Transient hygro-thermal analysis during concrete hardening: concrete slab

Analysis of cracking during hardening is often studied by only studying stresses due to effect of thermal expansion (warming) and contraction (cooling).

The short-term effect of creep and shrinkage is not always considered but will handled in separate example.

In this example on temperature variation is determined according to principal workflow below:

1. Generate static 3D model using volume elements.
2. Define thermal nonlinear transient material properties of concrete.
3. Define structural material properties of concrete (not performed in example).
4. Define thermal transient boundary conditions.
5. Define structural boundary conditions (not performed in example).
6. Define thermal transient loads.
7. Perform transient thermal analysis to determine temperature.
8. Perform transient structural analysis to determine stress, crack risk and crack width (not performed in example).

CONTENTS

1. GENERAL / MEASUREMENT

1.1 CONSTRUCTION TYPE

A concrete base slab is cast against soil.

1.2 TIME PERIOD

The risk of cracking is studied over a time persiod of 30 days.

1.3 REMOVAL OF FORMWORK

Form work (plywood) s removed after 3 days.

1.4 AIR TEMPERATURE

Outside air (T_{air}) : +20° C

1.5 CONCRETE

Concrete : C35/45

Water/cementious ratio (vct_{ekv}) : 0.45

Cementhalt: 390 kg/m^3

Type : II (LH)

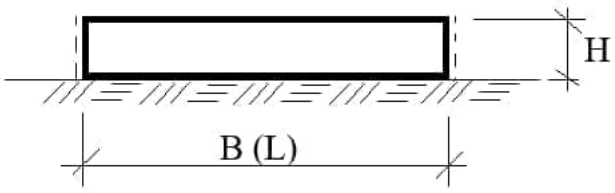
Casting tempeature: +15° C
Casting speed: max. 1 m/h

1.6 CONCRETE NONLINEAR MODELL

When studying risk of cracking and occurring crack width the concrete nonlinear model CEB-FIP modell 109 is used. This material model takes into account the effects of heat of hydration, creep and shrinkage, along when deteminating transient evolution of properties $E_c(t)$, $f_{cc}(t)$ and $f_{ct}(t)$.

1.7 MEASUREMENTS

Bottom slab: B x L x H = 20 m x 40 m x 3 m



2. SYSTEM ANALYSIS

2.1 GENERAL

The concrete slab is modelled only as one quarter due to symmetry.

The slab is modelled in 3D using *volume elemen*t (HF20) vid nodes in vertical direction at distance 0.15 m and at distance 2.0 m in horizontal plan.

No structural constraints are considered in this modell since both formwork and soil are considered soft, this all outer surfaces of slab are modelled as *thermal broundry conditions* that are free.

Changing enviroment at outer surfaces of slab are modelled used transient *thermal loading.*

Two analysis are performed constant ambient air temperature (Analysis 1) and varying ambient air temperature (Analysis 2).

Analysis 1: constant air temperature T_{air} = +20° C.

Analysis 2: cyclic varying air temperature over day T_{air} = +10° C → +30° C with mean daily temparature T_{air} = +20° C.

Appendices:

Appendix	Name
1	Input receipt
2	Results

2.2 SKETCH SYSTEM ANALYSIS

The single VOLUME is described by SURFACES (S1-S6).

SURFACES are described by LINES (L1-L12).

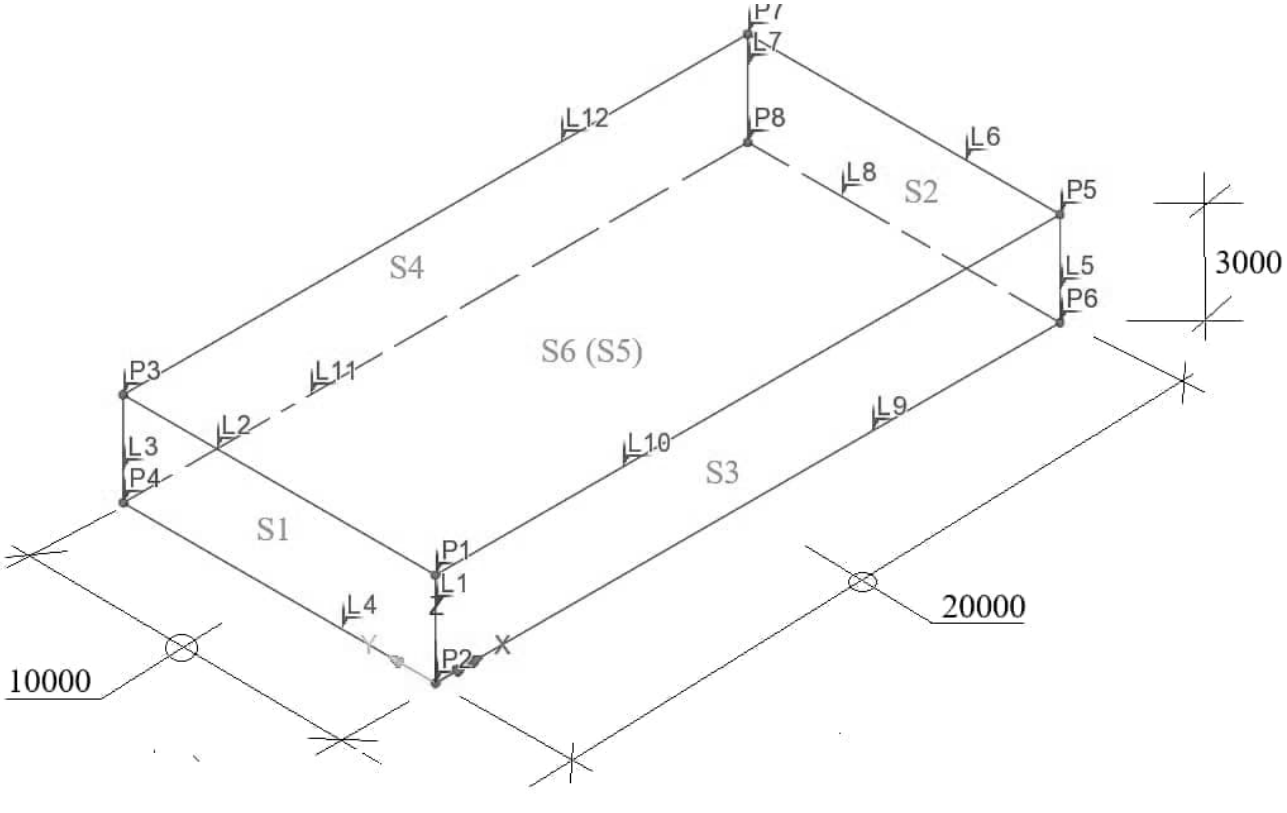
LINES are described by POINTS (P1-P8).

All coordinates needed to describe POINTS are found in appendix 1.

All POINTS needed to describe LINES are found in appendix 1.

All LINES needed to describe SURFACE are found in appendix 1.

All SURFACES needed to describe the VOLUME are found in appendix 1.

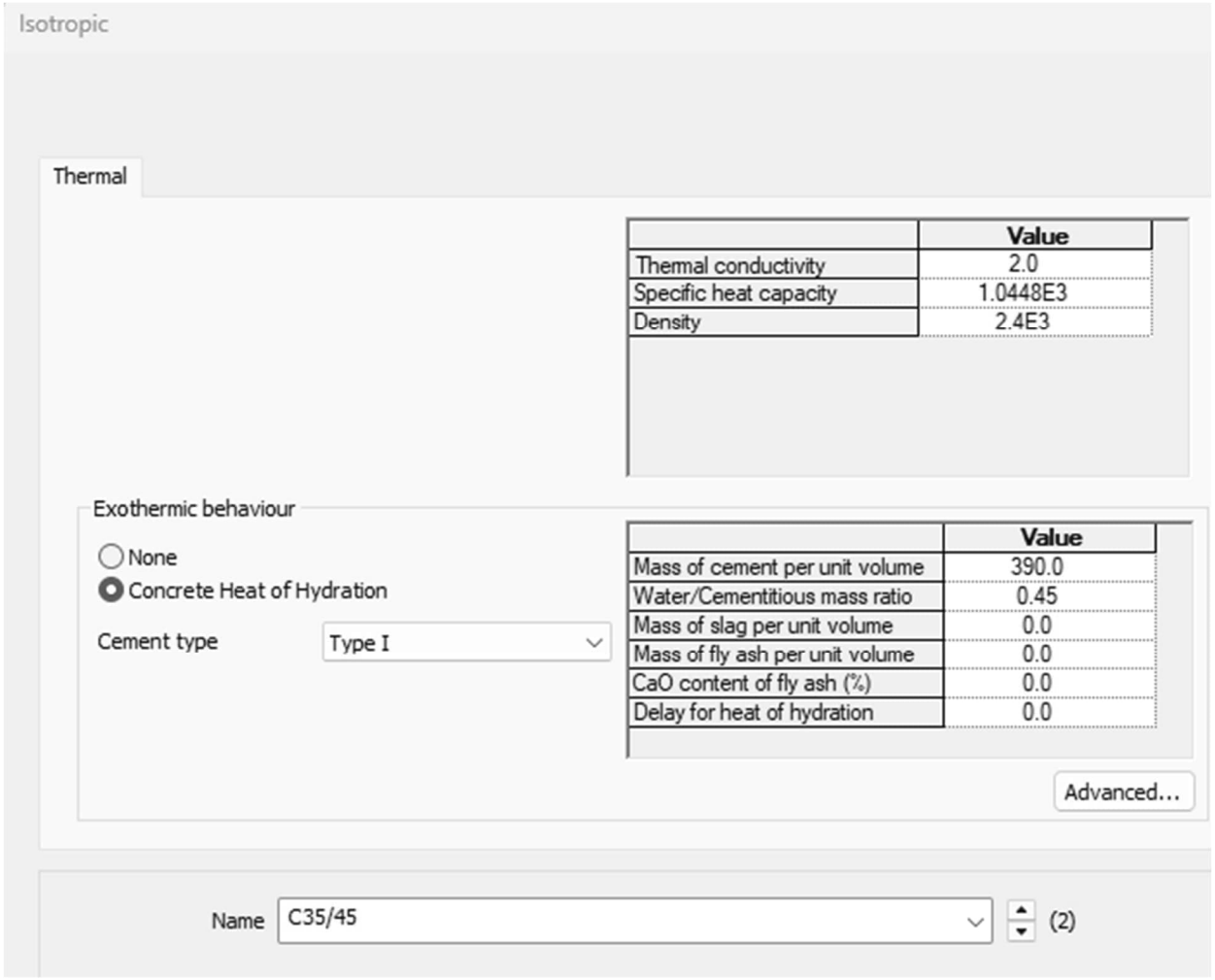


Overview 3D
Geometry

2.3 MATERIAL

The are different cement types according to CEM (I-V) depending on amount of furnace ash. In this case cement type I (≤ 5 % furnace ash) is used.

Isotropic thermal material below is applied to wet concrete to determines temperature in slab.

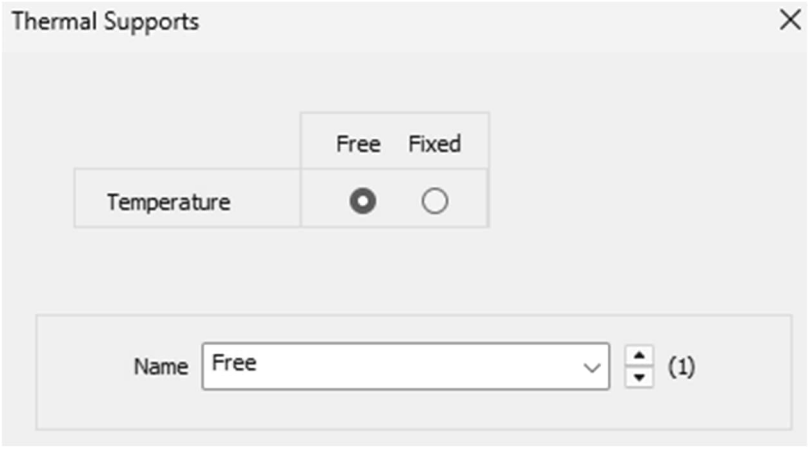


Remark
In this analysis no stress or crack width has been studied. This requires definition of structural nonlinear material properties.

2.4 BOUNDARY CONDITIONS

2.4.1 Thermal boundary condition

To all surfaces *thermal broundry conditions* are set as free, thus allways surface tempeature follows enviroment.



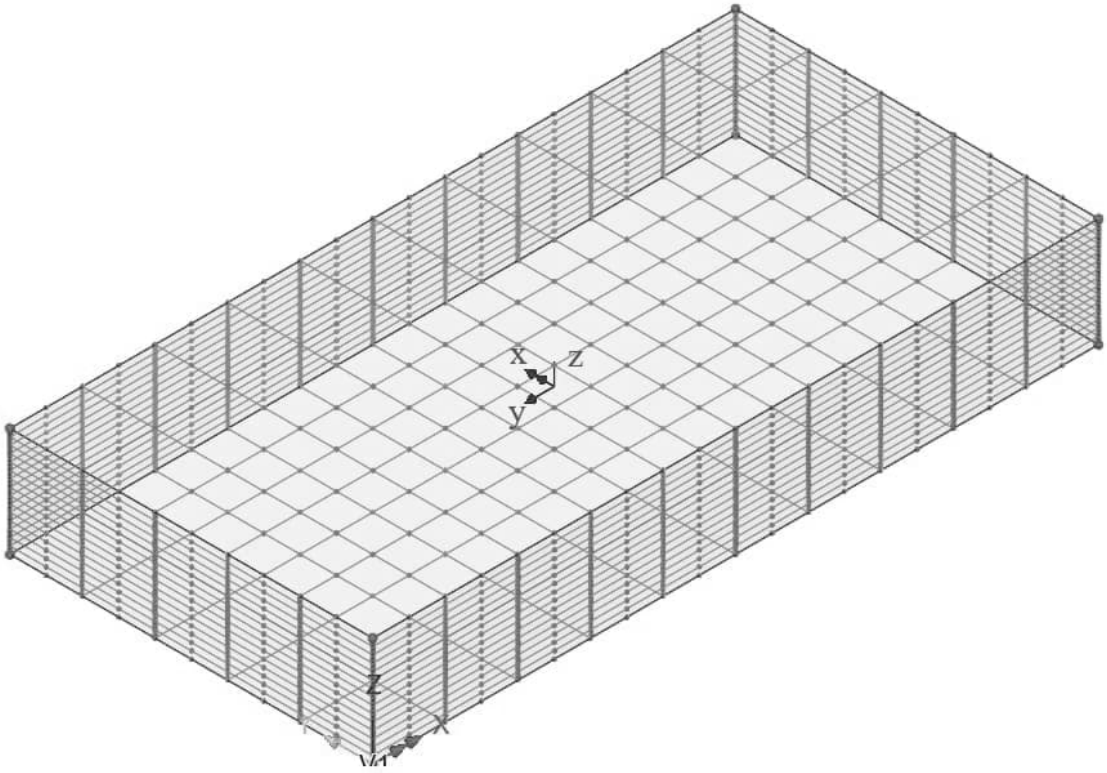
2.4.2 Structural boundary condition

In this analysis no stress or crack width has been studied, thus no structural boundary conditions have been applied.

2.5 MESH

Studied slab is modelled as a thermal volume field element (”Volume hexahedral”/ HF20).

Name	Division x-direction	Division y-direction	Division z-direction
Solide	5	10	15



3D overview

3. THERMAL LOADING

3.1 CONSTANT AMBIENT TEMPERATURE: ANALYSIS 1

Loads are applied thermal loads with constant environmental conditions.

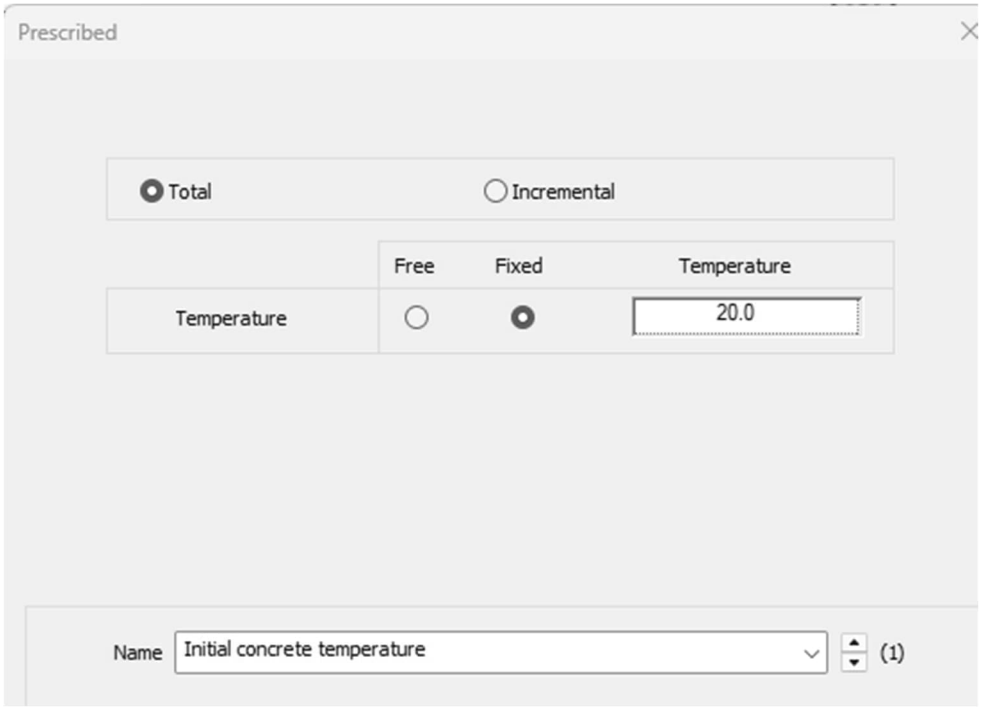
3.1.1 Load curves

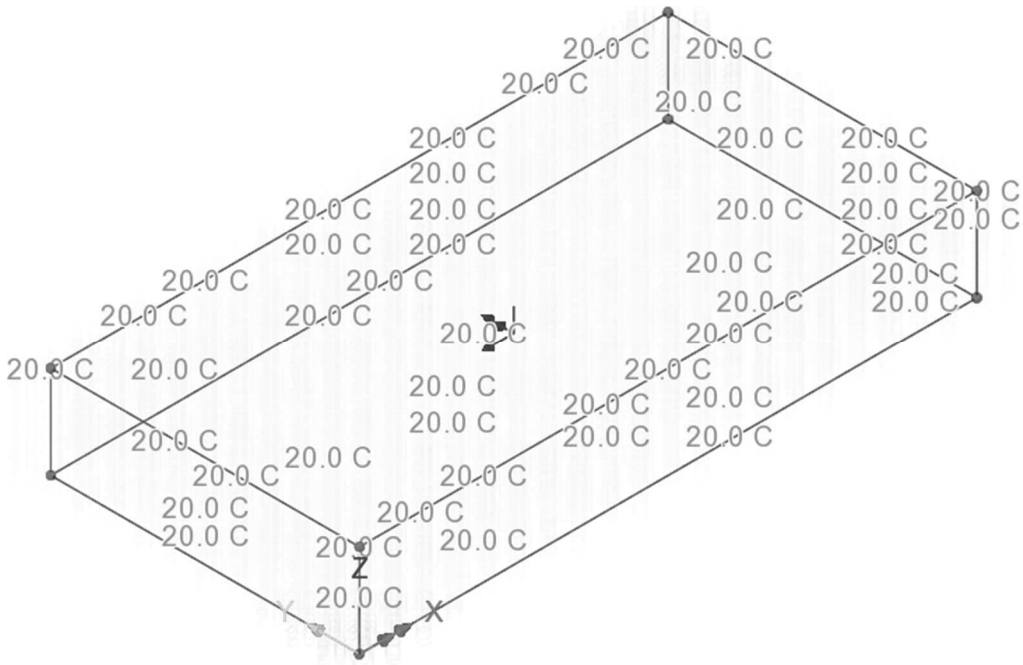
Since thermal loads are constant no load curves are used.

3.1.2 Concrete temperature

Initial concrete temperature at casting (T_{cast}) is +20° C. This loadcase is applied to entire slab.

Load: Initial temperature





3D VIEW

Loadcase : Casting stage – analysis 1

Analysis: Analysis 1

Load: Initial temperature

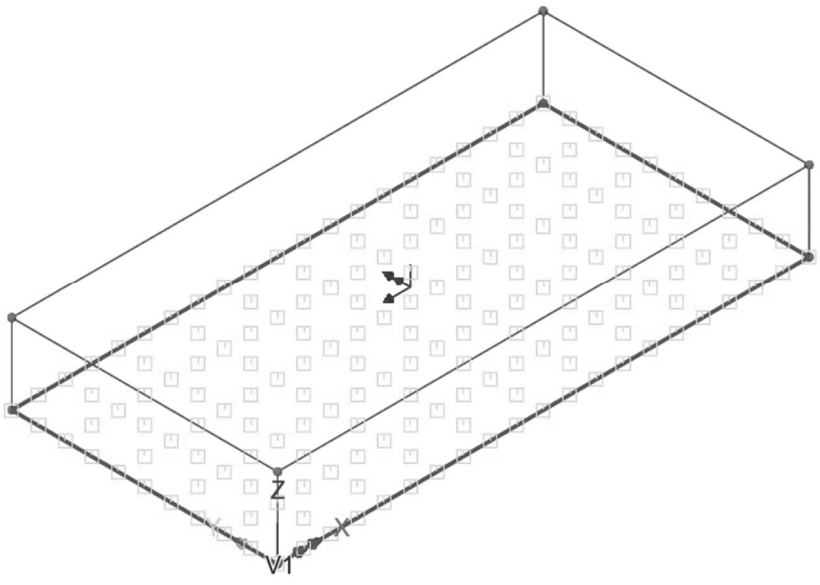
Load curve: None

3.1.3 Ground temperature

Ground temperature (T_{soil}) is considered to be constantly +10° C. This loadcase is applied to bottom face of slab. This load is applied to loadcases before ("Formwork for formwork") and after ("Exposed until 30 days") removal of formwork.

Loads is applied thermal loads using constant environmental conditions.

Load: Ground temperature



3D VIEW

Loadcase : "Formwork for 3 days"

Analysis:	Analysis 1
Thermal loading:	Ground temperature
Enviromental temperature :	+10° C.
Convection heat transfer coefficient:	2.8
Radiation heat transfer coefficient:	0
Load curve:	None

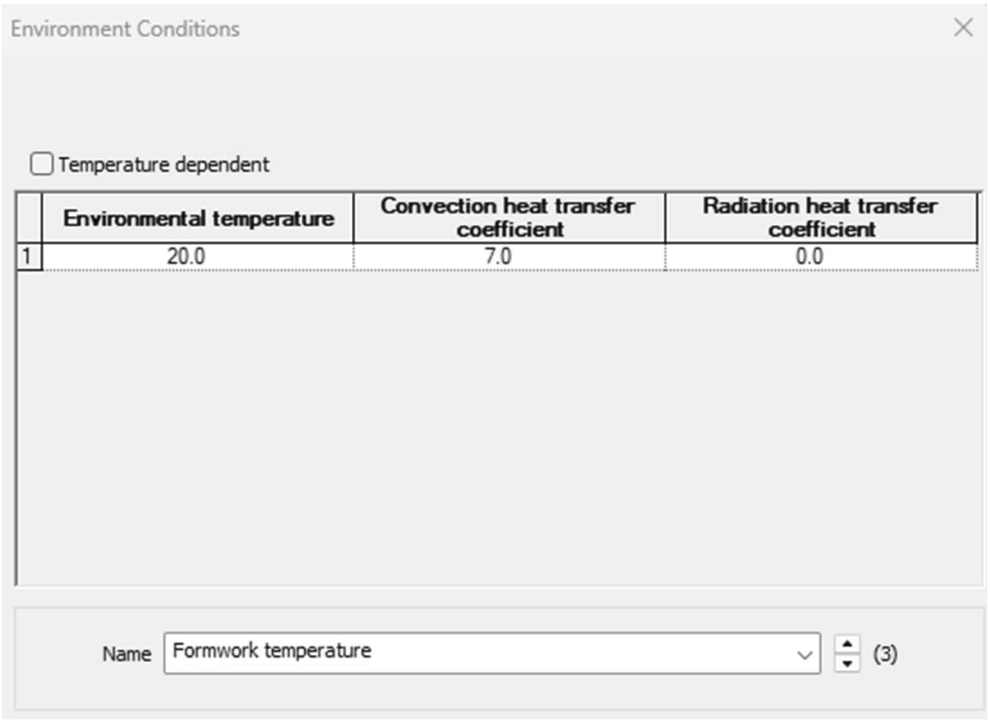
Loadcase : "Exposed until 30 days"

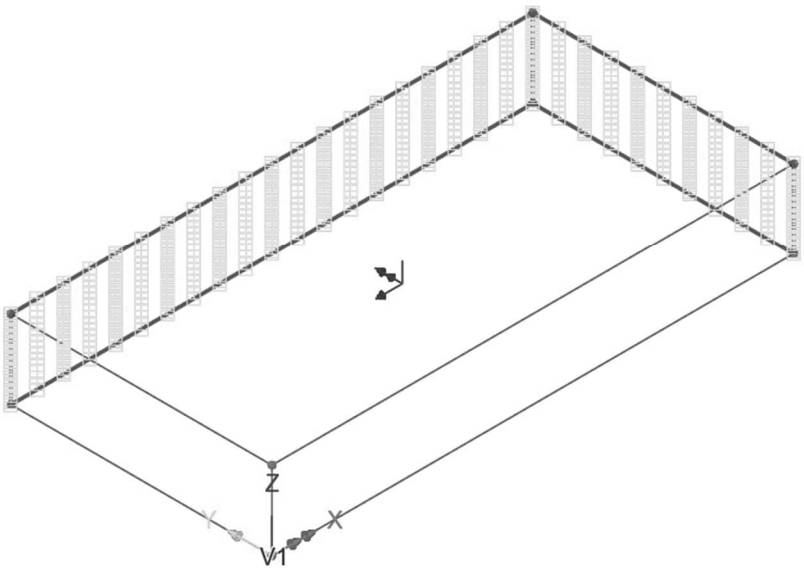
Analysis:	Analysis 1
Thermal loading:	Ground temperature
Environmental temperature :	+10° C.
Convection heat transfer coefficient:	2.8
Radiation heat transfer coefficient:	0
Load curve:	None

3.1.4 Formwork temperature

Temperature (T_{aorm}) is considered to be constantly +20° C. This loadcase is applied to external side faces of slab. This load is applied to loadcases before ("Formwork for 3 days").

Load: Formwork temperature





3D VIEW

Loadcase : "Formwork for 3 days"

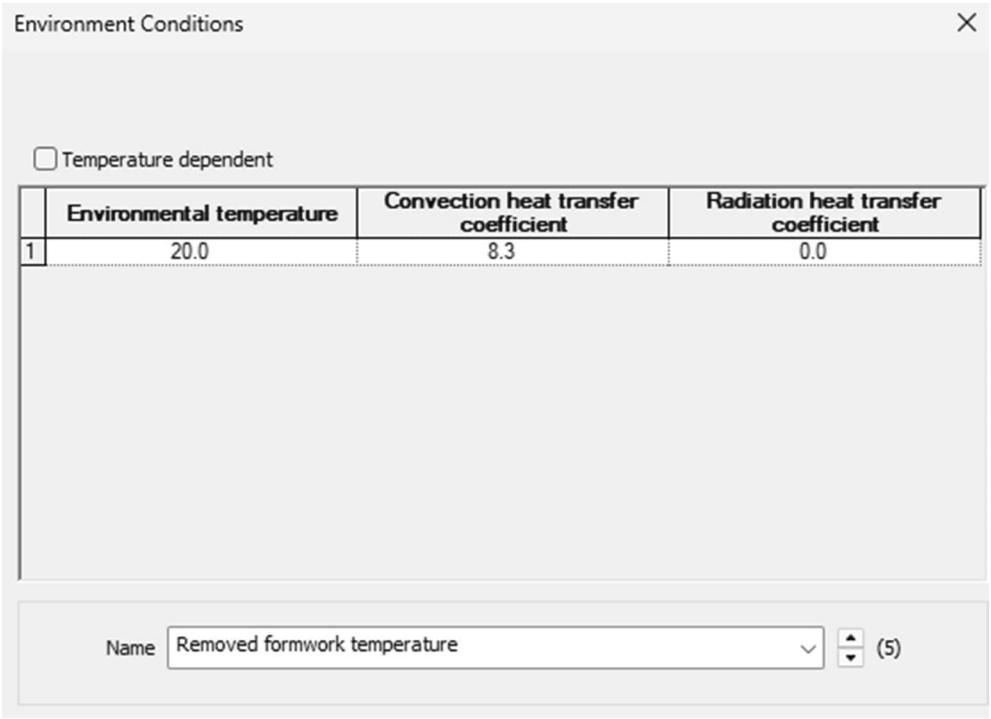
Analysis:	Analysis 1
Thermal loading:	Formwork temperature
Environmental temperature :	+20° C.
Convection heat transfer coefficient:	7.0
Radiation heat transfer coefficient:	0
Load curve:	None

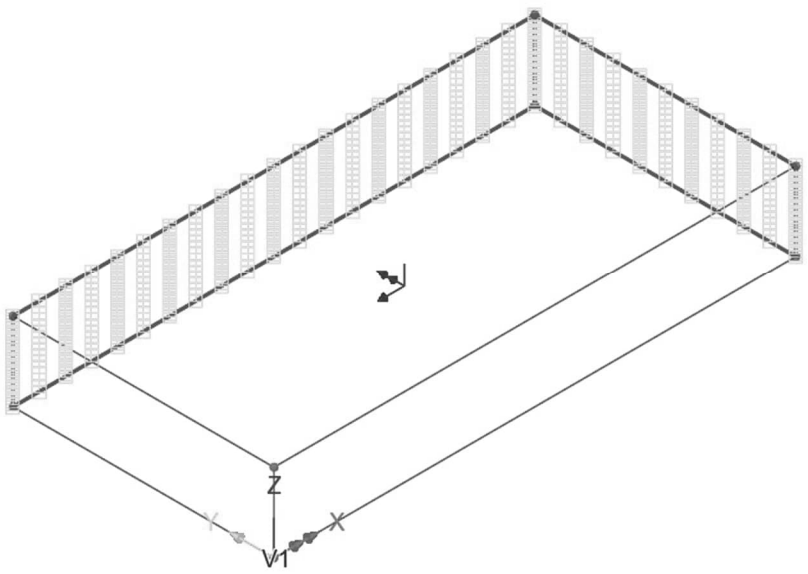
3.1.5 Removed formwork temperature

Air temperature (T_{aorm}) is considered to be constantly +20° C. This loadcase is applied to externa

l side faces of slab. This load is applied to loadcases after removal of formwork ("Exposed until 30 days").

Load: Removed formwork temperature





3D VIEW

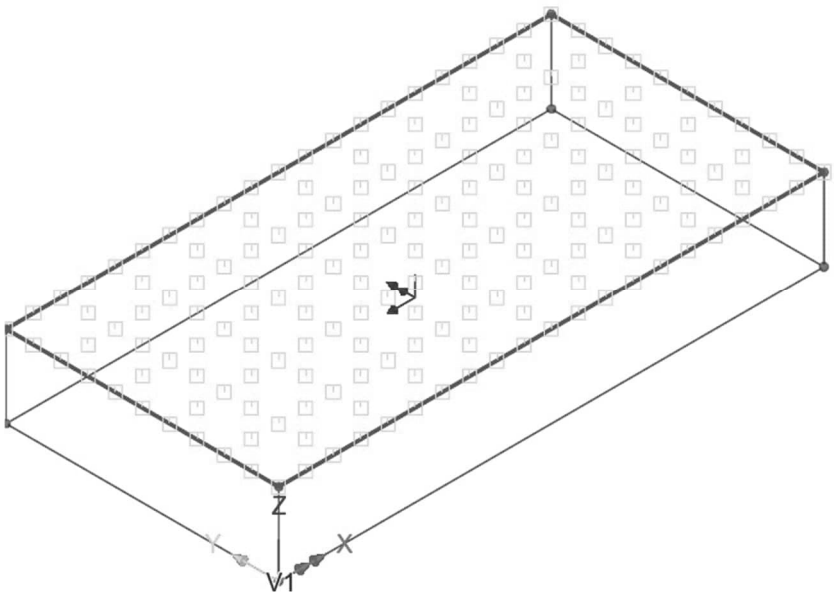
Loadcase : "Exposed until 30 days"

Analysis:	Analysis 1
Thermal loading:	Removed formwork temperature
Environmental temperature :	+20° C
Convection heat transfer coefficient:	8.3
Radiation heat transfer coefficient:	0
Load curve:	None

3.1.6 Air temperaure

Air temperature (T_{air}) is considered to be constantly +20° C. This loadcase is applied top face of slab. This load is applied to loadcases before ("Formwork for formwork") and after ("Exposed until 30 days") removal of formwork.

Load: Air temperature



3D VIEW

Loadcase : "Formwork for 3 days"

Analysis:	Analysis 1
Thermal loading:	Air temperature
Environmental temperature :	+20° C
Convection heat transfer coefficient:	8.3
Radiation heat transfer coefficient:	0
Load curve:	None

Loadcase : "Exposed until 30 days"

Analysis:	Analysis 1
Thermal loading:	Air temperature
Environmental temperature :	+20° C.
Convection heat transfer coefficient:	8.3
Radiation heat transfer coefficient:	0
Load curve:	None

3.2 VARYING AMBIENT TEMPERATURE: ANALYSIS 2

The analysis is same as for constant ambient air temperature (ANALYSIS 1) cyclic varying air temperature.

This is achived by applying varying load curves.

3.2.1 Load curves

Air temperature varies from day to night cyclic using load curves.

Load curve during casting of concrete

Name load curve: Casting stage curve

Type: User-defined (table)

Time	Factor
0	1
0.001	1
days	-

Activation time: 0 days

Load curve for ground temperature

Name load curve: Ground surface curve

Type: User-defined (table)

Time	Factor
0	1
30	1
days	-

Activation time: 0 days

Load curve air temperature day 0 → 3 day

Name load curve:	Day-night curve 3 days
Type:	Cosine
Amplitude:	10
Mean value:	20
Frequency:	1 day
Activation time:	0 days

Load curve air temperature day 3 → 30 day

Name load curve:	Day-night curve 3 to 30 days
Type:	Cosine
Amplitude:	10
Mean value:	20
Frequency:	1 day
Activation time:	3 days

3.2.2 Concrete tempeature

Initial concrete temperature at casting (T_{cast}) is +20° C. This loadcase is applied to entire slab.

Loadcase : Casting stage – analysis 2

Load: Initial concrete temperature

Load curve: Casting stage curve

3.2.3 Ground temperature

Ground temperature (T_{soil}) is considered to be constantly +10° C. This loadcase is applied to bottom face of slab. This load is constant.

Loadcase : Ground surface curve

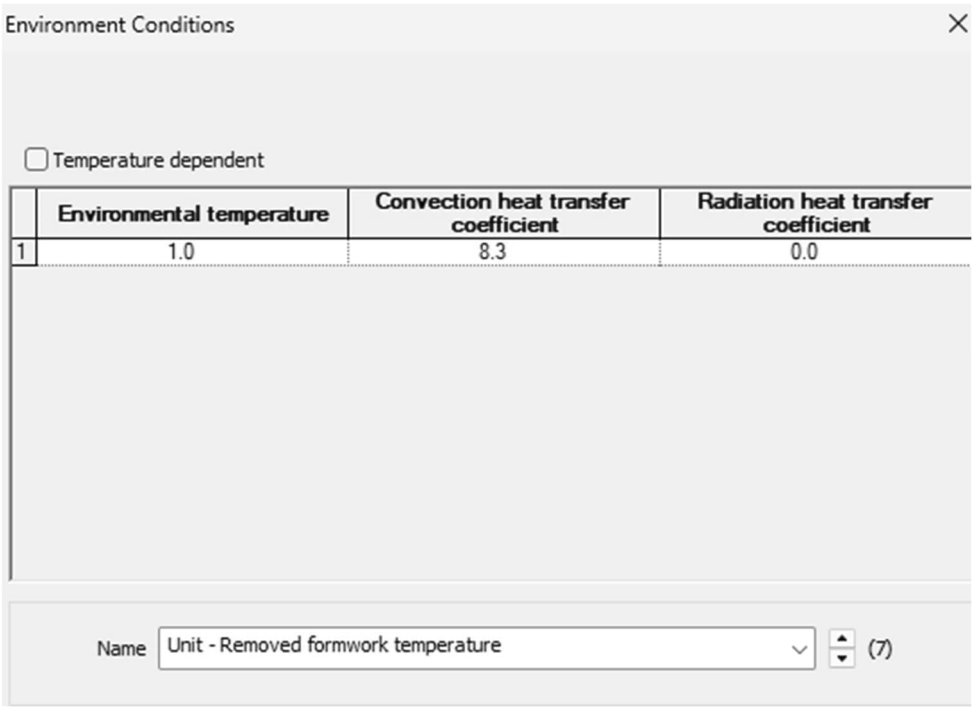
Load: Ground temperature

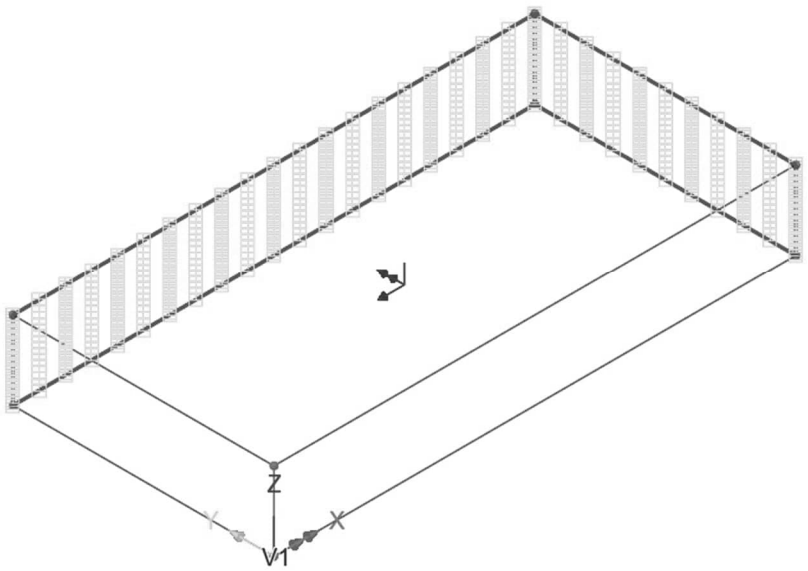
Load curve: Ground surface curve

3.2.4 Formwork temperature

Temperature (T_{aorm}) is considered to be constantly +20° C. This loadcase is applied to external side faces of slab. This load is applied to loadcases before ("Formwork for 3 days").

Load: Unit - Formwork temperature





3D VIEW

Loadcase : "Formwork for 3 days"

Analysis: Analysis 2

Thermal loading: Unit - Formwork temperature

Environmental temperature : +1° C (unit load)

Convection heat transfer coefficient: 7.0

Radiation heat transfer coefficient: 0

Load curve: Day-night curve 3 days

Remark

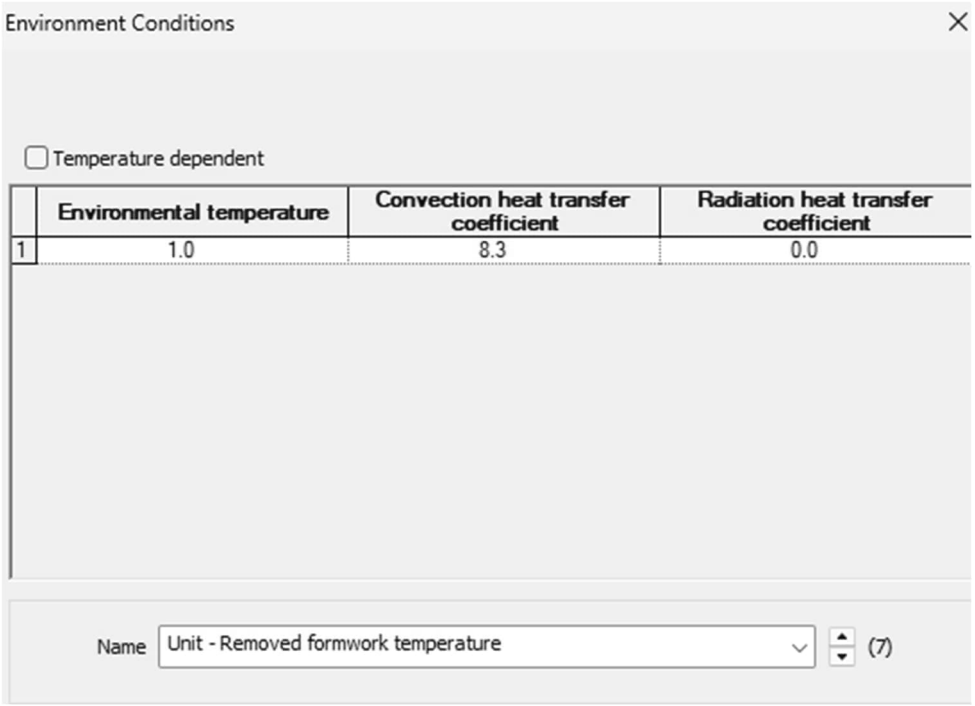
Unit load is amplified using load-curve so varies cyclic +10° C → +30° C.

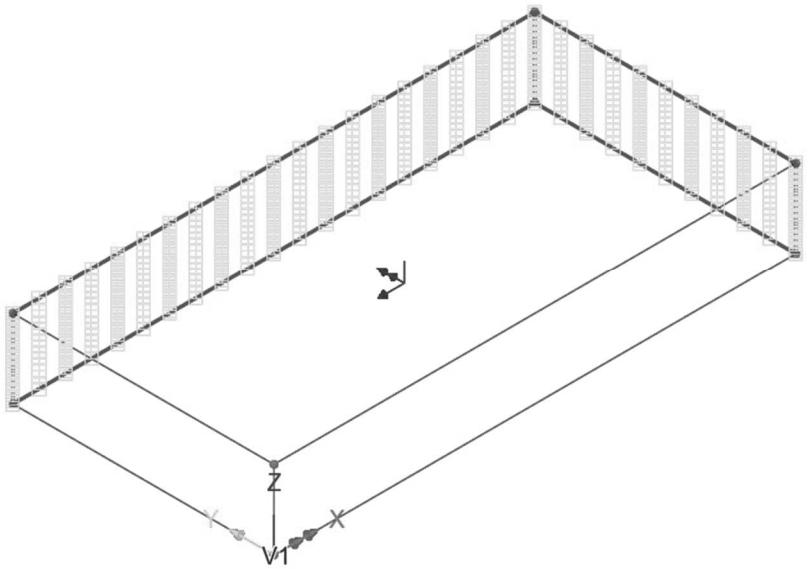
3.2.5 Removed formwork temperature

Air temperature (T_{aorm}) is considered to be constantly +20° C. This loadcase is applied to externa

l side faces of slab. This load is applied to loadcases after removal of formwork ("Exposed until 30 days").

Load: Unit - Removed formwork temperature





3D VIEW

Loadcase : "Exposed until 30 days"

Analysis: Analysis 1

Thermal loading: Removed formwork temperature

Environmental temperature : +1° C (unit load)

Convection heat transfer coefficient: 8.3

Radiation heat transfer coefficient: 0

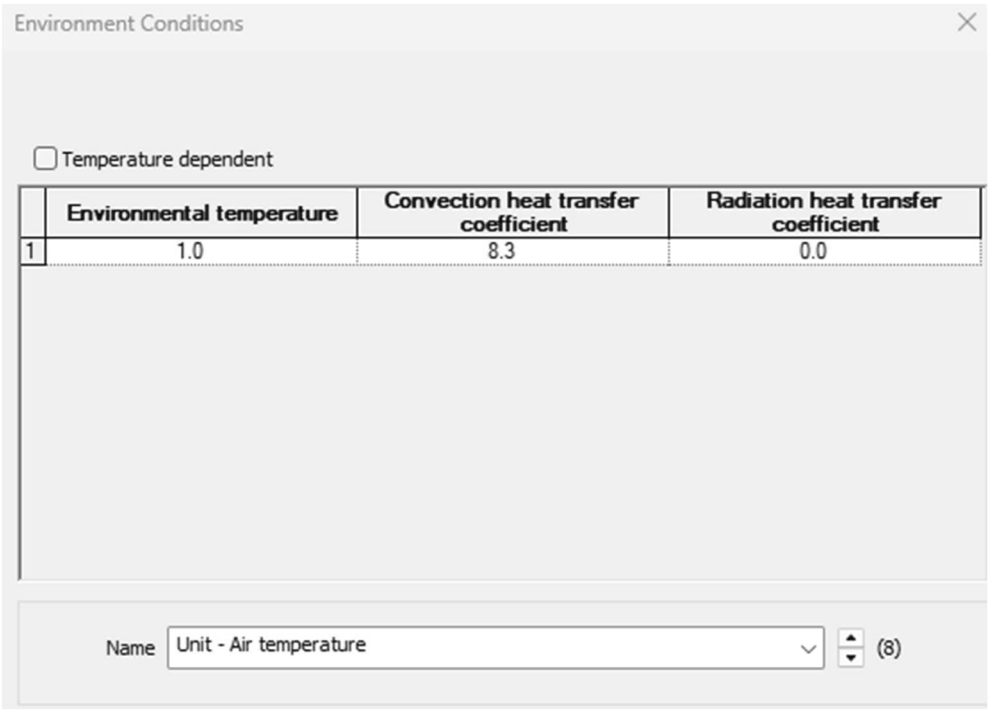
Load curve: Day-night curve 3 to 30 days

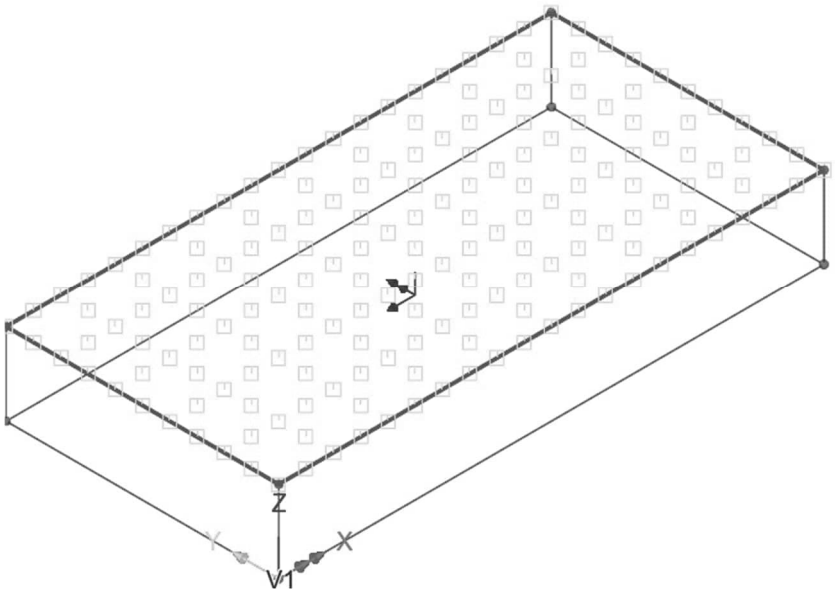
Remark
Unit load is amplified using load-curve so varies cyclic +10° C → +30° C.

3.2.6 Air temperaure

Air temperature (T_{air}) is considered to be constantly +20° C. This loadcase is applied top face of slab. This load is applied to loadcases before ("Formwork for formwork") and after ("Exposed until 30 days") removal of formwork.

Load: Unit- Air temperature





3D VIEW

Loadcase : "Formwork for 3 days"

Analysis: Analysis 1

Thermal loading: Unit - Air temperature

Environmental temperature : +1° C (unit load)

Convection heat transfer coefficient: 8.3

Radiation heat transfer coefficient: 0

Load curve: Day-night curve 3 days

Loadcase : "Exposed until 30 days"

Analysis: Analysis 1

Thermal loading: Air temperature

Environmental temperature : +1° C (unit load)

Convection heat transfer coefficient: 8.3

Radiation heat transfer coefficient: 0

Load curve: Day-night curve 3 to 30 days

Remark

Unit load is amplified using load-curve so varies cyclic +10° C → +30° C.

4. RESULTS

4.1 WORKFLOW

Principal workflow for transient hygro-thermal analysis:

1. Generate static 3D model using volume elements.
2. Define thermal nonlinear transient material properties of concrete.
3. Define structural material properties of concrete (not performed in example).
4. Define thermal transient boundary conditions.
5. Define structural boundary conditions (not performed in example).
6. Define thermal transient loads.
7. Perform transient thermal analysis to determine temperature.
8. Perform transient structural analysis to determine stress, crack risk and crack width (not performed in example).

4.2 TEMPEATURE ANALYSIS

See appendix 2.

4.3 STRUCTURAL ANALYSIS

Not performed in example.

Title: Input receipt

Model Units: kN,m,t,s,C
Report Units: kN,m,t,s,C

Model Title: System 001
Model File: System 001

Clarification of definitions.

In the report, the letter “T” is used to describe a range. The letter is an abbreviation of “to”.

See example of assignment below.

Assignment to Lines:
105T110;114T119

This expression means that the assignment occurs to the lines L105 → L110 and L114 → L119.

Assignment to Surfaces:
3T17;19T24
This expression means that the assignment occurs to the surfaces S3 → S17 and S19 → S24.

Table of Contents

1. Points

Point	X coordinate	Y coordinate	Z coordinate
1	0.0	0.0	3.0
2	0.0	0.0	0.0
3	0.0	10.0	3.0
4	0.0	10.0	0.0
5	20.0	0.0	3.0
6	20.0	0.0	0.0
7	20.0	10.0	3.0
8	20.0	10.0	0.0

2. Lines

Line	Points	Line	Points
1	2,1	2	1,3
3	3,4	4	4,2
5	5,6	6	7,5
7	8,7	8	6,8
9	2,6	10	5,1
11	8,4	12	3,7

3. Surfaces

Surface	Lines	Surface	Lines
1	1,2,3,4	2	5,8,7,6
3	9,5,10,1	4	11,3,12,7
5	4,11,8,9	6	2,10,6,12

4. Volumes

Volume	Surfaces
1	5,6,1,2,3,4

5. MESH: Volume

Attribute: 2 **Title: Solide**
Sub Type = Volume Mesh **Element Type = HF20**

Property	Symbol	Value
Element size	size	-1.0
Number of divisions in x	xDivisions	5
Number of divisions in y	yDivisions	10
Number of divisions in z direction	zDivisions	15
Transition mesh	transition	false
Allow irregular mesh	allowIrregular	false
Element defined by name	DefinedByName	false
Single feature joint	isSingleFtrJnt	false

Assignment to Volumes: 1

6. Material

Attribute: 2 **Title: C35/45**

Sub Type = Isotropic Material

Assigned in: Analysis 1

Property	Symbol	Value
Mass of cement per unit volume	wcem	0.4
Mass of slag per unit volume	wslg	0.0
Mass of fly ash per unit volume	wpfa	0.0
Delay for heat of hydration	admix_1	0.0
Water/Cementitious mass ratio	wcra	0.5
CaO content of fly ash (%)	pfacao	0.0
C3S content (%)	C3S	0.0
C2S content (%)	C2S	0.0
C3A content (%)	C3A	0.0
C4AF content (%)	C4AF	0.0
Free CaO content (%)	FCaO	0.0
SO3 content (%)	SO3	0.0
MgO content (%)	MgO	0.0
Blaine value	Blaine	0.0
Cement type	icem	"Type I"
Ultimate degree of hydration	rdh	1.0
Heat of hydration	rhh	1.0
Hydration time	rht	1.0
Activation energy	rae	1.0
Hydration slope	rhs	1.0

Assignment to Volumes: 1

7. Boundary condition: thermal

Attribute: 1 **Title: Free**

Sub Type = Thermal Support

Assigned in: Analysis 1

Property	Symbol	Value
Reference temperature	T	"F"
Stiffness distribution type	springType	"Total"
Conductance	Tstiff	0.0
Capillary pressure stiffness	CPStiff	0.0

Assignment to Surfaces: 5,6,1,2,3,4

8. Load curves

Attribute: 6
Title: Casting stage curve
Type: Uses-defined table

Time	Factor
0	1
0.001	1

Activation time: 0 days

Attribute: 7
Title: Ground surface curve
Type: Uses-defined table

Time	Factor
0	1
30	1

Activation time: 0 days

Attribute: 8
Title: Day-night curve 3 days
Type: Cosine
Amplitude: 10
Mean value: 20
Frequency: 1
Activation time: 0

Attribute: 9
Title: Day-night curve 3 to 30 days
Type: Cosine
Amplitude: 10
Mean value: 20
Frequency: 1
Activation time: 3

9. Loads: thermal

Attribute: 1

Title: Initial concrete temperature

Sub Type = Prescribed Temperature

Property	Symbol	Value
Attribute type	type	"Total"
Prescribed temperature	T	20.0
Fixed temperature	havePhi	true
Humidity	humidity	0.0
Fixed humidity	haveHumidity	false
Saturation	saturation	0.0
Fixed Saturation	haveSaturation	false
using humidity	isDlgHumidity	false

Loadcase ID: 1
Title: Casting stage - analysis 1
Factor = 1.0
Assigned in: Analysis 1
Assignment to Volumes: 1

Loadcase ID: 6
Title: Casting stage - analysis 2
Assigned in: Analysis 2
Factor = ”Casting stage curve”
Assignment to Volumes: 1

Attribute: 2

Title: Ground temperature

Sub Type = Environmental

Property	Symbol	Value
Environmental temperature	envT	10.0
Convection heat transfer coefficient	hc	0.0
Radiation heat transfer coefficient	hr	0.0
Relative humidity	humidity	0.0
Vapour mass transfer coefficient	vapourMass	0.0
Reference temperature	T	0.0

Loadcase ID: 2
Title: Formwork for 3 days
Factor = 1.0
Assigned in: Analysis 1
Assignment to Surfaces: 5

Loadcase ID: 3
Title: Exposed until 30 days
Factor = 1.0
Assigned in: Analysis 1
Assignment to Surfaces: 5

Loadcase ID: 7
Title: Ground surface curve
Factor = ”Constant ground surface curve”
Assigned in: Analysis 2
Assignment to Surfaces: 5

Attribute: 3

Title: Formwork temperature

Sub Type = Environmental

Property	Symbol	Value
Environmental temperature	envT	20.0
Convection heat transfer coefficient	hc	0.0
Radiation heat transfer coefficient	hr	0.0
Relative humidity	humidity	0.0
Vapour mass transfer coefficient	vapourMass	0.0
Reference temperature	T	0.0

Loadcase ID: 2
Title: Formwork for 3 days
Factor = 1.0
Assigned in: Analysis 1
Assignment to Surfaces: 2;4

Attribute: 4

Title: Removed formwork temperature

Sub Type = Environmental

Property	Symbol	Value
Environmental temperature	envT	20.0
Convection heat transfer coefficient	hc	0.0
Radiation heat transfer coefficient	hr	0.0
Relative humidity	humidity	0.0
Vapour mass transfer coefficient	vapourMass	0.0
Reference temperature	T	0.0

Loadcase ID: 3
Title: Exposed until 30 days
Factor = 1.0
Assigned in: Analysis 1
Assignment to Surfaces: 2;4

Attribute: 5

Title: Air Temperature

Sub Type = Environmental

Property	Symbol	Value
Environmental temperature	envT	20.0
Convection heat transfer coefficient	hc	0.0
Radiation heat transfer coefficient	hr	0.0
Relative humidity	humidity	0.0
Vapour mass transfer coefficient	vapourMass	0.0
Reference temperature	T	0.0

Loadcase ID: 2
Title: Formwork for 3 days
Factor = 1.0
Assigned in: Analysis 1
Assignment to Surfaces: 6

Loadcase ID: 3
Title: Exposed until 30 days
Factor = 1.0
Assigned in: Analysis 1
Assigment to Surfaces: 6

Attribute: 6

Title: Unit - Formwork Temperature

Sub Type = Environmental

Property	Symbol	Value
Environmental temperature	envT	1.0
Convection heat transfer coefficient	hc	0.0
Radiation heat transfer coefficient	hr	0.0
Relative humidity	humidity	0.0
Vapour mass transfer coefficient	vapourMass	0.0
Reference temperature	T	0.0

Loadcase ID: 8
Title: Day-night curve 3 days
Factor = ” Day-night curve 3 days”
Assigned in: Analysis 2
Assignment to Surfaces: 2;4

Attribute: 7

Title: Unit - Removed formwork temperature

Sub Type = Environmental

Property	Symbol	Value
Environmental temperature	envT	1.0
Convection heat transfer coefficient	hc	0.0
Radiation heat transfer coefficient	hr	0.0
Relative humidity	humidity	0.0
Vapour mass transfer coefficient	vapourMass	0.0
Reference temperature	T	0.0

Loadcase ID: 9
Title: Day-night curve 3 days
Factor = ” Day-night curve 3 to 30 days”
Assigned in: Analysis 2
Assignment to Surfaces: 2;4

Attribute: 8

Title: Unit - Air temperature

Sub Type = Environmental

Property	Symbol	Value
Environmental temperature	envT	1.0
Convection heat transfer coefficient	hc	0.0
Radiation heat transfer coefficient	hr	0.0
Relative humidity	humidity	0.0
Vapour mass transfer coefficient	vapourMass	0.0
Reference temperature	T	0.0

Loadcase ID: 10
Title: Day-night curve 3 days
Factor = ” Day-night curve 3 days”
Assigned in: Analysis 2
Assignment to Surfaces: 6

Loadcase ID: 11
Title: Day-night curve 3 to 30 days
Factor = ” Day-night curve 3 to days”
Assigned in: Analysis 2
Assignment to Surfaces: 6

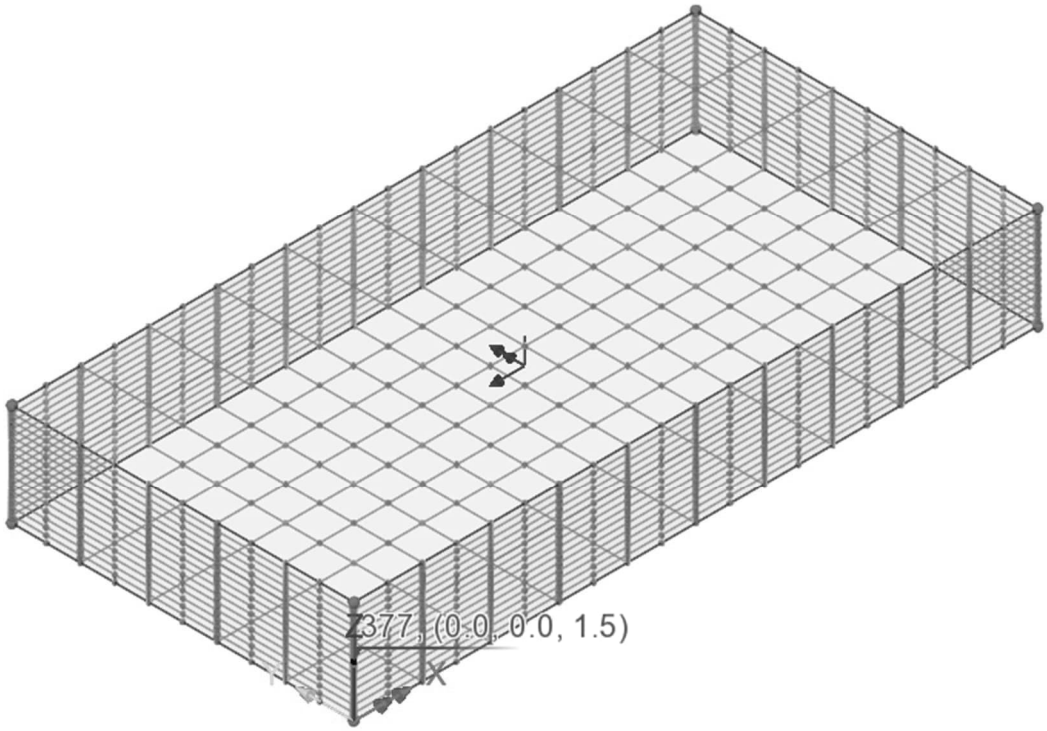
Title: Results

Model Units: kN,m,t,s,C
Report Units: kN,m,t,s,C

Model Title: System 001
Model File: System 001

Table of Contents

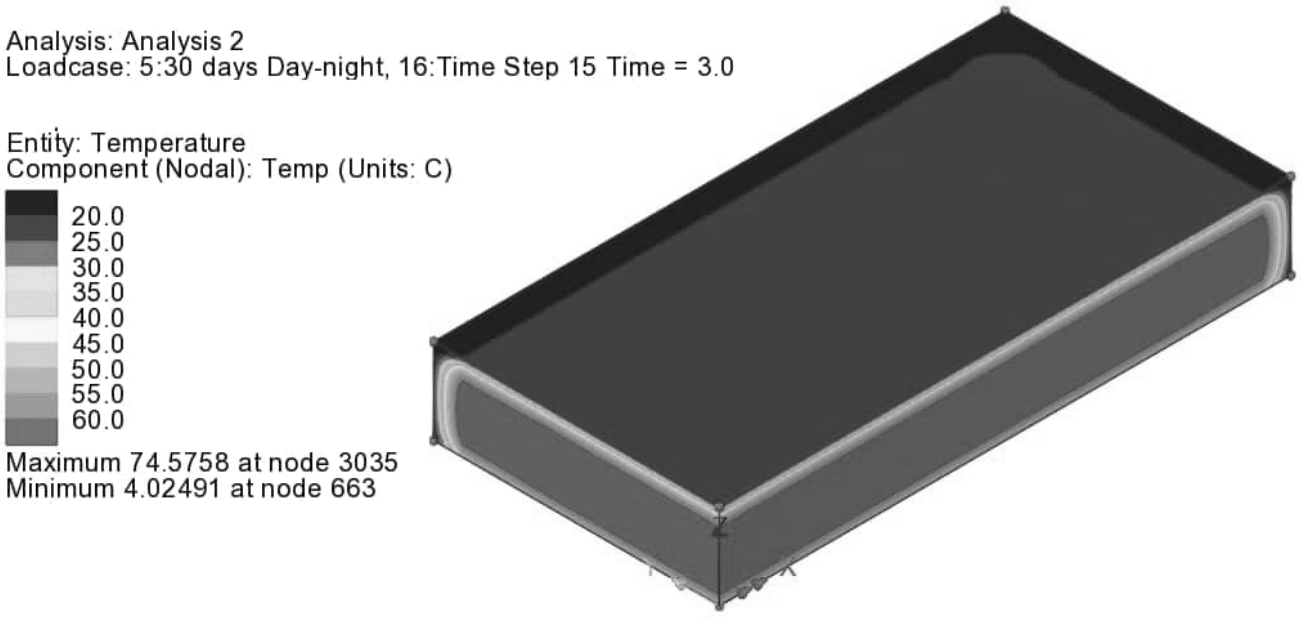
1. Result nodes



3D Overview
Location N377

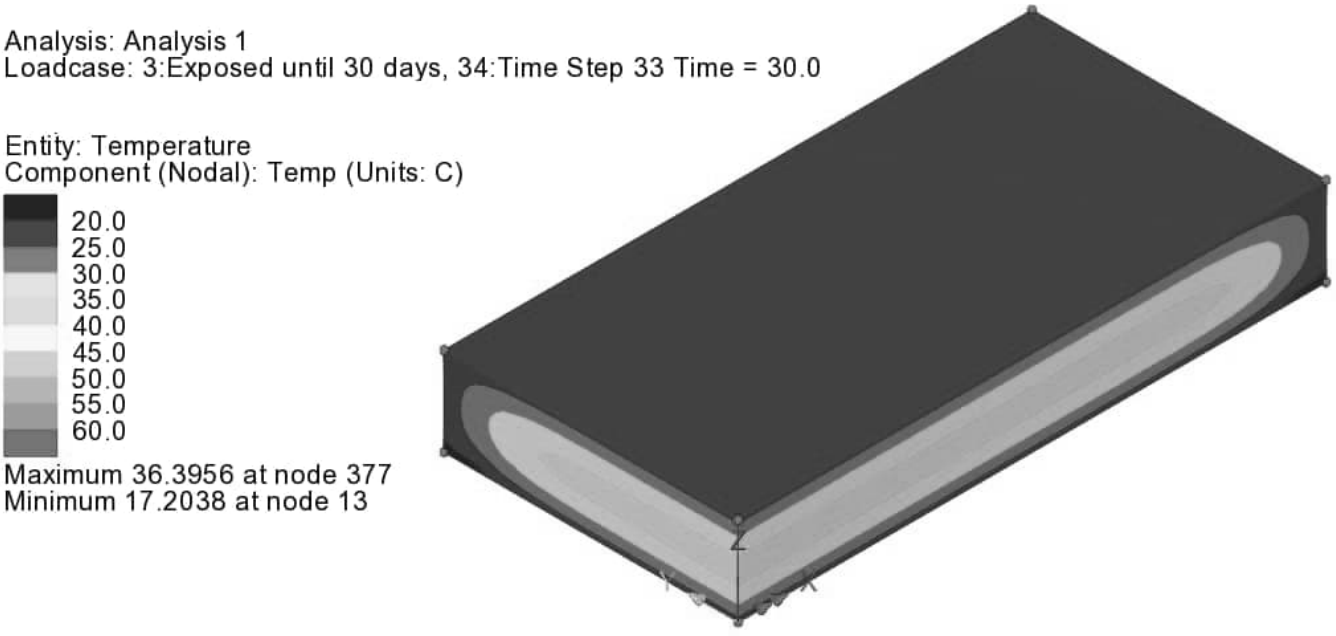
2. Analysis 1: constant air temperature

2.1 Contour temperature t = 3 days



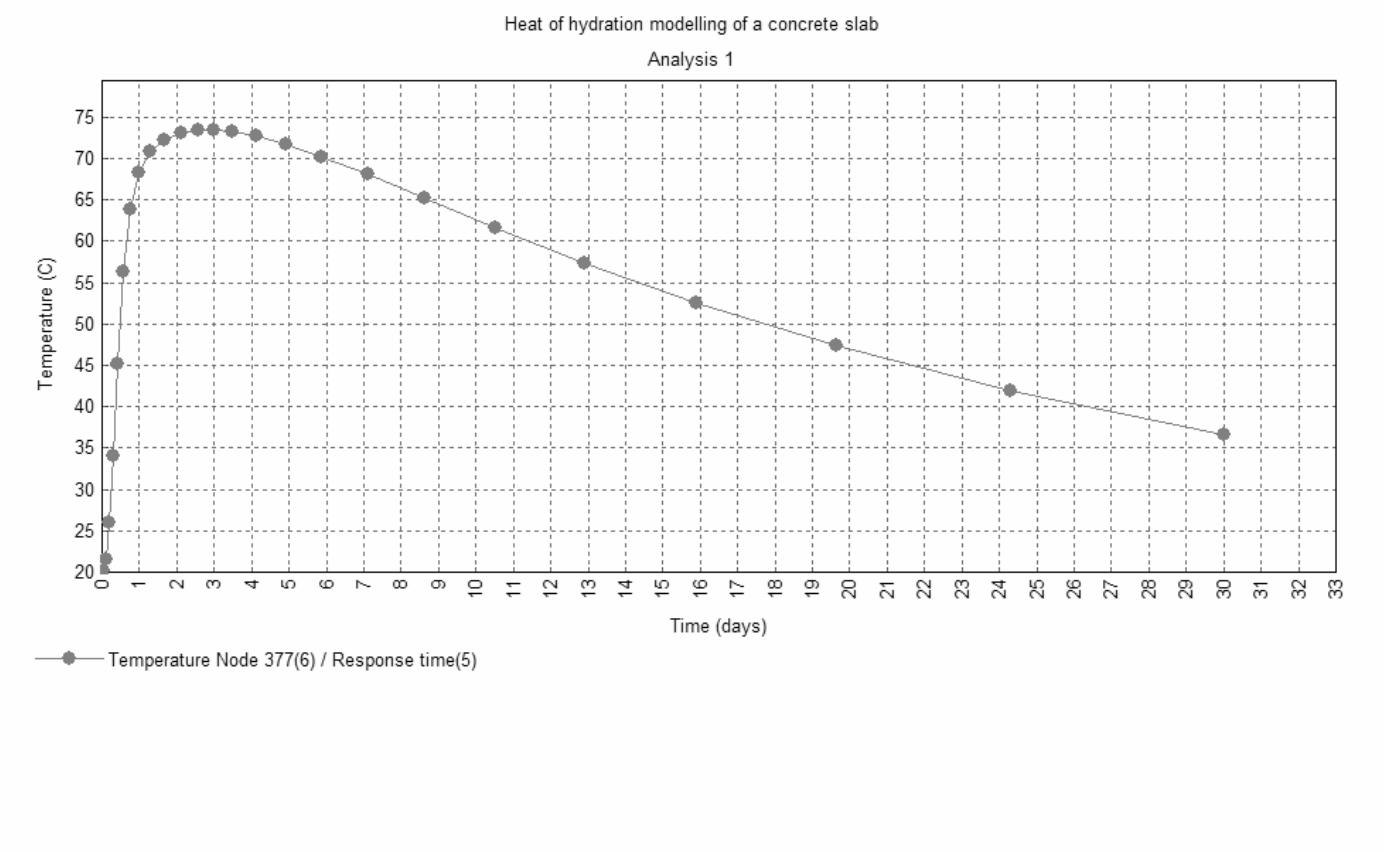
3D Overview

2.2 Contour temperature t = 30 days



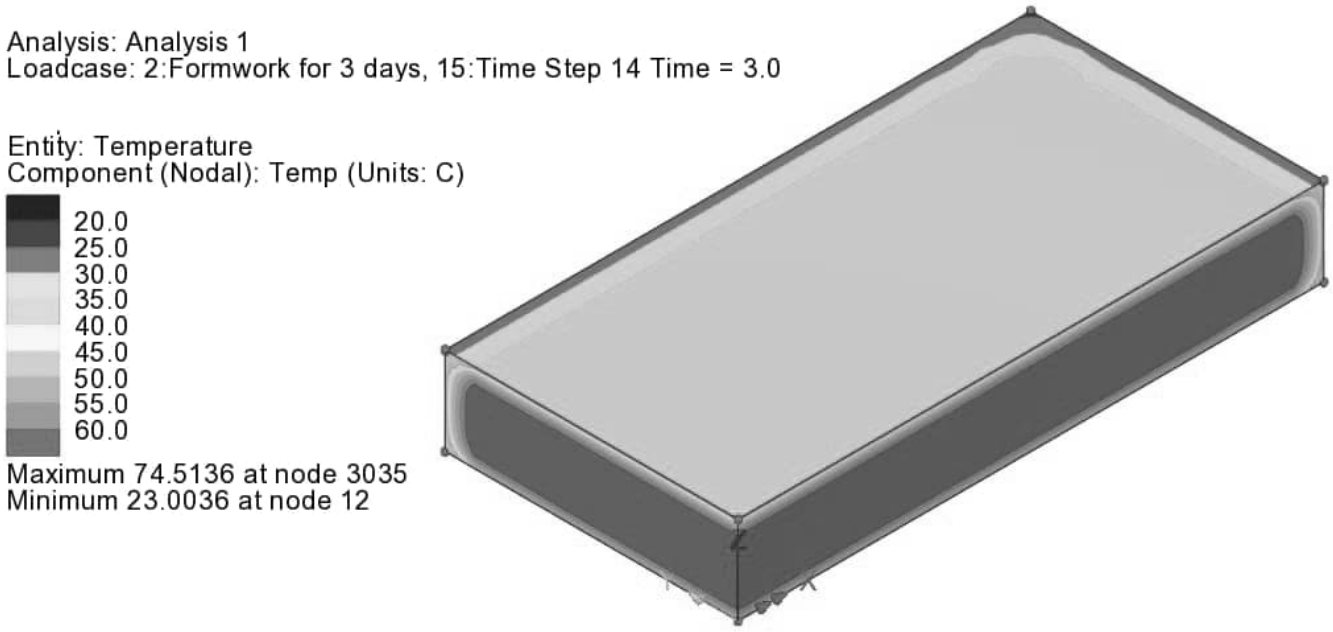
3D Overview

2.3 Table temperature at N377: t = 0 to 30 days



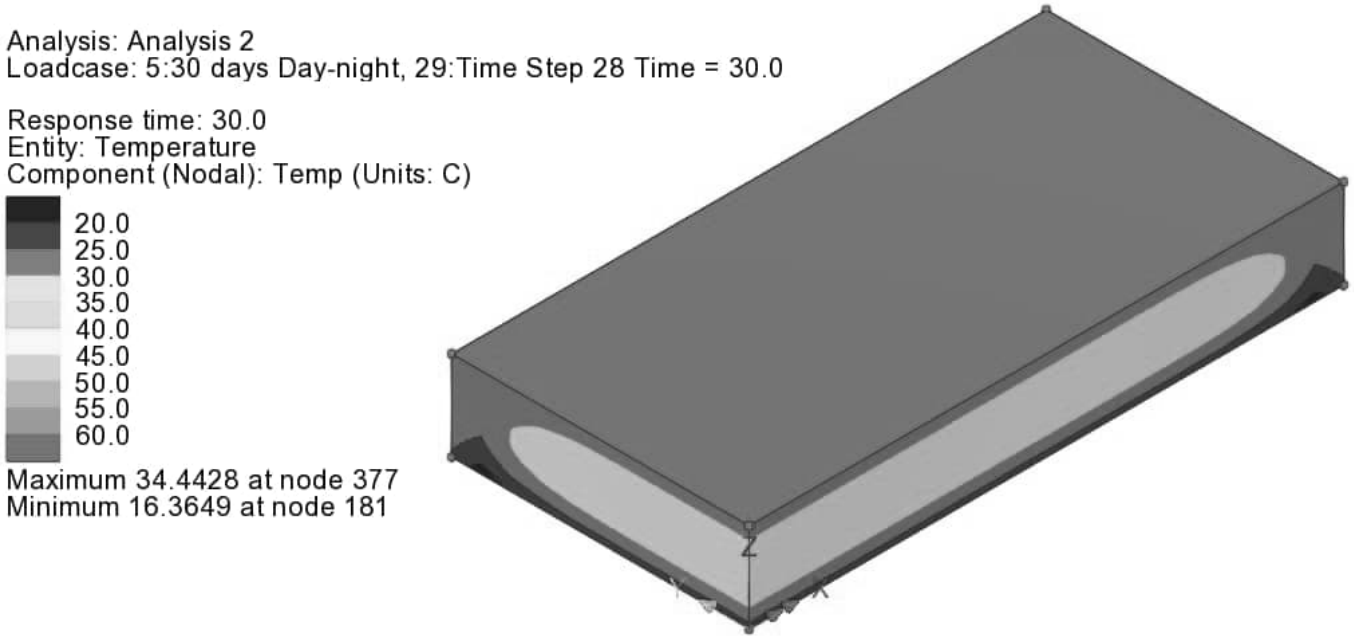
3. Analysis 2: cylclic air temperature

3.1 Contour temperature t = 3 days



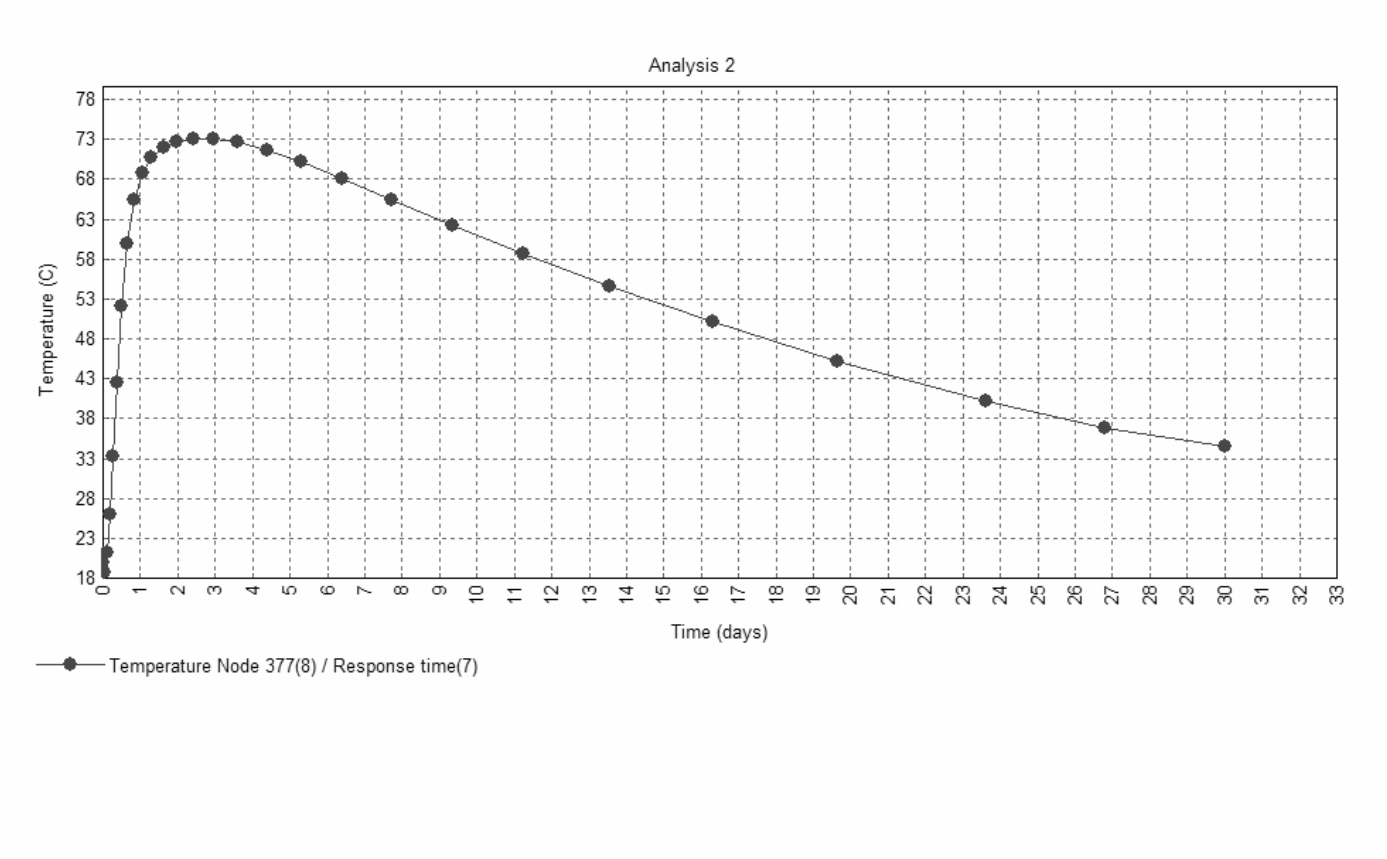
3D Overview

3.2 Contour temperature t = 30 days



3D Overview

3.3 Table temperature at N377: t = 0 to 30 days



4. Combined table of analysis 1-2

Table temperature at N377 (t = 0 to 30 days).