This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

RE4 Project

REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction

D3.5 Fire Modelling	
Author(s)[1]:	STRESS, RINA-C
Date:	29/05/2019
Work package:	WP3 - Innovative concept for modular/easy installation and disassembly of eco-friendly prefabricated elements
Distribution[2]	PU
Status[3]:	Final
Abstract:	The document describes the outcome of the Subtask 3.4.3, based on thermal and thermal-structural simulations, able to replicate the fire test described in the ISO 834, and performed on the structure named as Timber Façade and Sandwich Panel. The aim of the activity is to define their fire resistance.
File Name	RE4_D3.5 Fire Modelling_Final_V2.0.docx

Version	Date	Description	Written By	Approved by
V0.0	24/05/2019	First version for quality check	RINA-C, STRESS	RISE
V1.0	28/05/2019	Revised version	RINA-C, STRESS	RISE
V2.0	29/05/2019	Final version ready for submission	RINA-C, STRESS	CETMA

[1] Just mention the partner(s) responsible for the Deliverable
[2] PU: Public, RE: restricted to a group specified by the consortium, CO: Confidential, only for members of the consortium; Commission services always included.
[3] Draft, Revised, Final

TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

BC	Boundary conditions
CAD	Computer Aided Design
CDW	Construction and Demolition Waste
FE	Finite Element
FEM	Finite Element Modelling
HPC	High-Performance Concrete
MIN	Time in minutes
NE	Northern Europe
SCC	Self-Compacting Concrete
SE	Southern Europe

1. EXECUTIVE SUMMARY

This document describes the outcome of the Subtask *3.4.3. Fire Modelling*, framed under work package *WP3 - Innovative concept for modular/ easy installation and disassembly of eco-friendly prefabricated elements*.

The aim of the Subtask is to simulate, through thermal and thermal-structural Finite Element (FE) analyses, the fire test described in the standard EN-ISO 834. The analysed structures are named RE^4 Timber Façade and RE^4 Concrete Sandwich Panel. The final purpose is to define their fire resistance through specific criteria described in the deliverable.

Starting from the technical drawings, three discretized models have been developed for the RE^4 Timber Façade: one for its configuration addressed to the Northern Europe and two designed for Southern Europe. For the RE^4 Concrete Sandwich Panel, one model for the cold climate and one for warm climate have been defined. Following the described approach and the guidelines reported in the standard [1], thermal analyses have been performed on each structure, by defining thermal boundary conditions able to simulate the presence of a fire on one side (inner side) of the model, through radiation and convection conditions. The results have been compared with the criterion useful to define the insulation index (I), by analysing the highest and the average temperature on the unexposed side and comparing them with their maximum allowable values (180°C as highest temperature anytime during fire and 140°C as maximum average temperature). The simulations have been performed establishing a total time equal to 360 min, since the maximum index is equal to 360, and all the analysed structures have shown an insulation capacity until the end of the analysis. As consequence, an index I=360 has been assessed.

Concerning the thermal-structural simulations, the RE^4 Concrete Sandwich Panel is the only load bearing component, consequently this kind of analysis has been performed only on this structure. The load bearing criterion (R), foresees a comparison between the maximum obtained deformation and the deformation rate with the respective calculated allowable values. The simulation has been performed by setting fully supported structural boundary conditions and the results have shown how the panel is able to respect the criteria until the end of the established time, allowing to assess an index R=360.

2. INTRODUCTION

The document describes the numerical Finite Element (FE) calculations performed on two different structures, denoted *RE^4 Timber Façade* and *RE^4 Concrete Sandwich Panel*. The aim of the analyses is to simulate the fire test according to the standard EN-ISO 834 Fire resistance tests – Elements of building construction – Part 1: General Requirements [1], in order to assess two of the three classification criteria, specifically:

- R – Load bearing criterion (mechanical resistance),
- I – Insulation criterion.

The approach, the standards used, and the calculation procedures are described in Chapter 3.

The employed software is briefly described in Chapter 4, while Chapter 5 exposes the geometries and lists the employed material in each structure.

Chapter 6 describes the main hypotheses and assumptions related to the material properties.
The discretized models and the applied boundary conditions of thermal and structural analysis are exposed respectively in Chapter 7 and Chapter 8.
In the end, the obtained results are described in Chapter 9 with the related conclusions reported in Chapter 10.

3. FIRE MODELLING APPROACH

According to the ISO 834-1:1999 standard [1], the fire resistance classification criteria (REI) foresee:

- R – Load bearing criterion (mechanical resistance),
- E – Integrity criterion,
- I – Insulation criterion.

The evaluation of these criteria is based on the elapsed time for which the construction element is able, respectively, to maintain its ability to support the load and to maintain its separating function, without developing temperature on its unexposed face of:

- 140 °C (considered as the average temperature above the average initial temperature),
- 180 °C (considered as the temperature of any location at any time, above the average initial temperature).

The thermal load consists of the heat flux coming from the ISO 834 Time-temperature curve. As the temperature of the heat source is varying with time, a transient thermal analysis is necessary to assess the insulation capacity of the components.

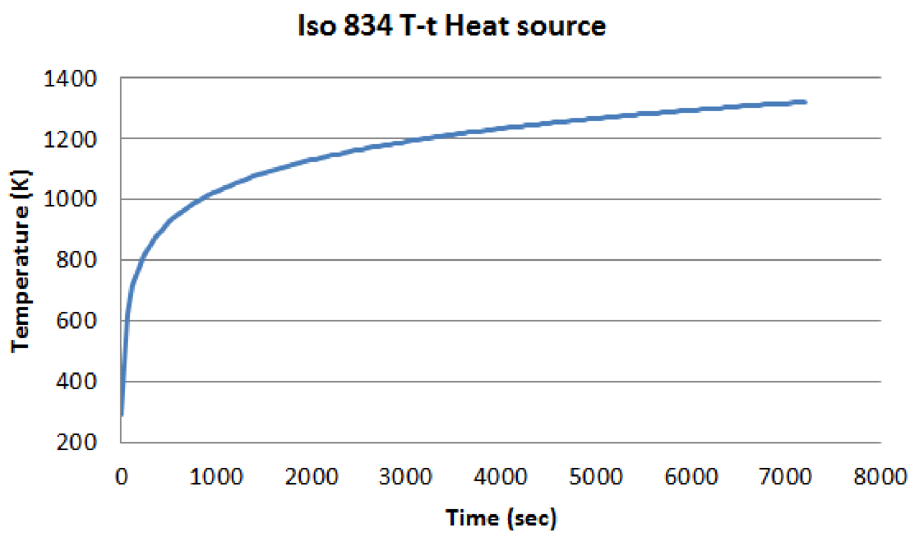

Figure 1. Temperature vs time on the exposed face of the components during a fire test according to ISO 834 standard

A coupled thermo-structural simulation allows the assessment of the theoretical insulation (I) and load bearing (R) capacity of the structures developed during the project.

The verification of the integrity criterion (E) is not foreseen to be checked with the FE modelling approach proposed since it is not possible to reproduce the experimental procedure suggested by the ISO 834 Standard (i.e. mainly, by the verification of the ignition of a cotton pad applied on the unexposed side of the prototype). It should be highlighted that the verification of the insulation and load bearing capacity of the component are quite enough to assess the fire resistance performance since the aim of the activity, within the RE^4 project, is not to certify the component for construction purpose but only to understand its overall fire performance and to compare different components solutions that have been developed during the project.

3.1. Insulation criterion (I)

According to ISO 834 Standard the insulation criterion consists of the verification of the elapsed time for which the temperature increases, on the component unexposed side, is below:

- 140 °C (considered as the average temperature above the average initial temperature),
- 180 °C (considered as the temperature of any location above the average initial temperature).

3.2. Loadbearing criterion (R)

According to ISO 834 Standard the loadbearing criterion consists of the verification of the elapsed time for which the component continues to maintain its ability to support the load during the fire event and the failure occurs when the following criteria have been exceeded:

a) For flexural elements

Limiting deflection: $D = \frac{L^2}{400\ d}\ (mm)$ and

Limiting rate of deflection: $\frac{dD}{dt} = \frac{L^2}{9000\ d}\ (mm/min)$

where *L* is the clear span of the component (in mm), *d* is the distance from the extreme fibre of the compression zone to the extreme fibre of the tensile zone of the structural section (in mm), and *t* is time (in min).

b) For axially loaded elements

Limiting axial contraction: $C = \frac{h}{100}\ (mm)$ and

Limiting rate of contraction: $\frac{dC}{dt} = \frac{3\ h}{1000}\ (mm/min)$

Where *h* is the initial height (in mm) and *t* is time (in min).

3.3. Boundary conditions & material properties

The following boundary conditions have been considered for performing the thermal analysis:

- radiative and convective heat transmission on the exposed side of the components,
- convective heat transmission on the unexposed side,
- uniform initial temperature distribution (T ambient).

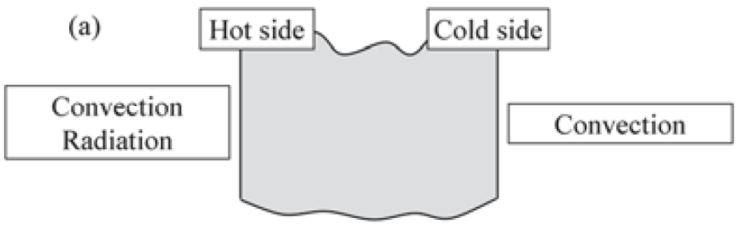

Figure 2. Schematic representation of the thermal boundary conditions

The following conditions have been considered for performing the structural analysis:

- temperature body forces coming from the thermal analysis,
- structural boundary conditions.

To properly model the phenomenon, the following time dependent characteristics of the materials of each constituent/layer of the components have been considered:

- thermal material properties: density, thermal conductivity, specific heat,
- mechanical material properties: thermal expansion coefficient, Young's modulus, Poisson coefficient, yield strength.

3.4. Input required for the fire assessment

The basic information needed to carry out the activities deal with:

- the geometry of the prototypes/components (CAD models and/or drawings), with a description of each constituent of the prototypes (i.e. layers stratification, material and thickness of each layer),
- Temperature (T) dependent thermal material properties: density (ρ), thermal conductivity (λ), specific heat (Cp), emissivity (ε) (see Table 1),
- Temperature dependent structural material properties: thermal expansion coefficient (ρ), Young's modulus (E), Poisson coefficient (ν), yield strength Fy(T), and/or stress-strain curves at different temperatures (see Table 2),
- Boundary conditions.

Table 1. Temperature dependent thermal material properties

Temperature dependent thermal material properties				
layer/constituent of the component	Density (kg/m³)	Specific heat (J/kg*K)	Thermal conductivity (W/m*K)	Emissivity[1]
1	ρ(T)	Cp(T)	λ(T)	ε(T)
2	ρ(T)	Cp(T)	λ(T)	
3	ρ(T)	Cp(T)	λ(T)	
…	ρ(T)	Cp(T)	λ(T)	
n	ρ(T)	Cp(T)	λ(T)	ε(T)

[1] *Emissivity should be provided only for the layer/constituent of the component exposed to the fire load*

Table 2. Temperature dependent structural material properties

Temperature dependent structural material properties				
layer/constituent of the component	Young's Modulus (Pa)	Poisson Ratio	Thermal Expansion Coefficient (1/K)	Nonlinear properties (Yield strength, tangent modulus…or stress vs strain curves)
1	E(T)	ν	α(T)	Fy(T); Et(T)…
2	E(T)	ν	α(T)	Fy(T); Et(T)…
3	E(T)	ν	α(T)	Fy(T); Et(T)…
…	E(T)	ν	α(T)	Fy(T); Et(T)…
n	E(T)	ν	α(T)	Fy(T); Et(T)…

In case of some data missing, the activity has started by accessing data provided in literature and standards.

3.5. Fire modelling steps

The main activities to be carried out for the thermal assessment are summarized hereafter:

- analysis of the geometry of the prototypes/components for the identification of the constituents to be modelled,
- definition of the thermal and structural material properties to be implemented in the FE models,
- boundary conditions definitions (thermal and structural ones),
- detailed definition of the criteria against which the fire performances of the components should be checked,
- thermal FE model stet-up and transient thermal simulations,
- structural FE model stet-up and coupled thermo- structural simulations,
- sensitivity analysis in order to investigate the effect of the main parameters (e.g. layers thickness and/or layers material properties, boundary conditions etc.) and to support the design of the prototypes/components,
- fire performance assessment of the developed components/prototypes.

4. SOFTWARE

The following code has been used to carry out the numerical FEM analyses within the RE^4 project:

- ANSYS Enterprise is a general-purpose FE (Finite Element) software for structural analysis, including linear, nonlinear and dynamic studies. The engineering simulation software provides a complete set of elements behavior, material models and equation solvers for a wide range of mechanical design problems [2].

5. GEOMETRY AND CONSTITUTING MATERIALS

The geometry of the RE^4 Timber Façade has been provided by ZRS Architekten Ingenieure [3], while the dimensions and the layers of the RE^4 Concrete Sandwich Panel have been given by RISE (Research Institutes of Sweden) [4] and ACCIONA [5]. Both structures present a layering related to Northern Europe climate and another one for Southern Europe climate. In particular, for warm weather conditions two options for the Timber Façade have been provided. FEM analyses have been performed on each version of the structure.
The following paragraphs describes the geometry of the analysed components, including also the material employed for each layer.

5.1. RE^4 Timber Façade

All the information related to geometry, layer thicknesses and material properties of the following Timber Facades have been provided by ZRS Architekten Ingenieure [3].

5.1.1. RE^4 CDW Timber Façade for Northern Europe

The repetitive unit of the Timber Façade, developed in RE^4 project for the cold climate, is shown in **Figure 3**. The dimension of each layer and the employed material are listed in **Table 3**.

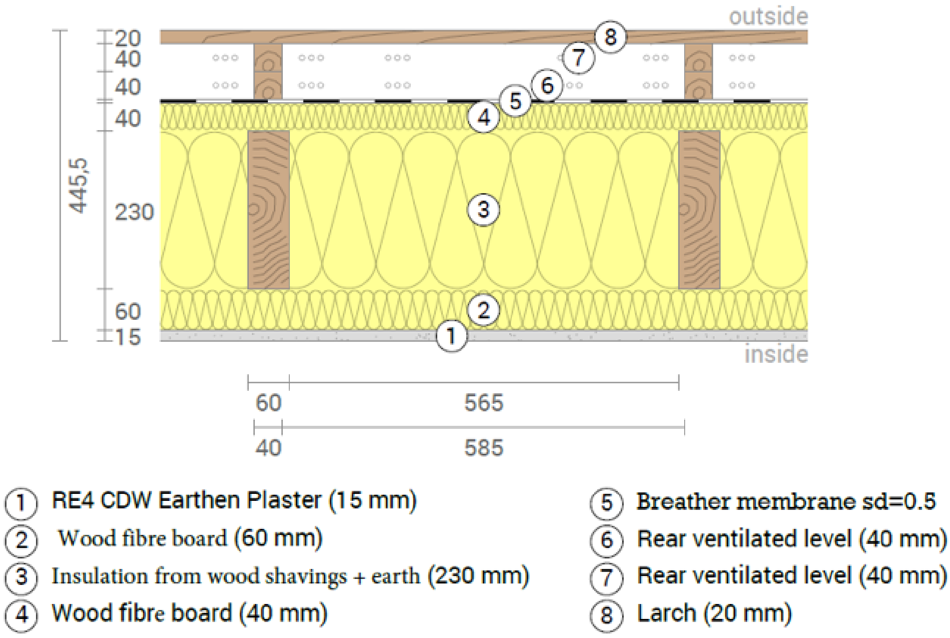

Figure 3. RE^4 CDW Timber Façade for NE climate

Table 3. Thicknesses and materials of NE RE4 CDW Timber Façade

Layer / Material	Status	Thickness [mm]	Water vapour resistance factor [μ]	λ [W/mK]
RE4 CDW Earthen plaster	RE4 product	15	5 / 10	1,1
Wood fibre board	commercial	60	5 / 5	0,048
Insulation from wood shavings + earth	commercial	230	2 / 3	0,045
Timber Stud - Spruce	RE4 product		20 / 50	0,13
Wood fibre board	commercial	40	3 / 5	0,044
Breather membrane	commercial	0.5	n/a	0,2

5.1.2. RE^4 CDW Timber Façade for Southern Europe

Concerning Southern Europe climate, two different solution have been developed within the RE^4 project. The first one (Option 1) is represented in **Figure 4**, where its repetitive unit is shown, while the material of each layer are listed in **Table 4**. The second one (Option 2) is shown in **Figure 5** with its related materials summarized in **Table 5**. The main difference between the two structures is based on the presence of a layer of earth blocks in the Option 1.

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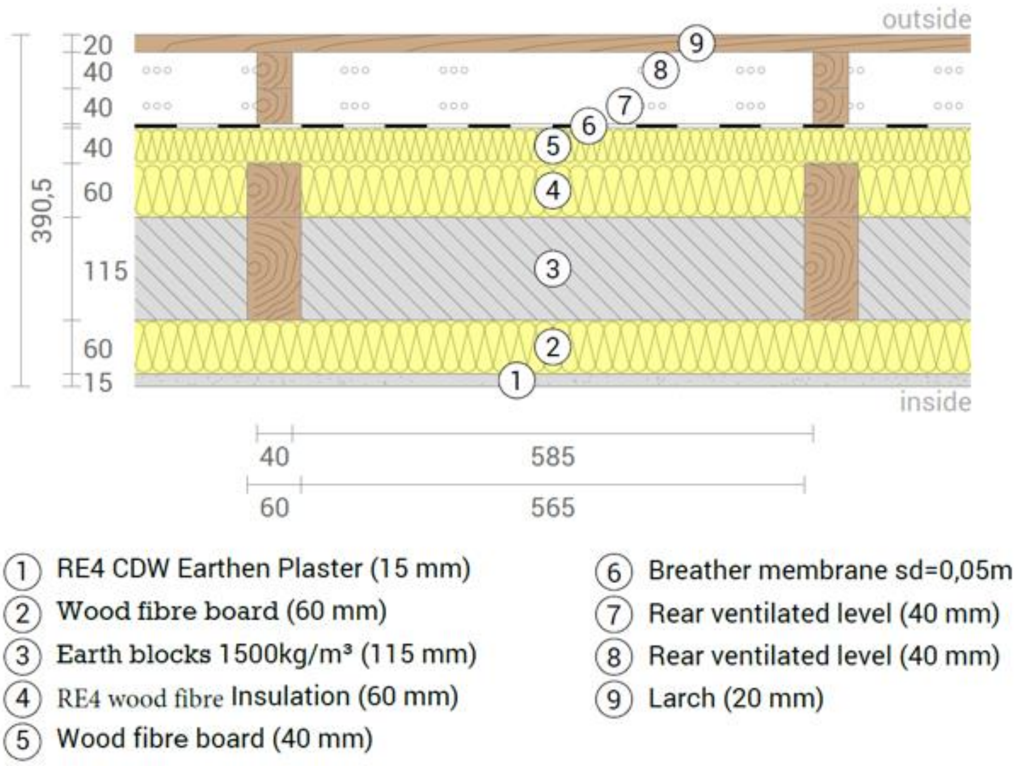

Figure 4. RE[4] CDW Timber Façade for SE climate – Option 1

Table 4. Thicknesses and materials of SE RE[4] CDW Timber Façade – Option 1

Layer / Material	Status	Thickness [mm]	Water vapour resistance factor [μ]	λ [W/mK]
RE4 CDW Earthen plaster	RE4 product	15	5 / 10	1,1
Wood fibre board	commercial	60	5 / 5	0,048
Earth blocks	commercial	115	5 / 10	0,66
Timber Stud - Spruce	RE4 product		20 / 50	0,13
RE4 Wood fibre insulation (CETMA)	RE4 product	60	3/5	0.05
Timber Stud - Spruce	RE4 product		20 / 50	0,13
Wood fibre board	commercial	40	3 / 5	0,044

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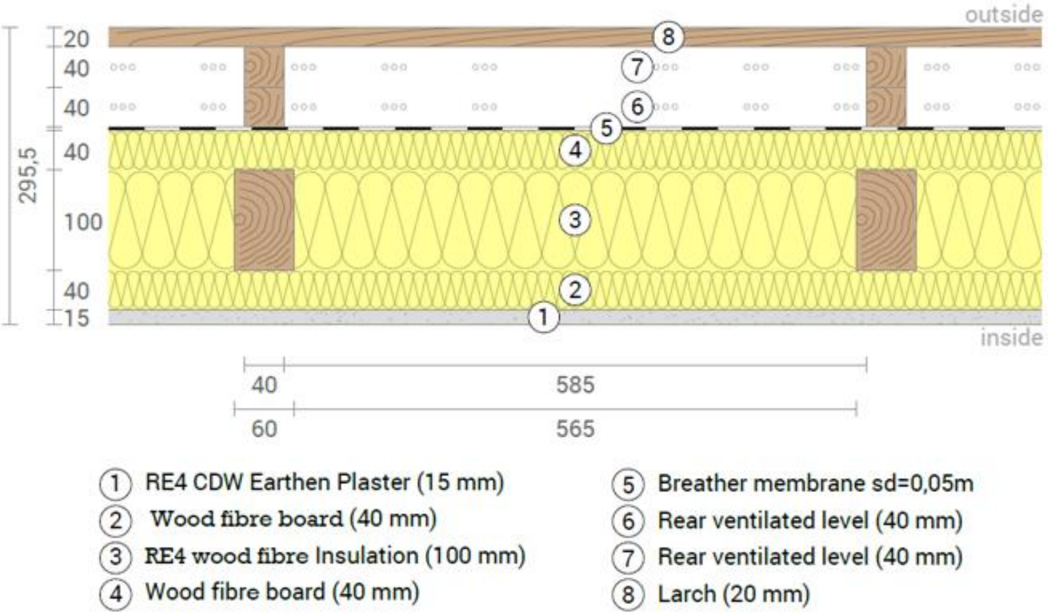

Figure 5. RE4 CDW Timber Façade for SE climate – Option 2

Table 5. Thicknesses and materials of SE RE4 CDW Timber Façade – Option 2

Layer / Material	Status	Thickness [mm]	Water vapour resistance factor [µ]	λ [W/mK]
RE4 CDW Earthen plaster	RE4 product	15	5 / 10	1,1
Wood fibre board	commercial	40	5 / 5	0,038
RE4 Wood fibre insulation (CETMA)	RE4 product	100	3/5	0,05
Timber Stud - Spruce	commercial		20 / 50	0,13
Wood fibre board	commercial	40	3 / 5	0,044

5.2. RE4 Concrete Sandwich Panel

5.2.1. RE4 Concrete Sandwich Panel for Northern Europe

The layering and the materials employed in the Sandwich Panel for cold climate are shown in **Figure 6**. Both the inner and outer layers consist of steel reinforced CDW-based SCC. In addition, the inner and the external layers are connected through pin connectors made of composite fiberglass.

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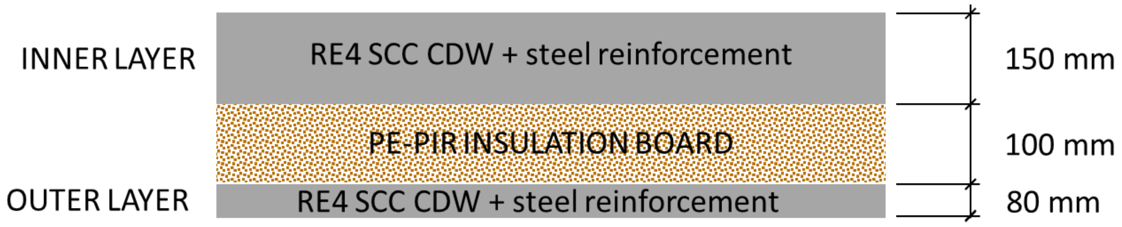

Figure 6. Layering of the Sandwich Panel for cold climate

Table 6. Thicknesses and materials of the Sandwich Panel for cold climate

Layer / Material	Status	Thickness [mm]	Water vapour resistance factor [μ]	λ [W/mK]
RE4 SCC CDW	RE4	150	120	1.6
PE-PIR	commercial	100	60	0.022
RE4 SCC CDW	RE4	80	120	1.6
Fiberglass composite	commercial	/	/	0.25

5.2.2. RE4 Concrete Sandwich Panel for Southern Europe

The Sandwich Panel for warm climate mainly differs from the previous one because of the thicknesses of the layers thicknesses of the layers (**Figure 7**). Furthermore, while the inner layer consists of steel reinforced CDW-based SCC, the outer layer is composed of carbon textile reinforced CDW-based HPC. As for the rest, the employed materials (

Table 7) are the same as in the panel for cold climate. Also in this case the inner and the outer layer are connected through pin connectors made of composite fiberglass.

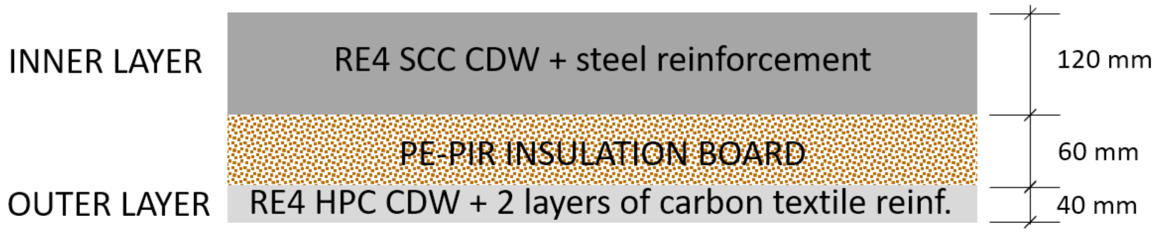

Figure 7. Layering of the Sandwich Panel for warm climate

Table 7. Thicknesses and materials of the Sandwich Panel for warm climate

Layer / Material	Status	Thickness [mm]	Water vapour resistance factor [μ]	λ [W/mK]
RE4 SCC CDW	RE4	120	120	1.6
PE-PIR	commercial	60	60	0.022
RE4 HPC CDW	RE4	40	120	1.6
Fiberglass composite	commercial	/	/	0.25

6. MATERIAL PROPERTIES

As explained in Section3.3, the developed transient thermal analyses require the definition of the material properties as function of the temperature, preferably until its highest predictable value (1200°C in this case considering the curve of the fire defined in [1]). Both experimental and literature data have been employed. The following paragraphs describe the assumptions, the hypothesis and the material properties of each layer.

6.1. Timber

Timber material properties have been provided by ZRS Architekten Ingenieure [3], by using the *EN 1995 -1-2:2005 Eurocode 5: Design of timber structures – Part 1-2: Structural fire design* [6]. The evolution as function of temperature of density, thermal conductivity and specific heat are shown in **Figure 8**, **Figure 9** and **Figure 10**.

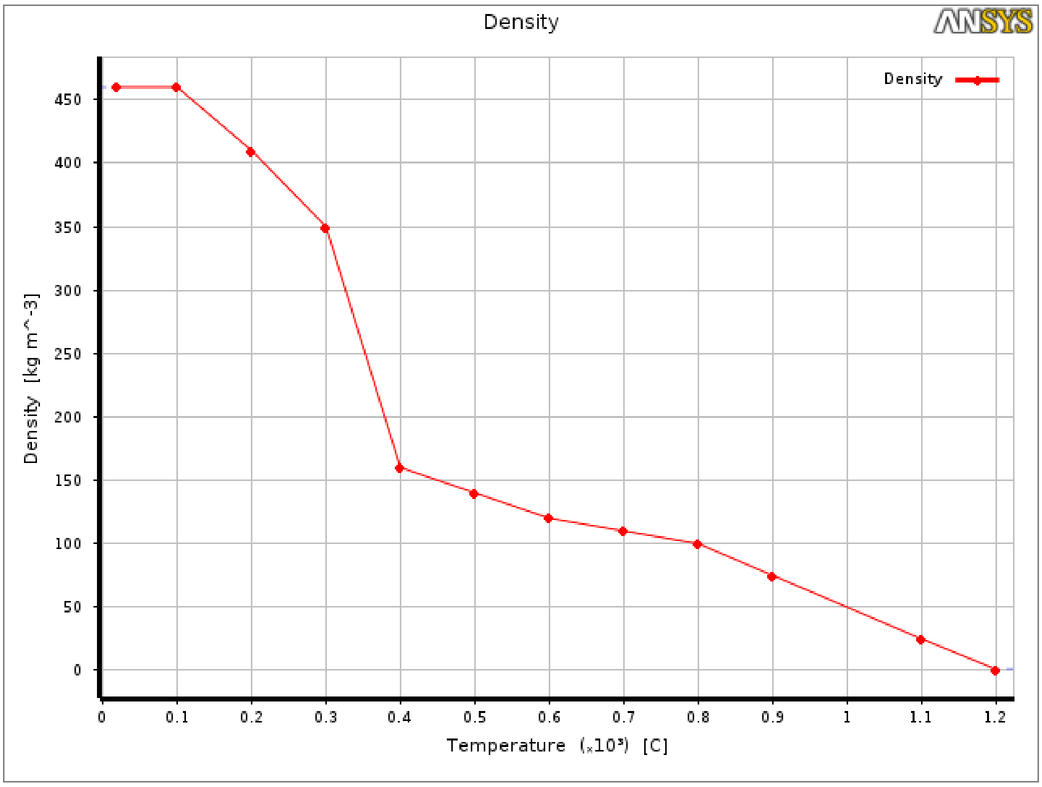

Figure 8. Timber Density *vs* Temperature

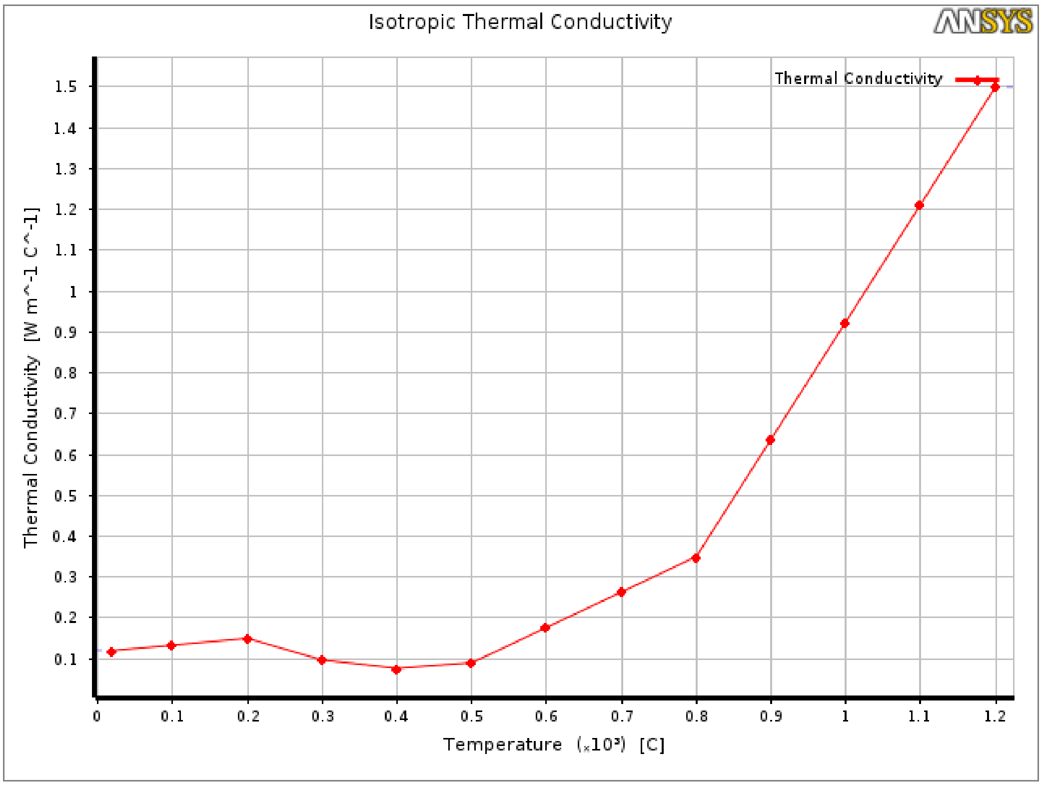

Figure 9. Timber Thermal Conductivity *vs* Temperature

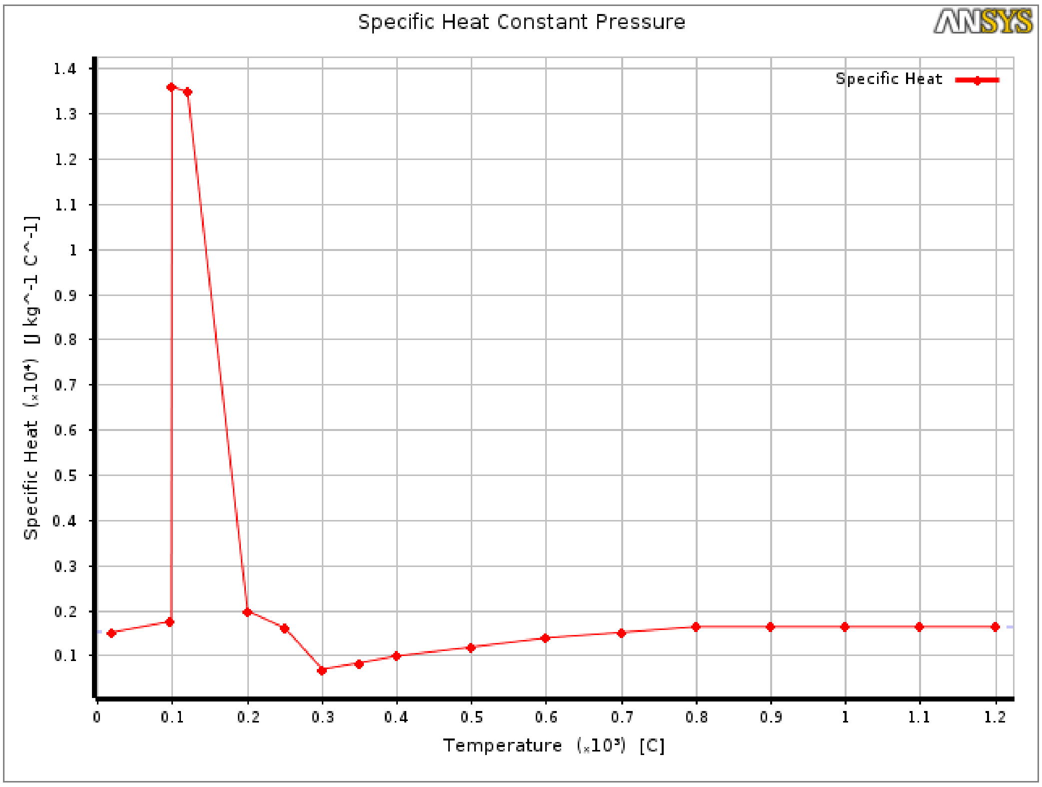

Figure 10. Timber Specific Heats *vs* Temperature

6.2. Wood fibreboard

Concerning wood fibreboard, in literature there are not detailed information about the material properties of this kind of product at high temperature. Consequently, it has been supposed that starting from the value at ambient temperature, the density decreases as function of the temperature by following the trend of the timber density (**Figure 8**). Its variation is shown in **Figure 11**. The conductivity of this layer has been defined by using the suggestion reported in [7], which recommends using a value equal to 35% of the solid wood. Consequently, by using the conductivity defined in the previous paragraph, the property has been defined and its variation as function of temperature is shown in **Figure 12**. In the end, the employed values for specific heat (**Figure 13**) have been provided by CETMA [8] as results of experimental tests.

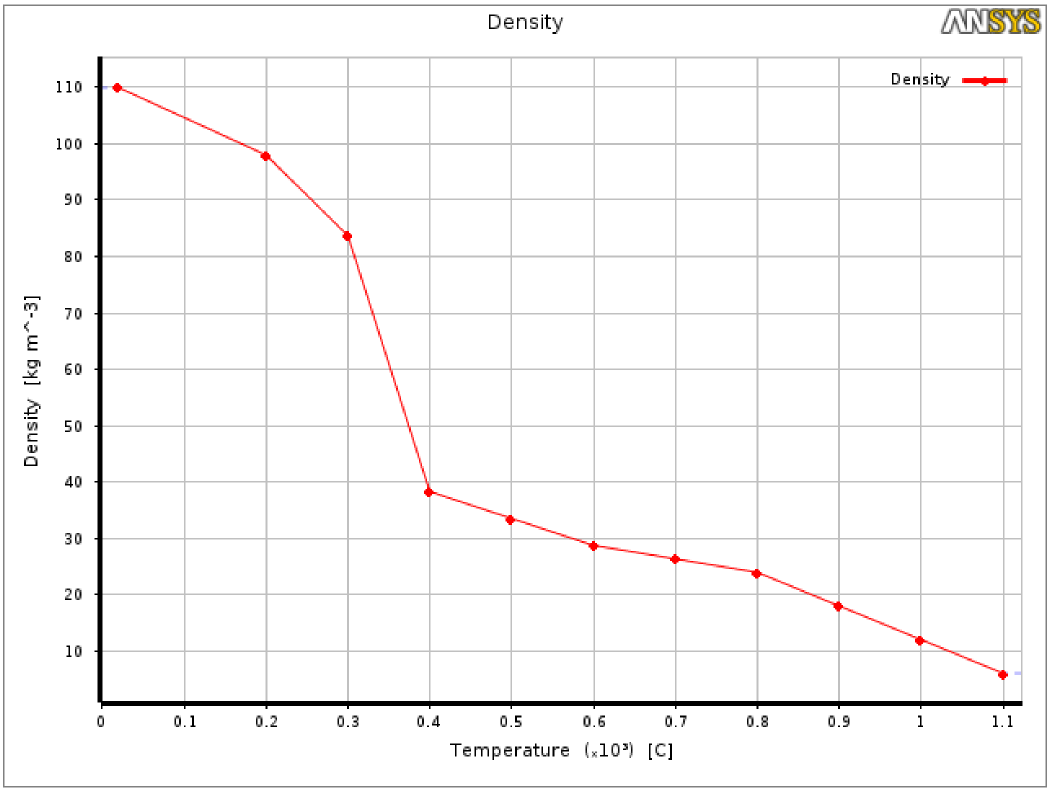

Figure 11. Wood fibreboard Density *vs* Temperature

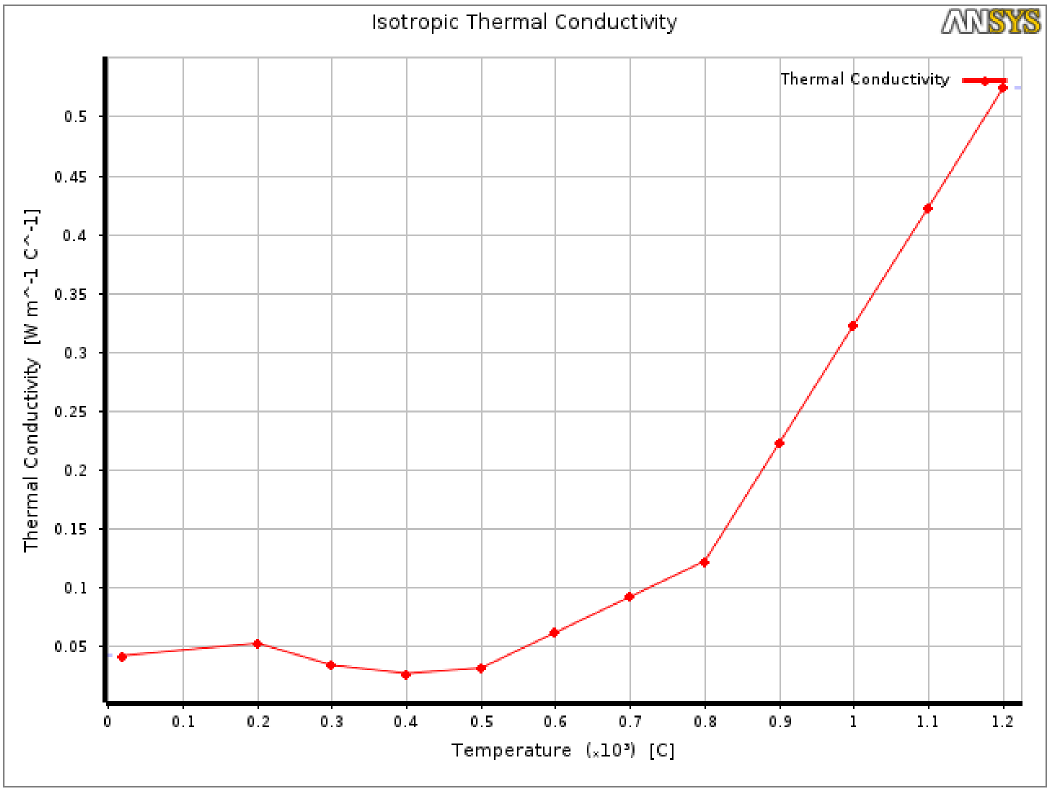

Figure 12. Wood fibreboard Thermal Conductivity *vs* Temperature

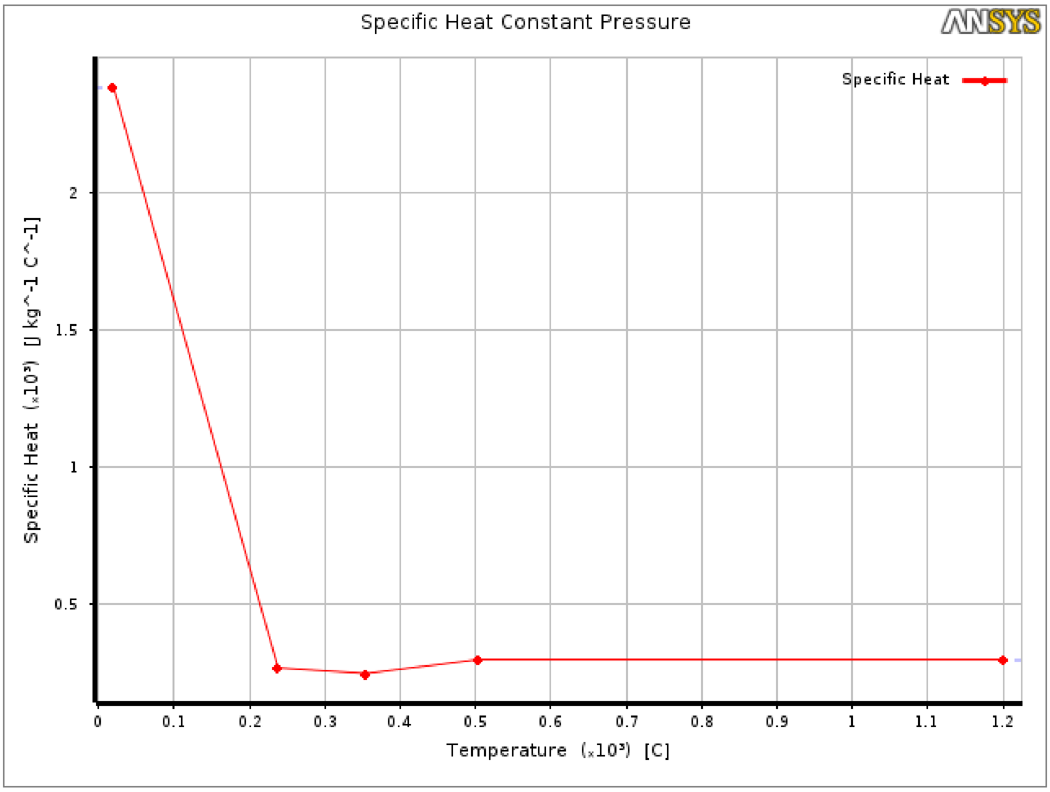

Figure 13. Wood fibreboard Specific Heat *vs* Temperature

6.3. Earthen plaster and earth blocks

Material properties of earthen plaster and of the earth blocks have been considered to be the same. All the implemented material properties have been provided by ZRS Architekten Ingenieure [3] and taken from [9]. **Figure 14**, **Figure 15** and **Figure 16** show the variation of density, thermal conductivity and specific heat as function of the temperature.

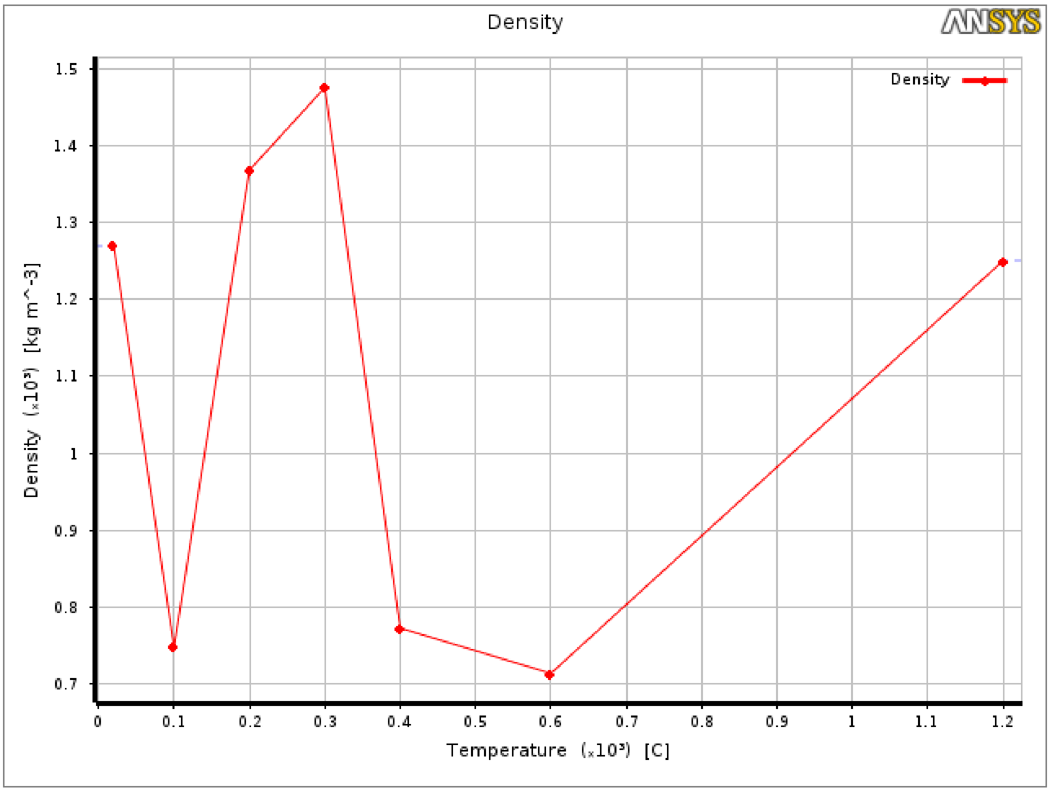

Figure 14. Clay Density *vs* Temperature

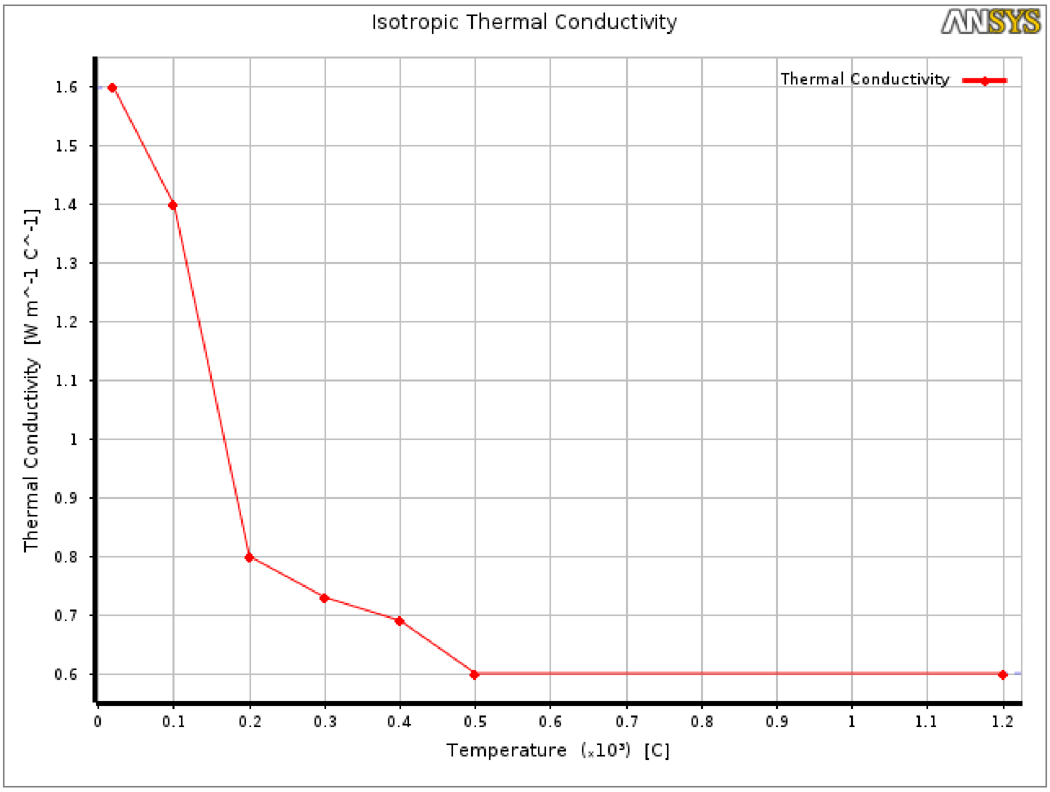

Figure 15. Clay Thermal Conductivity *vs* Temperature

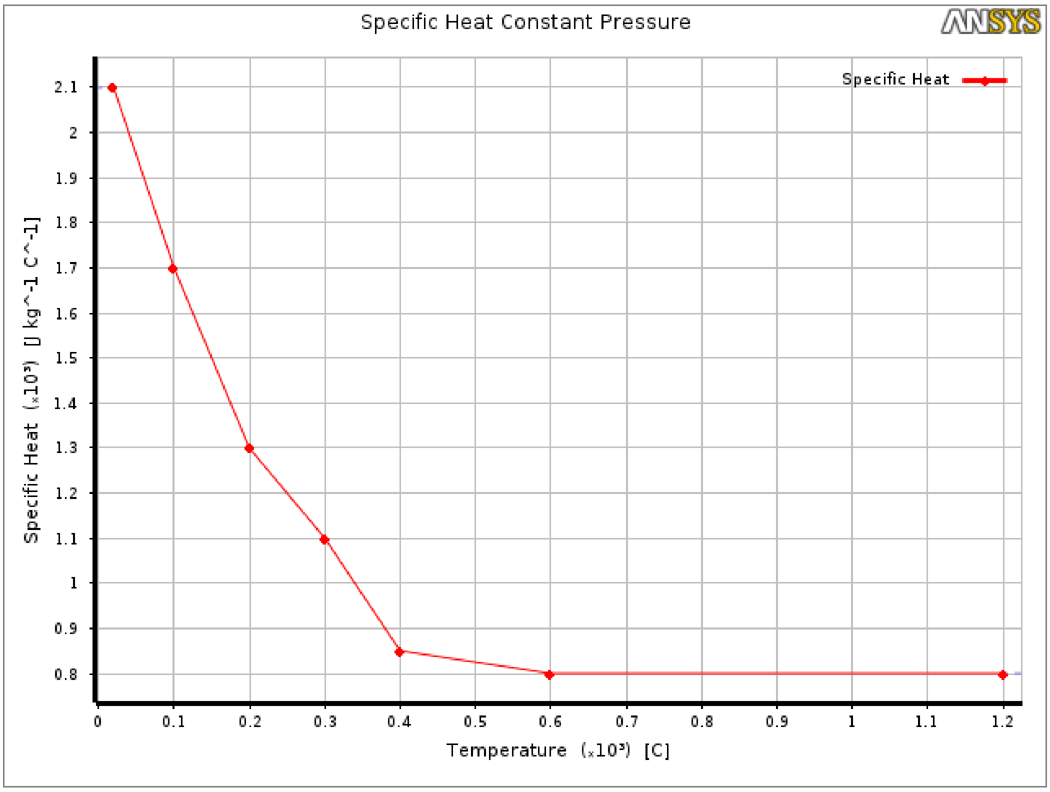

Figure 16. Clay Specific Heat *vs* Temperature

6.4. Concrete

Concrete thermal material properties have been defined by using the EN 1992-2-2005 Eurocode 2: Design of concrete structures – Part 1-2: General rules – structural fire design [10]. The density, the thermal conductivity and the specific heat as function of the temperature are shown in **Figure 17**, **Figure 18** and **Figure 19**.

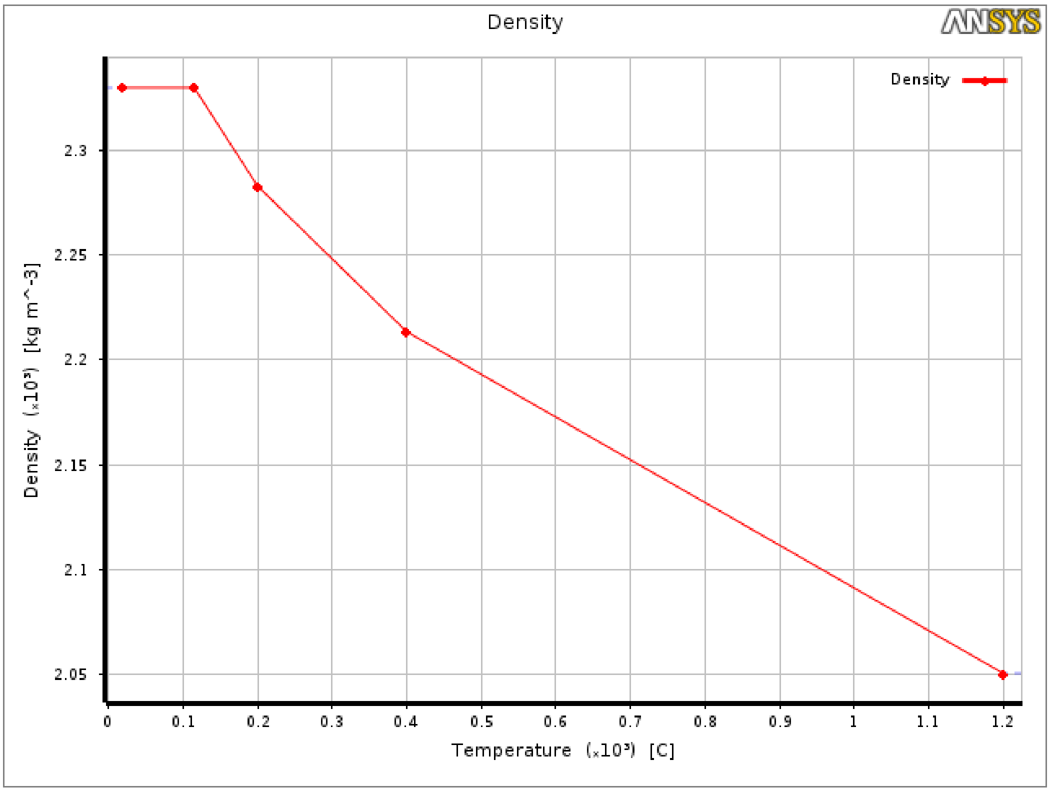

Figure 17. Concrete Density *vs* Temperature

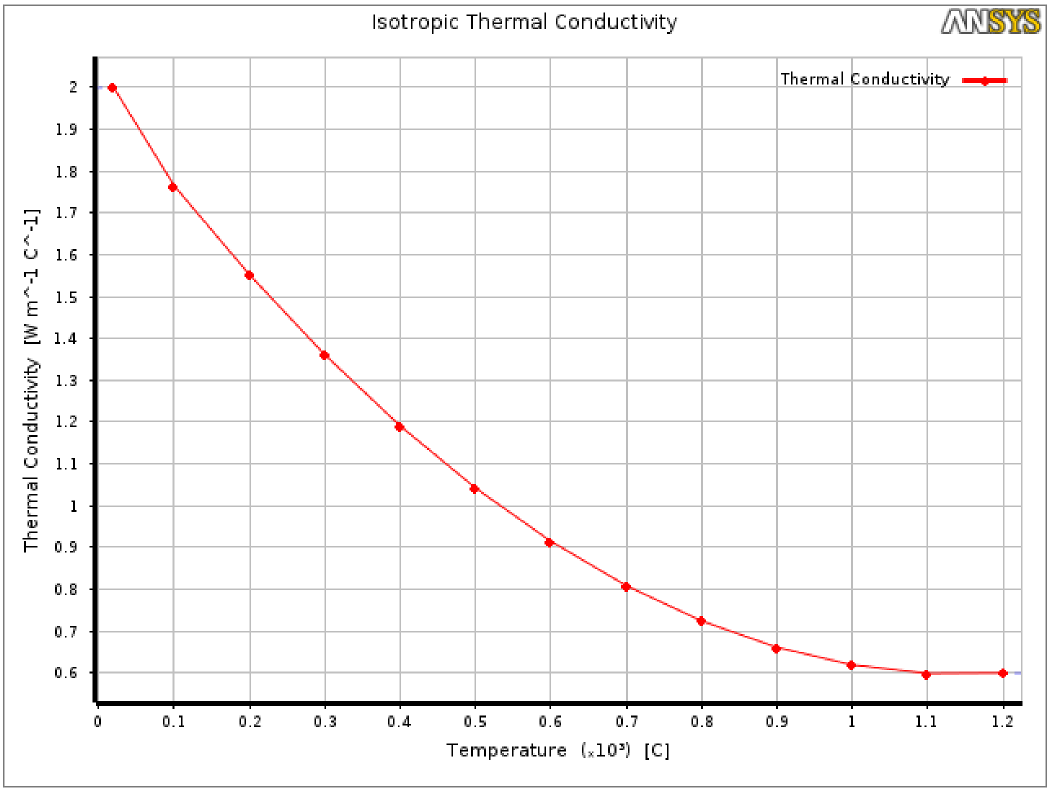

Figure 18. Concrete Thermal Conductivity *vs* Temperature

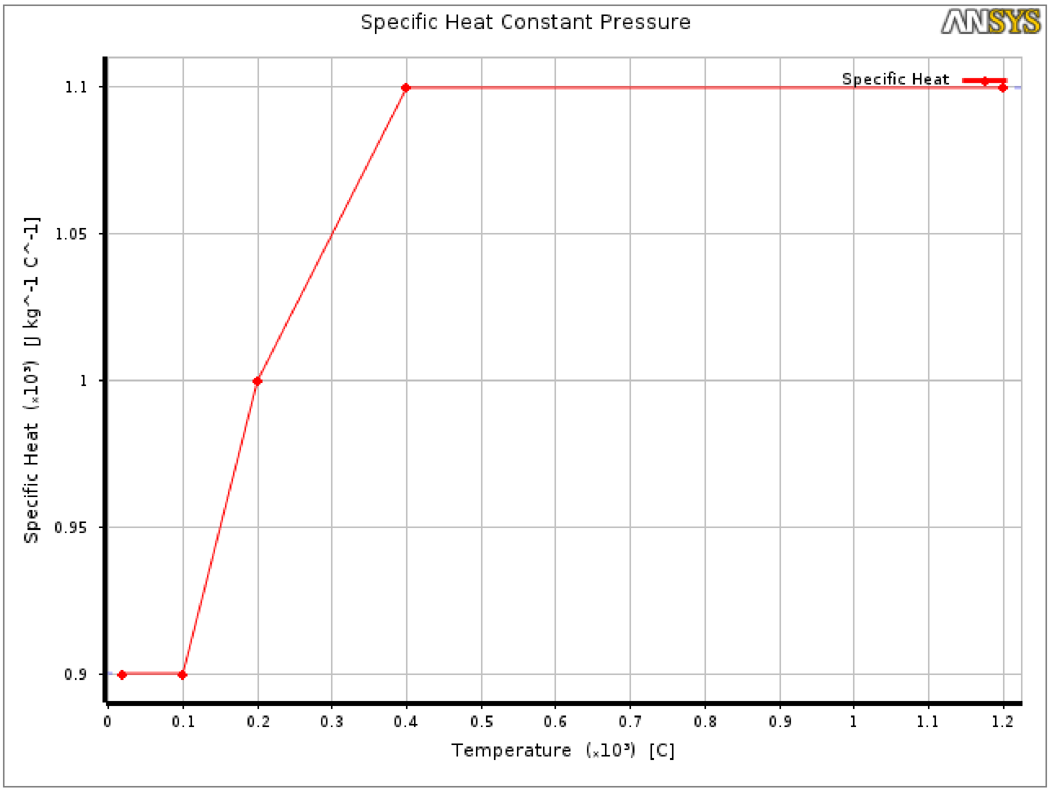

Figure 19. Concrete Specific Heat *vs* Temperature

In addition, since structural analysis has been performed only on the Sandwich Panel, the variation of mechanical properties of concrete at temperature higher than ambient has been defined. In particular, the elastic modulus [11], the Poisson's ratio [12] and the coefficient of thermal expansion [13] are reported in **Figure 20**, **Figure 21** and **Figure 22**.

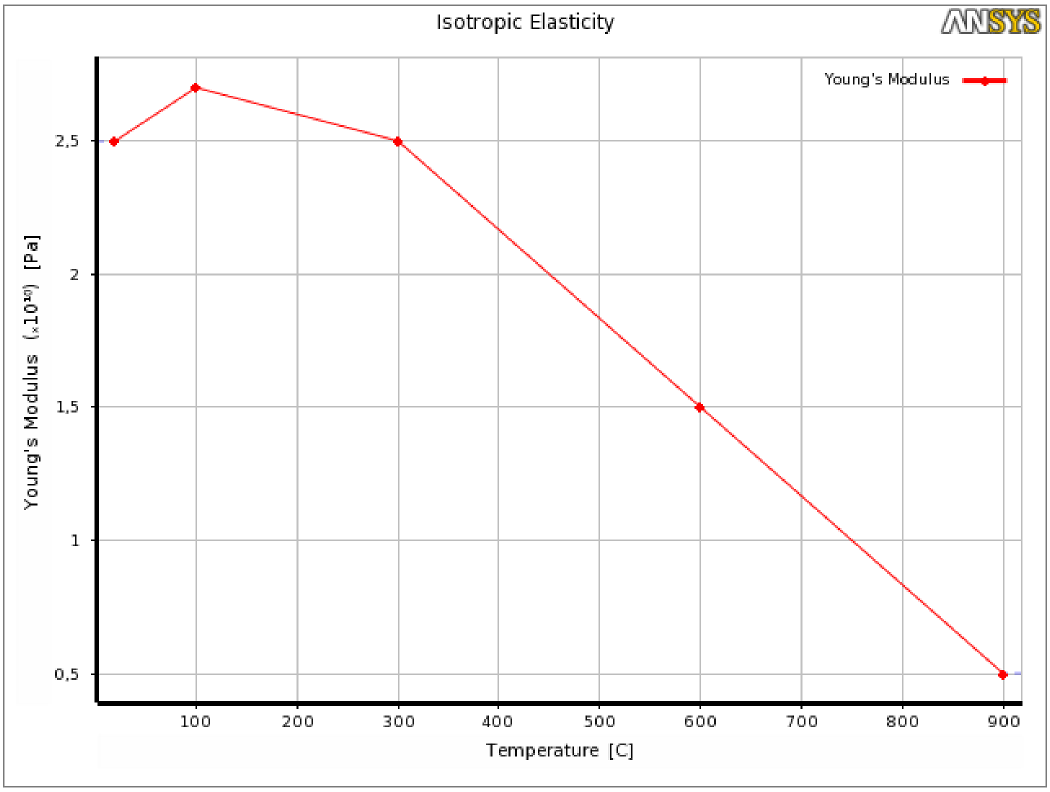

Figure 20. Concrete Elastic Modulus *vs* Temperature

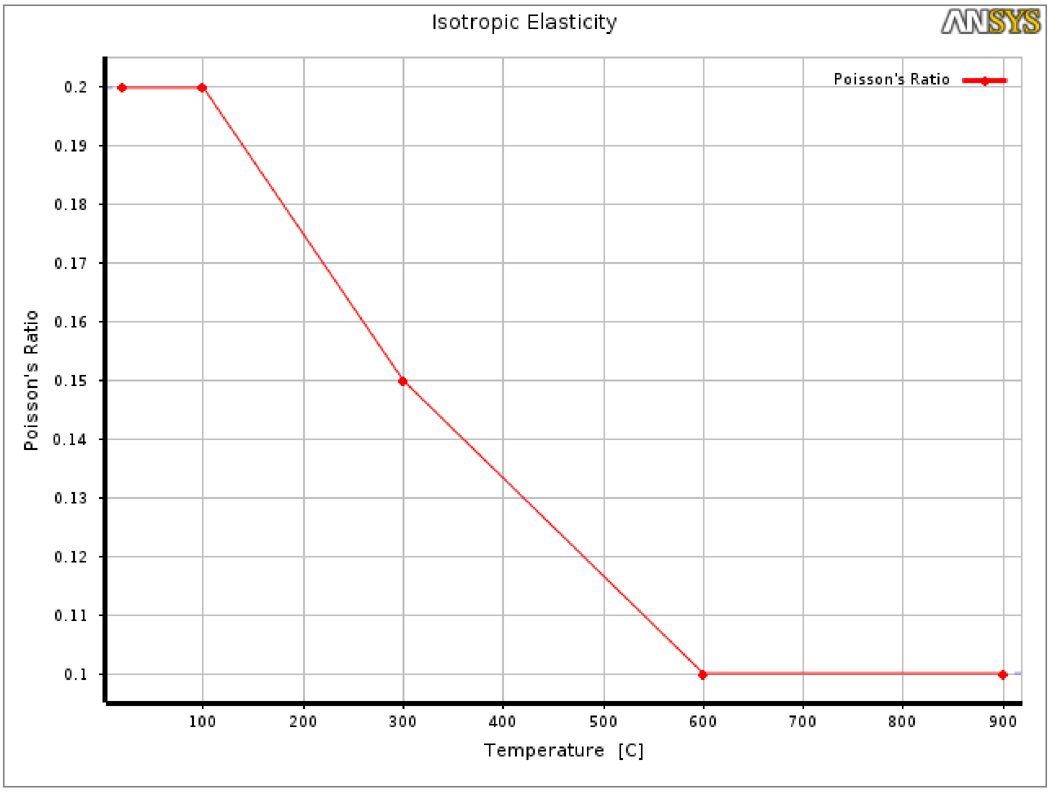

Figure 21. Concrete Poisson's ratio *vs* Temperature

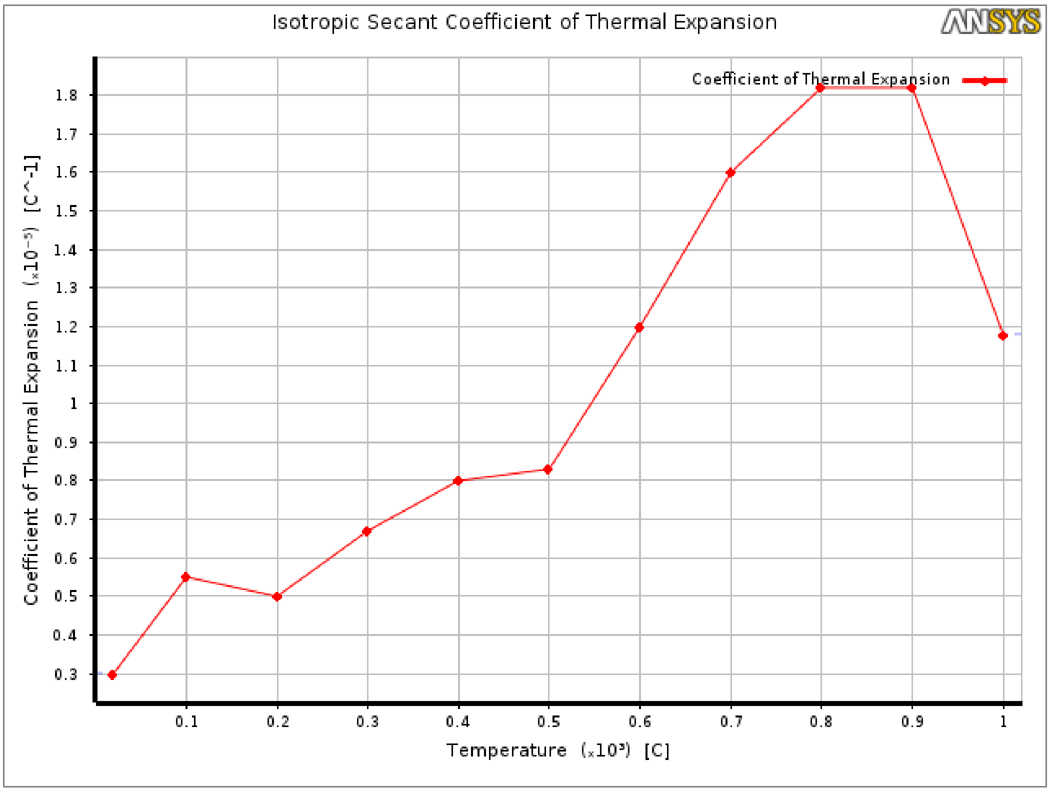

Figure 22. Concrete coefficient of thermal expansion *vs* Temperature

6.5. PE-PIR

Literature data for this kind of material at high temperature are very poor. [14] Therefore, the decision was to consider constant values for density and specific heat. In particular, from [15] a density value equal to 40 kg/m^3 has been used, while a specific heat equal to 1.478 kJ/kg K [16] has been considered. Concerning thermal conductivity (λ), [17] specifies the following equation as function of the temperature:

$$\lambda(T) = 0.02064 + 11.28\text{ e-}5 \times T \text{ (W/mK)}$$

However, its validity could be limited in a not wide temperature range because of the degradation of the material around 300-400°C.

7. DISCRETIZED MODEL

7.1. RE^4 Timber Façade

The FE models of the RE^4 Timber Façade have been developed by considering a bi-dimensional repetitive unite of the entire structure. In particular, a portion of the geometry around the stud, which is a thermal bridge as confirmed in the *Deliverable 3.4 Hygrothermal Modelling* [18], has been modelled. It is sufficient to analyse just this portion of the geometry and to develop a 2D model rather than a 3D one, since the Timber Façade is not a structural component. As consequence, only the thermal analysis has been performed.

7.1.1. RE^4 CDW Timber Façade for Northern Europe

Figure 23 shows the discretized model of the Timber Façade for Northern Europe developed within RE^4 project. 2374 nodes and 2267 quadrilateral PLANE 55 elements have been used, with an average element dimension equal to 0.01 m. More information related to PLANE 55 element can be found in Section.7.3.

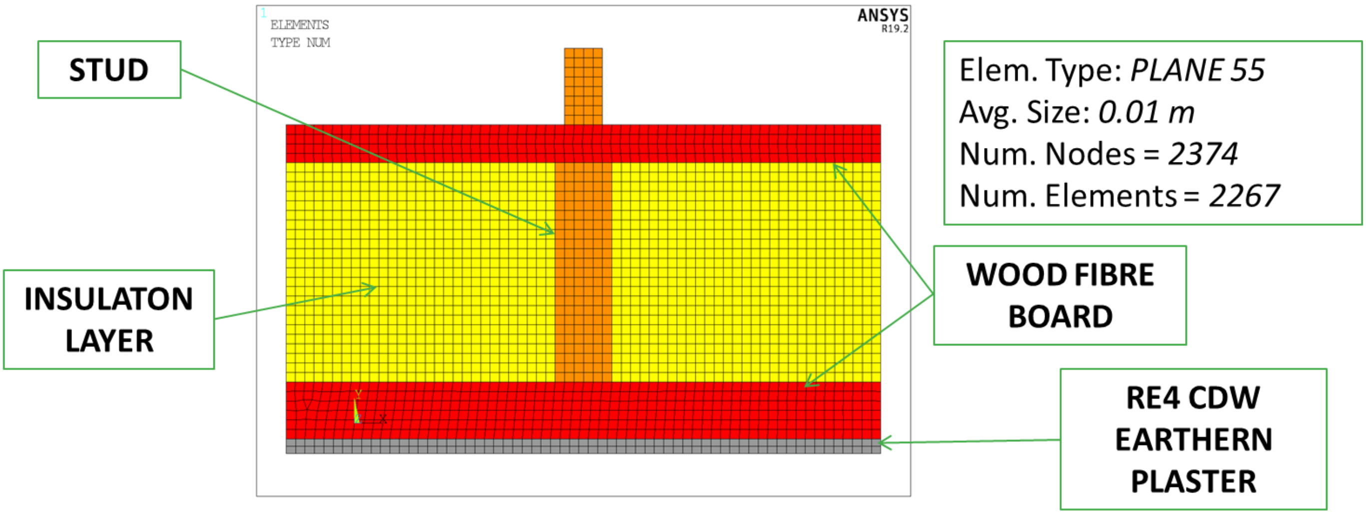

Figure 23. FE model of the RE^4 CDW Timber Façade for cold climate

7.1.2. RE4 CDW Timber Façade for Southern Europe (Option 1)

Figure 24 shows the FE model of the first option of the RE4 CDW Timber Façade for warm climate. It has been created by using 2049 nodes and 1947 PLANE 55 elements.
More information related to PLANE 55 element can be found in Section 7.3.

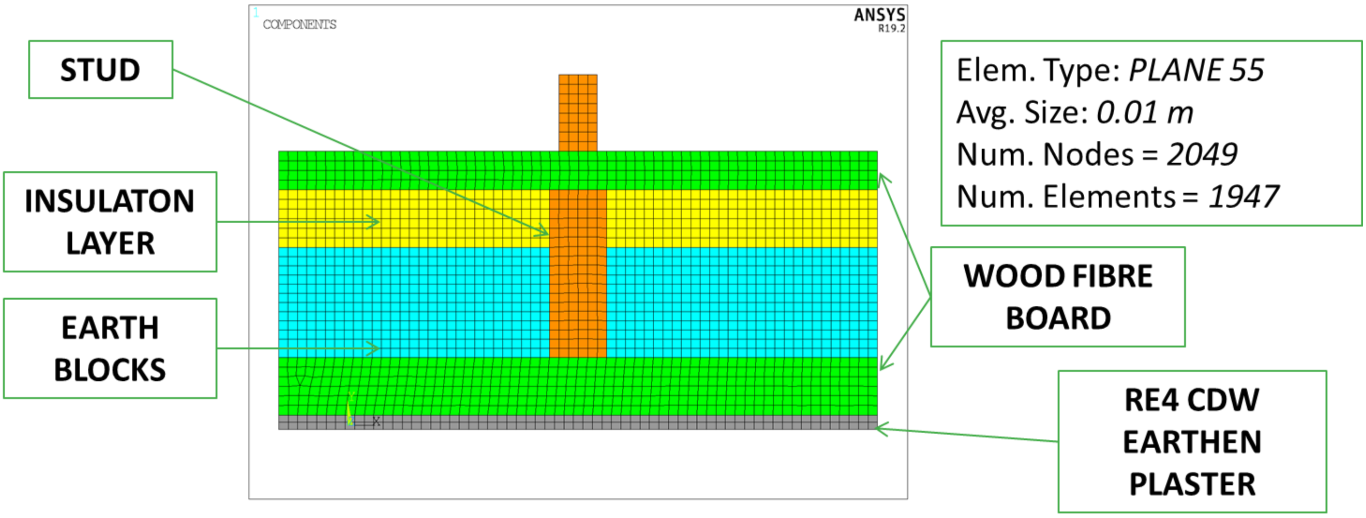

Figure 24. FE model of the RE4 CDW Timber Façade for warm climate – Option 1

7.1.3. RE4 CDW Timber Façade for Southern Europe (Option 2)

The FE model of the second option of the RE4 CDW Timber Façade for warm climate is shown in **Figure 25**. 1530 nodes and 1436 PLANE 55 elements have been employed in order to build the model.
More information related to PLANE 55 element can be found in Par.7.3.

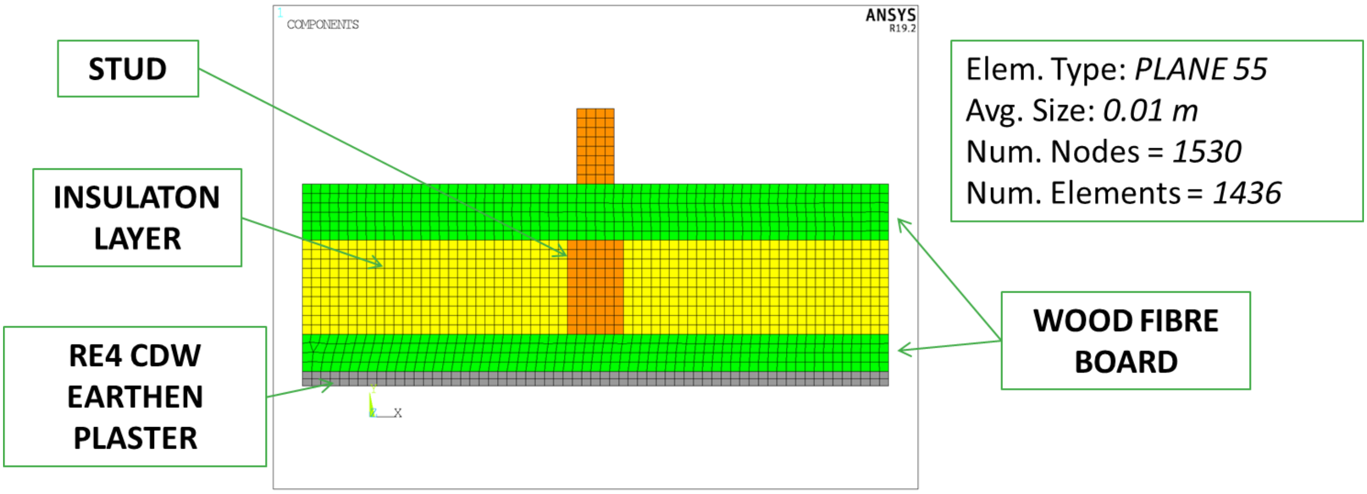

Figure 25. FE model of the RE4 CDW Timber Façade for warm climate – Option 2

7.2. RE4 Concrete Sandwich Panel

A 2D model and a 3D model have been developed for the RE4 Concrete Sandwich Panel for warm climate and for the one related to cold climate, respectively. In the first case, only thermal analysis has been performed, since the panel is not structural and considering that the effect of the pin connectors as 3D thermal bridge is negligible, as demonstrated in [18]. Concerning the panel for Northern Europe, it is characterized by structural functionality and a structural simulation has been performed. As consequence, the development of a 3D model has been necessary.

7.2.1. RE4 Concrete Sandwich Panel for Northern Europe

The dimension of the FE model of the Sandwich Panel for Northern Europe can be found in Appendix A. The discretized model is shown in **Figure 26**. 190132 nodes and 40698 hexahedral elements, with an average element size equal to 0.020 m. SOLID 90 element type has been used for thermal analysis, while for the structural one SOLID 185 has been employed.
More information related to SOLID 90 and SOLID 185 element can be found in Sections 7.4 and 7.5., respectively.

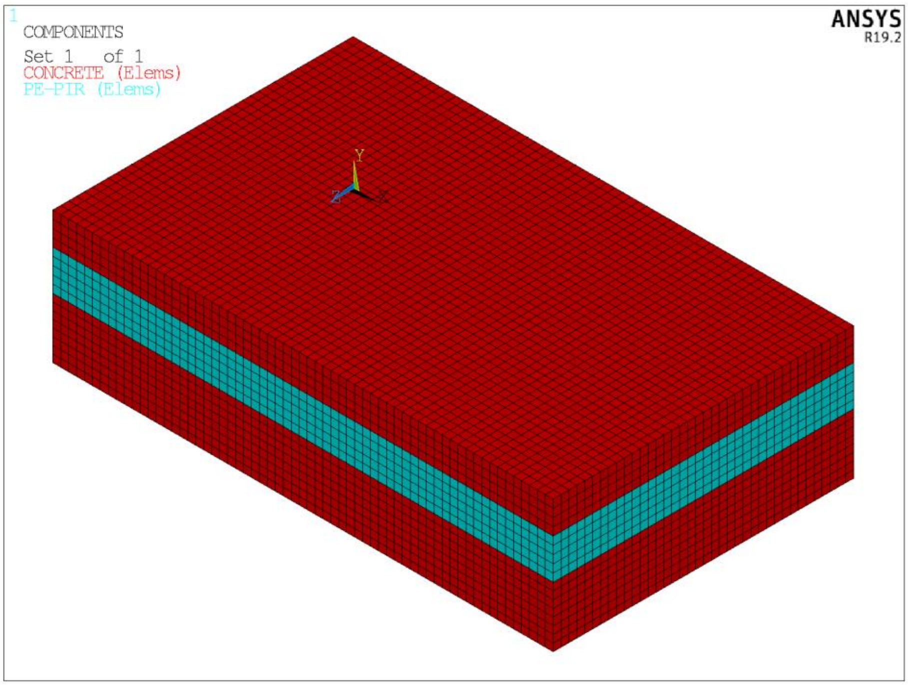

Figure 26. FE model of the Sandwich Panel for cold climate

7.2.2. RE4 Concrete Sandwich Panel for Southern Europe

The dimension of the analysed section can be found in Appendix B. **Figure 27** shows the 2D FE model of the Sandwich Panel for warm climate. The model has been built with 2482 node and 693 PLANE 55 elements.
More information related to PLANE 55 element can be found in Section 7.4.

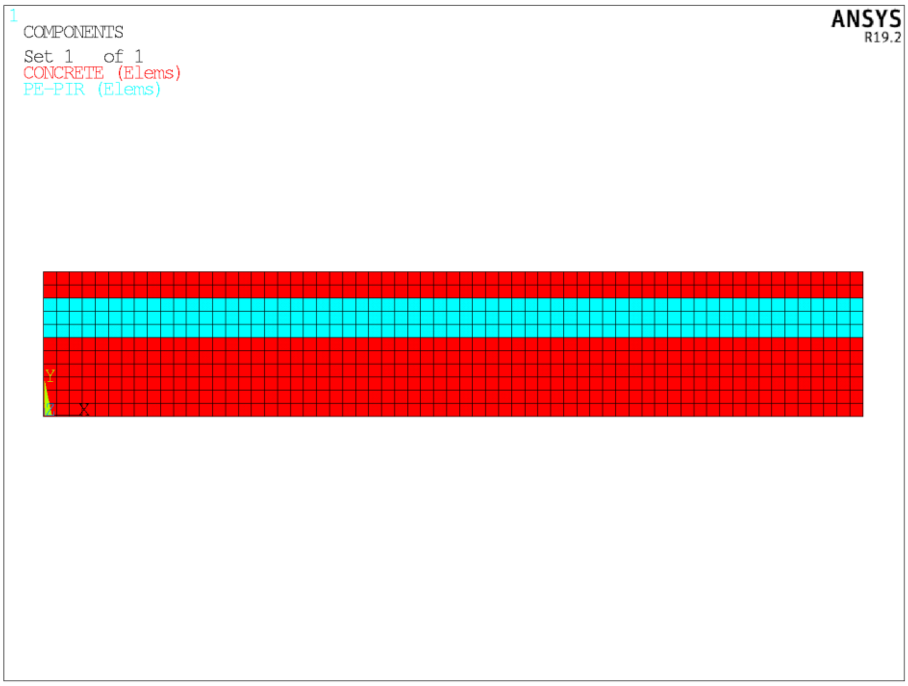

Figure 27. FE model of the Sandwich Panel for warm climate

7.3. PLANE 55

PLANE55 can be used as a plane element or as an axisymmetric ring element with a 2-D thermal conductivity capability. The element has four nodes with a single degree of freedom, temperature, at each node. The element is applicable to a 2-D, steady-state or transient thermal analysis [2].

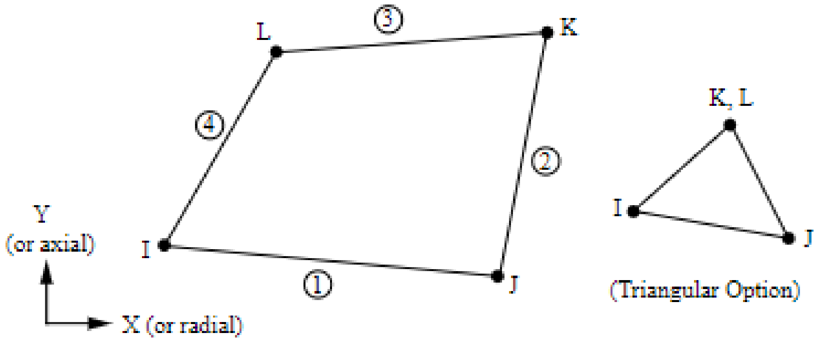

Figure 28. PLANE 55 Geometry

7.4. SOLID 90

SOLID 90 has 20 nodes with a single degree of freedom, temperature, at each node. The 20-node elements have compatible temperature shapes and are well suited to model curved boundaries. The 20-node thermal element is applicable to a 3-D, steady-state or transient thermal analysis [2].

7.5. SOLID 185

SOLID 185 is used for 3-D modelling of solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, hyperelasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyperelastic materials [2].

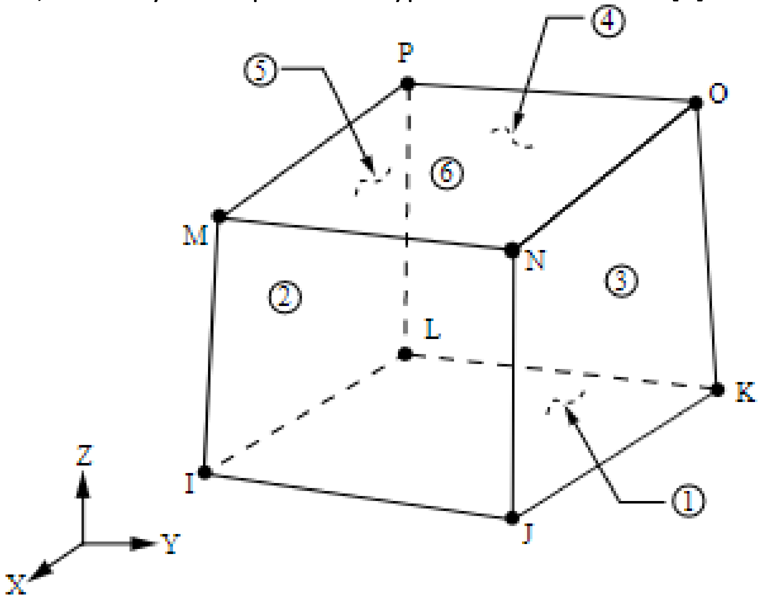

Figure 29. SOLID 185 Geometry

8. BOUNDARY CONDITIONS

8.1. Thermal Boundary Conditions

The same thermal boundary condition has been employed for each RE[4] Timber Façade and for the two RE[4] Concrete Sandwich Panels. As explained in the approach described in Section 3.3, three conditions can be defined:

- radiative and convective heat transmission on the exposed side of the components
- convective heat transmission on the unexposed side
- uniform initial temperature distribution (T ambient)

The exposed side corresponds to the inner side of each panel, while the unexposed one is the outer side of the structures. The boundary conditions can be summarized as follows:

- Convection on the outer surface with air temperature equal to 20°C and film coefficient equal to 25 W/m^{2}K (**T_{bulk} = 20 C°, h_{ext} = 25 W/m^{2}K)**

- Convection on the inner surface with air temperature equal to the equation as function of the time: *T = 345*Log [((8*time)/60)+1] + 20°C* [1] and film coefficient equal to 10 W/m^{2}K (**T_{bulk} = 345*Log [((8*time)/60)+1] + 20°C°, h_{int} = 10 W/m^{2}K)**
- Radiation on the inner surface with ambient temperature defined by the function *T = 345*Log [((8*time)/60)+1] + 20°C* and emissivity as function of the material
- Uniform initial temperature equal to 20°C

Concerning emissivity, a value equal to 0.91 has been used for Timber Façade and 0.92 for Sandwich Panel [19].

8.2. Structural Boundary Conditions

Structural boundary conditions have been defined as fully supported boundary conditions and they can be summarized as it follows:

- Fixed displacements along all the direction on the perimeter of the panel **Figure 30**;
- Earth gravity load along Z-axis of the **Figure 30**;
- Thermal transient load obtained as results of the previous thermal analysis.

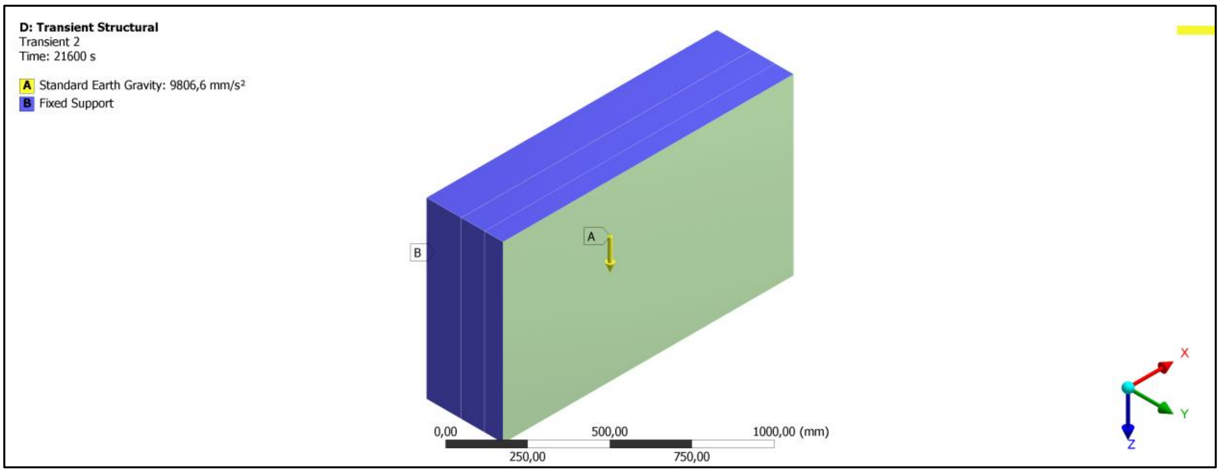

Figure 30. Fully supported boundary conditions

9. RESULTS

9.1. Thermal analysis – RE^4 Timber Façade

9.1.1. RE^4 CDW Timber Façade for Northern Europe

The following pictures report the contour plot of the temperature of the RE^4 CDW Timber Façade for Northern Europe, at different instants of time. Specifically, since the index of the REI classification are 10, 15, 20, 30, 45, 60, 90, 120, 180, 240 and 360, some of these specific minutes have been considered.

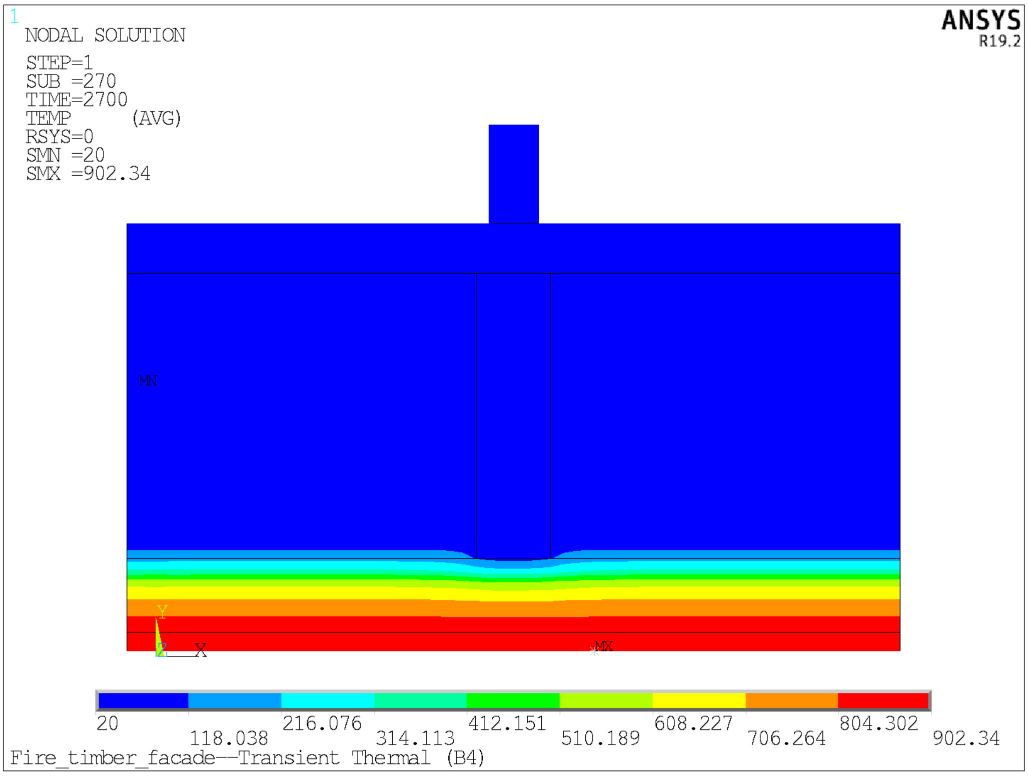

Figure 31. Temperature distribution (°C) on RE[4] CDW Timber Façade for Northern Europe after 45 min.

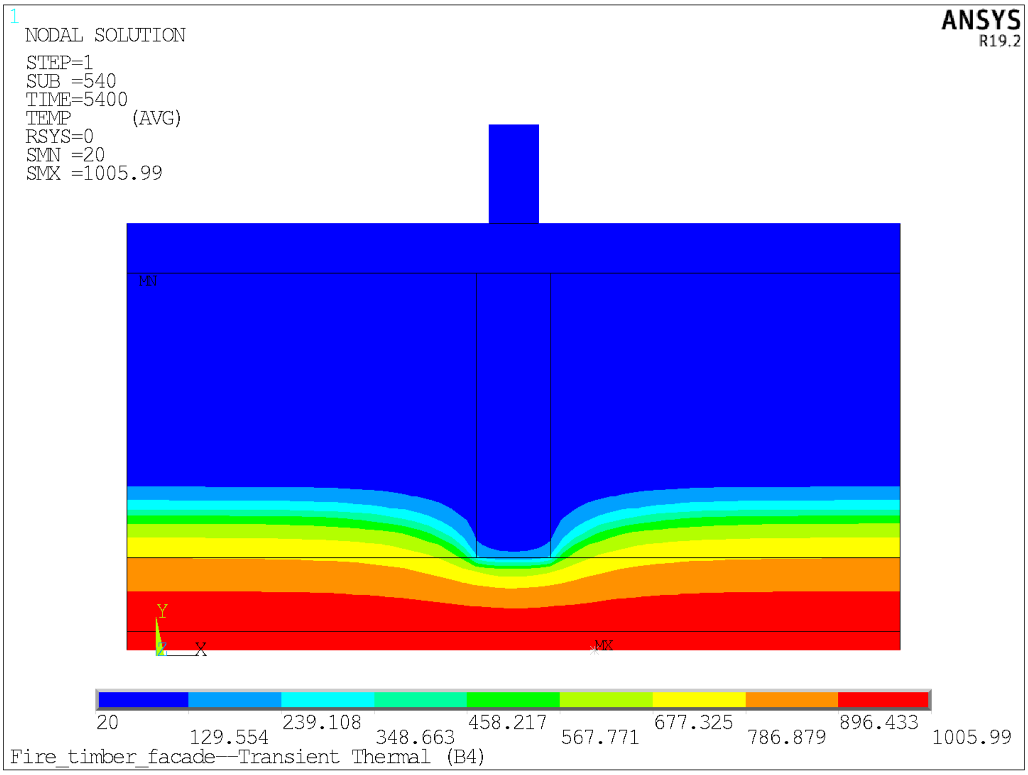

Figure 32. Temperature distribution (°C) on RE[4] CDW Timber Façade for Northern Europe after 90 min.

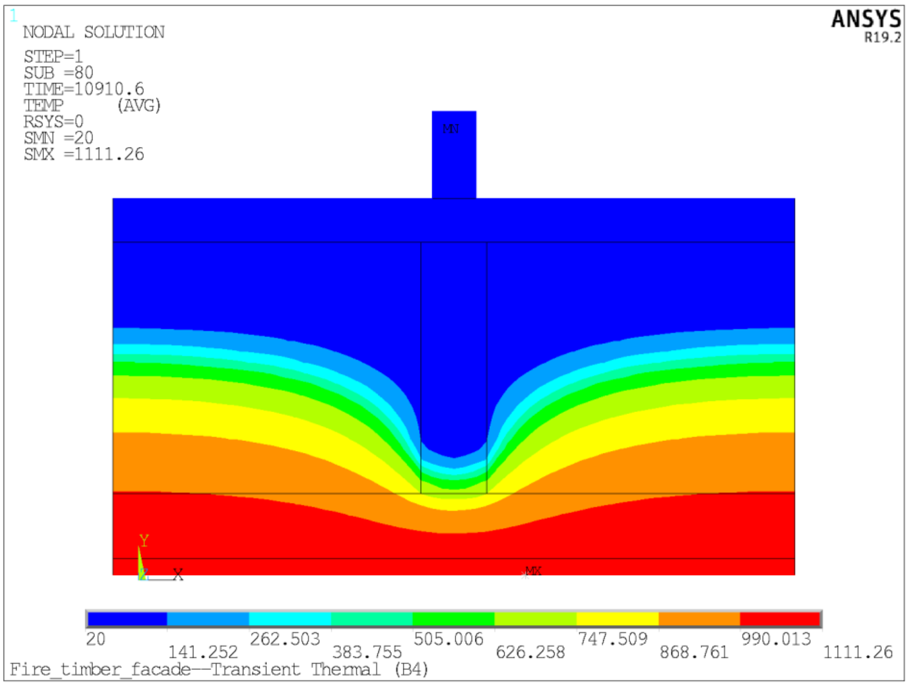

Figure 33. Temperature distribution (°C) on RE^4 CDW Timber Façade for Northern Europe after 180 min.

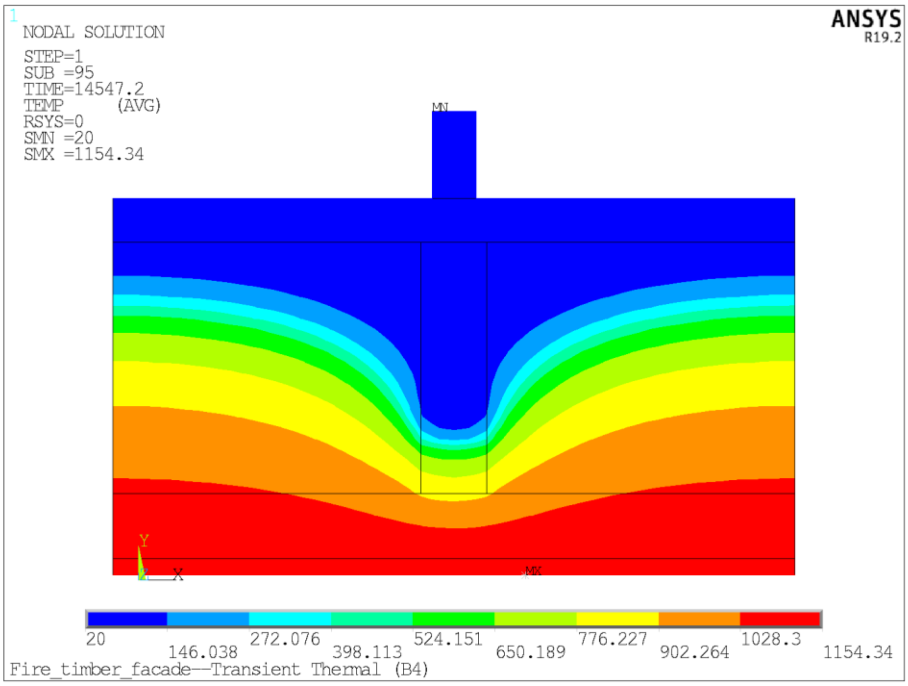

Figure 34. Temperature distribution (°C) on RE^4 CDW Timber Façade for Northern Europe after 240 min.

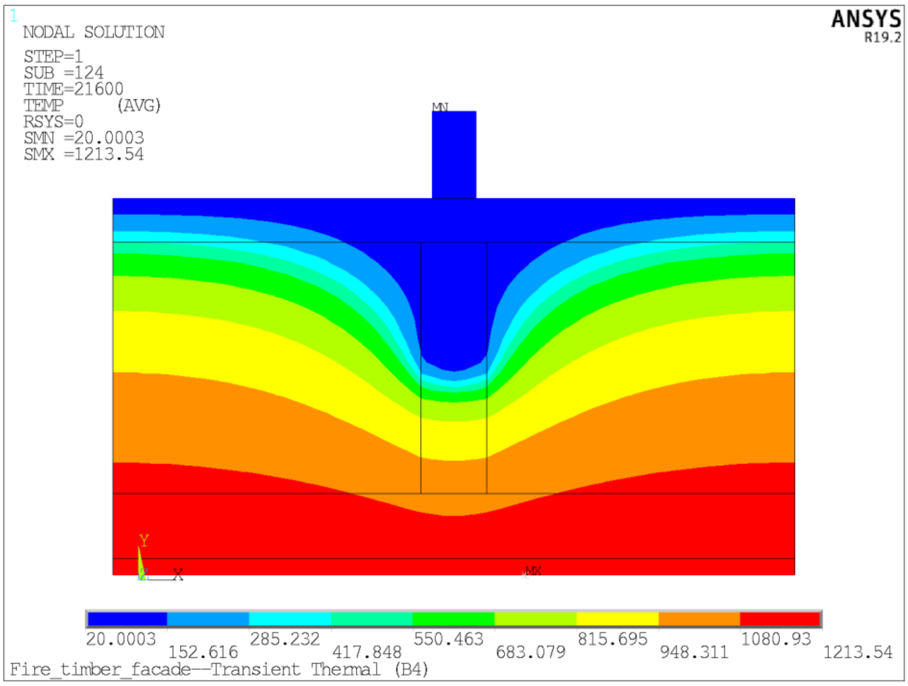

Figure 35. Temperature distribution (°C) on RE4 CDW Timber Façade for Northern Europe after 360 min.

Figure 36 and Figure 37 show the temperature on the warmest node of the exposed side and of the one on the unexposed side, respectively, as function of the time. Considering the criteria defined in Section 3.1, the highest predicted temperature on the outer layer, which is ca 35°C, is lower than 180°C and consequently also the average temperature is lower than 140°C at the minute 360.

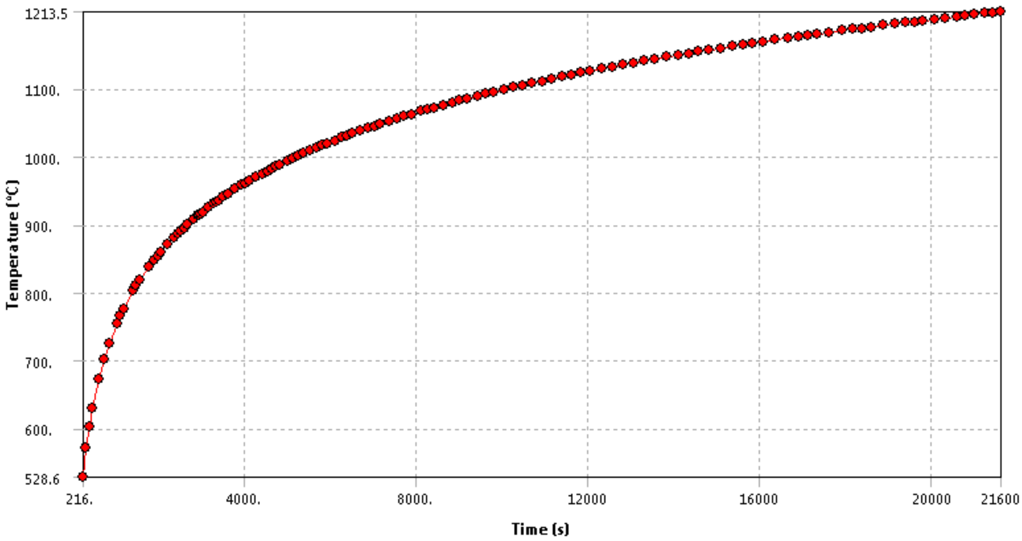

Figure 36. Maximum temperature on the exposed side *vs* Time

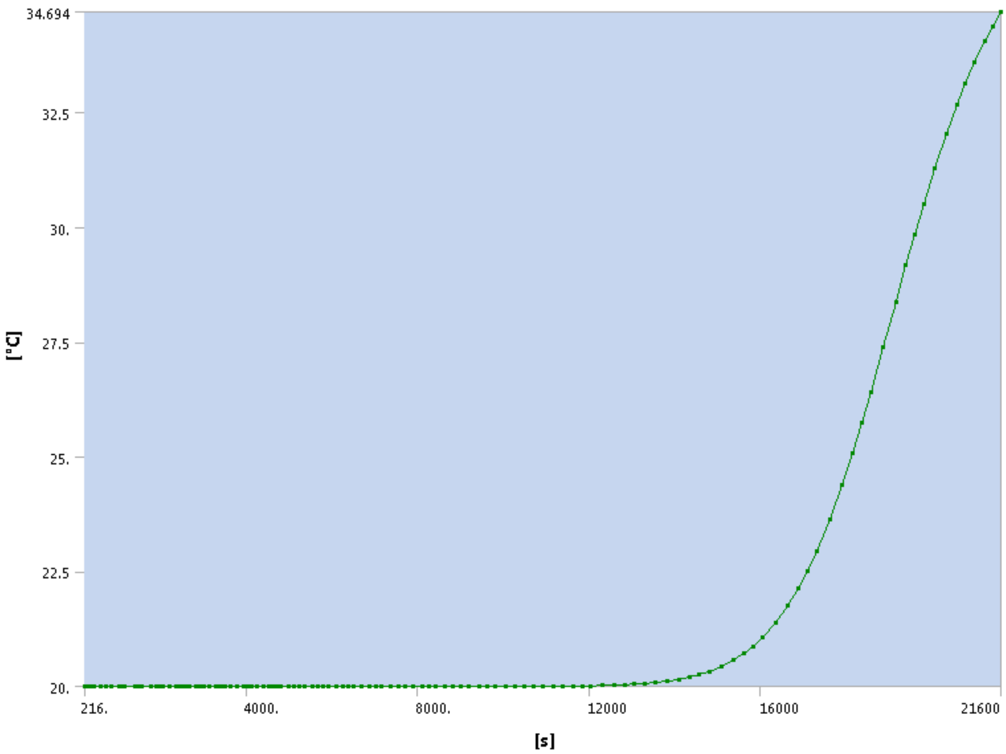

Figure 37. Maximum temperature on the unexposed side *vs* Time

9.1.2. RE[4] CDW Timber Façade for Southern Europe (Option 1)

Similar to the previous analysis, the following figures show the temperature contour plot of the Timber Façade for warm climate (option 1) at the minutes 45, 90, 180, 240 and 360.

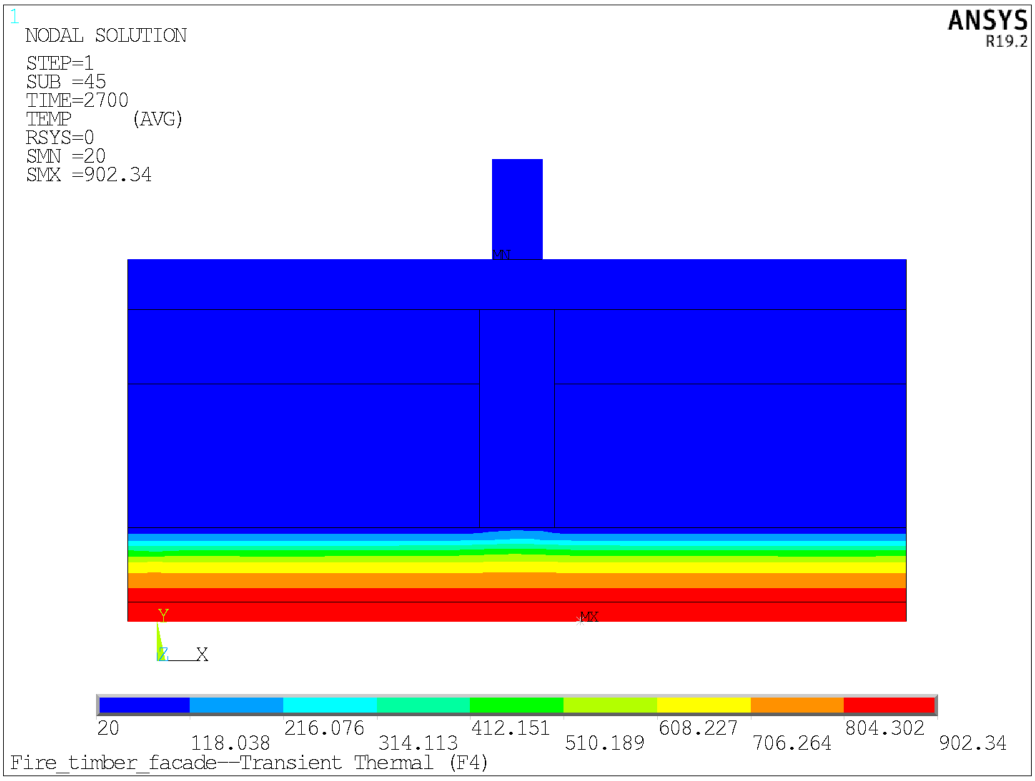

Figure 38. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 1 – after 45 min.

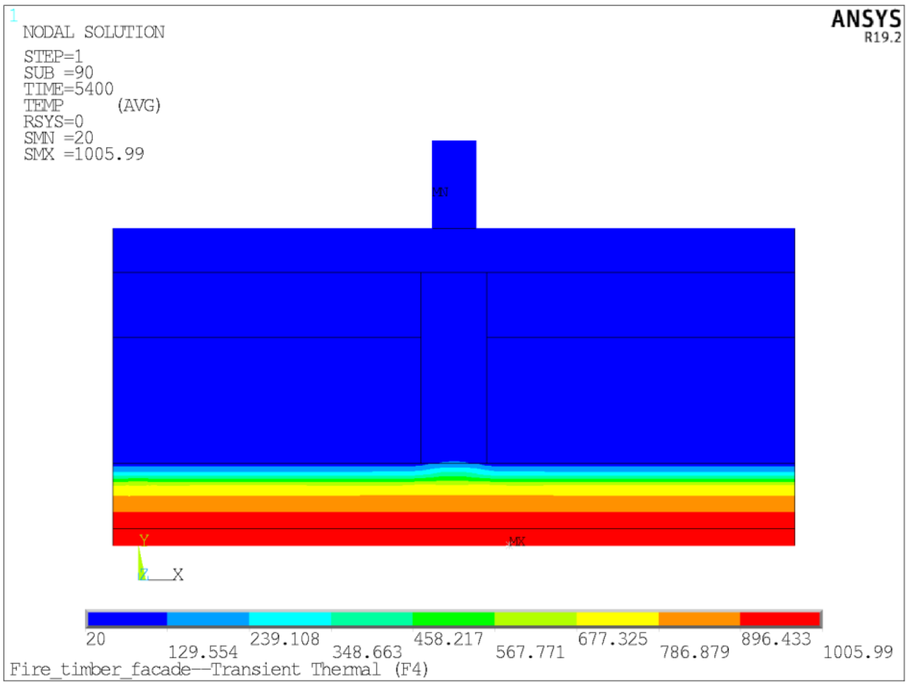

Figure 39. Temperature distribution (°C) on RE4 CDW Timber Façade for Southern Europe – Option 1 – after 90 min

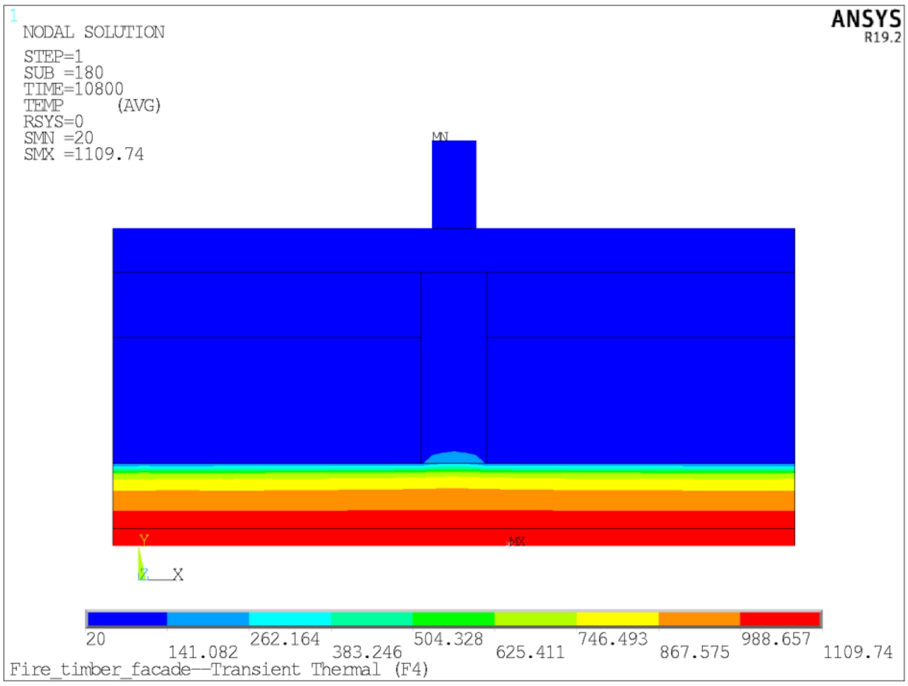

Figure 40. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 1 – after 180 min

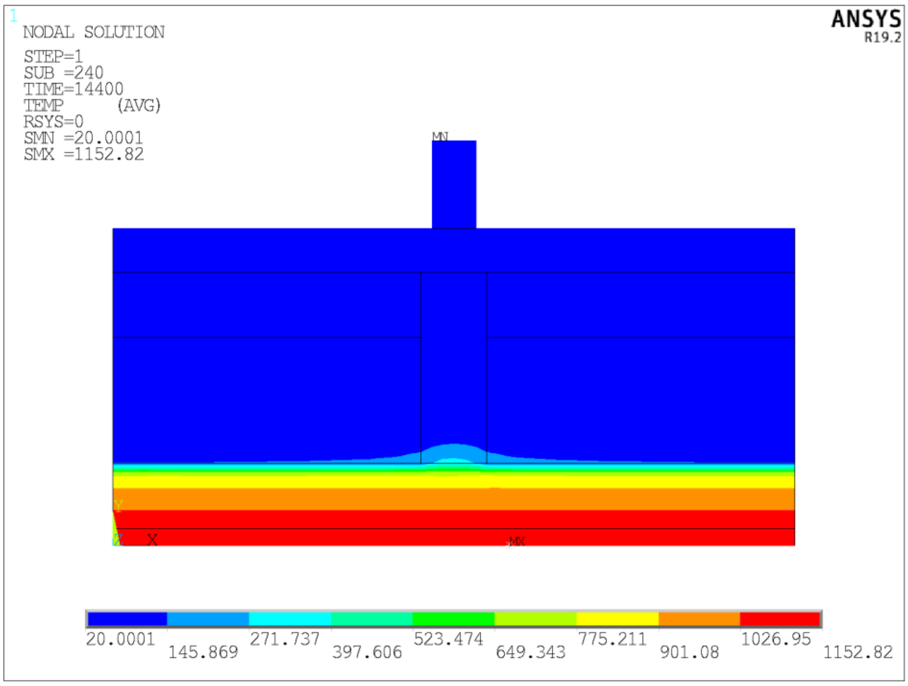

Figure 41. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 1 – after 240 min

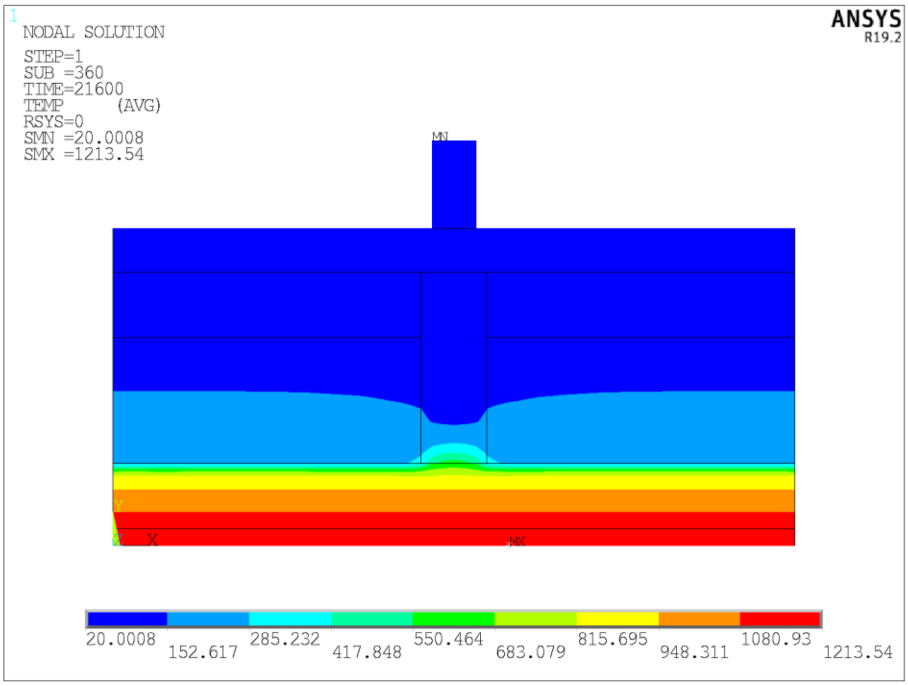

Figure 42. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 1 – after 360 min

Figure 43 shows the highest temperature at the warmest node as function of time of the exposed side of the structure. **Figure 44** displays the same graph but evaluating the unexposed layer and predicting a peak equal to 21 °C at 360 min, which is well below 180°C, and by consequence also the average temperature is lower than 140°C.

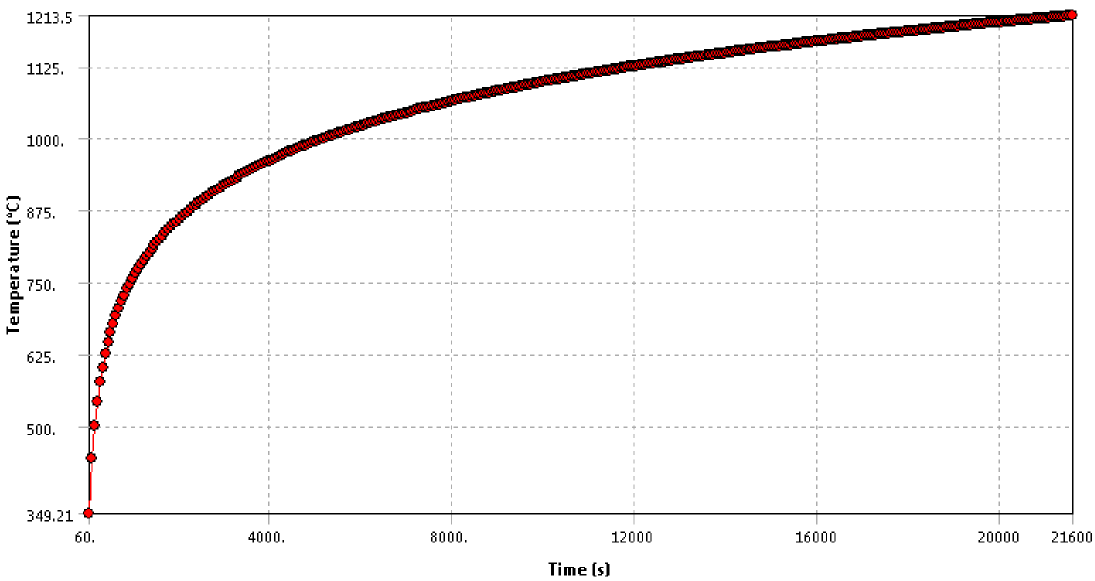

Figure 43. Maximum temperature on the exposed side *vs* Time

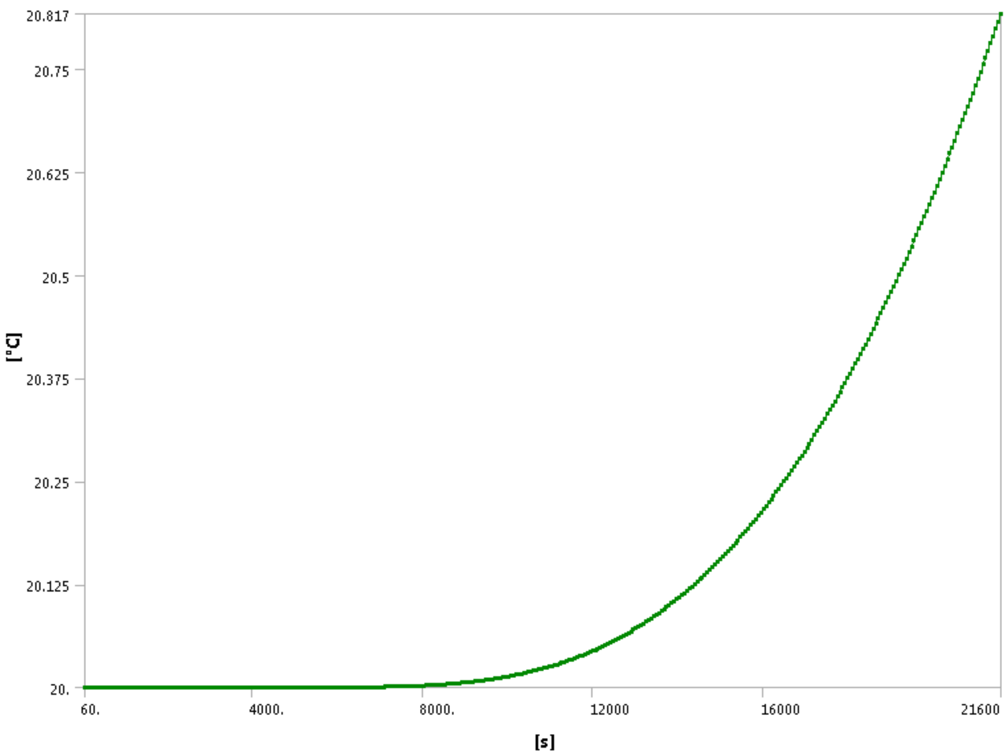

Figure 44. Maximum temperature on the exposed side *vs* Time

9.1.3. RE4 CDW Timber Façade for Southern Europe (Option 2)

The temperature distribution on the Timber Façade for warm climate (Option 2) at the minutes 45, 90, 180, 240 and 360 are shown in the following figures.

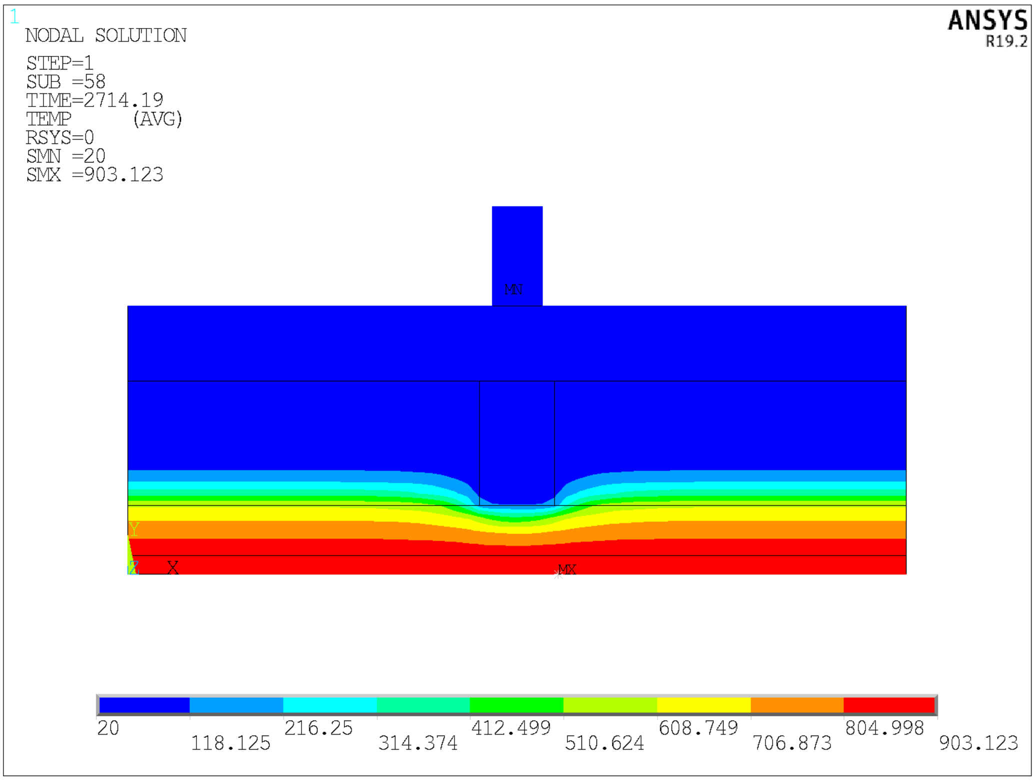

Figure 45. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 2 – after 45 min.

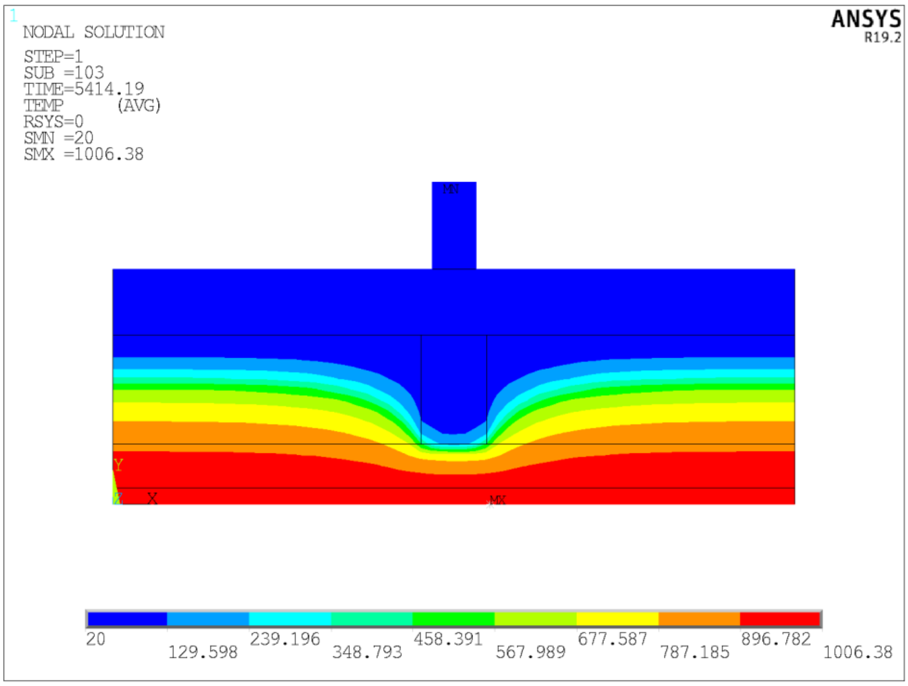

Figure 46. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 2 – after 90 min.

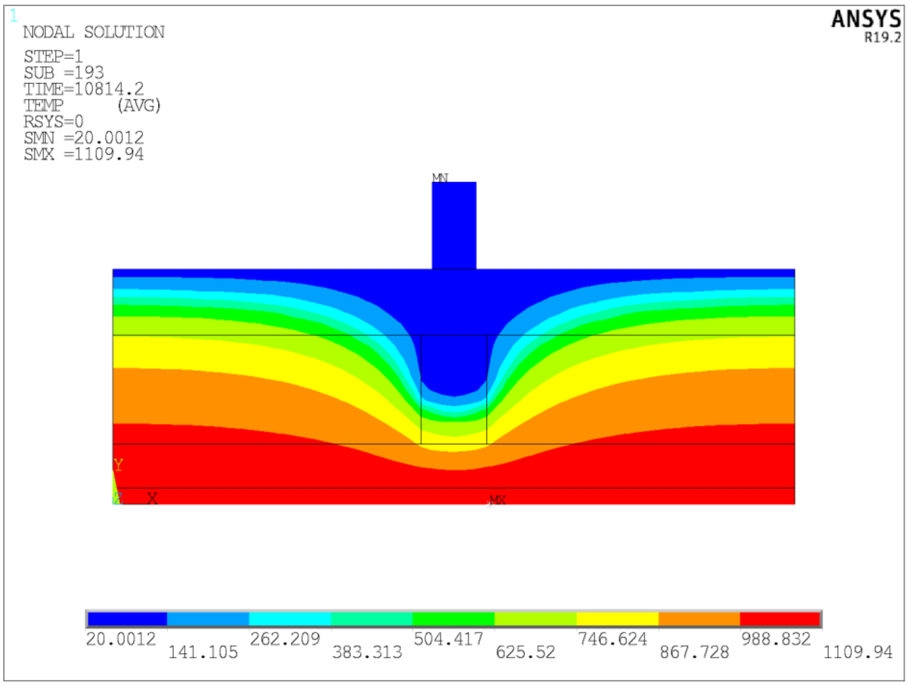

Figure 47. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 2 – after 180 min.

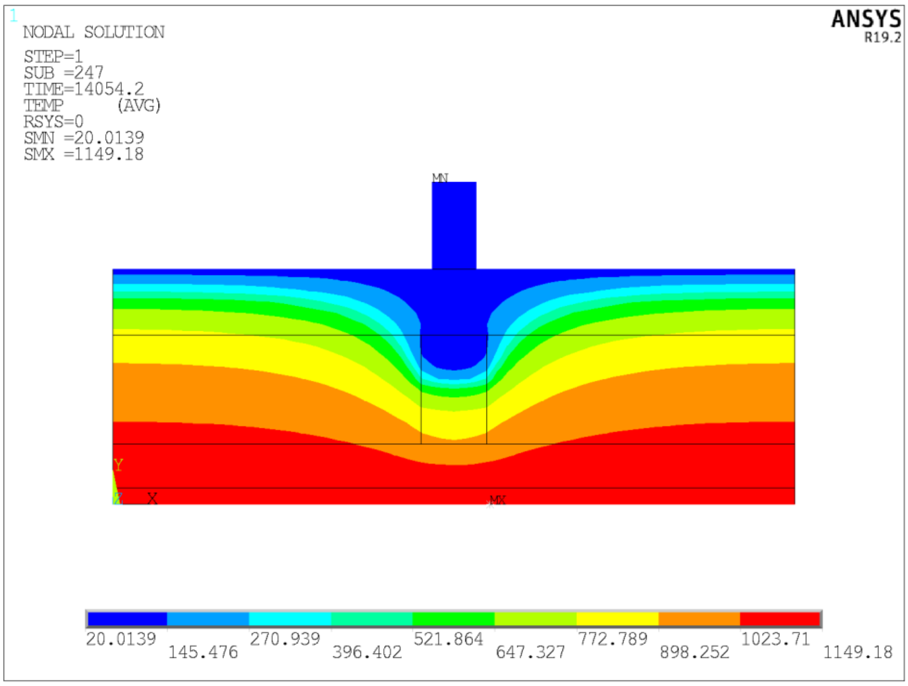

Figure 48. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 2 – after 240 min.

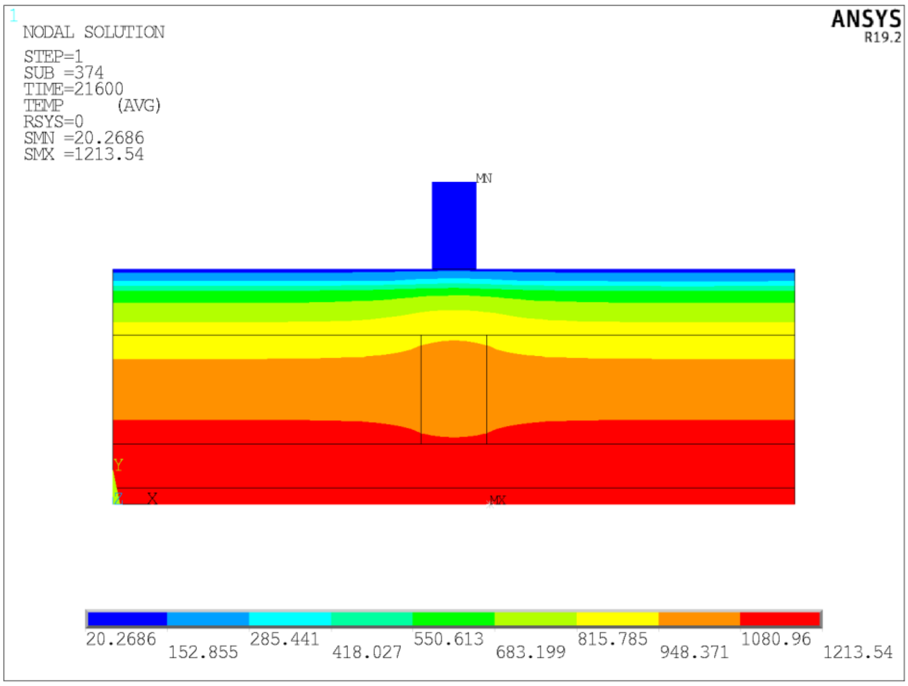

Figure 49. Temperature distribution (°C) on RE[4] CDW Timber Façade for Southern Europe – Option 2 – after 360 min.

The maximum temperature on the exposed side as function of the time is shown in **Figure 50**. **Figure 51** shows that on the unexposed side, after 360 min the highest temperature is about 116 °C, which is lower than 180°C and ensure an average temperature on the outer layer lower than 140°C.

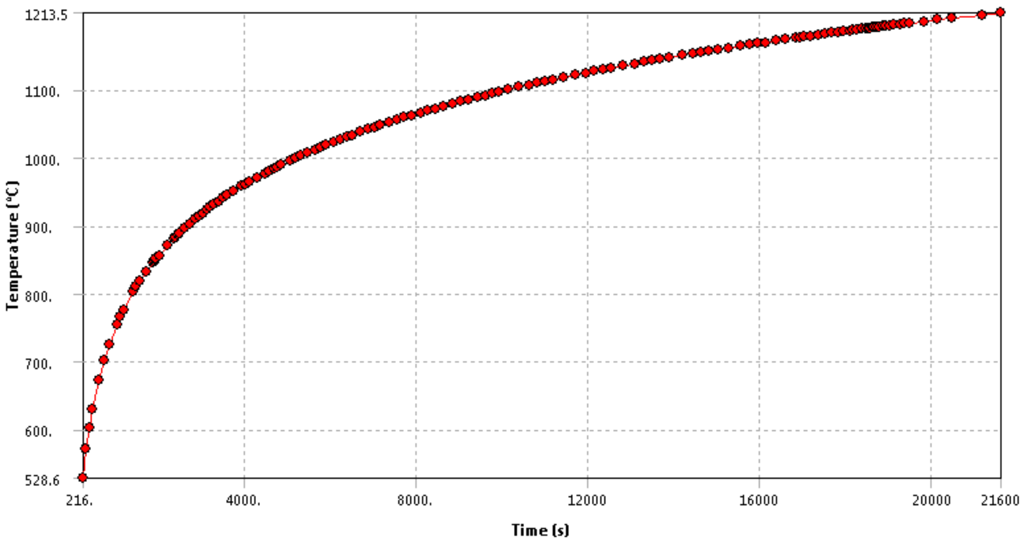

Figure 50. Maximum temperature on the exposed side *vs* Time

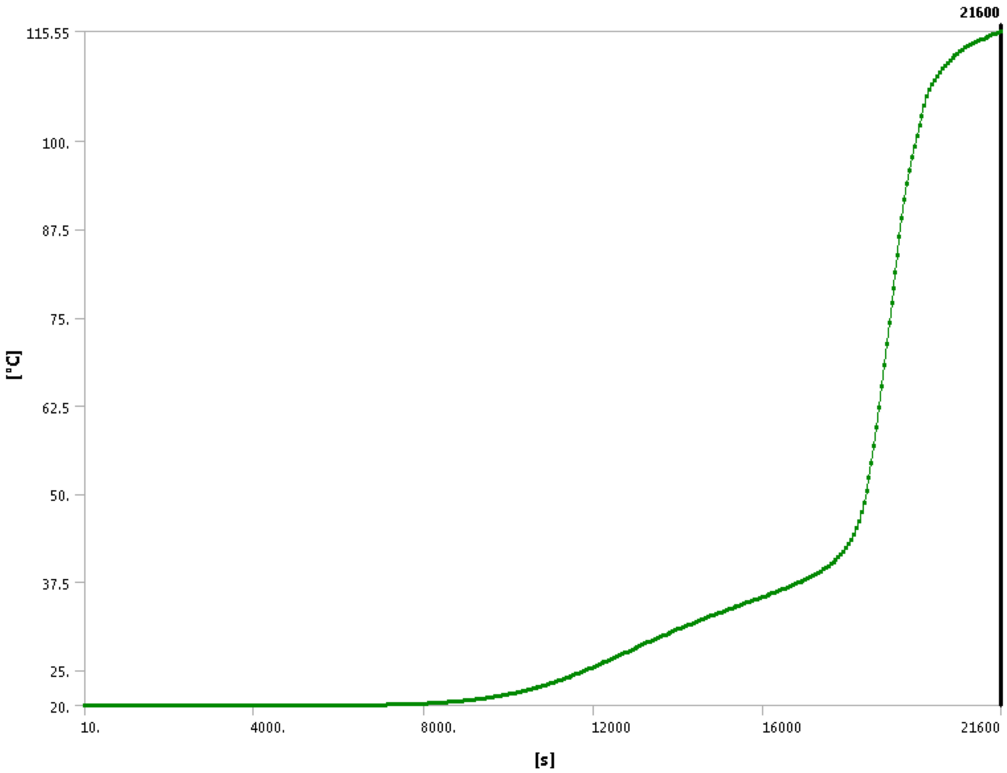

Figure 51. Minimum temperature on the unexposed side *vs* Time

9.2. Thermal analysis – RE^4 Concrete Sandwich Panel

9.2.1. RE^4 Concrete Sandwich Panel for Northern Europe

The temperature contour plot on the Sandwich Panel for Northern Europe is shown in the following figures for the minutes 45, 90, 180, 240 and 360.

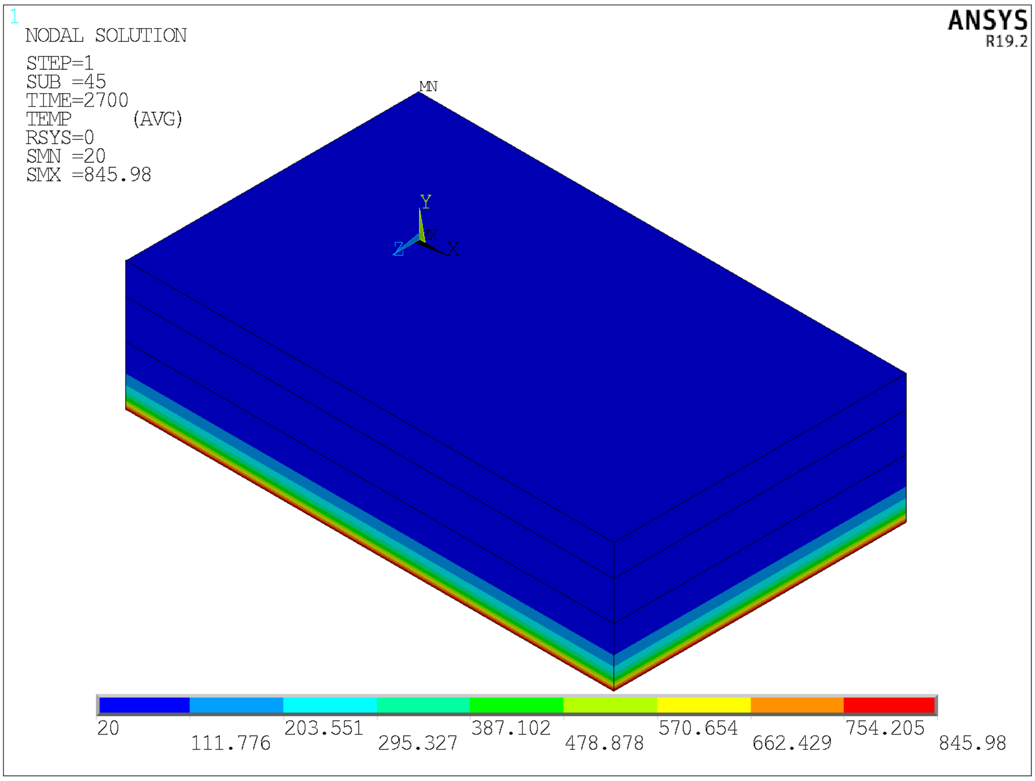

Figure 52. Temperature distribution (°C) on Sandwich Panel for Northern Europe after 45 min.

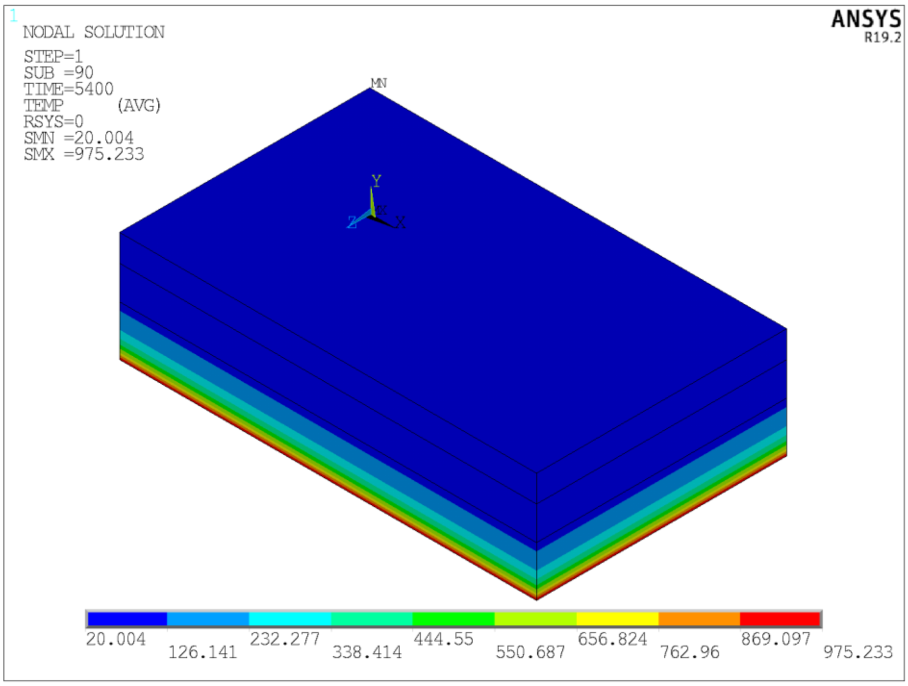

Figure 53. Temperature distribution (°C) on Sandwich Panel for Northern Europe after 90 min.

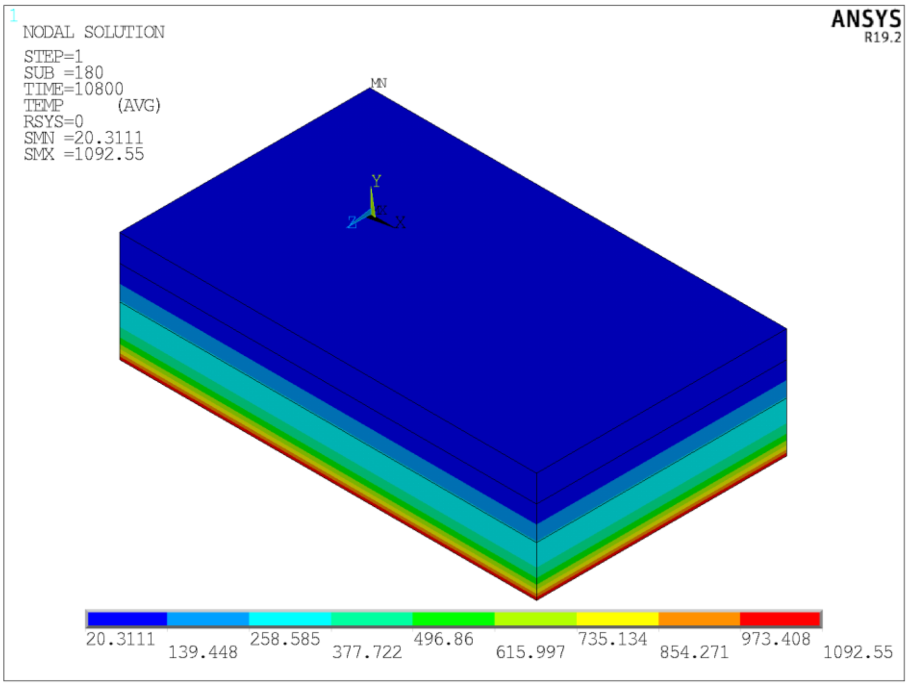

Figure 54. Temperature distribution (°C) on Sandwich Panel for Northern Europe after 180 min.

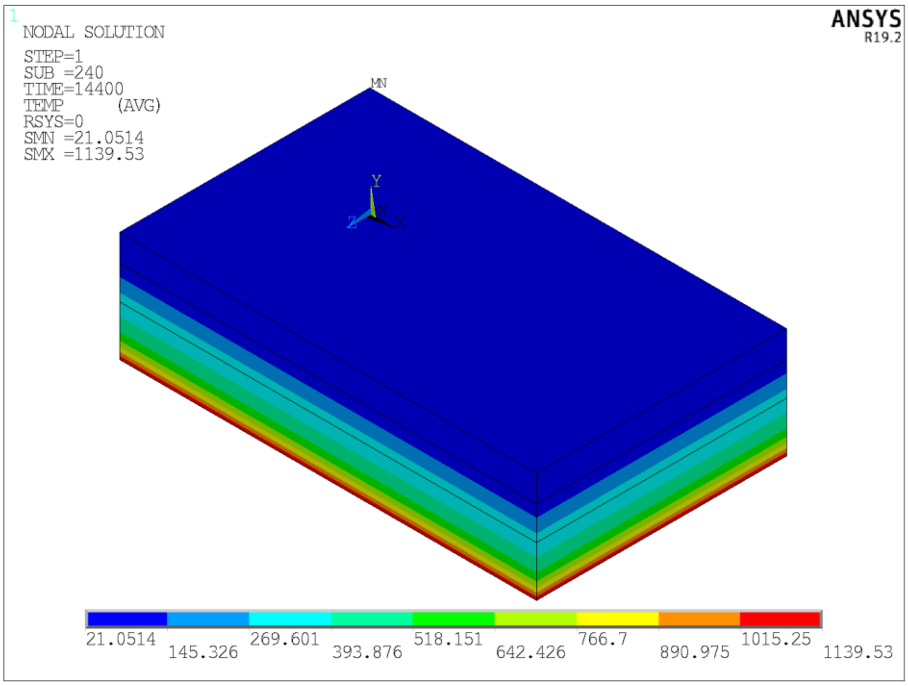

Figure 55. Temperature distribution (°C) on Sandwich Panel for Northern Europe after 240 min.

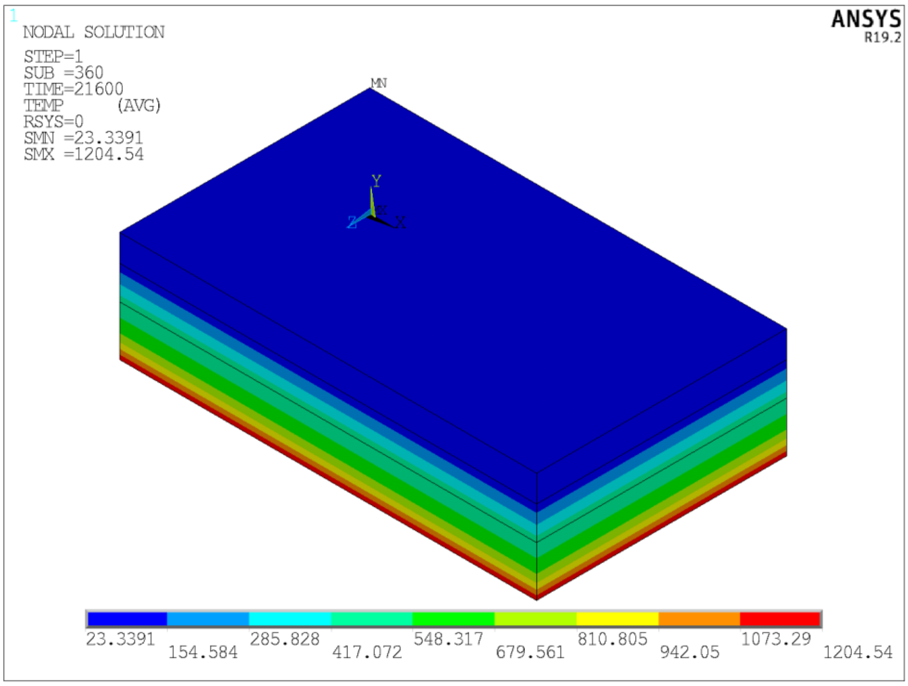

Figure 56. Temperature distribution (°C) on Sandwich Panel for Northern Europe after 360 min.

The maximum temperature on the exposed side and on the unexposed one, as function of the time, is shown in **Figure 64** and **Figure 65** respectively. The outer layer reaches a maximum temperature equal to 23.4°C at 360 min, satisfying the criteria defined in Section 3.1.

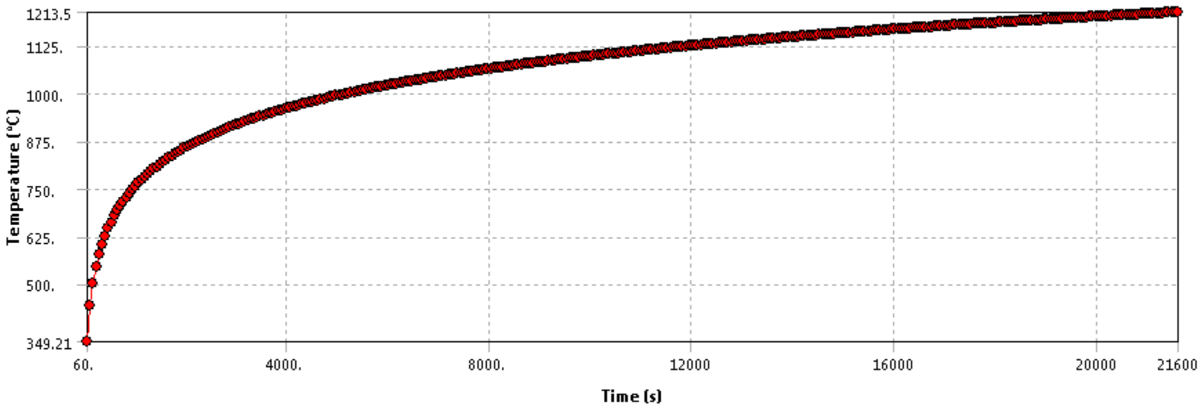

Figure 57. Maximum temperature on the exposed side *vs* Time

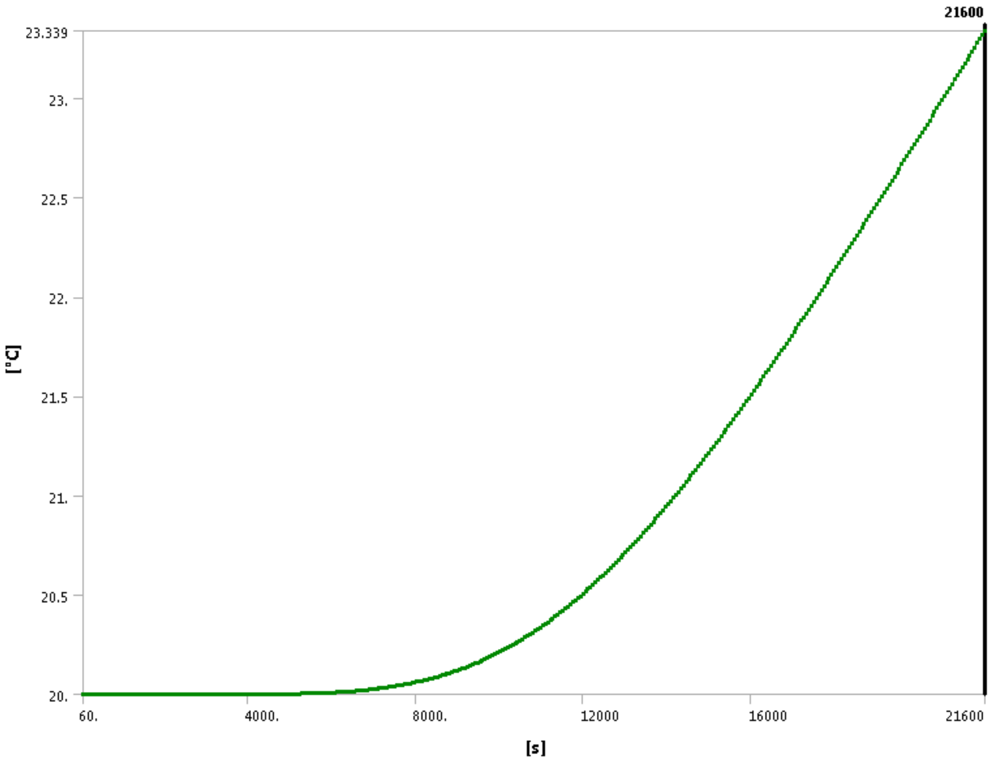

Figure 58. Maximum temperature on the unexposed side *vs* Time

9.2.2. RE4 Concrete Sandwich Panel for Southern Europe

The figures below show the temperature distribution at the minutes 45, 90,180,240 and 360, on the Sandwich Panel for Southern Europe.

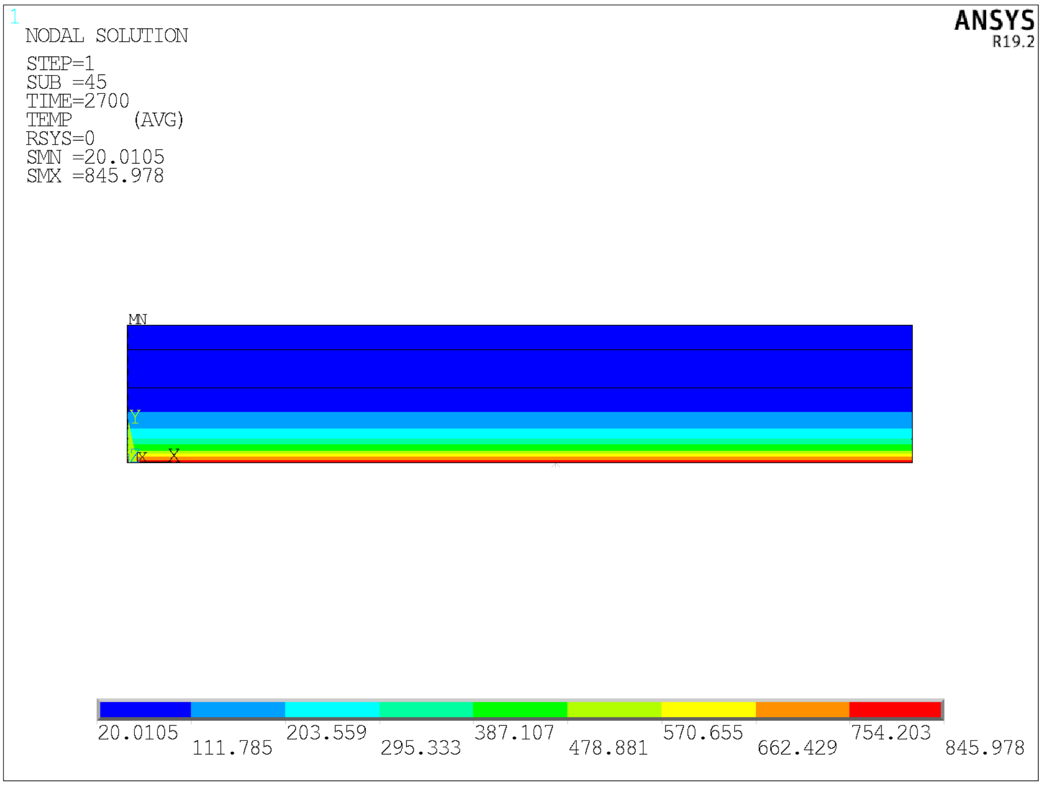

Figure 59. Temperature distribution (°C) on RE^4 Concrete Sandwich Panel for Southern Europe after 45 min.

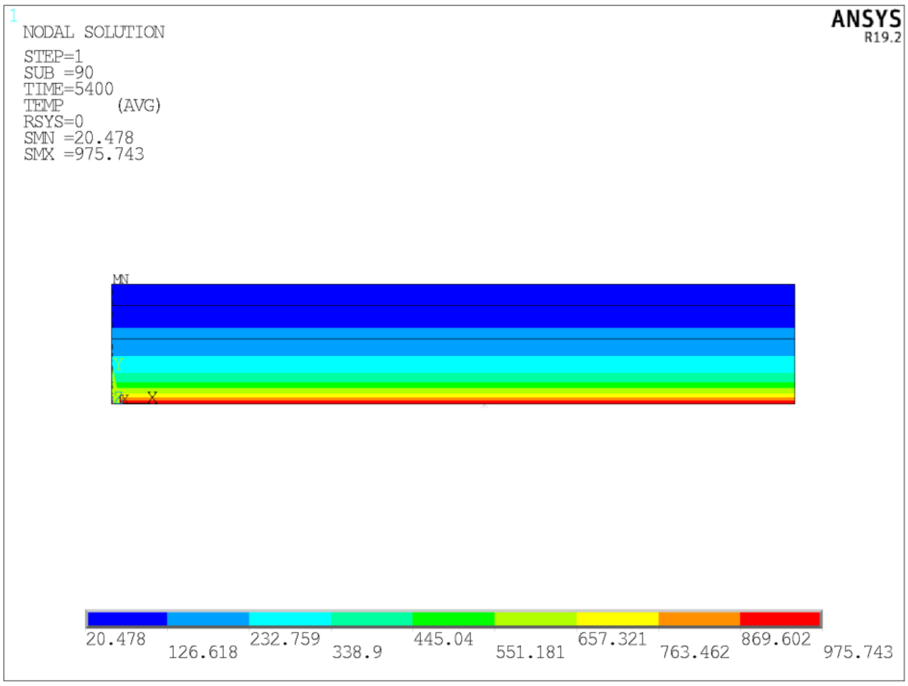

Figure 60. Temperature distribution (°C) on RE^4 Concrete Sandwich Panel for Southern Europe after 90 min.

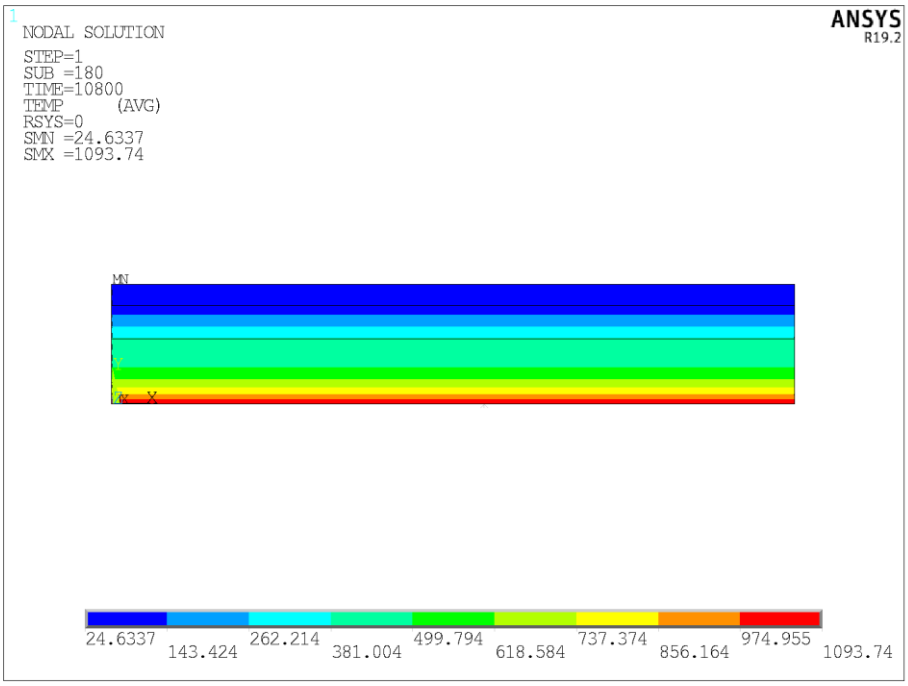

Figure 61. Temperature distribution (°C) on RE^4 Concrete Sandwich Panel for Southern Europe after 180 min.

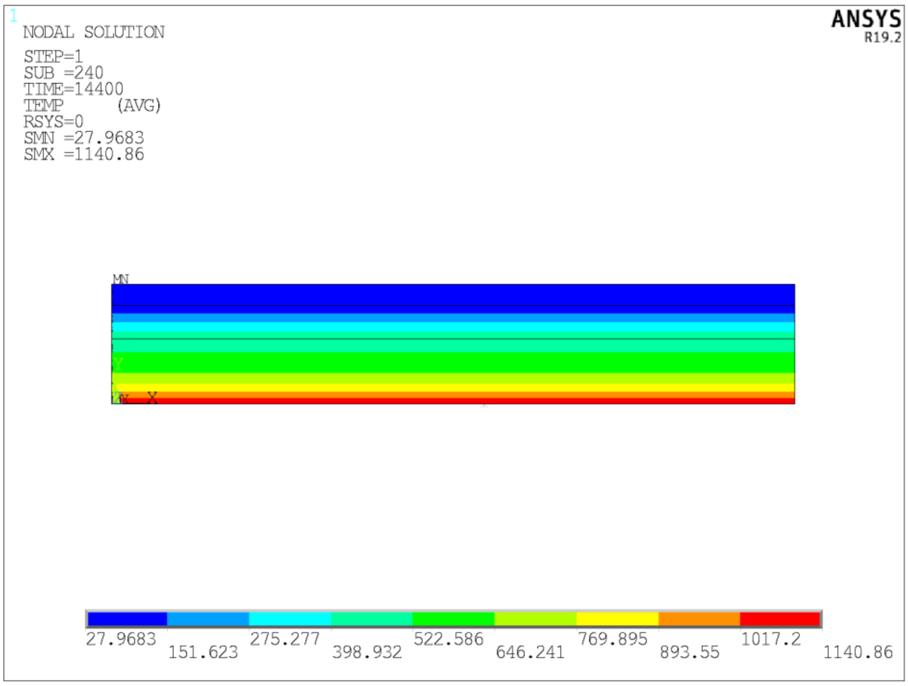

Figure 62. Temperature distribution (°C) on RE^4 Concrete Sandwich Panel for Southern Europe after 240 min.

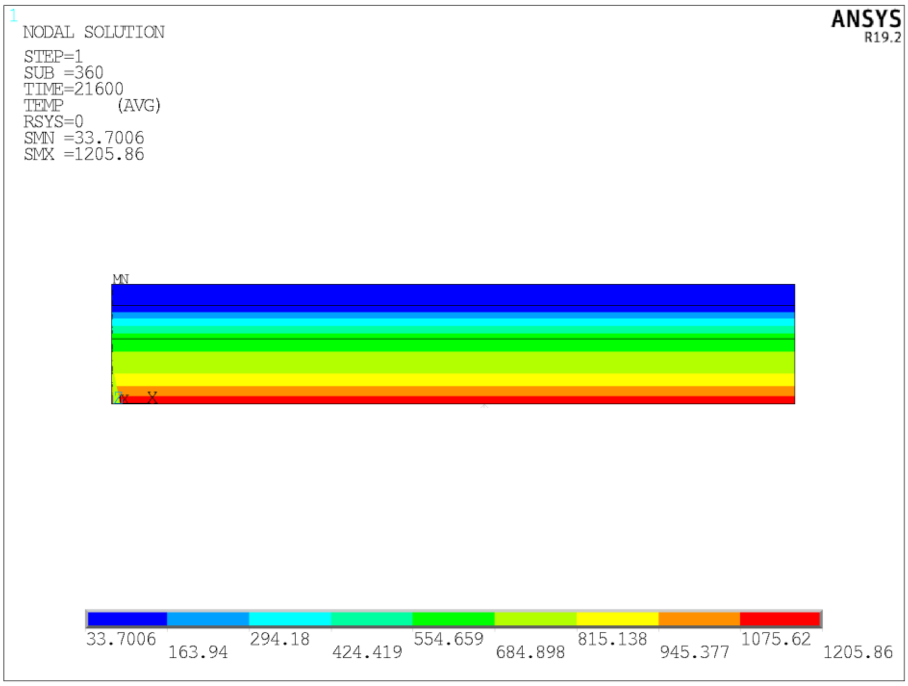

Figure 63. Temperature distribution (°C) on RE⁴ Concrete Sandwich Panel for Southern Europe after 360 min.

Figure 64 shows how the maximum temperature on the exposed side increases with time, while **Figure 65** shows the graph of the highest temperature on the unexposed side during all the time of the simulation. The latter figure displays a peak equal to about 34°C at 360 min, which is lower than 180°C and able to guarantee a mean value lower than 140°C.

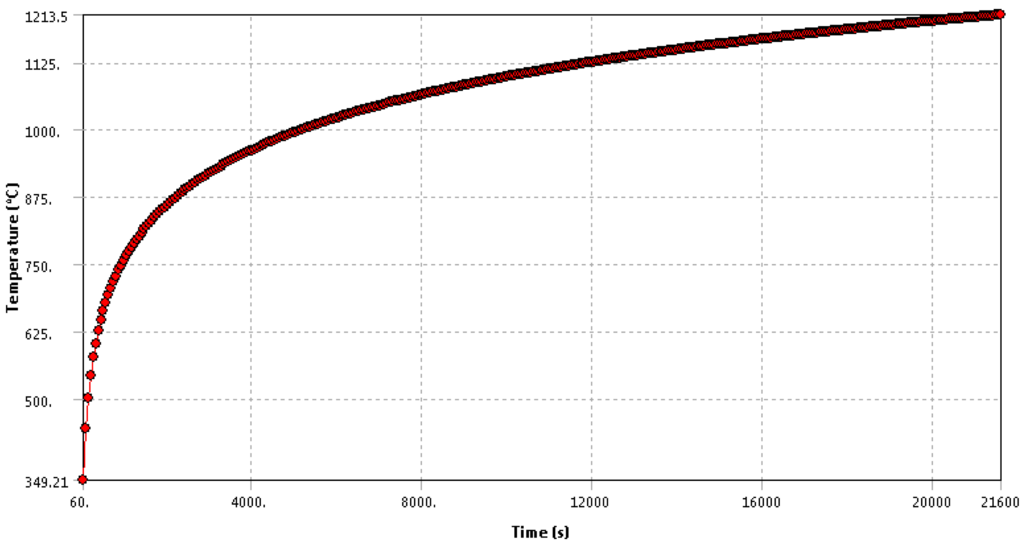

Figure 64. Maximum temperature on the exposed side *vs* Time

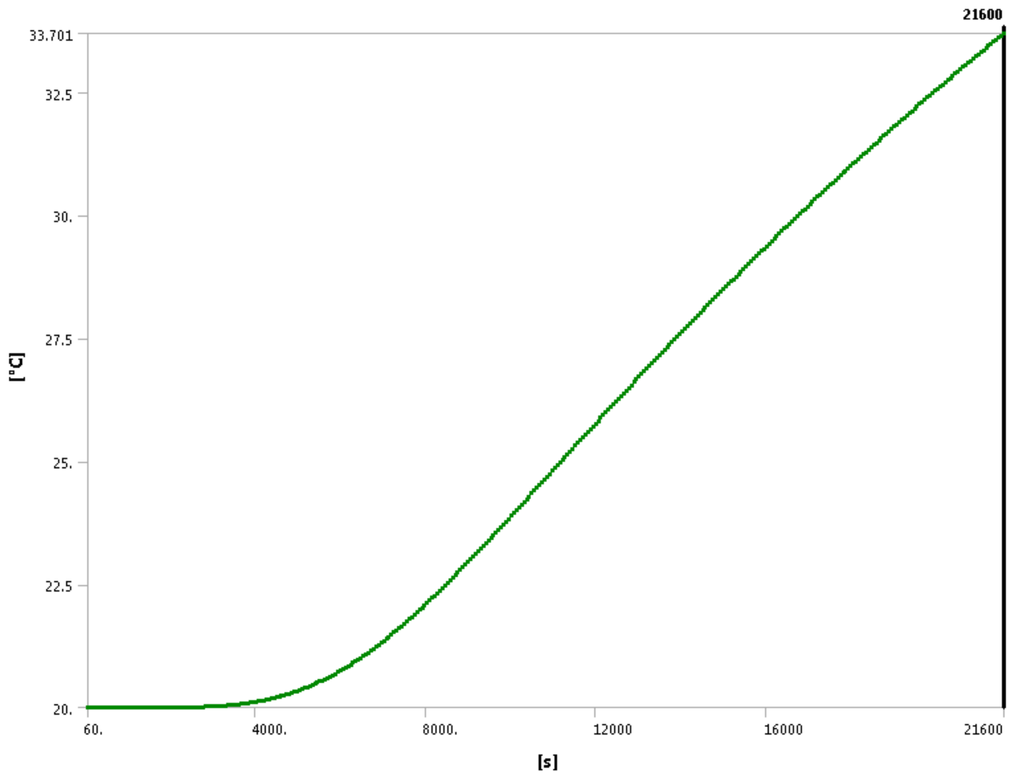

Figure 65. Maximum temperature on the unexposed side *vs* Time

9.3. Structural analysis – RE[4] Concrete Sandwich Panel

The contour plot of the total displacement [mm] on the exposed side for the minutes 90, 180, 240 and 360 is shown in **Figure 66**, **Figure 67**, **Figure 68** and **Figure 69**, respectively. The structure exhibits a deflection and the maximum displacement, equal to about 2.74 mm, has been reached on the exposed panel. The graph in **Figure 70** shows how the maximum deflection increases over time. The highest value has been used in order to check the criteria defined in Section 3.2. The limiting deflection has been calculated as following:

$$\text{Limiting deflection, } D = \frac{L^2}{400\ d}\ (mm) = 11.83 \text{ mm}$$

With
d = 330 mm
L = 1250 mm

The obtained value is higher than the maximum deflection and the first criterion is satisfied.
The limiting rate of deflection can be evaluated as:

$$\text{Limiting rate of deflection, } \frac{dD}{dt} = \frac{L^2}{9000\ d}\ (mm/min) = 0.52 \text{ mm/min}$$

The maximum registered rate of deflection is equal to 0.288 mm/min from minute 129 to minute 130, as visible in **Figure 71**, and consequently also the second criterion is satisfied.

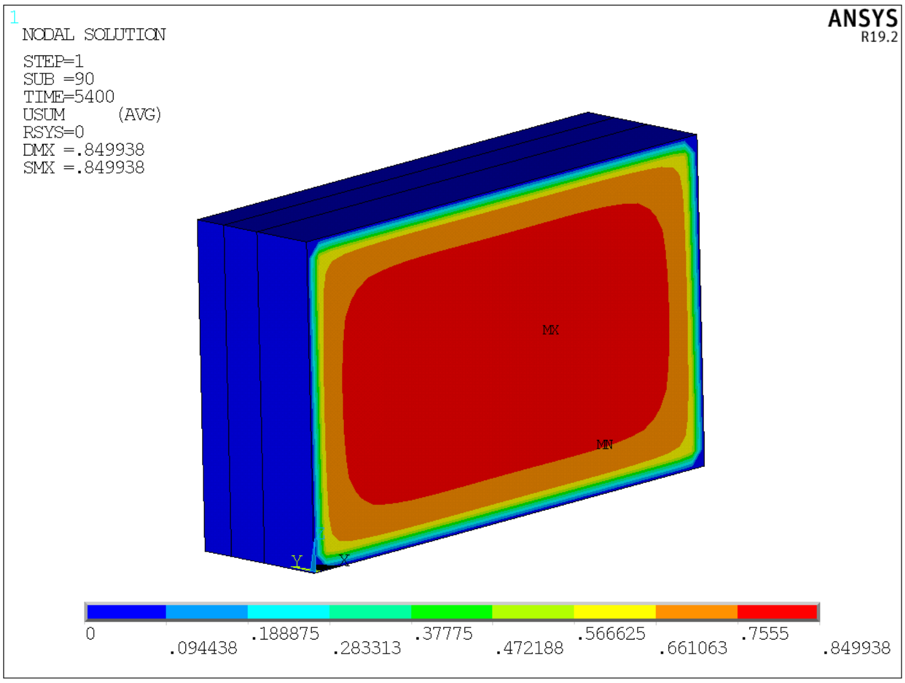

Figure 66. Total displacement (mm) on the exposed side - minute 90

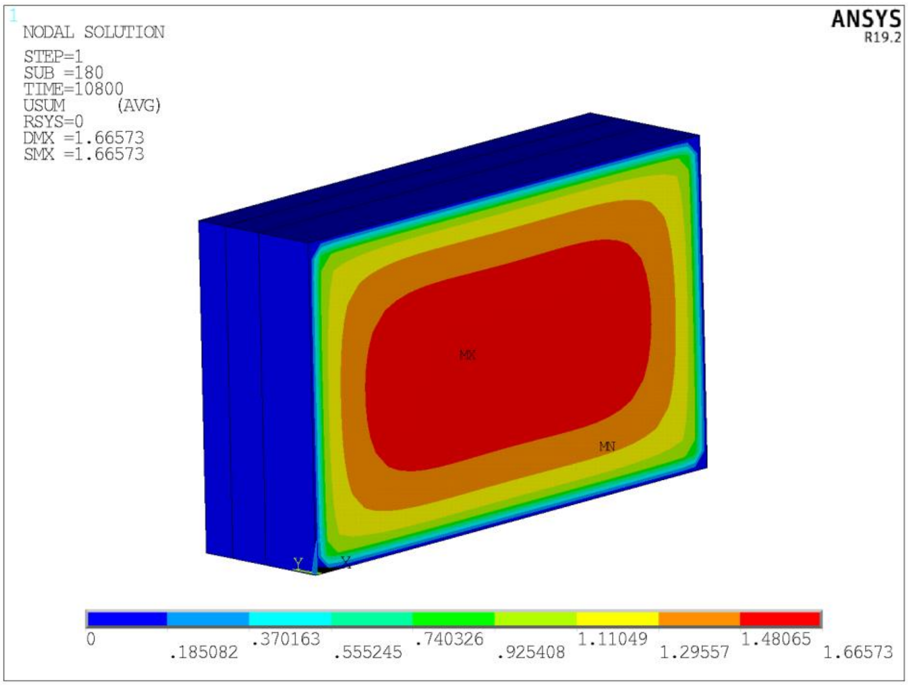

Figure 67. Total displacement (mm) on the exposed side - minute 180

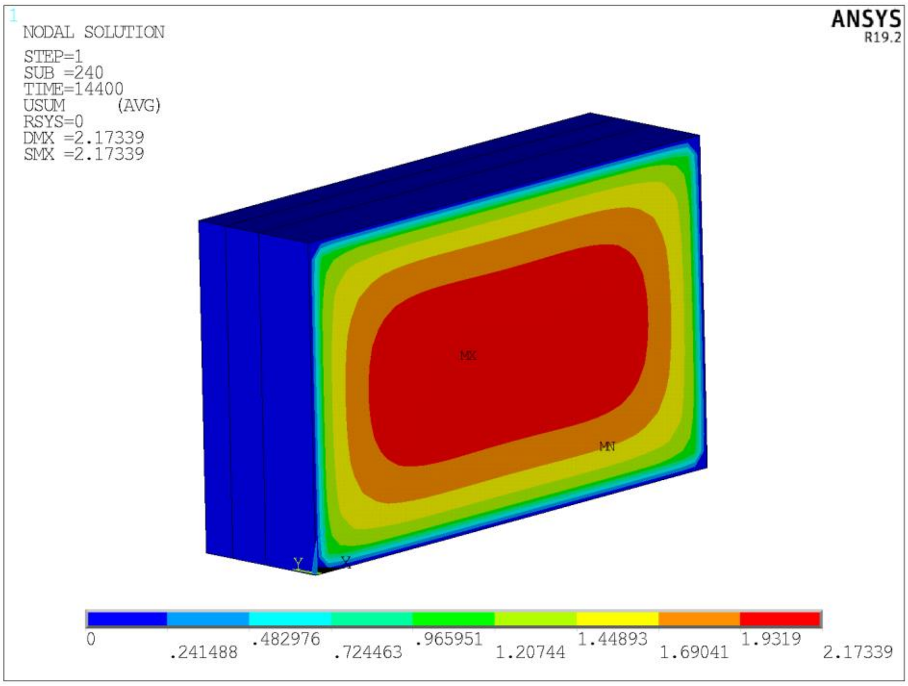

Figure 68. Total displacement (mm) on the exposed side - minute 240

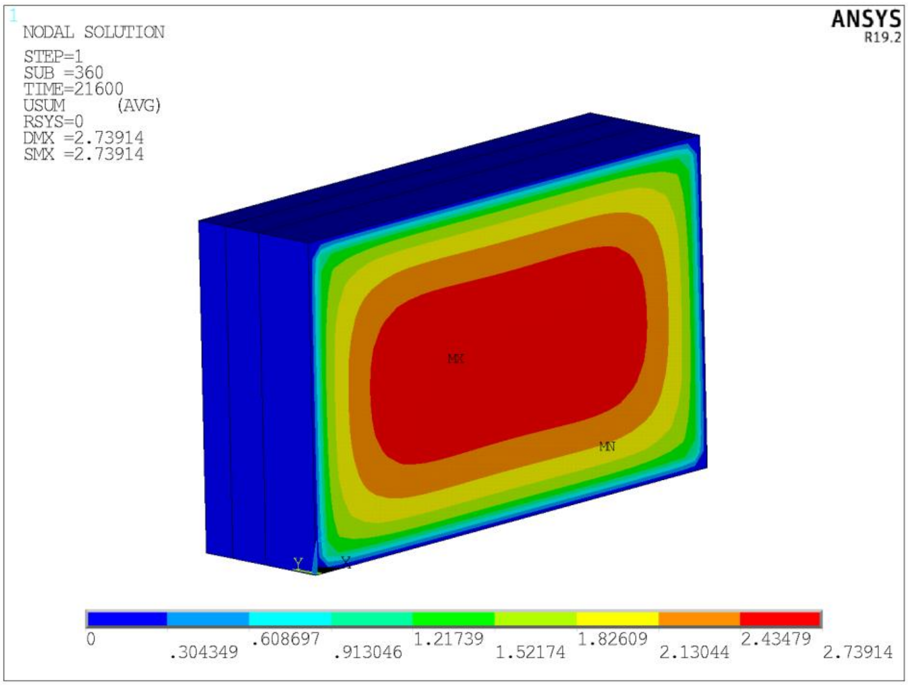

Figure 69. Total displacement (mm) on the exposed side - minute 360

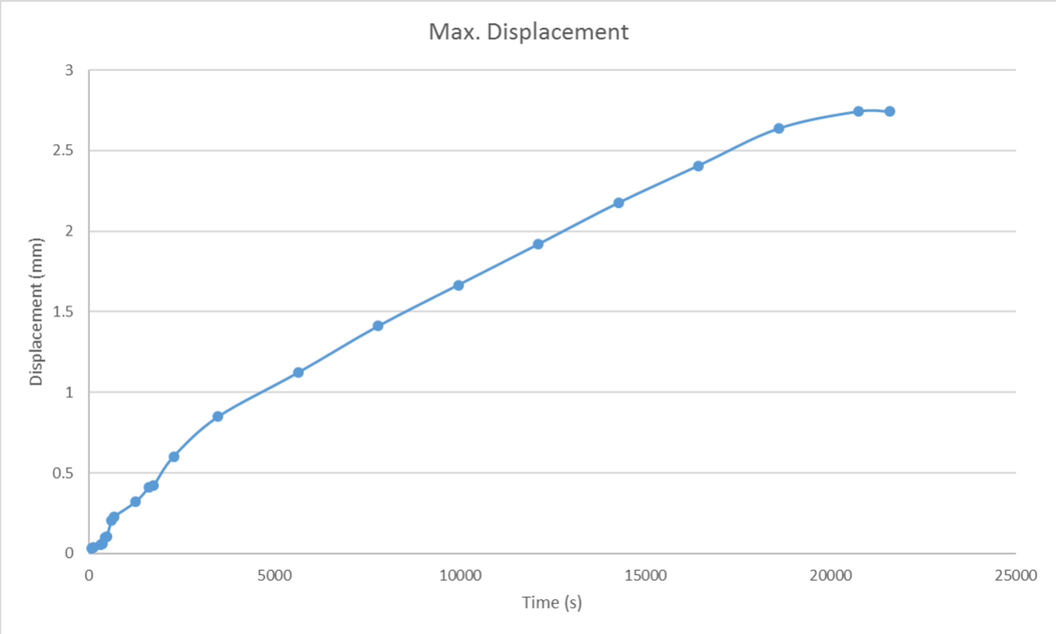

Figure 70. Deflection (mm) *vs* Time (s) – Exposed side

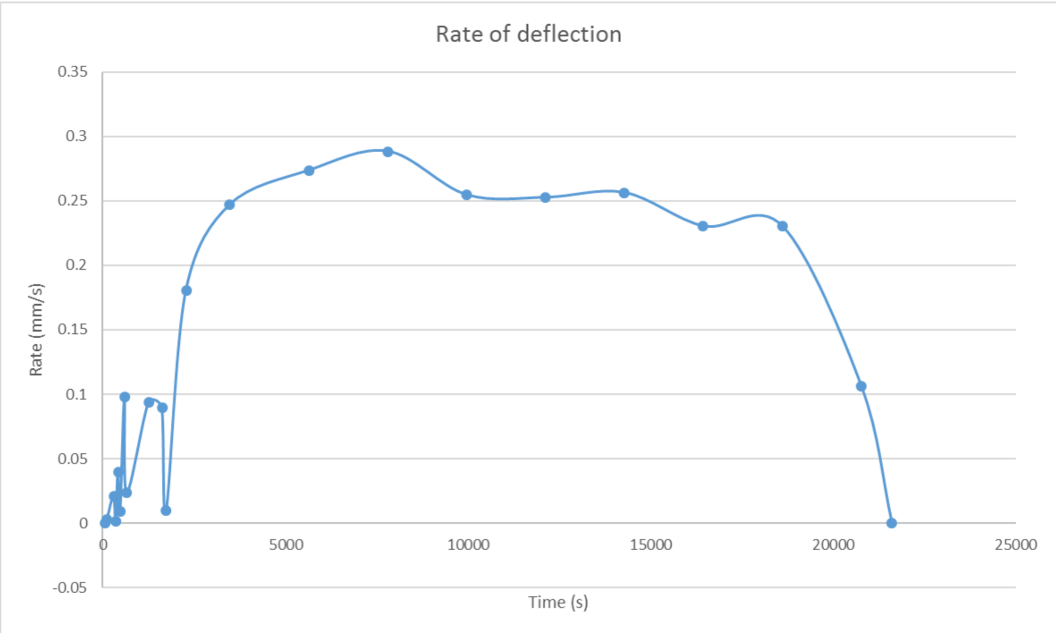

Figure 71. Rate of deflection (mm/s) *vs* Time (s) – Exposed side

Looking at the unexposed side, the following Figures shows the contour plot of the total displacement for the minutes 90, 180, 240 and 360. The graph in **Figure 76** shows how the maximum displacement increases over the time, reaching a maximum equal to 2.02 mm and consequently lower than the previous limiting deflection calculated. The rate of the deflection is shown in **Figure 77**, displaying a peak equal to about 0.29 mm/min, which is below the limiting value calculated.

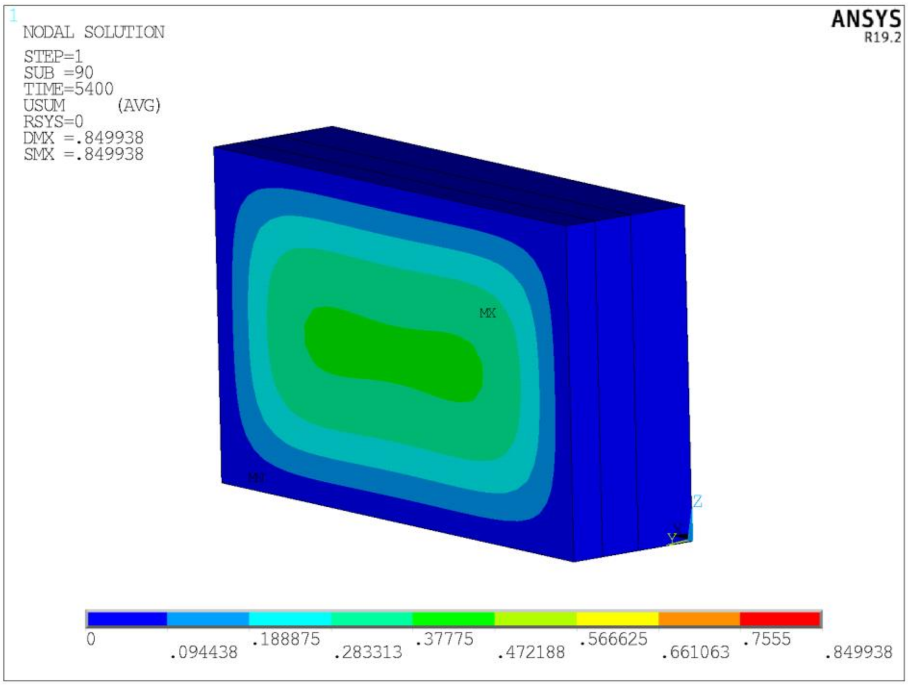

Figure 72. Total displacement (mm) on the unexposed side - minute 90

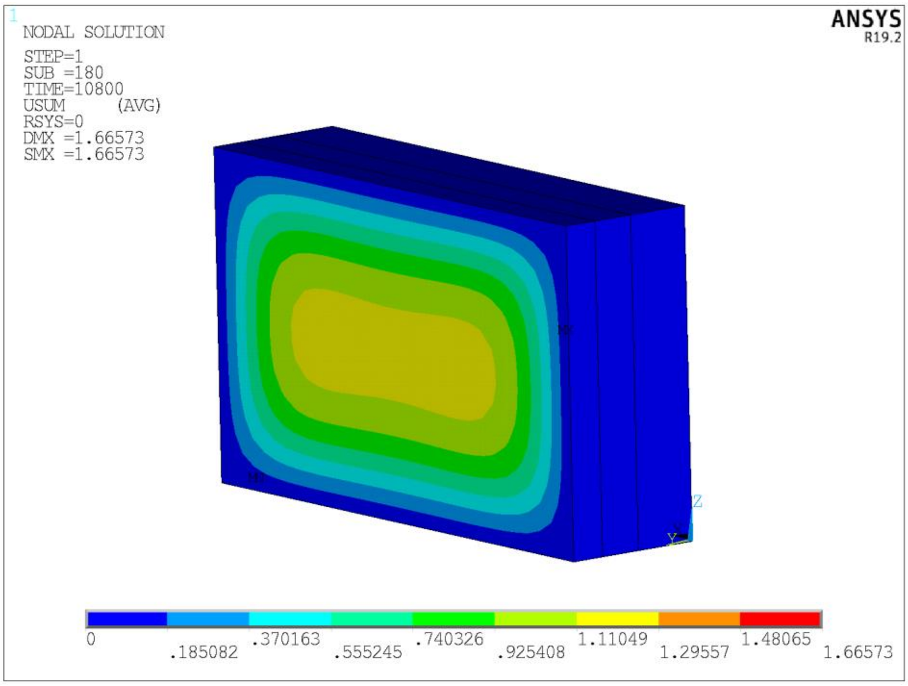

Figure 73. Total displacement (mm) on the unexposed side - minute 180

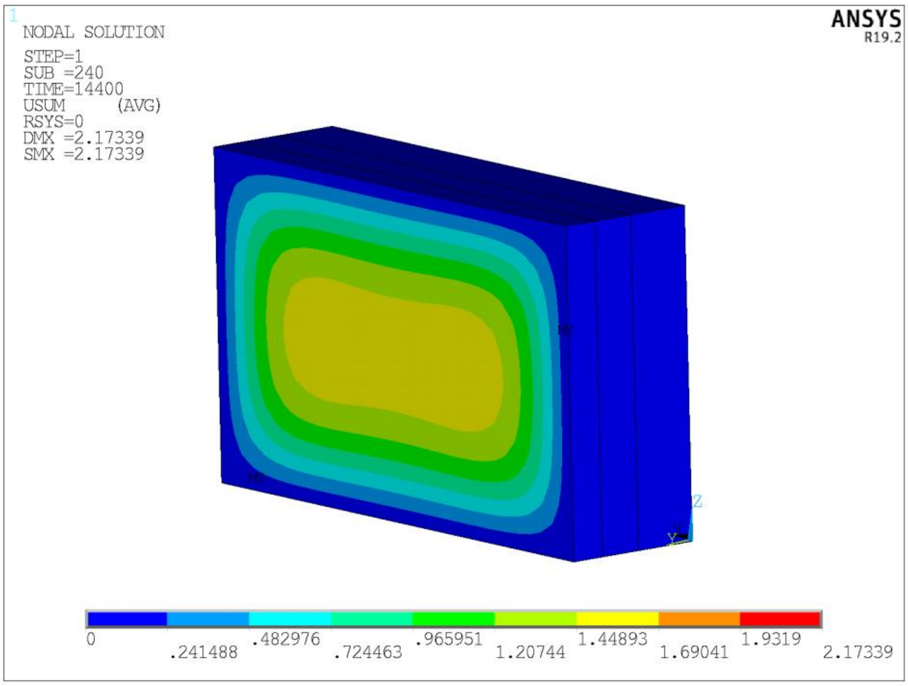

Figure 74. Total displacement (mm) on the unexposed side - minute 240

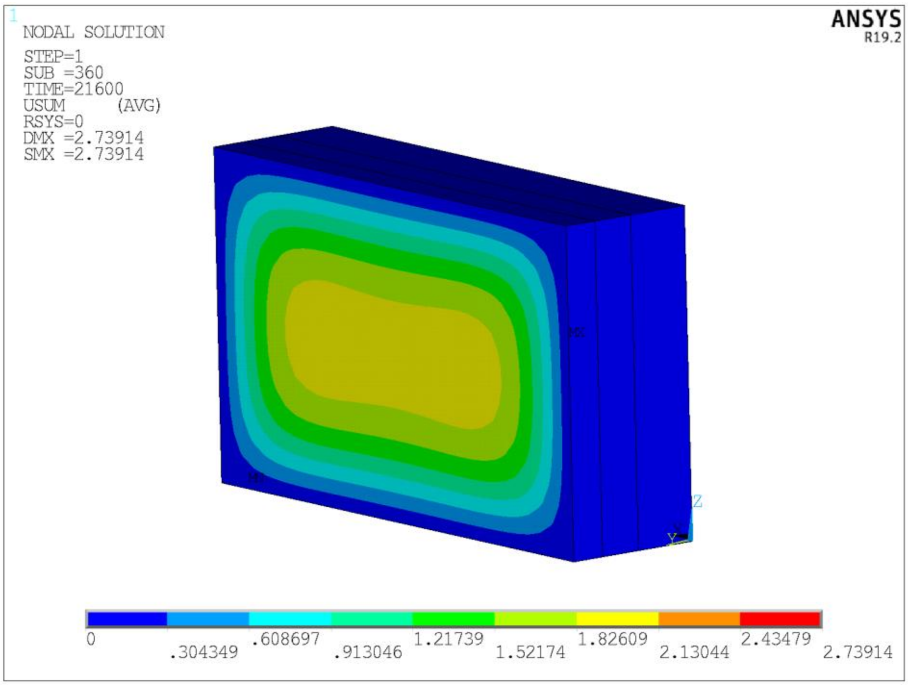

Figure 75. Total displacement (mm) on the unexposed side - minute 360

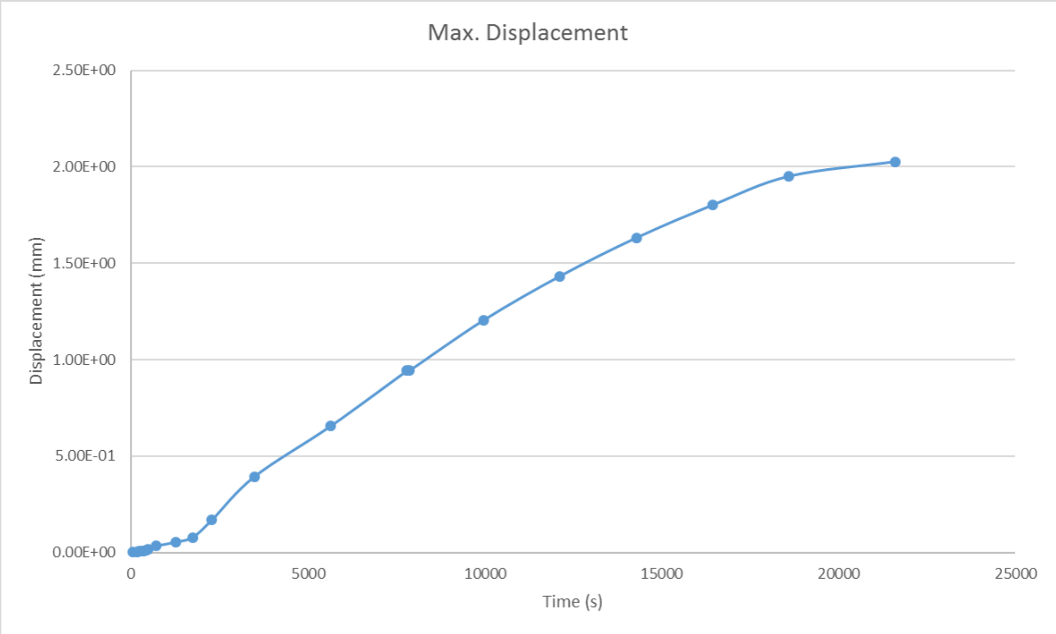

Figure 76. Deflection (mm) *vs* Time (s)

Figure 77. Rate of deflection (mm/s) *vs* Time (s)

9.4. Summary of results

The thermal results analyses are summarized in **Table 8**. In particular, the maximum and the average temperature on the unexposed side (T_{max} and $T_{average}$, respectively), the allowable maximum and average temperature on the unexposed side ($T_{max\ allowable}$ and $T_{avg\ allowable}$ respectively) and, in the end, the insulation index *I* are reported. Following the criteria exposed in the approach in Section 3.1, each structure has been classified with an insulation index I=360.

Table 8. Thermal analysis results

Structure	T_{Max} (°C)	$T_{average}$ (°C)	$T_{maxallowable}$ (°C)	$T_{avg\ allowable}$ (°C)	Index I
RE⁴ CDW - NE Timber Façade	35	26.6	180	140	360
RE⁴ CDW SE Timber Façade (Option 1)	20.87	20.57			360
RE⁴ CDW SE Timber Façade (Option 2)	116	85.6			360
RE⁴ NE Concrete Sandwich Panel	23.4	23.4			360
RE⁴ SE Concrete Sandwich Panel	34	34			360

Table 9 summarizes the structural results obtained on the analysed structure, i.e. the Sandwich Panel for cold climate. The maximum deflection and the maximum deflection rate are reported with their limit values, calculated following the approach described in Section 3.2. The obtained results show how the loadbearing criteria are satisfied until the minute 360.

Table 9. Structural analysis results

Boundary conditions	Max. Deflection (mm)	Max.Deflection Rate (mm/min)	Max.Deflection Allowable (mm)	Max.Deflection Rate Allowable(mm/min)	Index R
Fully supported	2.74	0.29	11.83	0.52	360

10. CONCLUSIONS AND RECOMMENDATIONS

This document describes the outcome of the Subtask *3.4.3*, namely *Fire Modelling*. The approach and the methodologies useful to define the fire resistance of the analysed structures have been previously established. In a second step, thermal and structural material properties as function of temperature has been defined by using both literature and experimental data and by making hypothesis and assumptions necessary to define the behaviour of some material at high temperature. Then, starting from the geometries provided by the partners, the 2D FE models of three version of the RE⁴ Timber Façade have been developed, followed by the 2D model of the RE⁴ Concrete Sandwich Panel for the warm climate and by the 3D model of the RE⁴ Concrete Sandwich Panel for cold climate. The performed transient thermal analyses have been able to replicate the fire test by applying a condition of radiation and a condition of convection on the exposed side (inner layer of the structures) with a temperature defined by the equation *T= 345*Log*

*[(8*time)/60)+1]+20°C* [1]. The results have been compared with the insulation criteria, which define a maximum allowable temperature and an average allowable temperature on the unexposed side, in order to assess an insulation index I. All the structures have been able to withstand the thermal load until the end of the simulation (360 min) and consequently an index I=360 has been assigned.

Structural analysis has been also performed on the load bearing component, i.e. the RE^4 Concrete Sandwich Panel for cold climate. A transient analysis has been performed by considering the results of the previous thermal analysis as thermal load, accompanied by the gravity earth load. Considering the loadbearing criteria, the results have shown how the structure with fully supported condition is able to respect the defined criteria until the end of the analysis and an index R=360 has been assessed.

In the end, it is important to stress the aspect related to components catching fire. It is impossible to include this kind of phenomenon in the developed simulations, though some physical transformations like water evaporation or charring formation have been considered by implementing the variation of the affected material properties.

11. BIBLIOGRAPHY

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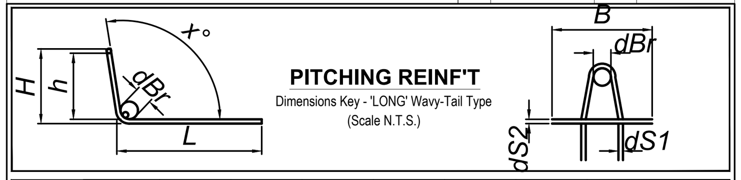
DISCLAIMER

The sole responsibility of this publication lies with the author. The European Union is not responsible for any use that may be made of the information contained therein.

FACTORY QUALITY CHECK	PRODUCTION PRE POUR	
DATE CAST		
	CHECKED	SIGNED
REQUIRED COVER 25mm		
ALL DETAILS & DIMENSIONS CORRECT		
RD36 LIFTERS IN CORRECT POSITION		

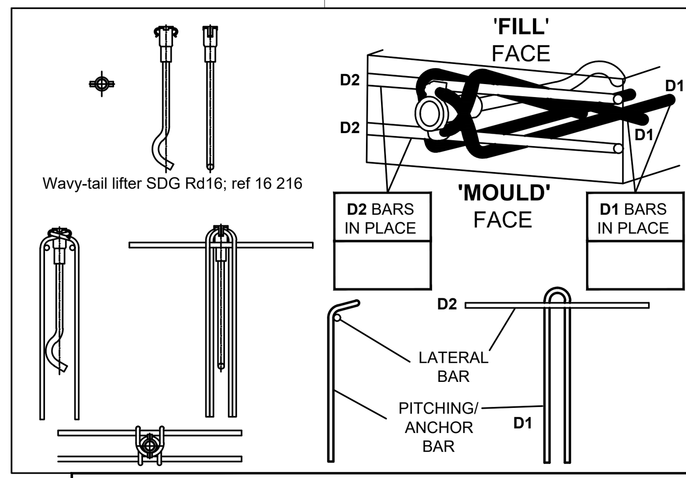


PITCHING REINF'T
Dimensions Key - 'LONG' Wavy-Tail Type
(Scale N.T.S.)

Lifter Size ('Long')	Min Unit Thk (mm)	dS1 (mm)	L (mm)	h (mm)	H (mm)	dBr (mm)	angle (x°)	B (mm)	dS2 (mm)
RD16	80	8 Ø	420	33	49	32	105°	400	12 Ø

dS1 Pitching Bar Factory Pre-Pour Check Completed & Bar In Place		**dS2** Longitudinal Bar Factory Pre-Pour Check Completed & Bar In Place	
SUPERVISOR SIGNATURE & DATE:			

FACTORY QUALITY CHECK	PRODUCTION POST POUR	
DATE CAST		
	CHECKED	SIGNED
ALL DETAILS & DIMENSIONS CORRECT		
LIFTERS IN CORRECT POSITION		



WAVY TAIL (Long Type)	D1 BAR Ø	D2 BAR Ø
RD12 RD16 RD20	Ø8 Ø8 Ø10	Ø8 Ø12 Ø12
RD24 RD30 RD36	Ø12 Ø12 Ø16	Ø14 Ø16 Ø16
RD42 RD52	Ø16 Ø20	Ø16 Ø20

DETAIL 'WTL1'
WAVY-TAIL LIFTER PITCHING REBAR
(MULTI-DIRECTIONAL)
(Scale N.T.S.)

CONCRETE	MIX TYPE	COVER	FINISH
SSC	C40/50	25mm	REFER TO FINISH SKETCH AS SHOWN.

VOLUME OF CONCRETE PER UNIT = $0.210 m^3$

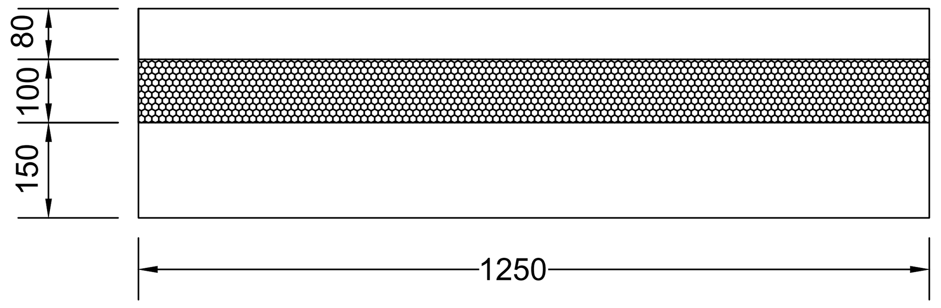
TOTAL WEIGHT OF EACH UNIT = 0.52 t

EACH PANEL CONTAINS :

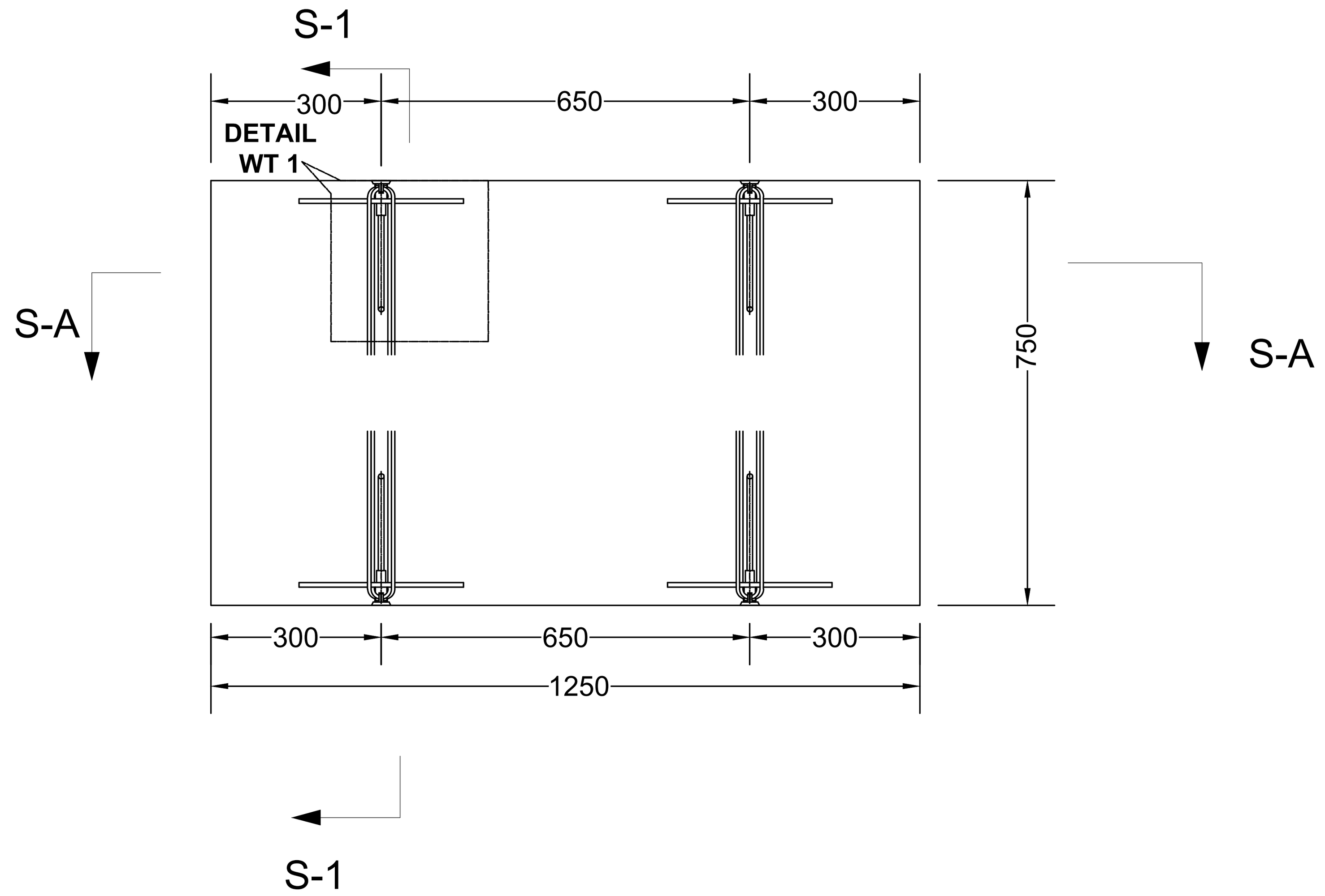
	TYPE :	No. / PANEL
SITE LIFTERS	RD16 ZP WAVY TAIL	4
DEMOULDERS	2.5 T 'DEHA' ref.6000–2.5–0085 SPHERICAL HEAD ANCHOR 85mm	0
VOID FORMER	50mmø WELL VOID SHEATH – 700mm Lg (EACH)	0
	80mmø WELL VOID SHEATH – 1700mm Lg (EACH)	0
CAST–IN FIXING SOCKETS	M20 BZP CAST–IN SOLID ROD	0
FIXED EARTHING TERMINAL ET	KLK PT–M16 SIMILAR OR APPROVED	0
CAST IN CHANNEL	CFS PEC–TA 54/33 COLD ROLLED BOLT ANCHOR 350mm LONG. 3 No ANCHORS SIMILAR OR APPROVED	0
WIRE ROPE BOXES	RVL–80 (CFS TYPE)	0

ID NUMBER: SP1 – T – n

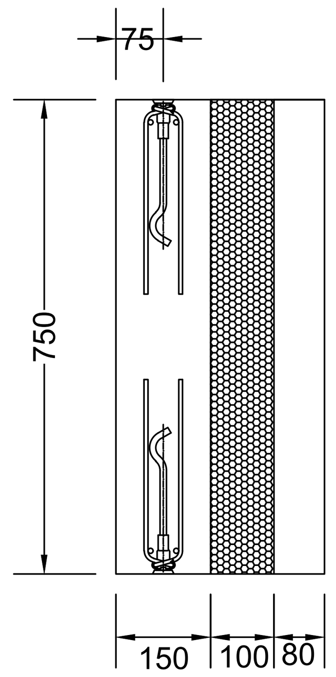
04 No REQUIRED AS DRAWN REF SP1–T



Section S-A
1/10



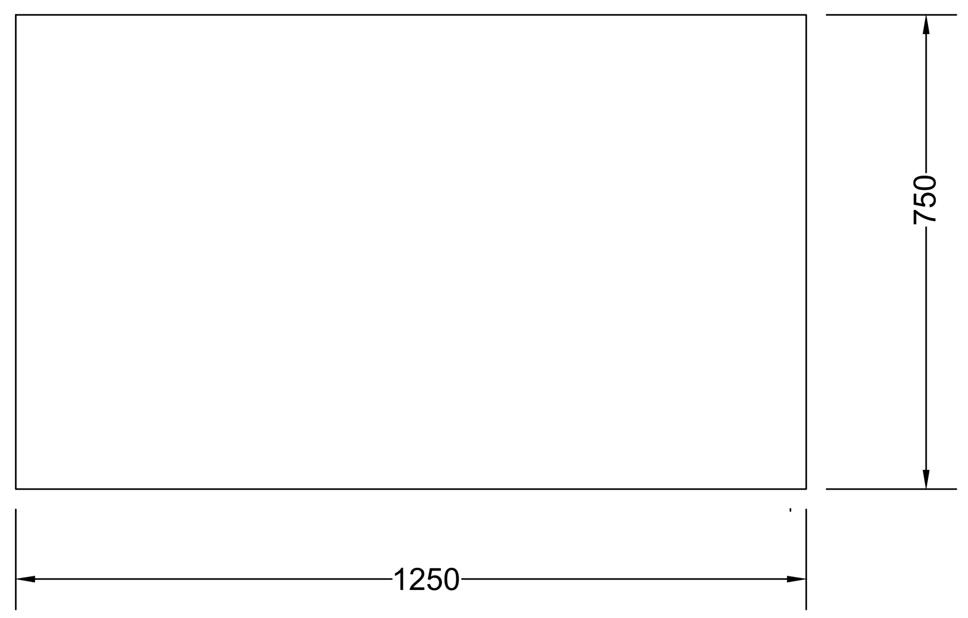
Elevation - Fill Face
1/10



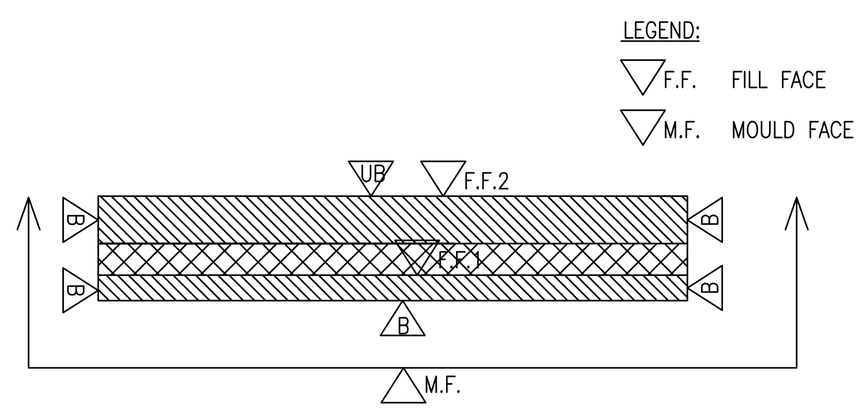
Section S-1
1/10

Concrete	
Concrete Grade	C40/50
Exposure Class	XC3, XD2
Finish	TYPE B ; UB
Reinforcement	
Cover To Reinforcement	25mm
Rebar	500B

NOTE FOR REBAR DETAILS RELATING TO THIS PANEL REFER TO CREAGH DRAWING No. 17–0832–E69.R



Elevation - mould face
1/10



FINISHES

ID NUMBER: SP1 - T - n

PIECE COUNT

REF. no	No.
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SP1 - T -2	1
SP1 - T -3	1
SP1 - T -4	1
TOTAL	4

No. REQUIRED

REV.	DATE	MADE BY	CHECKED BY	DETAILS
		RC		FOR CONSTRUCTION

CREAGH
CONCRETE PRODUCTS LTD
Blackpark Rd, Toomebridge,
Co. Antrim, N. Ireland. BT41 3SE
Tel : 028 79650500 Fax : 028 79650804

CONTRACTOR	RE4 project– ACCIONA
CONTRACT	16 – RE4 WP5
TITLE	Production Details Testing S Panel Ref SP1 – T

DRAWN BY: RC DATE: 31.10.18	CHECKED BY: DATE:	INSPECTED BY: DATE:
BASE SCALE: 1:10 @ A1	ISSUE STATUS: CONSTRUCTION	
CONTRACT No. 16–RE4	DRG. No. SP1–T.M	REV.

FACTORY QUALITY CHECK	PRODUCTION PRE POUR	
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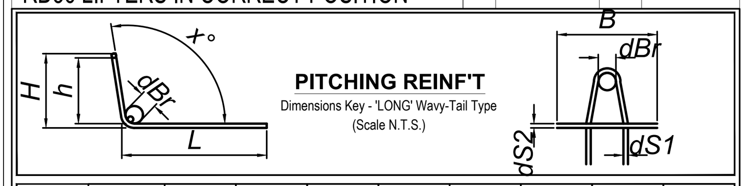
	CHECKED	SIGNED
REQUIRED COVER 25mm		
ALL DETAILS & DIMENSIONS CORRECT		
RD36 LIFTERS IN CORRECT POSITION		

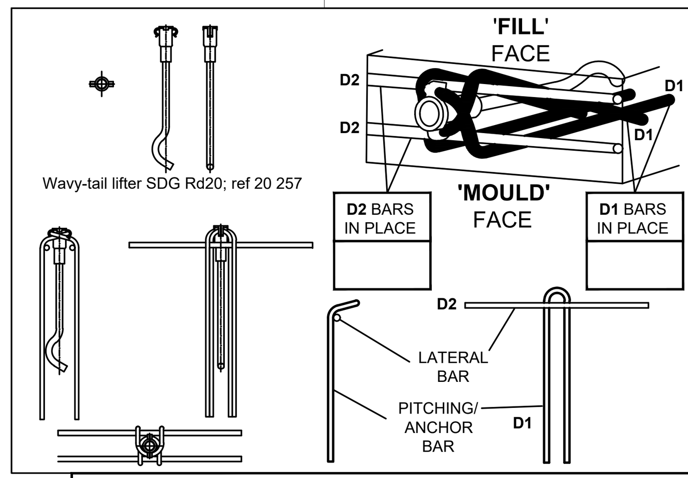


PITCHING REINF'T
Dimensions Key - 'LONG' Wavy-Tail Type
(Scale N.T.S.)

Lifter Size ('Long')	Min Unit Thk (mm)	dS1 (mm)	L (mm)	h (mm)	H (mm)	dBr (mm)	angle (x°)	B (mm)	dS2 (mm)
RD20	110	10 Ø	490	44	64	40	105°	490	14 Ø

dS1 Pitching Bar Factory Pre-Pour Check Completed & Bar In Place		**dS2** Longitudinal Bar Factory Pre-Pour Check Completed & Bar In Place	
SUPERVISOR SIGNATURE & DATE:			

FACTORY QUALITY CHECK	PRODUCTION POST POUR	
DATE CAST		
	CHECKED	SIGNED
ALL DETAILS & DIMENSIONS CORRECT		
LIFTERS IN CORRECT POSITION		



WAVY TAIL (Long Type)	D1 BAR Ø	D2 BAR Ø
RD12 RD16 RD20	Ø8 Ø8 Ø10	Ø8 Ø12 Ø12
RD24 RD30 RD36	Ø12 Ø12 Ø16	Ø14 Ø16 Ø16
RD42 RD52	Ø16 Ø20	Ø16 Ø20

DETAIL 'WTL1'
WAVY-TAIL LIFTER PITCHING REBAR
(MULTI-DIRECTIONAL)
(Scale N.T.S.)

CONCRETE	MIX TYPE	COVER	FINISH
RE4 SCC	C40/50	25mm (Strc. layer)	Type B ; UB As shown in sketch
RE4 HPC	C50/60	15mm (outer layer)	

VOLUME OF CONCRETE Structural Layer (SCC) PER UNIT = 0.300m^3

VOLUME OF CONCRETE Outer Layer (HPC)PER UNIT = 0.100m^3

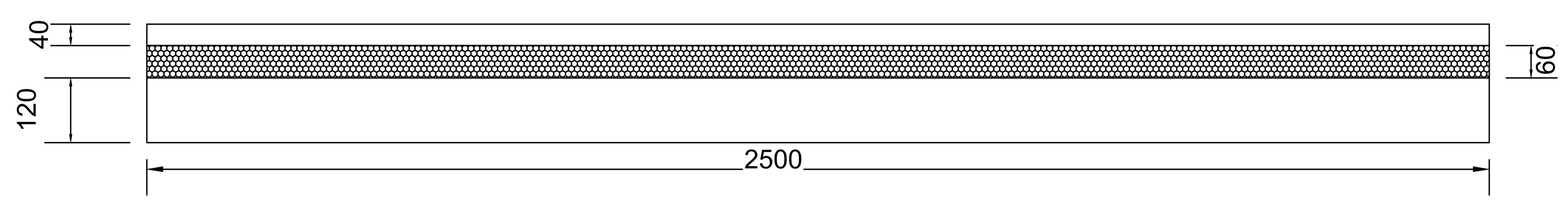
TOTAL WEIGHT OF EACH UNIT = 1.05 t

EACH PANEL CONTAINS :		
	TYPE :	No. / PANEL
SITE LIFTERS	RD20 ZP WAVY TAIL 257MM long	4
DEMOULDERS		0
VOID FORMER		0
		0
CAST-IN FIXING SOCKETS		0
FIXED EARTHING TERMINAL ET		0
CAST IN CHANNEL		0
WIRE ROPE BOXES		0

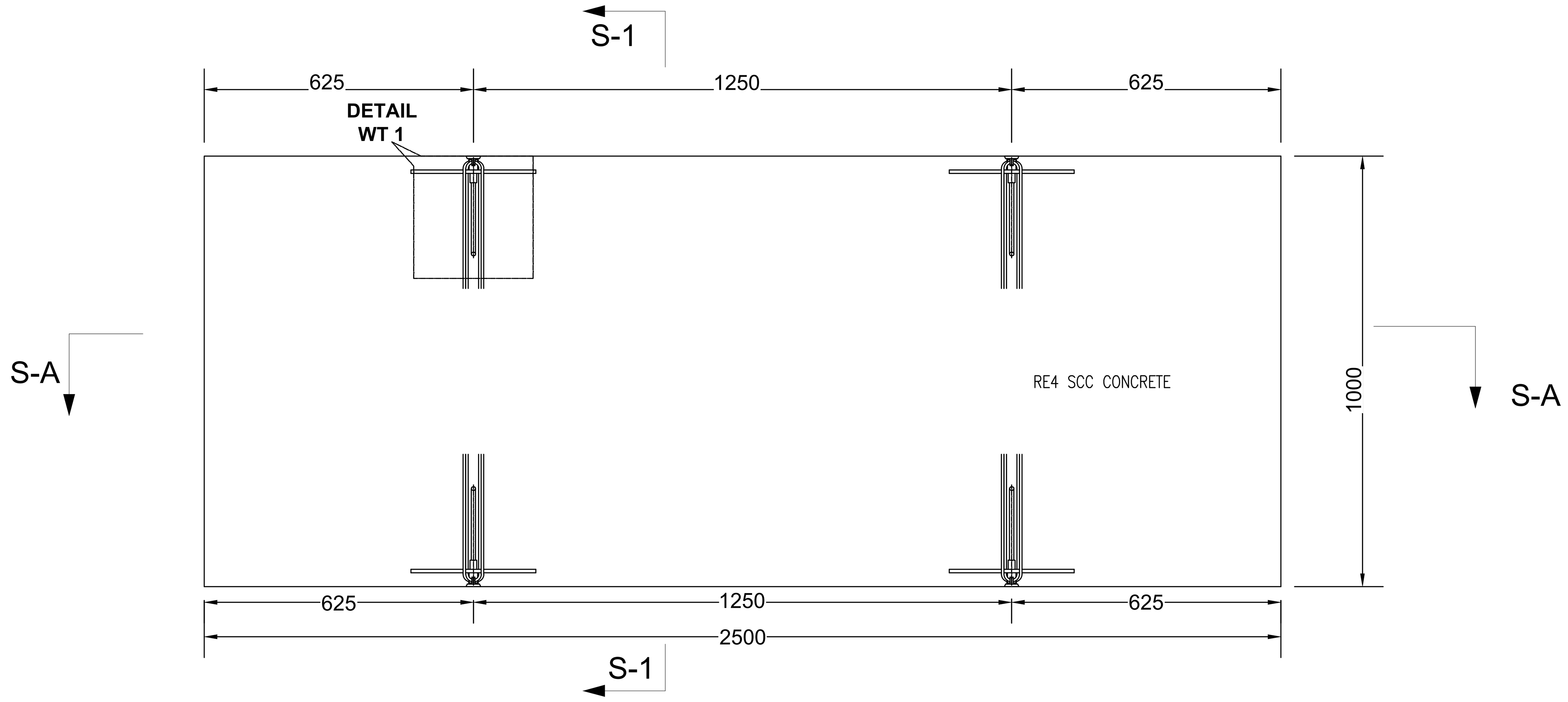
ID NUMBER: SP-HPC – T – n

03 No REQUIRED AS DRAWN REF SP-HPC-T.R

SP-HPC-T.R



Section S-A
1/10



Elevation - Structural layer (Fill Face)
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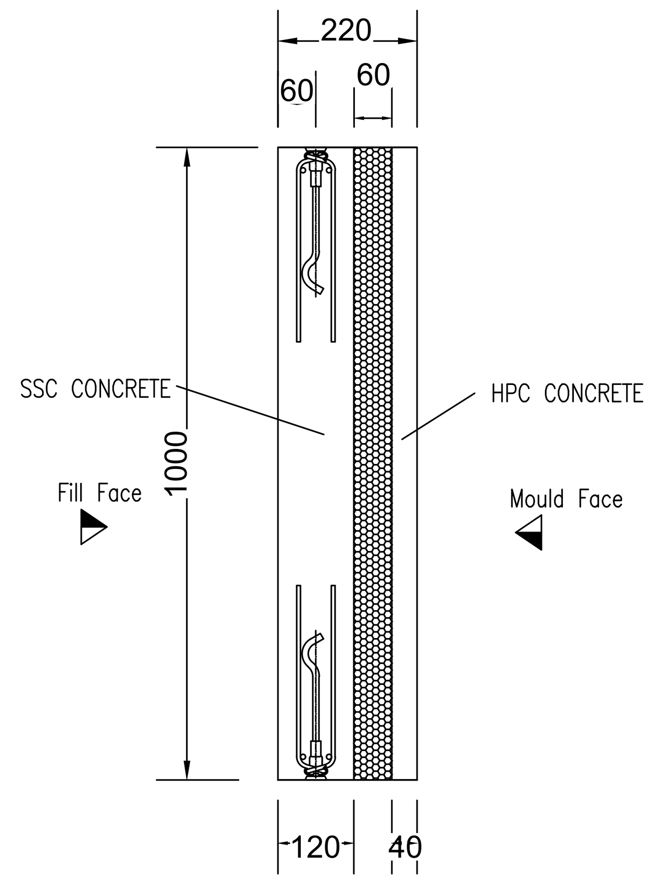
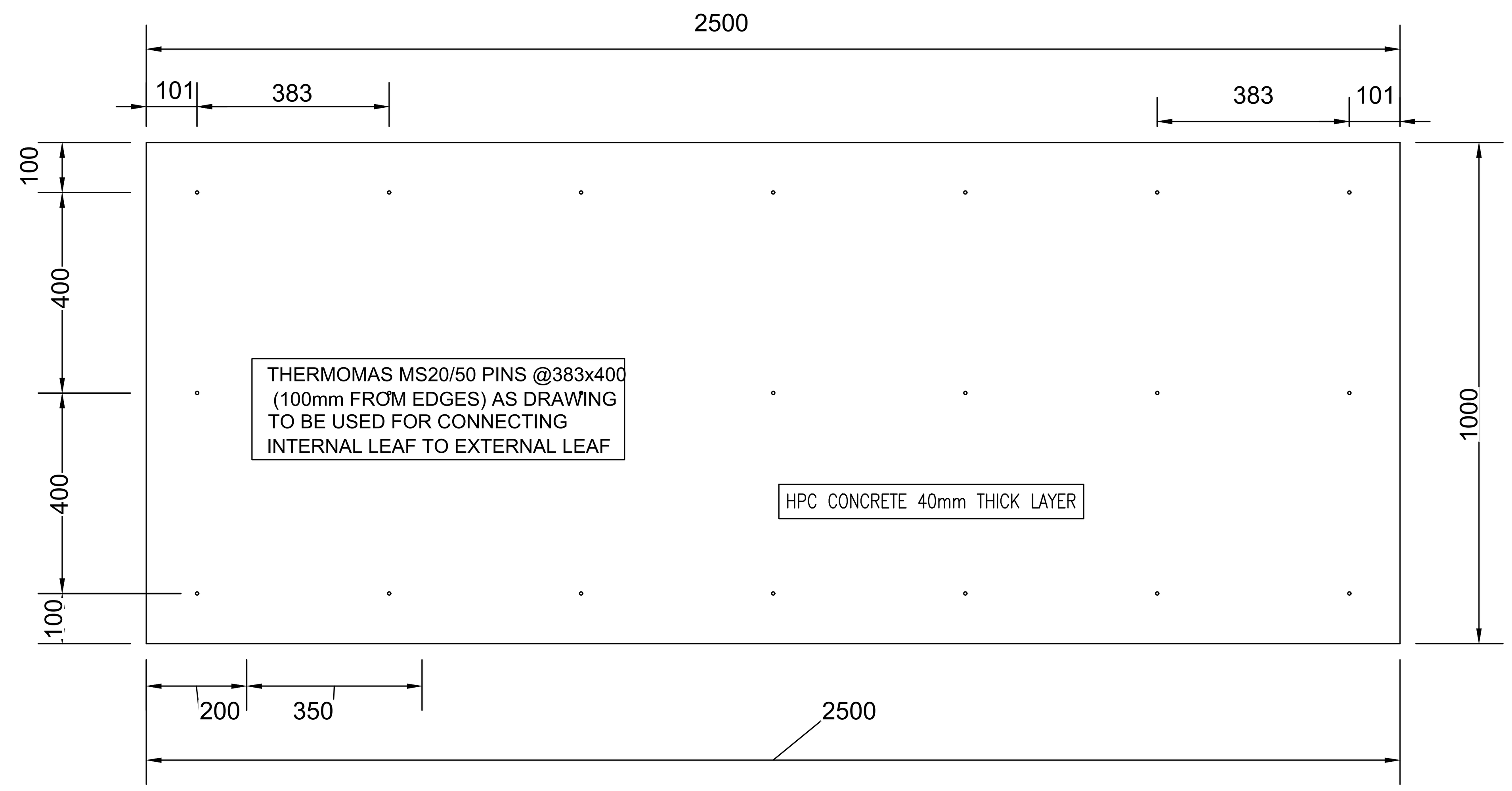


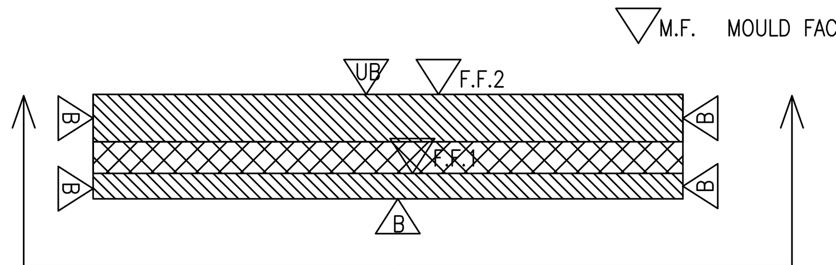
Section S-1
1/10

Concrete	
Concrete Grade	C40/50
Exposure Class	XC3, XD2
Finish	TYPE B; UB
Reinforcement	
Inner/Structural layer:	
Cover To Reinforcement	25mm
Rebar	500B
Outer/Mould layer:	
Cover to Reinforcement	15mm
Rebar	Carbon Reinf. type: Solidian GRID Q85/85 CCE-21



Elevation - Outer layer (mould face)
sc: 1/10

LEGEND:
F.F. FILL FACE
M.F. MOULD FACE



FINISHES

ID NUMBER: SP-HPC - T - n

PIECE COUNT

REF. no	No.
SP-HPC - T - 1	1
SP-HPC - T - 2	1
SP-HPC - T - 3	1
TOTAL	3

3 No. REQUIRED

NOTE FOR REBAR DETAILS RELATING TO THIS PANEL REFER TO CREAGH DRAWING No. 16-RE4- SP-HPC-T.R

REV.	DATE	MADE BY	CHECKED BY	DETAILS
		RC		FOR CONSTRUCTION

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CONCRETE PRODUCTS LTD
Blackpark Rd, Toomebridge,
Co. Antrim, N. Ireland. BT41 3SE
Tel : 028 79650500 Fax : 028 79650804

CONTRACTOR: RE4 project- RISE

CONTRACT: WP5

TITLE: Production Details Drawing Ref: SP-HPC-T.M

DRAWN BY: RISE DATE:	CHECKED BY: RC DATE:	INSPECTED BY: DATE:
BASE SCALE: 1:10 @ A1	ISSUE STATUS: CONSTRUCTION	
CONTRACT No. 16-RE4	DRG. No. SP-HPC-T.M	REV.