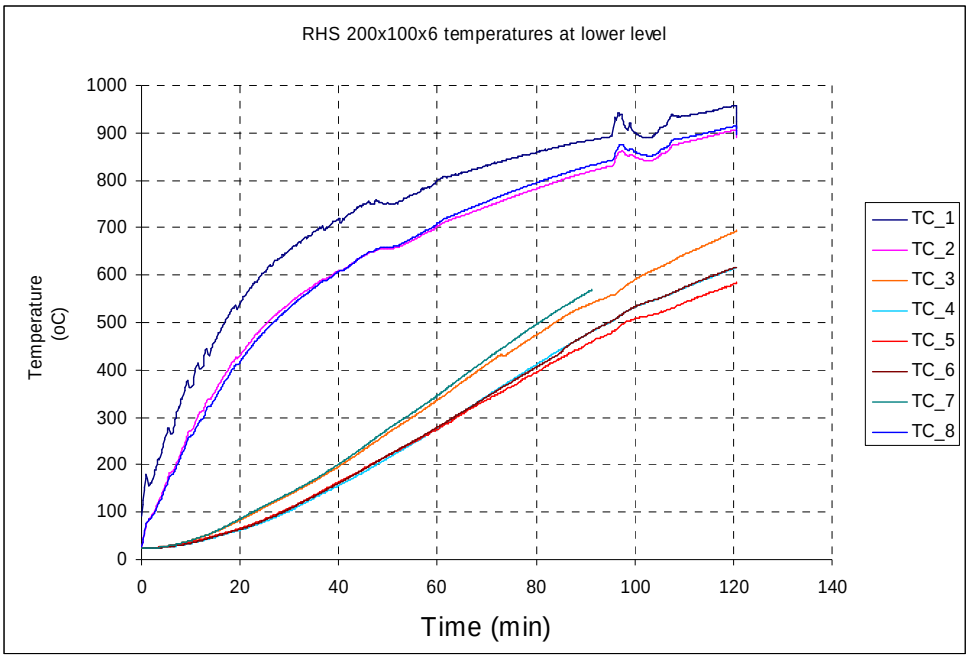

Unexposed flange centre
Temperature (oC)
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Time (min)
Bottom TC_3
Bottom TC_5
Mid-height TC_19
Mid-height TC_21
Top TC_11
Top TC_13

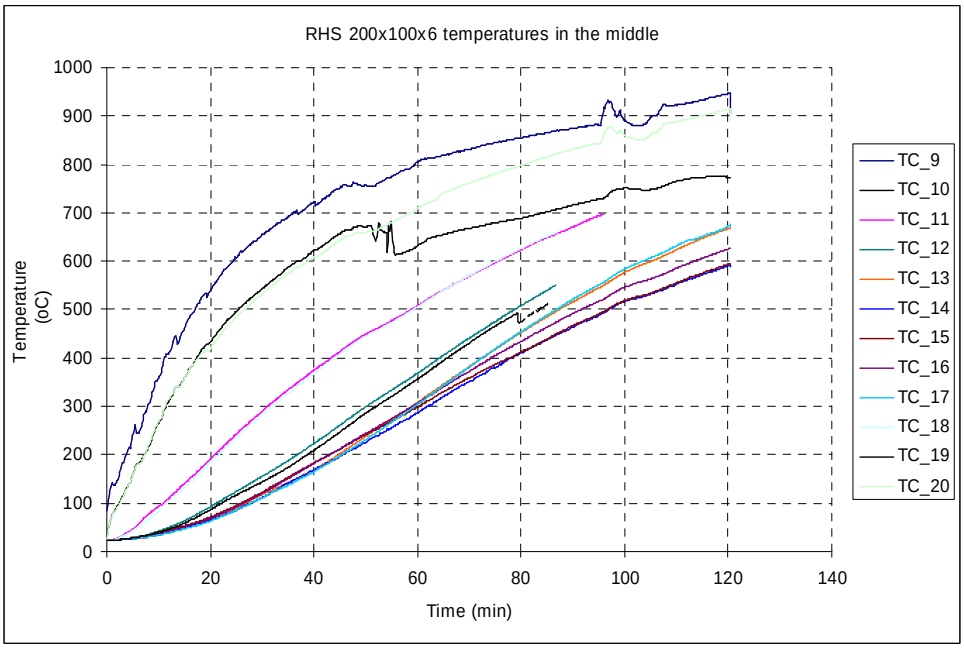

Unexposed side corner
Temperature (oC)
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Time (min)
Bottom TC_4
Mid-height TC_20
Top TC_12

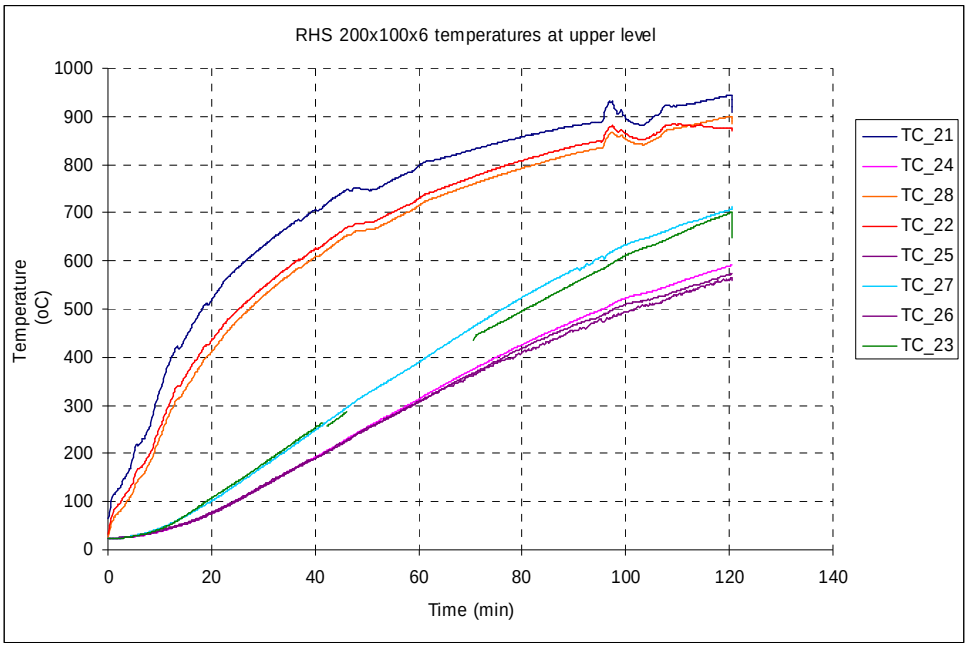

Horizontal wall
Temperature (oC)
600
500
400
300
200
100
0
0
20
40
60
80
100
Time (min)
TC_29
TC_30
TC_31
TC_32
TC_33
TC_34
TC_35
TC_36


Vertical wall
Temperature (oC)
600
500
400
300
200
100
0
0
20
40
60
80
100
Time (min)
TC_37
TC_38
TC_39
TC_40
TC_41
TC_42
TC_43
TC_44

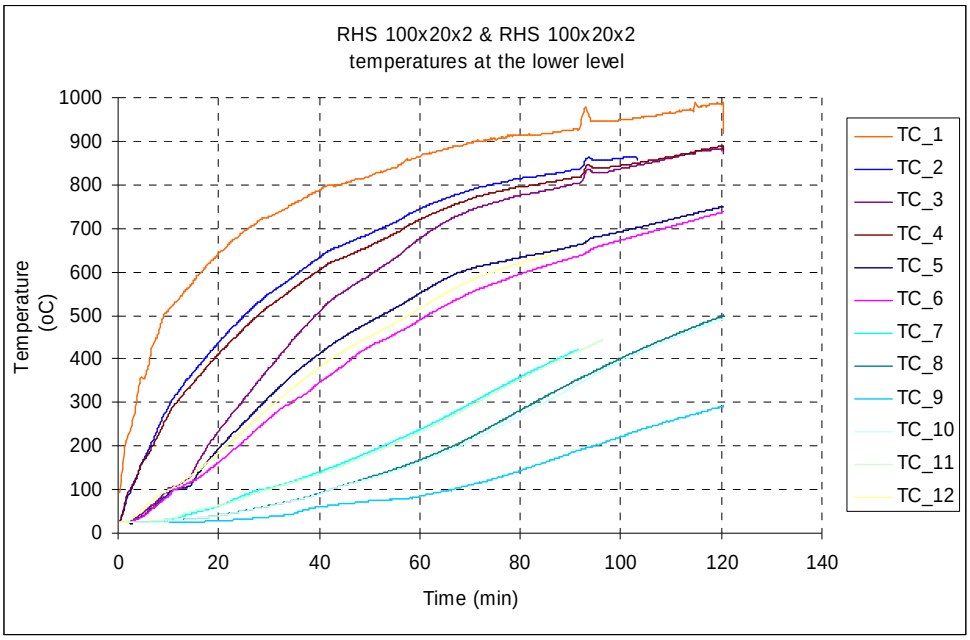
# APPENDIX 13: MEASURED TEMPERATURES OF THE COLUMN RHS 200X100X6 INSIDE THE WALL

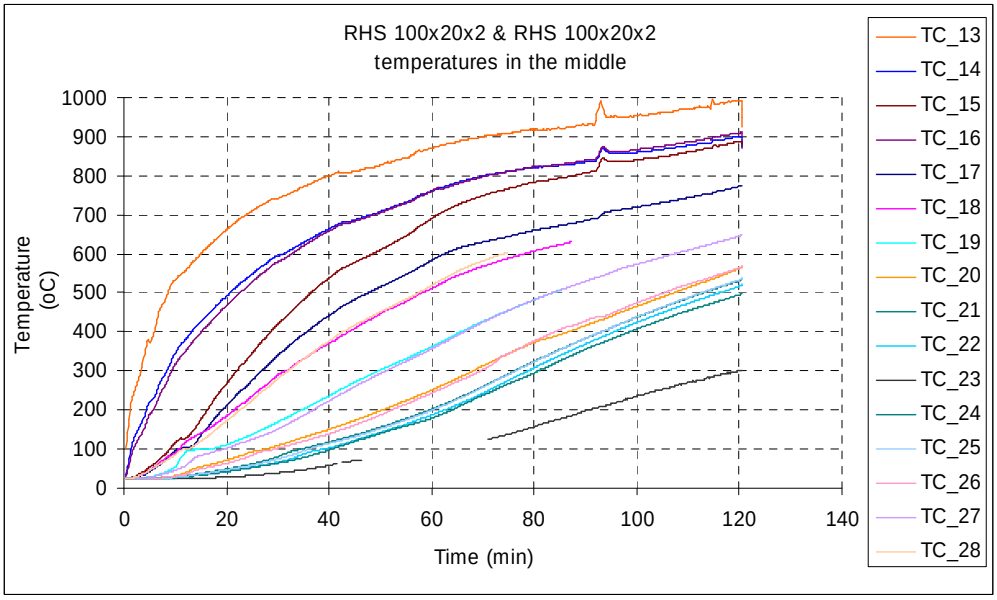


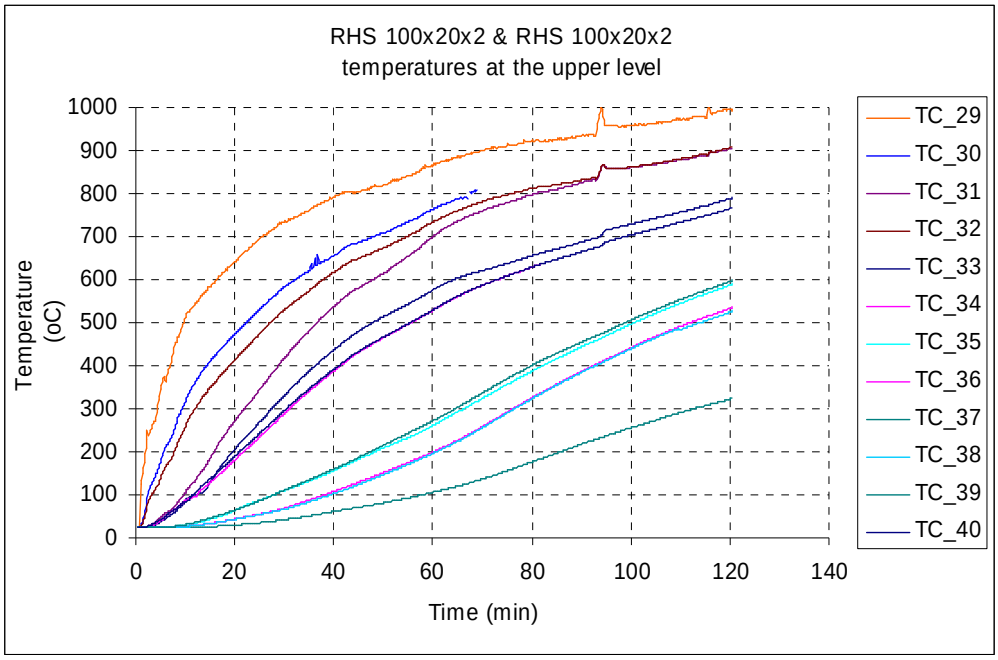




RHS 200x100x6 temperatures at upper level
Temperature (oC)
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
Time (min)
TC_21
TC_24
TC_28
TC_22
TC_25
TC_27
TC_26
TC_23

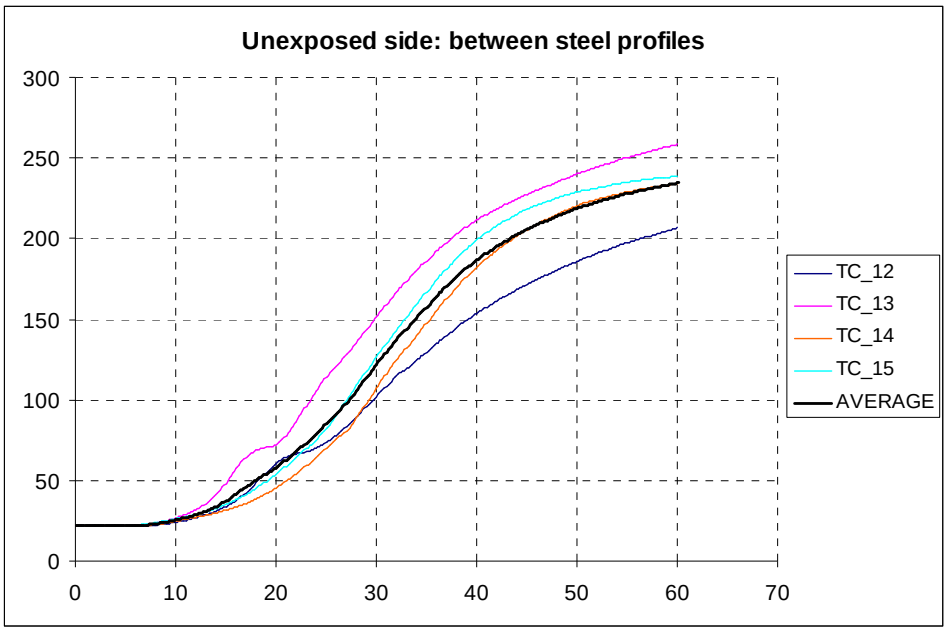
# APPENDIX 14 : MEASURED TEMPERATURES OF THE COLUMN RHS 150x100x6 & RHS 100x20x2 INSIDE THE WALL

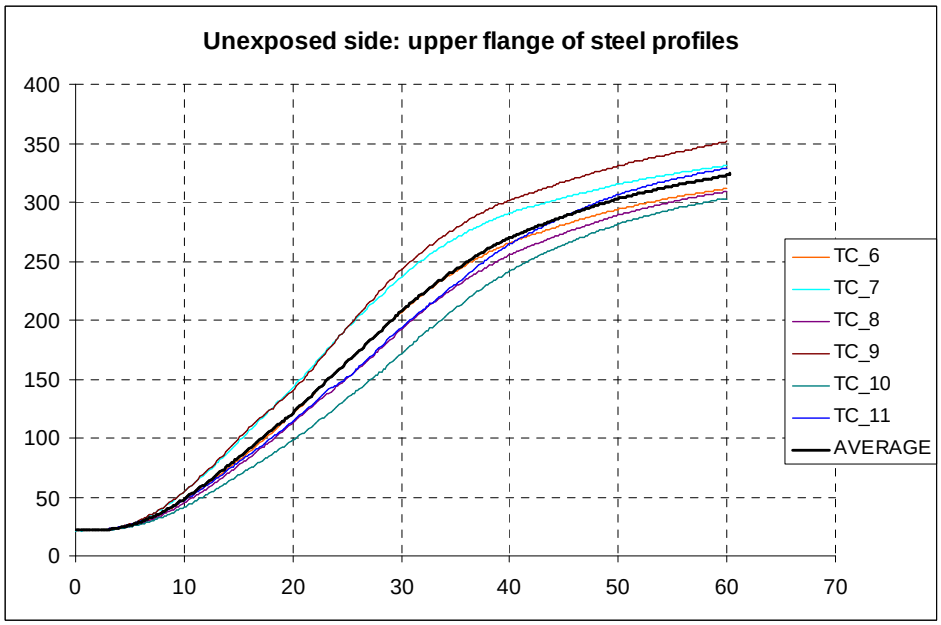


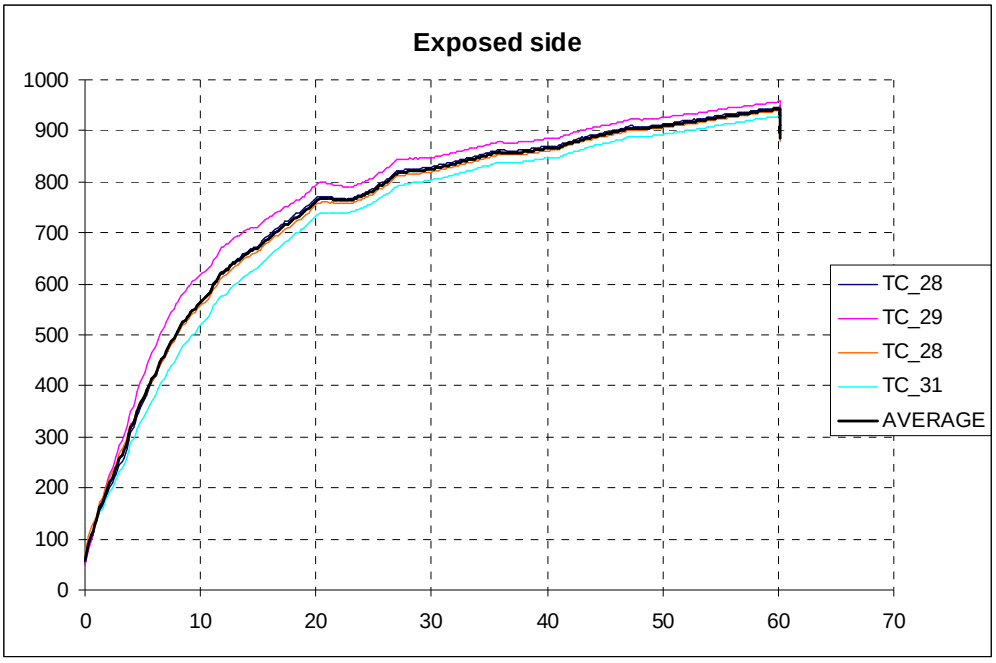



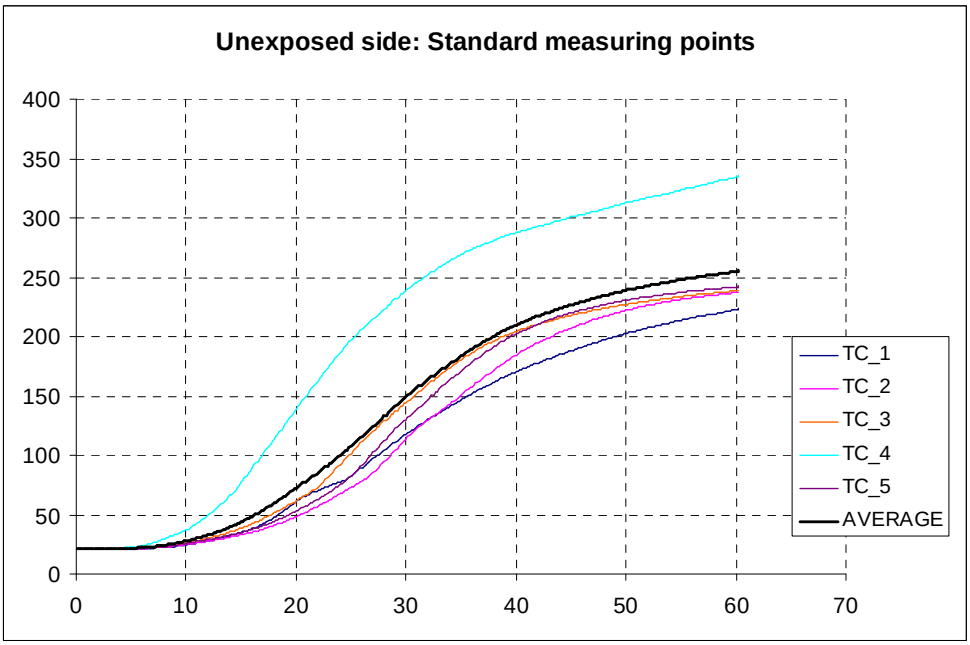

RHS 100x20x2 & RHS 100x20x2
temperatures at the upper level
Temperature (oC)
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
Time (min)
TC_29
TC_30
TC_31
TC_32
TC_33
TC_34
TC_35
TC_36
TC_37
TC_38
TC_39
TC_40

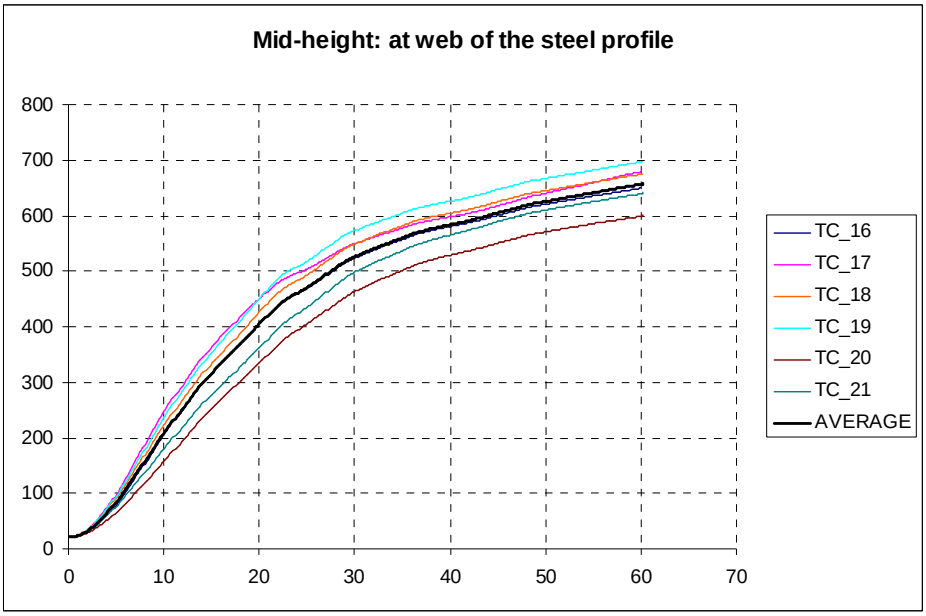
# APPENDIX 15: MEASURED TEMPERATURES OF THE WALL STRUCTURE, TEST DATE 18.8.2005

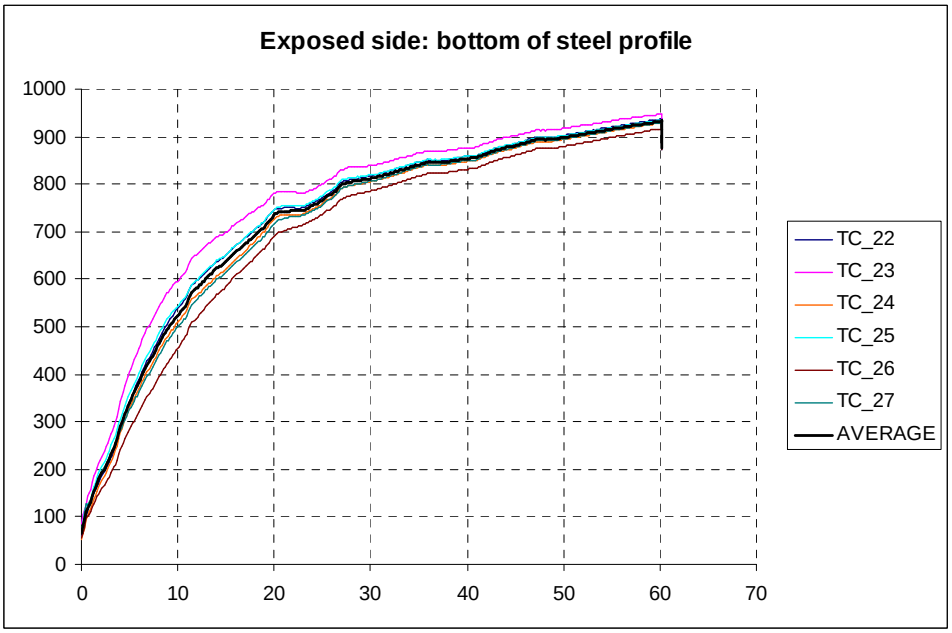


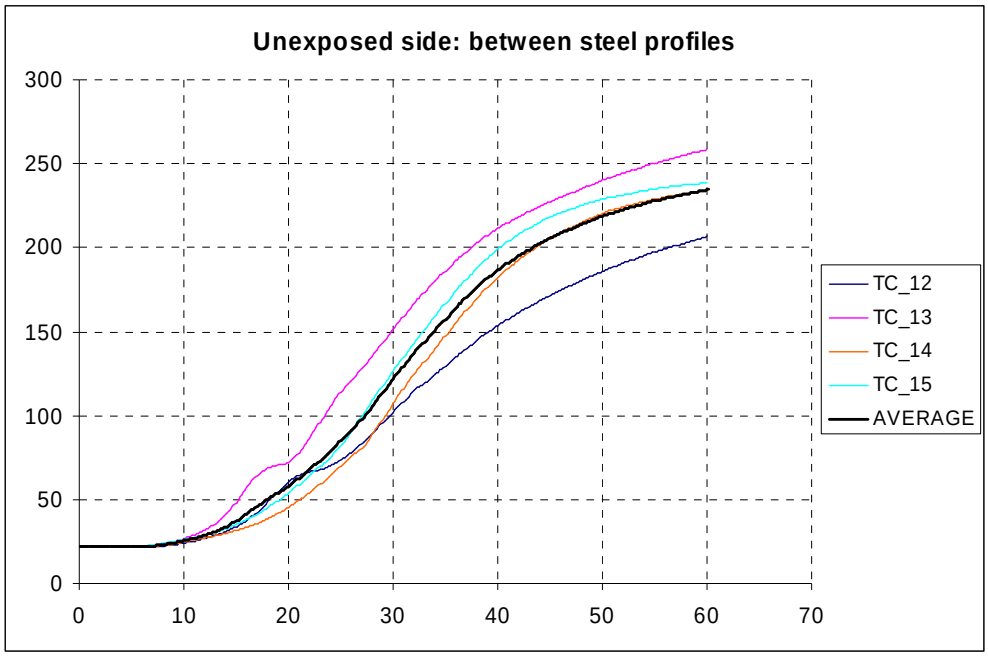

Exposed side
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
TC_28
TC_29
TC_28
TC_31
AVERAGE

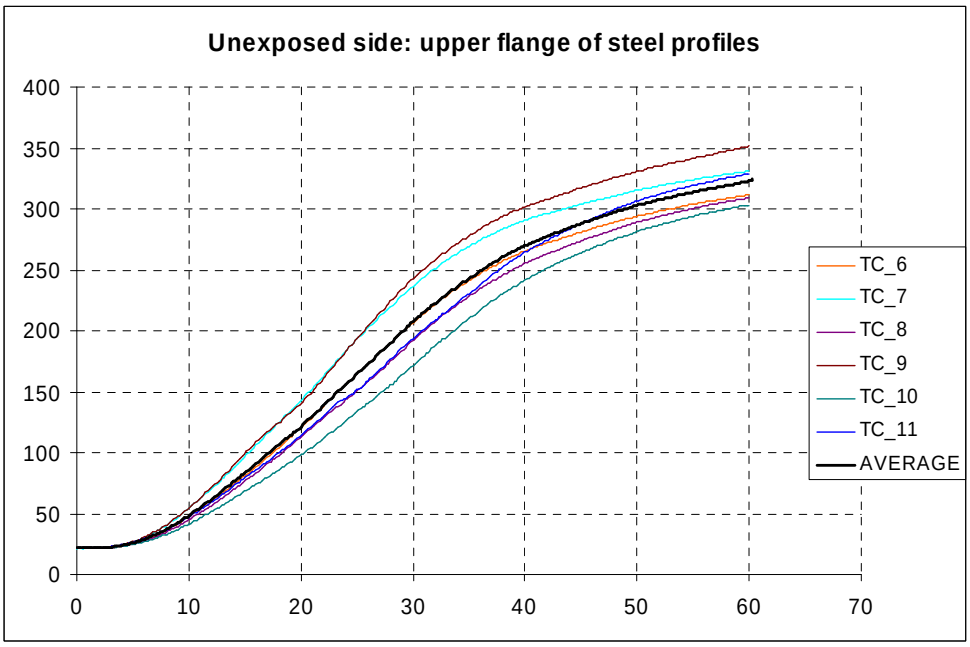

Unexposed side: Standard measuring points
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
TC_1
TC_2
TC_3
TC_4
TC_5
AVERAGE

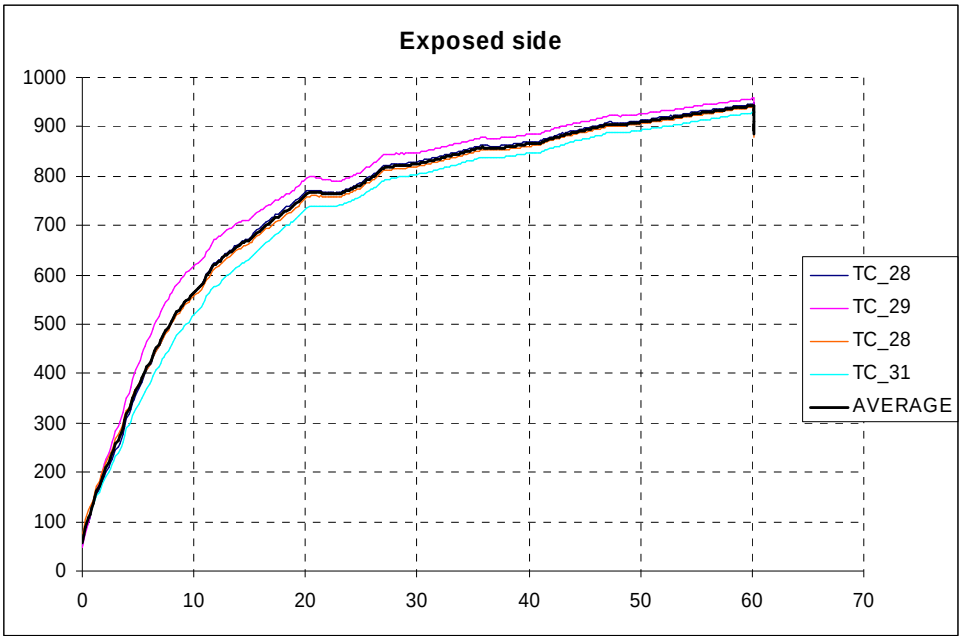

Mid-height: at web of the steel profile
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
TC_16
TC_17
TC_18
TC_19
TC_20
TC_21
AVERAGE

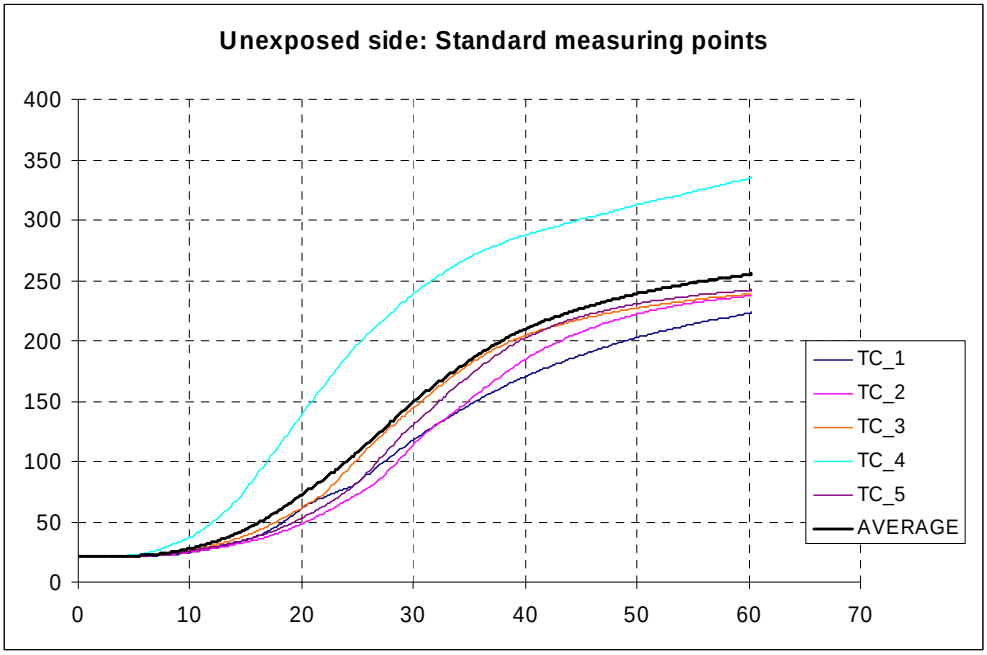

Exposed side: bottom of steel profile
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
TC_22
TC_23
TC_24
TC_25
TC_26
TC_27
AVERAGE

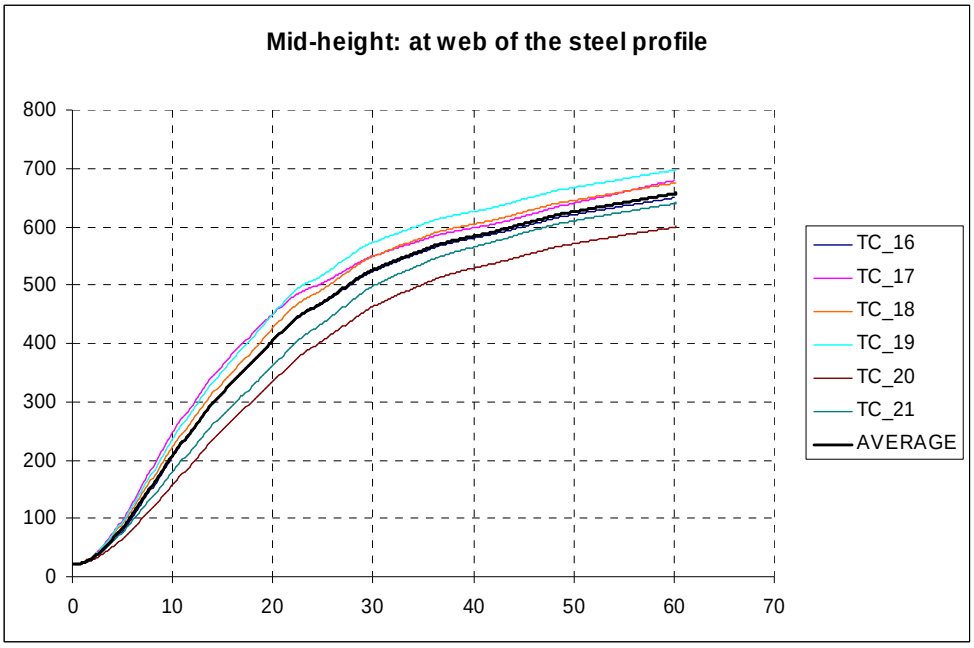
# APPENDIX 16: MEASURED TEMPERATURES OF THE WALL STRUCTURE, TEST DATE 13.10.2005

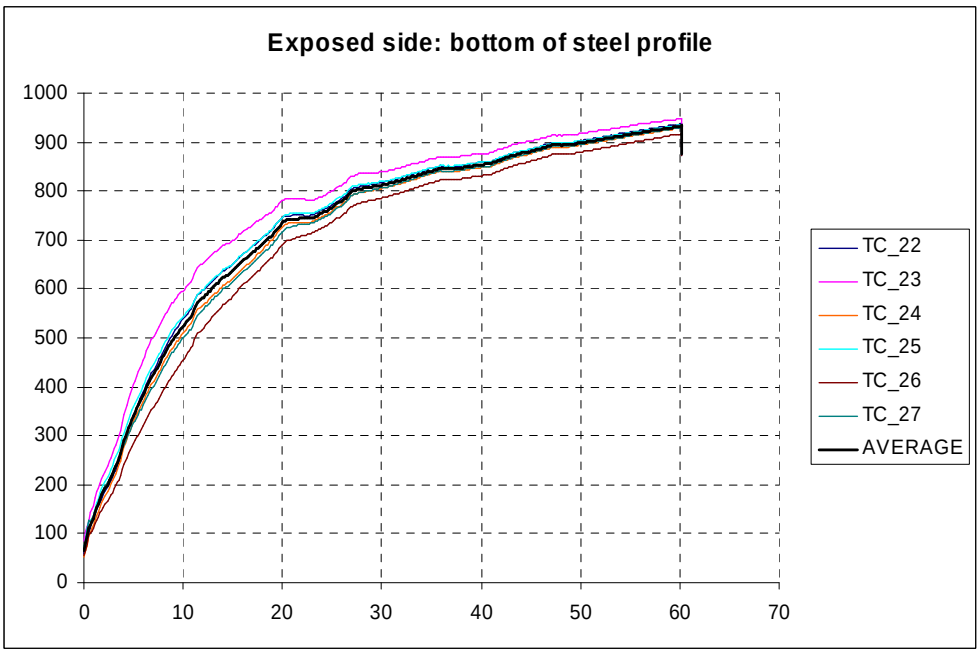


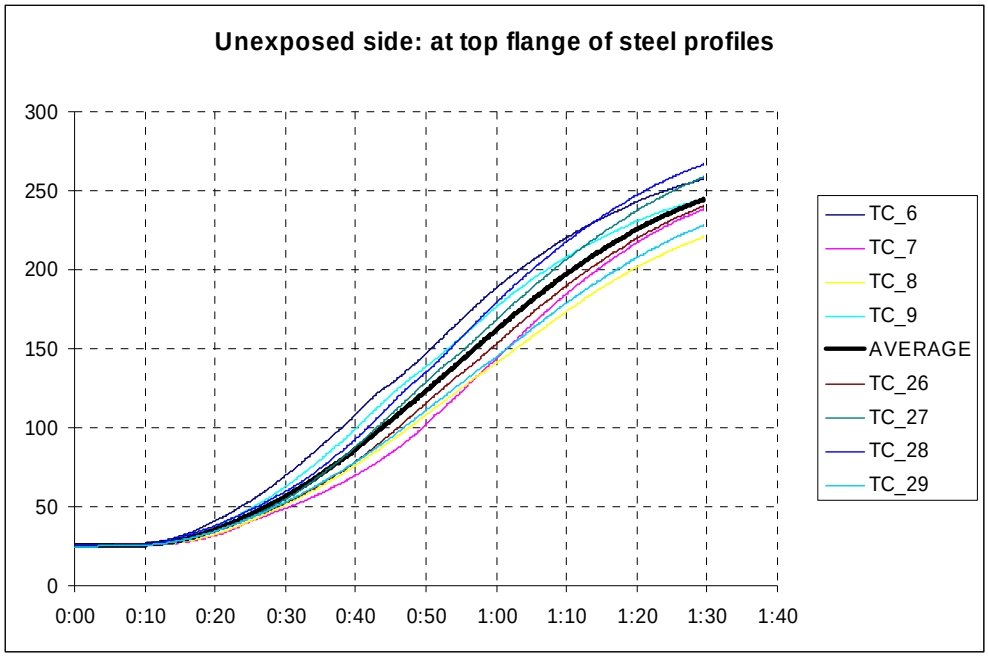

Exposed side
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
TC_28
TC_29
TC_28
TC_31
AVERAGE

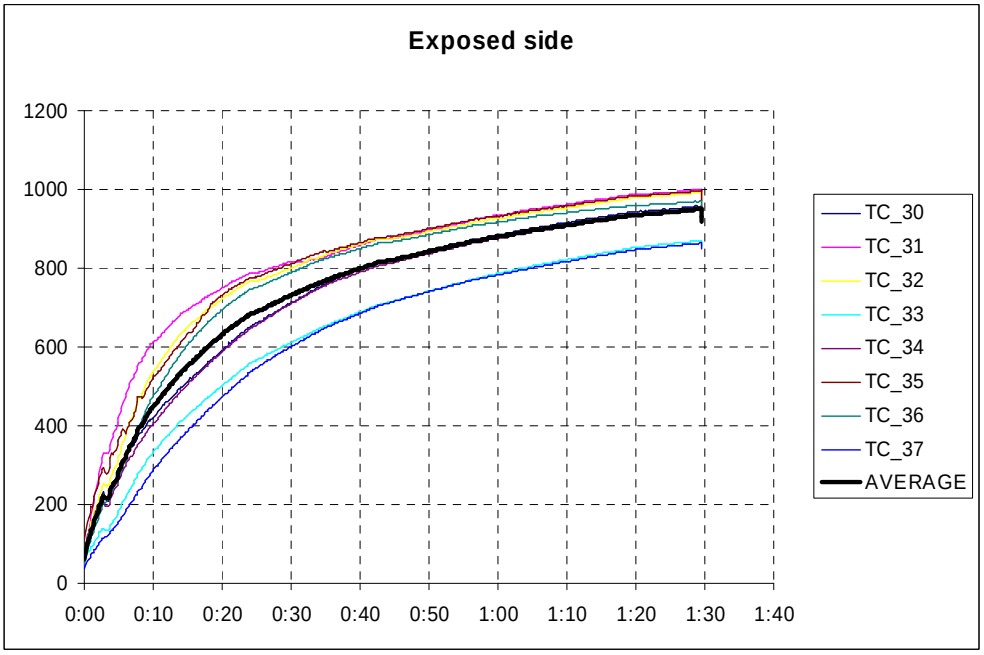

Unexposed side: Standard measuring points
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
TC_1
TC_2
TC_3
TC_4
TC_5
AVERAGE

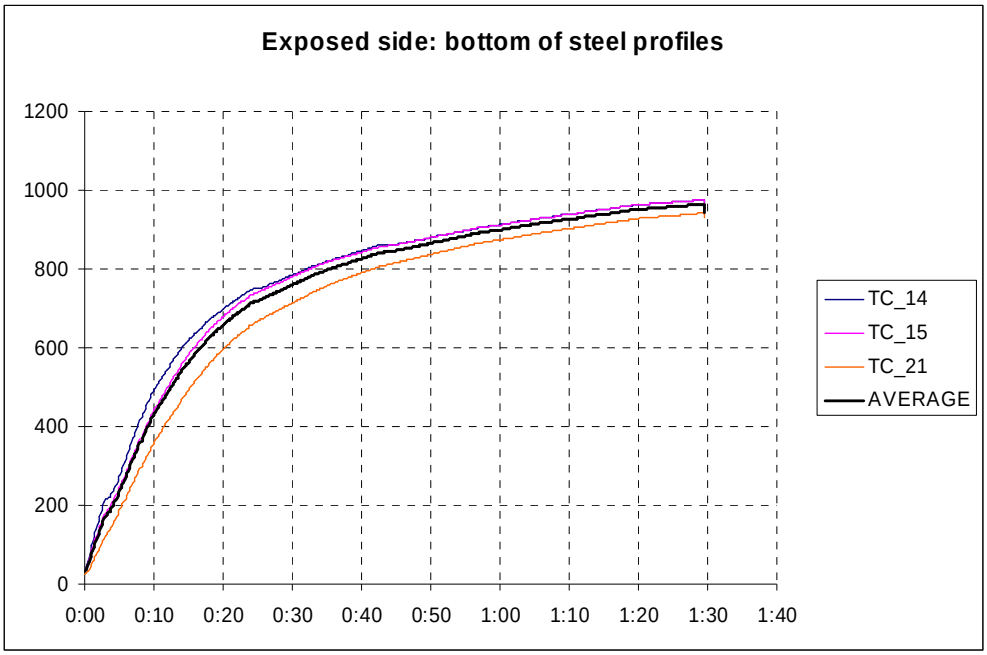

Mid-height: at web of the steel profile
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
TC_16
TC_17
TC_18
TC_19
TC_20
TC_21
AVERAGE

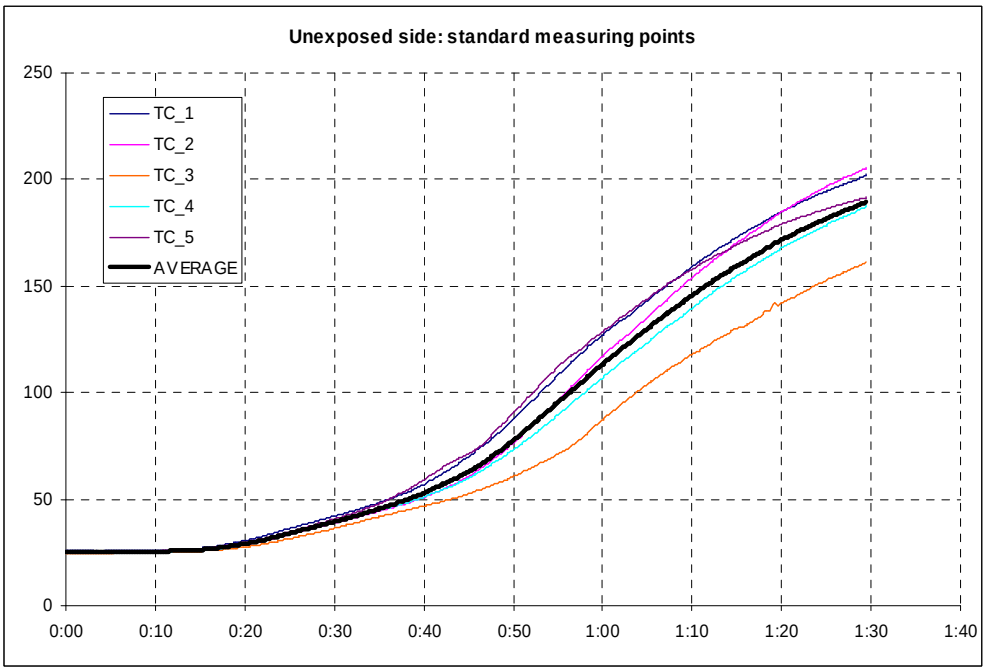

Exposed side: bottom of steel profile
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
TC_22
TC_23
TC_24
TC_25
TC_26
TC_27
AVERAGE

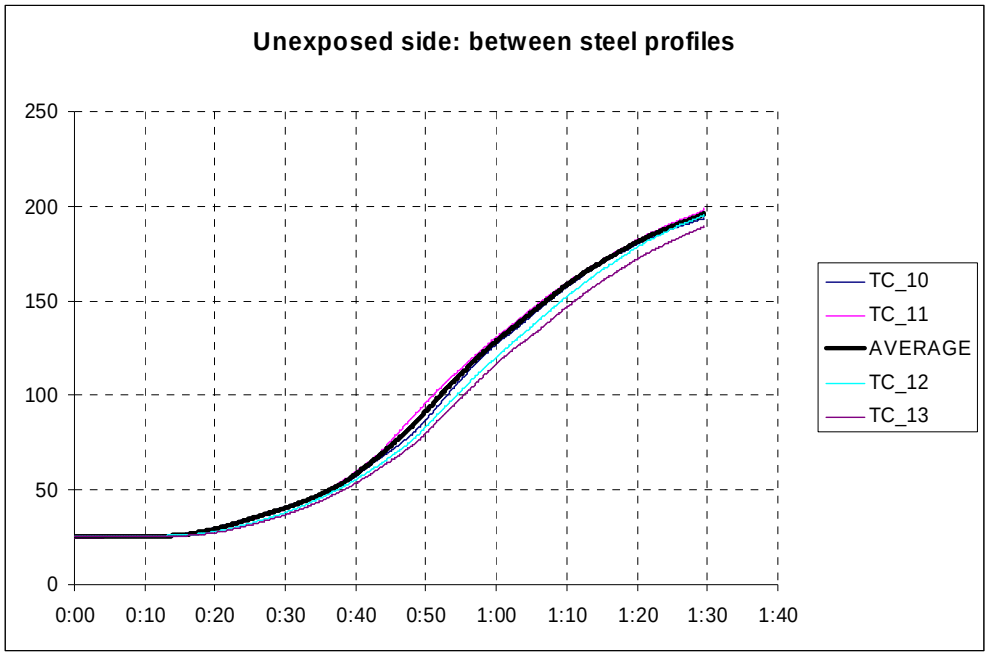
# APPENDIX 17: MEASURED TEMPERATURES OF THE FLOOR STRUCTURE, TEST DATE 7.9.2005

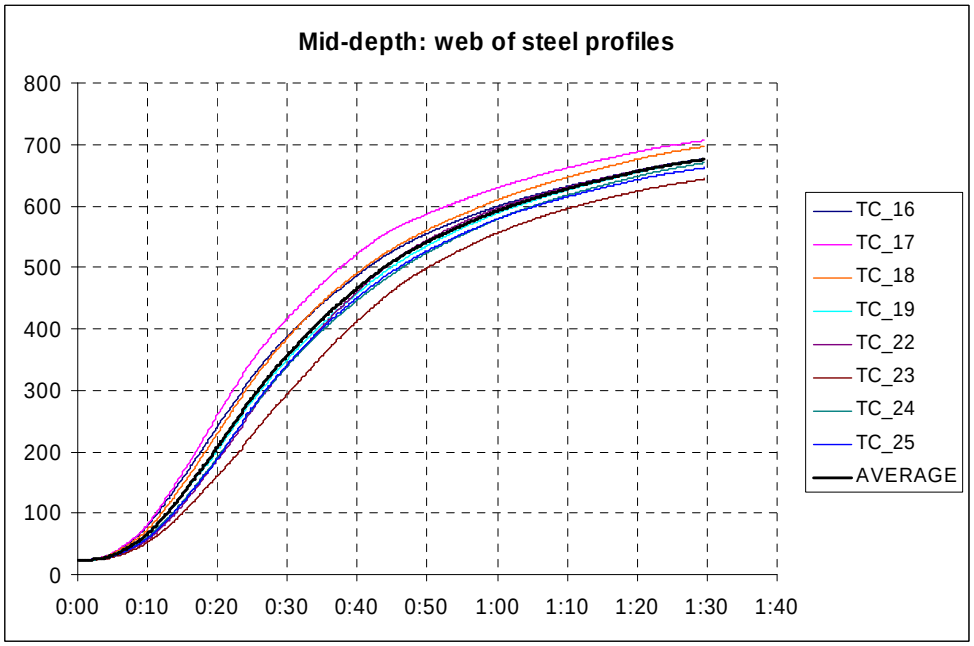



Exposed side: bottom of steel profiles
1200
1000
800
600
400
200
0
0:00
0:10
0:20
0:30
0:40
0:50
1:00
1:10
1:20
1:30
1:40
TC_14
TC_15
TC_21
AVERAGE


Unexposed side: standard measuring points
250
200
150
100
50
0
0:00
0:10
0:20
0:30
0:40
0:50
1:00
1:10
1:20
1:30
1:40
TC_1
TC_2
TC_3
TC_4
TC_5
AVERAGE


Unexposed side: between steel profiles
250
200
150
100
50
0
0:00
0:10
0:20
0:30
0:40
0:50
1:00
1:10
1:20
1:30
1:40
TC_10
TC_11
AVERAGE
TC_12
TC_13


Mid-depth: web of steel profiles
800
700
600
500
400
300
200
100
0
0:00
0:10
0:20
0:30
0:40
0:50
1:00
1:10
1:20
1:30
1:40
TC_16
TC_17
TC_18
TC_19
TC_22
TC_23
TC_24
TC_25
AVERAGE