SAFIR®
A software for modeling the behavior of structures subjected to the fire

Course by

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Basic theory of thermal analyses

1) Different representation of the fire – boundary conditions
2) 2D or 3D discretization
3) The basic equations
4) The discretized field of temperatures
5) Material properties
6) Numerical integration on the surface
7) Cavities
8) Symmetries
9) Limitations
10) Examples

Three steps in the structural fire design

1. *Define the fire (not made by SAFIR).*

2. *Calculate the temperatures in the structure (thermal analysis).*

3. *Calculate the mechanical behaviour (mechanical analysis).*

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Step 1: Define the fire (that will then be taken as a data by SAFIR).

Option 1: a design fire $T_g = f(t)$

Command: `FRONTIER`

- Either
  - ISO 834,
  - hydrocarbon curve of Eurocode 1,
  - external fire curve of Eurocode 1,
  - ASTM E119,

  all embedded in SAFIR.
- Or choose your own time-temperature curve (from zone modelling for example) and describe it point by point in a text file.

Option 1: a design fire $T_g = f(t)$

Command: `FRONTIER`

Heat flux at the surface $q^{\cdot}$ linked to a T_g-t curve:

$$q^{\bullet} = h\left(T_g - T_S\right) + \sigma\,\varepsilon\left(T_g^4 - T_S^4\right)$$

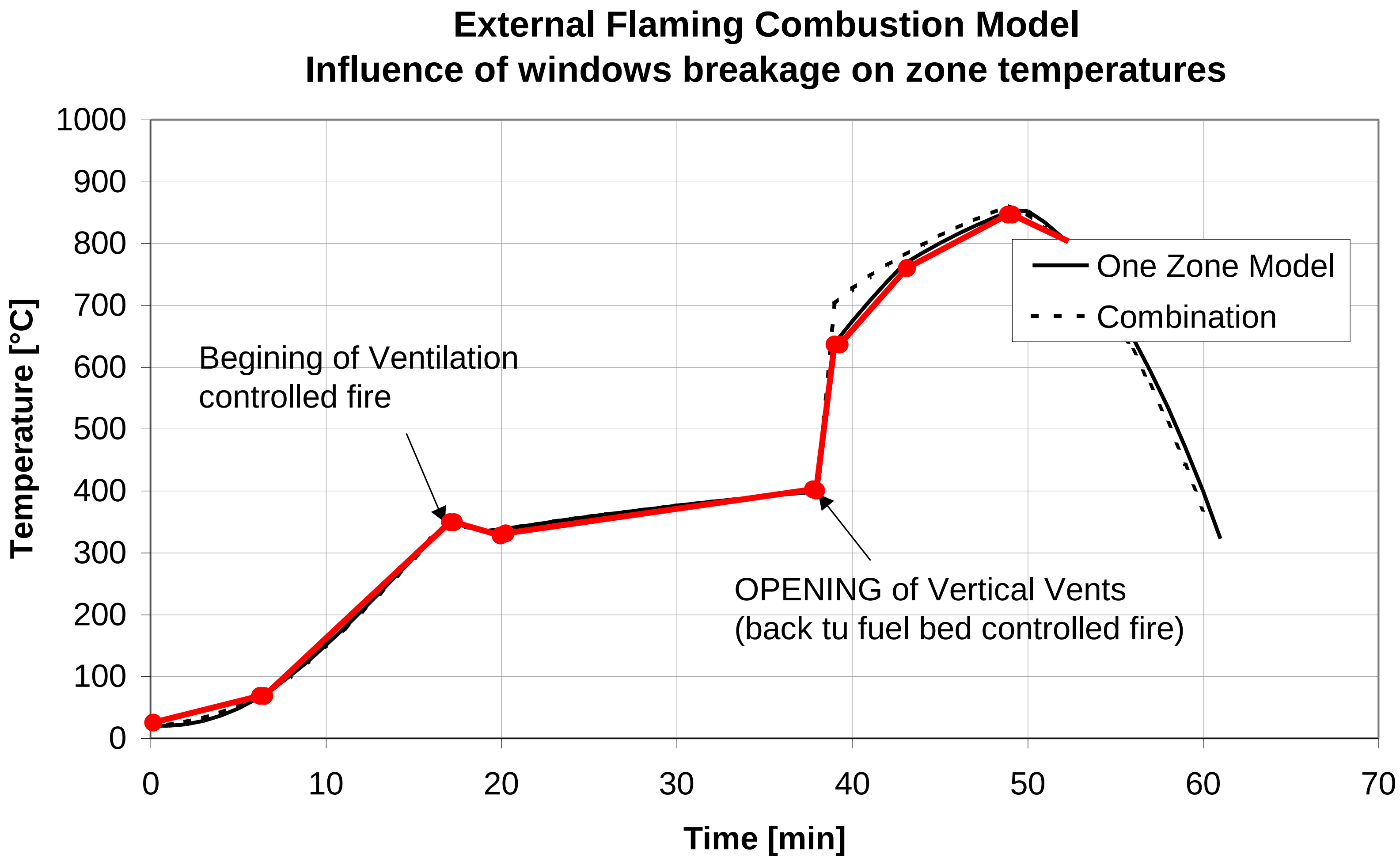
With	T_g	gaz temperature;
	T_S	surface temperature;
	h	coefficient of convection;
	σ	constant of Stefan-Boltzmann;
	ε	relative emissivity.

Example of a tool for determining Temperature-time curves in a fire compartment:

OZone

OZone

Result to be used by SAFIR : <u>the time-temperature curve</u>



Option 2: a flux at the boundary

Command: `FLUX`

$$\boxed{q^{\bullet} = f(t)}$$

f(t) is described point by point in a text file.

Note: If the flux is continuous and positive, the temperature keeps on rising to infinite values.

=> It is possible (and recommended) to combine a flux with a T_g-t condition, with T_g = 20°C.

Option 3: temperature evolution imposed at one or several nodes.

Command: `BLOCK`

Note:

Imposing the temperature in the air T_g with a `FRONTIER`

is different from

imposing the temperature at the nodes on the boundary of the section T_n.

Option 4: impose nothing on a boundary

Command: -

This will make this boundary adiabatic (no heat exchange).

$\Rightarrow$ This will make this boundary act as a line of symmetry.

=> Not a good option on the unexposed side of a wall or of a concrete slab (it is recommended to use a `FRONTIER` command with the air at 20°C: F20).

Option 5: a flux defined by a local fire model

- Either from EN 1991-1-2 (Hasemi's model),
- Or from LOCAFI model,
- Or from FDS calculation.

See advanced SAFIR courses.

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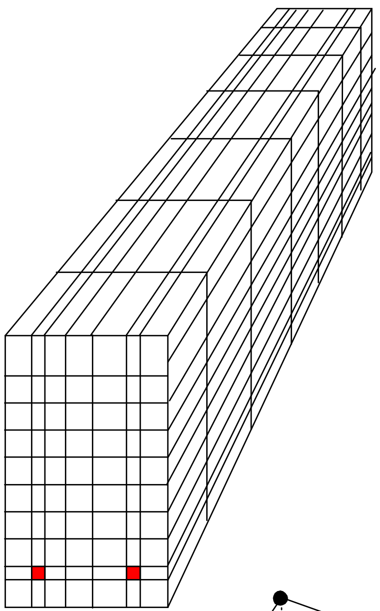
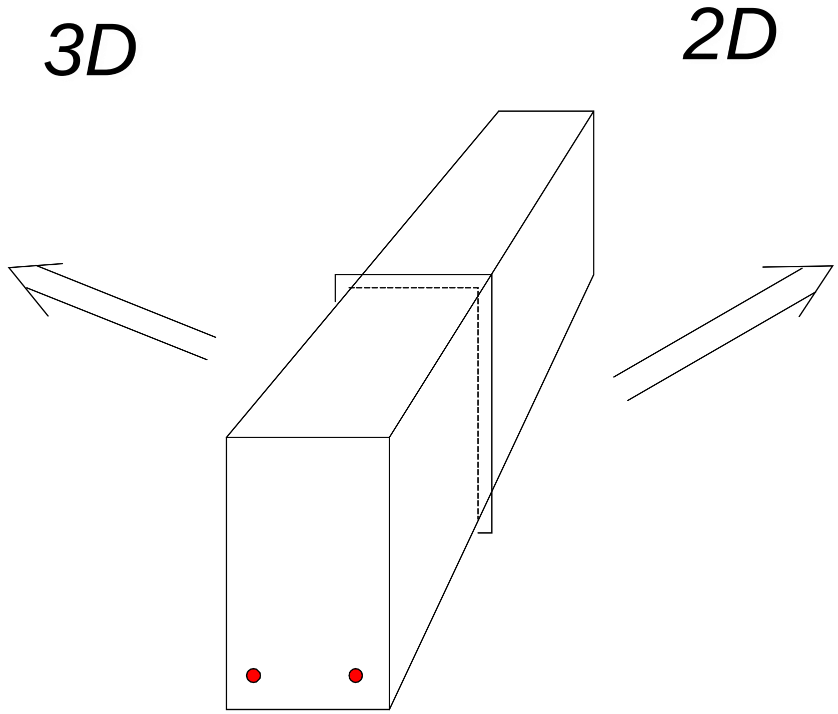
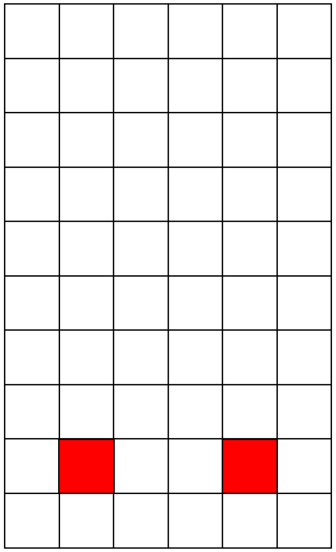
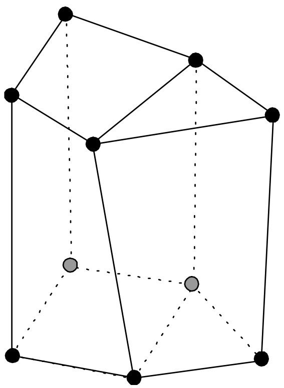
Step 2. Thermal analysis - discretization of the structure

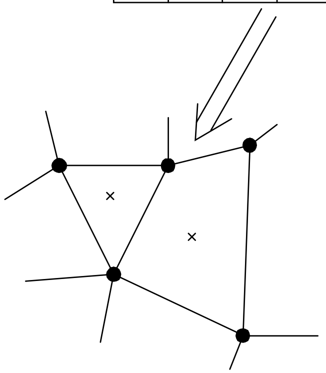
2 options are possible: 3D (for details) or 2D (for beams)











Example
A concrete beam

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The local (strong formulation) of the heat equation in 2D is:
(transient partial differential equation)

$$\frac{\partial}{\partial x}\left(k\,\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\,\frac{\partial T}{\partial y}\right)+\dot{q}_v=\rho\,c_\rho\,\frac{\partial T}{\partial t}$$

with boundary conditions of the type:

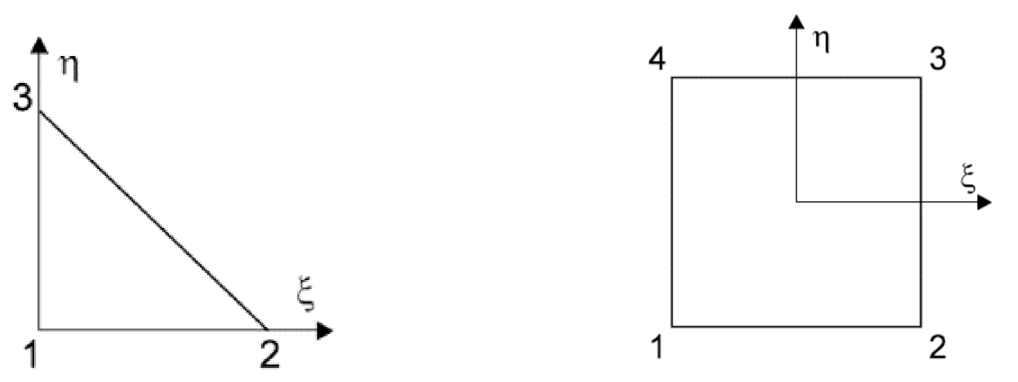
- Specified temperature: $T_s = T_1(x, y, z)$
- Specified heat flux: $q_x n_x + q_y n_y = -q_S$ Note: $q_x = -k\,\frac{\partial T}{\partial x}$
- Convection boundary condition: $q_x n_x + q_y n_y = \alpha_c\left(T_g - T_s\right)$
- Radiation boundary condition: $q_x n_x + q_y n_y = \Phi\,\varepsilon^*\,\sigma\left(T_g^4 - T_s^4\right)$
- Initial condition for transient problems: $T(x, y, 0) = T_0(x, y)$

Finite Element method

- Transform the local differential equation into a system of algebraic equations

- Solve for approximate values of the unknowns at discrete number of points over the domain

Shape functions (interpolation)



The local and steady state equilibrium equation for conduction in 2D is:

$$\left(k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} \right) + Q = 0$$

It is transformed into an element equilibrium equation. For a 4 nodes element, it has the form:

$$\left[K\right]\left\{T\right\} \quad = \quad \left\{q\right\}$$

$$\begin{bmatrix} k_{1,1} & k_{1,2} & k_{1,3} & k_{1,4} \\ & k_{2,2} & k_{2,3} & k_{2,4} \\ & & k_{3,3} & k_{3,4} \\ Sym & & & k_{4,4} \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{Bmatrix} = \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{Bmatrix}$$

$$\left(k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} \right) + Q = 0 \qquad \text{(Eq. 1)}$$

$$[K]\{T\} = \{q\} \qquad \text{(Eq. 2)}$$

The temperatures that are the solution of Eq. 2, do not satisfy Eq. 1 exactly. They satisfy it *in average*.

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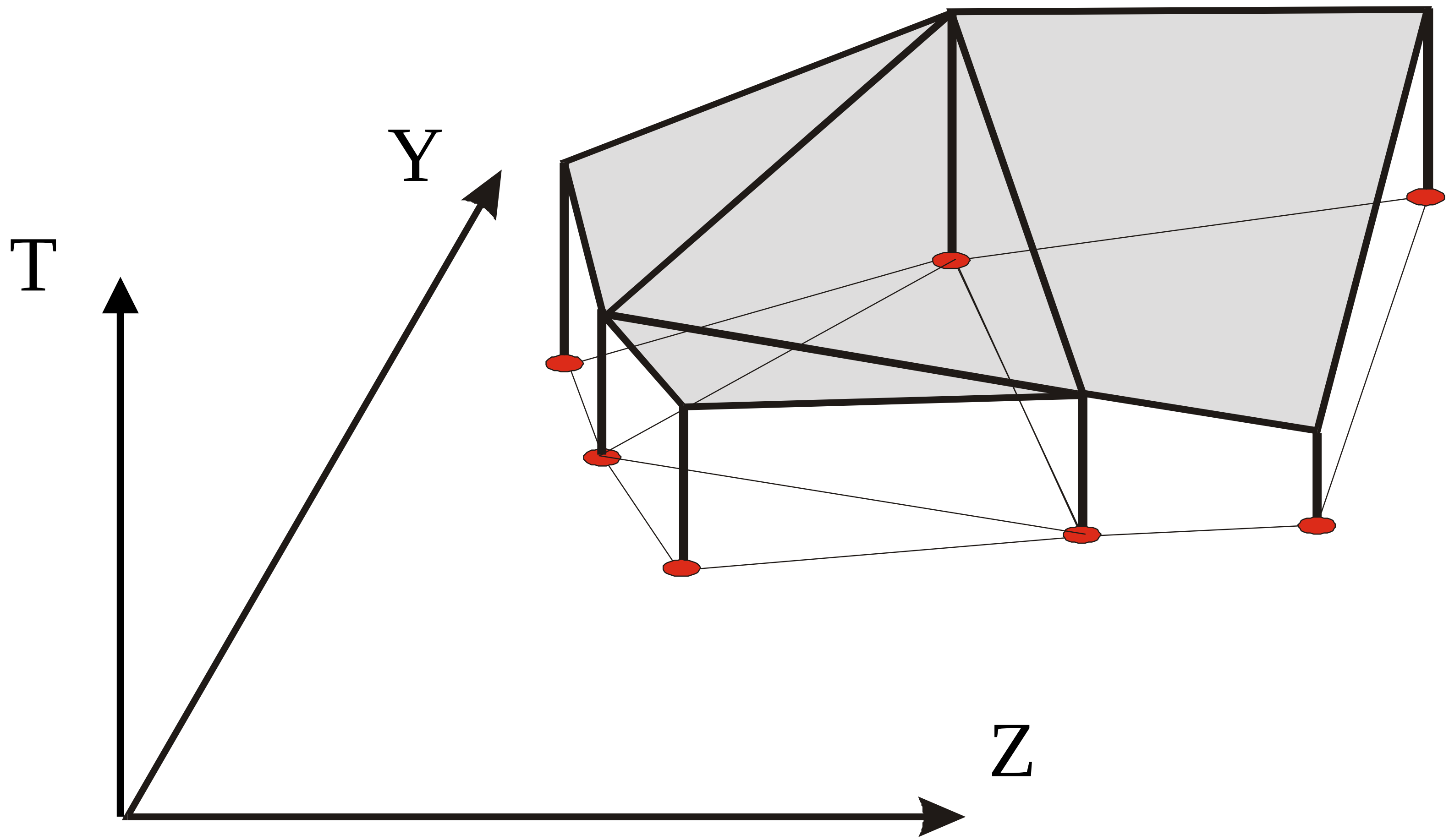
2D thermal model

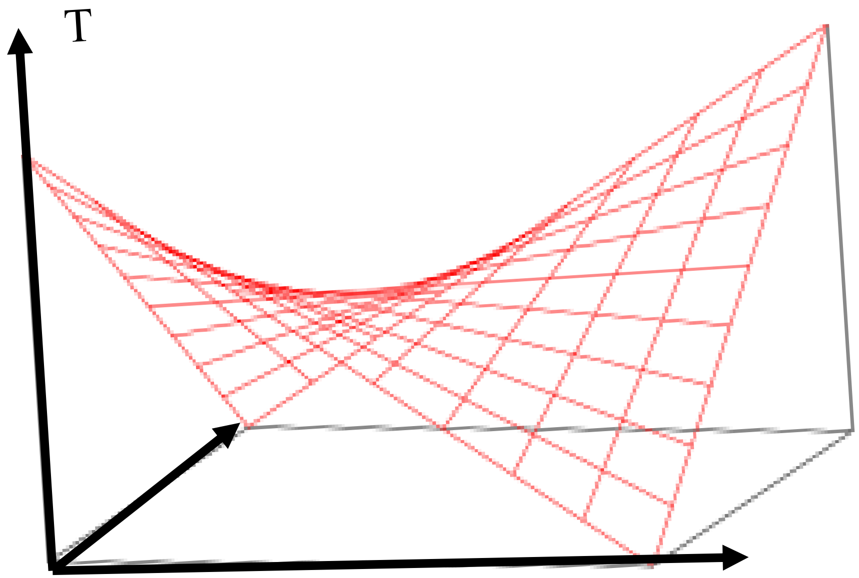
Meshing of the section with 3 or 4 noded linear elements.

The temperature is represented here graphically by the vertical elevation. It defines a surface in the (Y, Z, T) space.



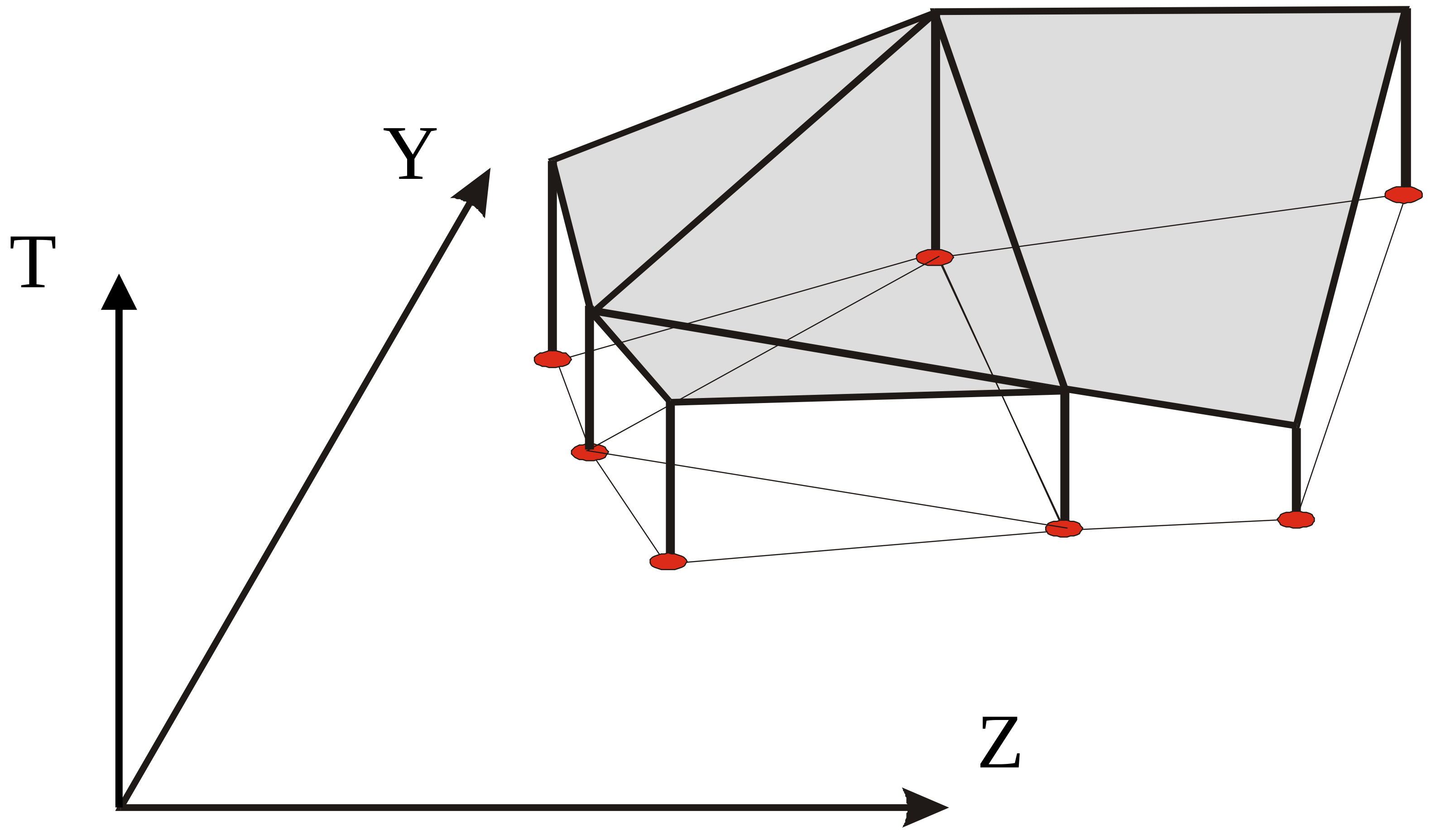
The temperature surface in 3 node elements can only be a plane.

The temperature surface in 4 node elements is a paraboloid hyperbolic



=> The temperature varies linearly along the edges of the elements

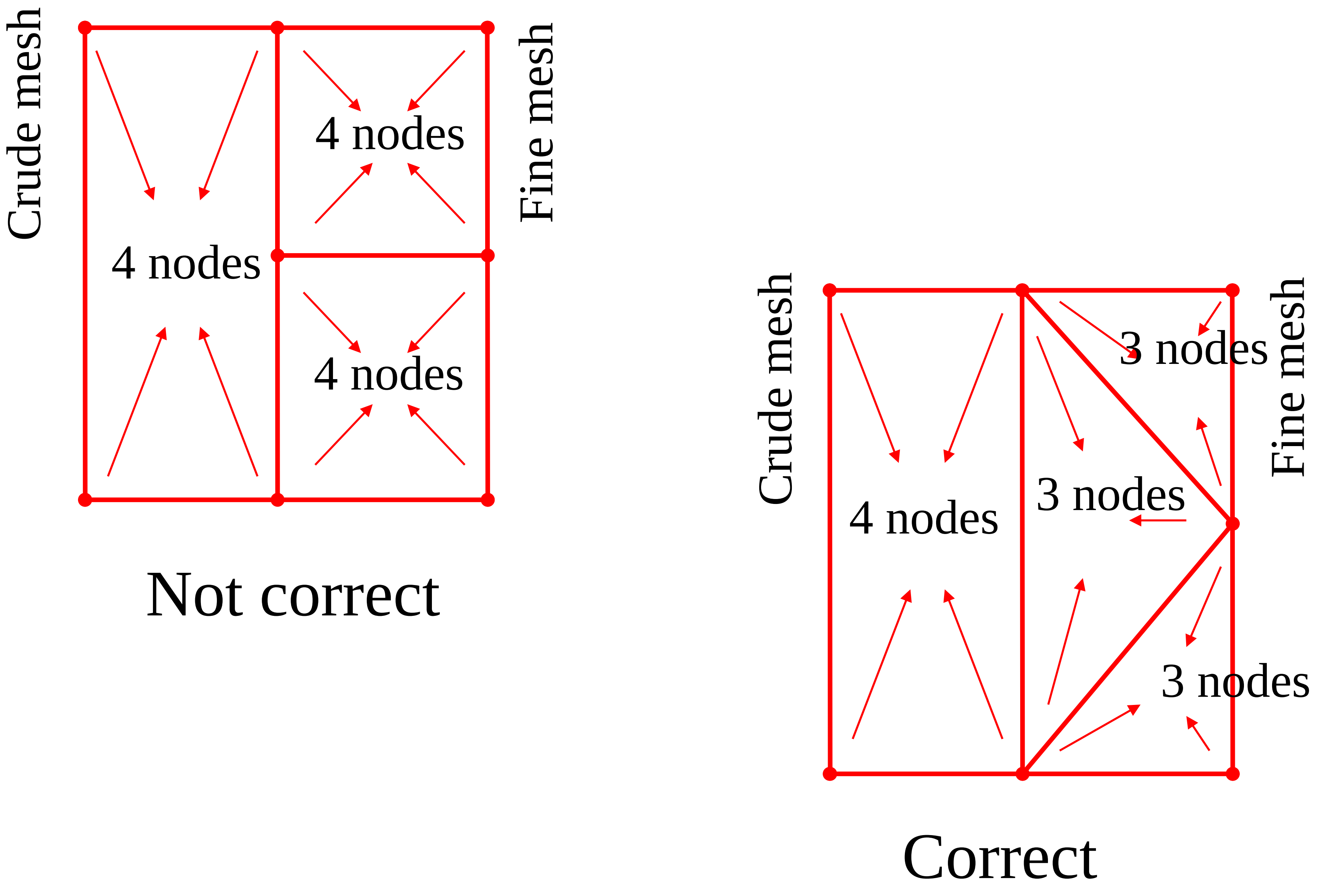
The temperature varies linearly along the edges of all elements => C_0 continuity for the temperature field



2 adjacent paraboloid hyperbolic and the common linear edge

Adjacent triangular and quadrangular surfaces with common linear edges

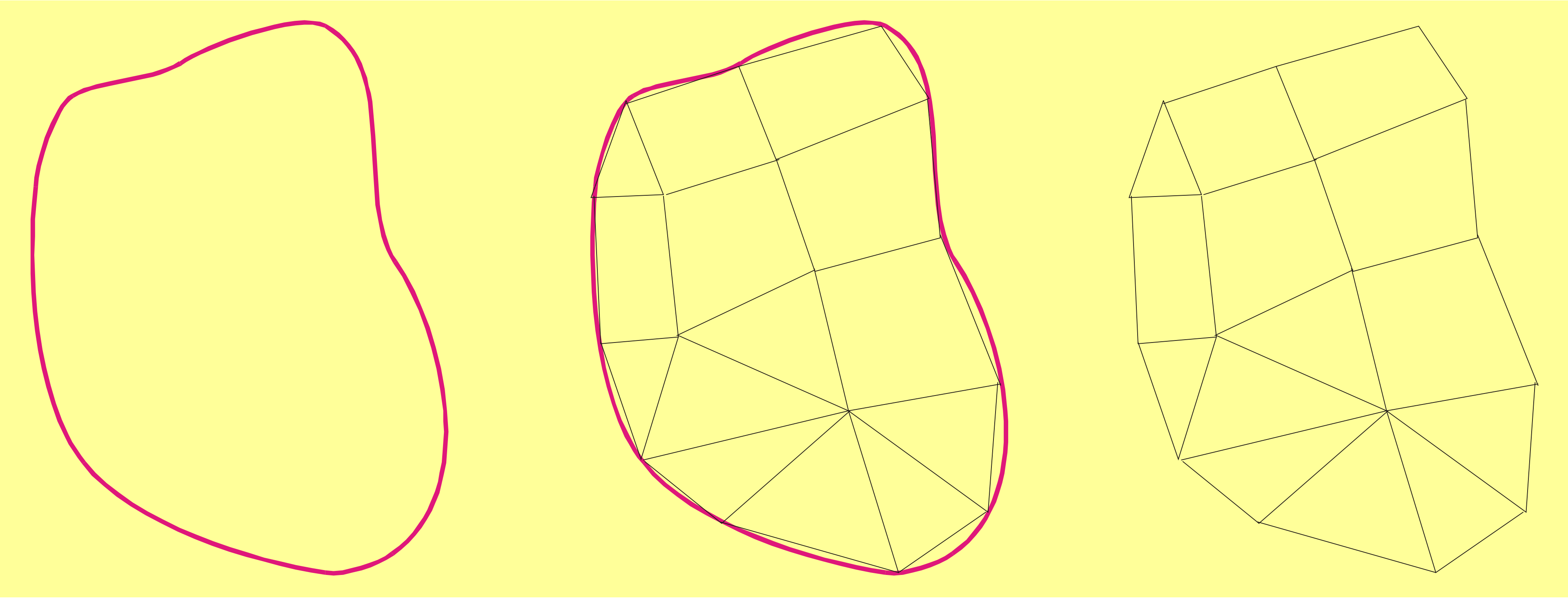
N.B.: one edge is missing (see next slide)



Crude mesh
4 nodes
4 nodes
4 nodes
Fine mesh
Not correct
Crude mesh
4 nodes
3 nodes
3 nodes
3 nodes
Fine mesh
Correct

⇒The discretised section

is an approximation of the real section.

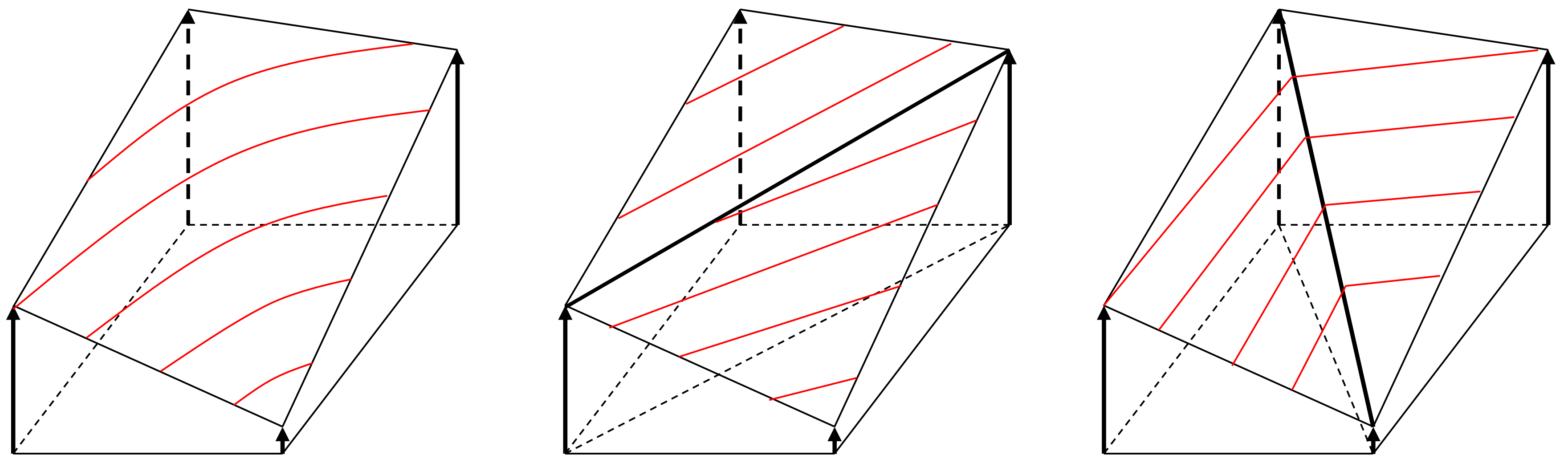


True section *Matching* *Discretised section*

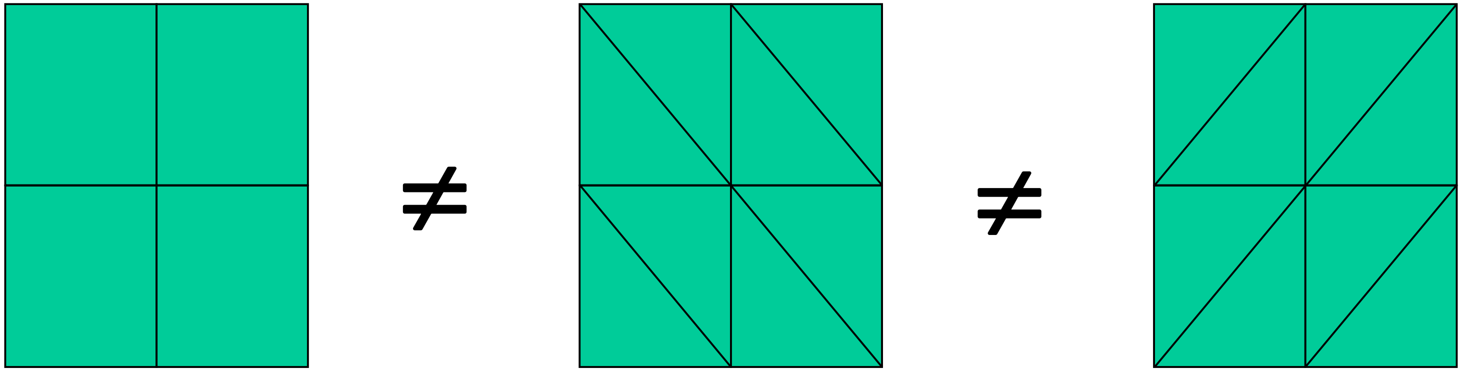
Different discretizations, different results.

Why is that?

Isotherms



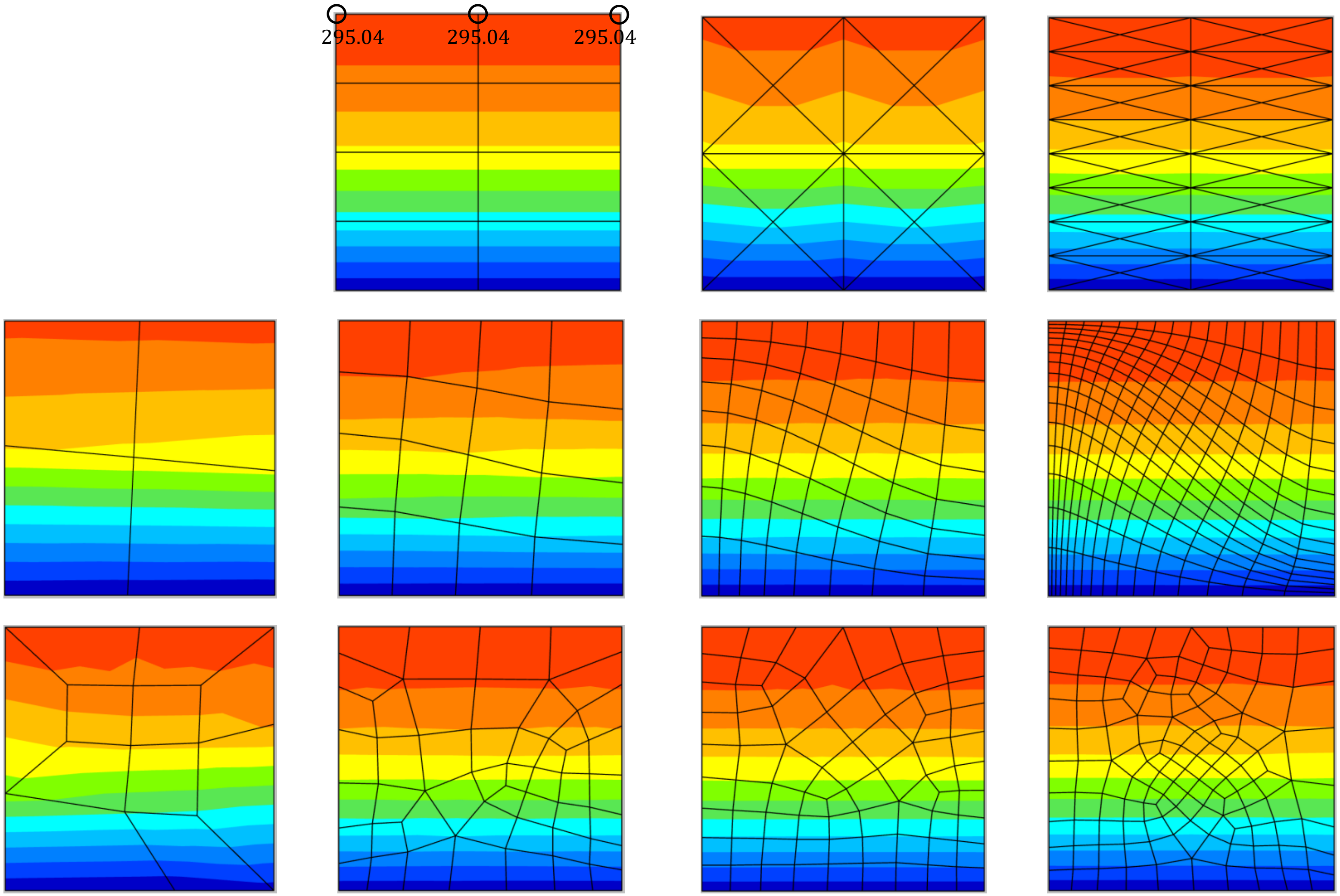
Same section, same temperature at the corners.
Different discretizations => different temperature distributions in the section



Same section.
Different discretizations.
⇒Different results

Note: the results tend toward the true solution when the size of the elements tends toward 0.

⇒Mesh sensitivity



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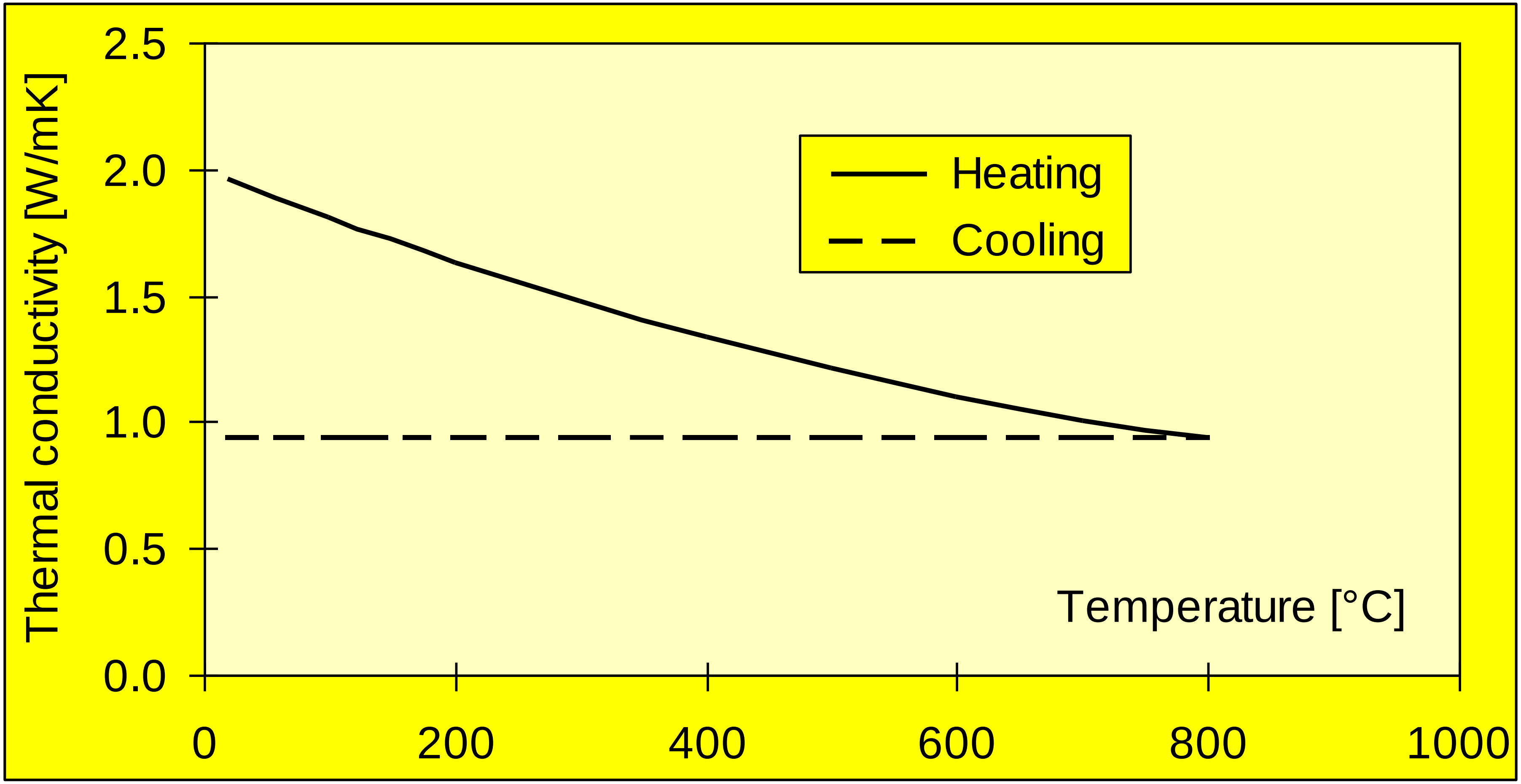
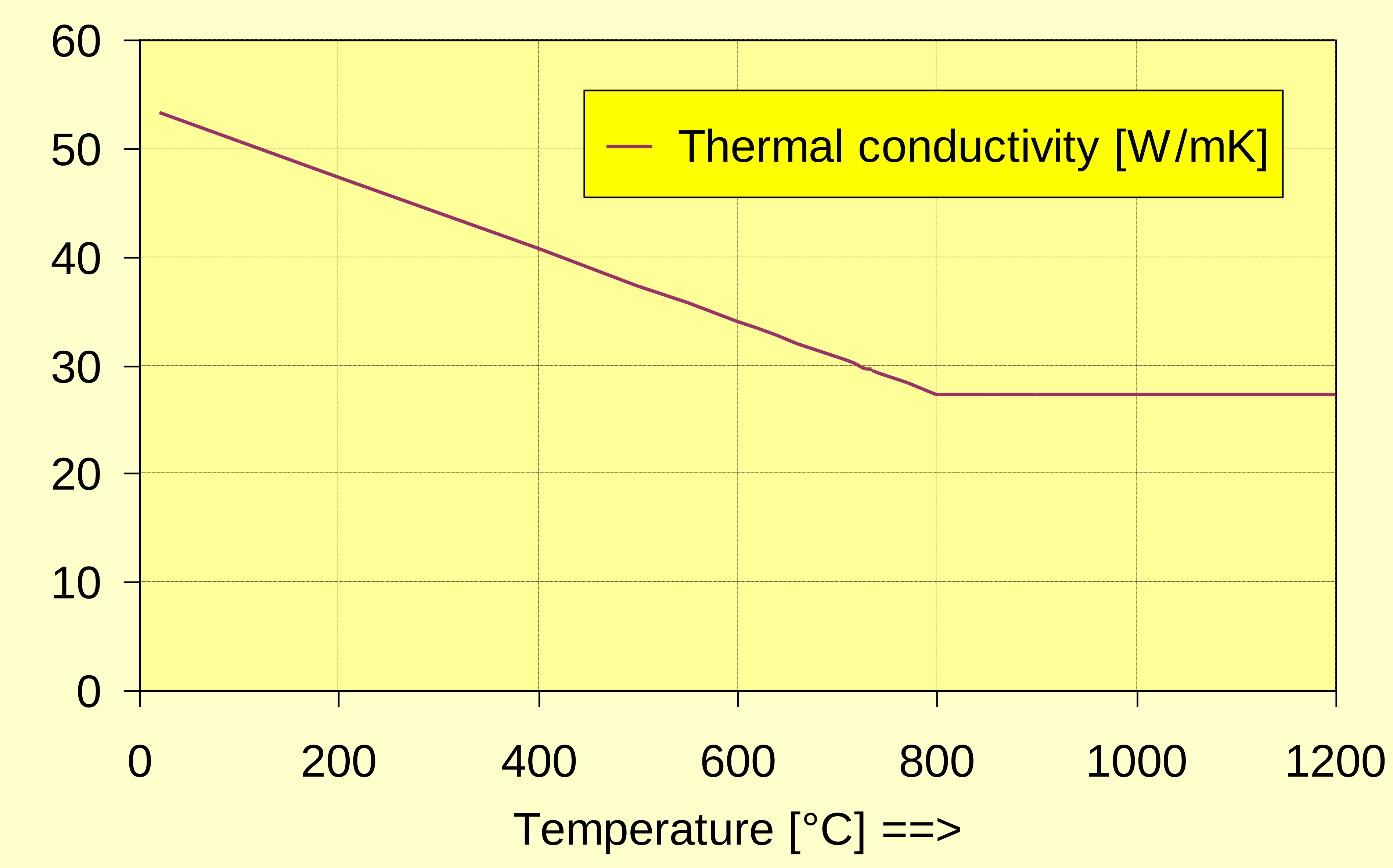


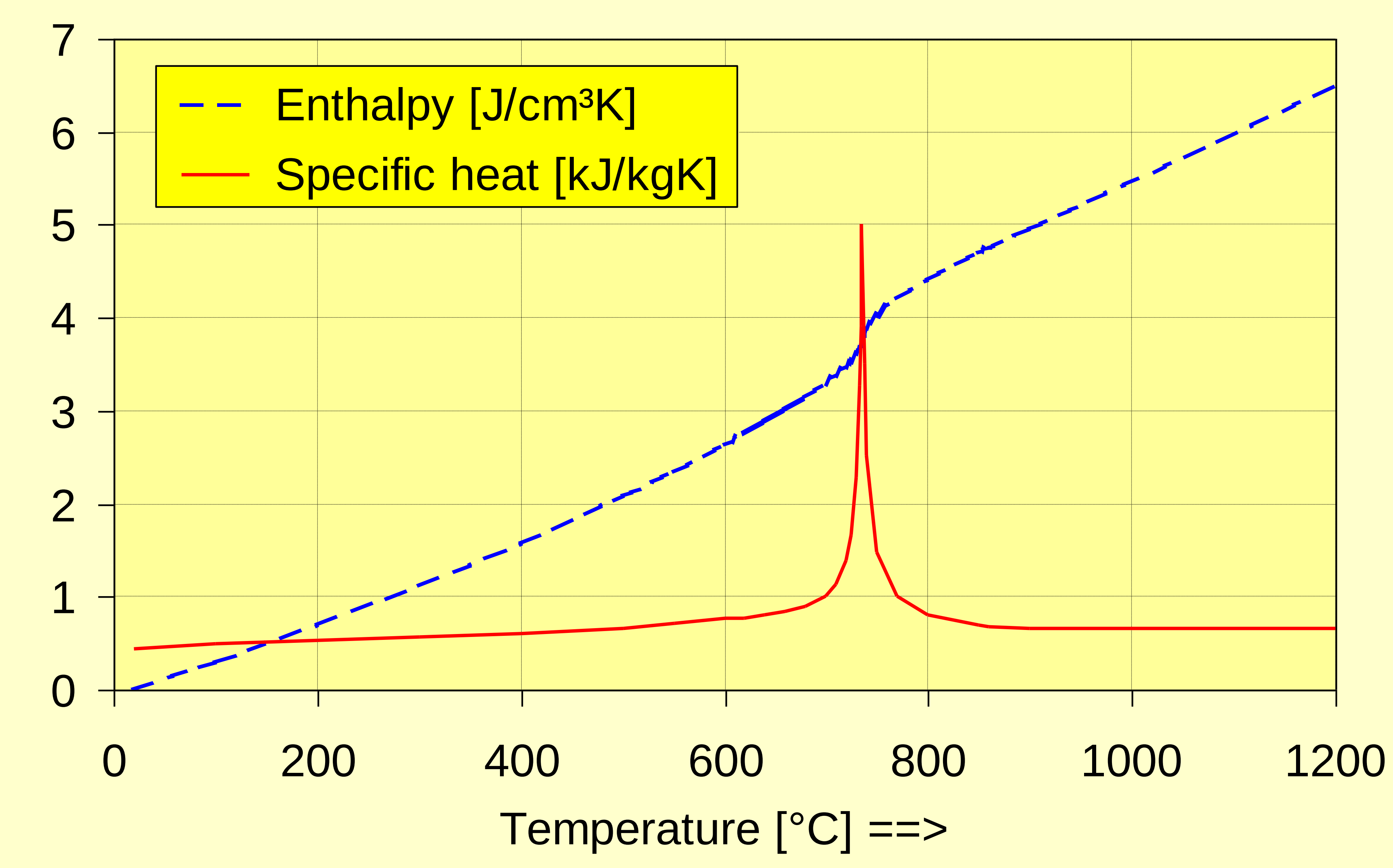
Non linear thermal properties are present in Eq. 2.

Here, thermal conductivity of concrete

(non reversible during cooling).



Thermal conductivity of steel



Specific heat of steel

USER Material

Temperature-dependent material properties defined by the user

USERx: material with some thermal properties that vary with temperature.

b) 1 card

`USERx`, *ntemperature*

- `USERx` [A5]

  Name of the material. Five different materials are possible, namely USER1, USER2, USER3, USER4 and USER5. As an exception to all other material types, only one material number can have the name USER1, only one material can have the name USER2, etc.

- *ntemperature* [real]

  Number of temperatures at which the thermal properties are given. Properties are given at a certain number of temperatures, given in increasing order. Linear interpolation is made for intermediate temperatures.
  The value of *ntemperature* cannot be smaller than 2 (because linear interpolation must be made.

c) *ntemperature* cards

Card 1.

T, k, c, rho, w, h_h*,* h_c*,* ε*, r*

- *T* [real]

  First[12] temperature (in degree Celsius) at which thermal properties are given

- *k* [real]

  Thermal conductivity at *T*, in W/mK

- *c* [real]

  Specific heat at *T*, in J/kg K

- *rho* [real]

  Specific mass of the dry material at *T*, in kg/m^3

- *w* [real]

  Water content, in kg/m^3

- h_h [real]

  Coefficient of convection on heated surfaces, in W/m^2K

- h_c [real]

  Coefficient of convection on unheated surfaces, in W/m^2K

- ε [real]

  Emissivity (no dimension)

- *r* [real]

  Any positive value (and 0) will force *k, c, rho* to be non reversible. This means that, during cooling from a maximum temperature T_{max}, these properties will keep the value that was valid for T_{max}. Any negative value will force these

USER Material

Temperature-dependent material properties defined by the user

As an example, the following 12 cards have been used to represent concrete of EN 1992-1-2 heated by the ISO curve, according to the French National Annex.

```
   USER1     12
   0.    2.0000    900.   2300.    34.5   25.   4.   0.7   1.
  50.    1.8801    900.   2300.
 100.    1.7656    900.   2300.
 115.    1.7323    915.   2300.
 140.    1.6778    940.   2286.
 160.    1.1570    960.   2276.
 200.    1.1108   1000.   2254.
 400.    0.9072   1100.   2185.
 600.    0.7492   1100.   2145.
 800.    0.6368   1100.   2105.
1000.    0.5700   1100.   2064.
1200.    0.5488   1100.   2024.
```

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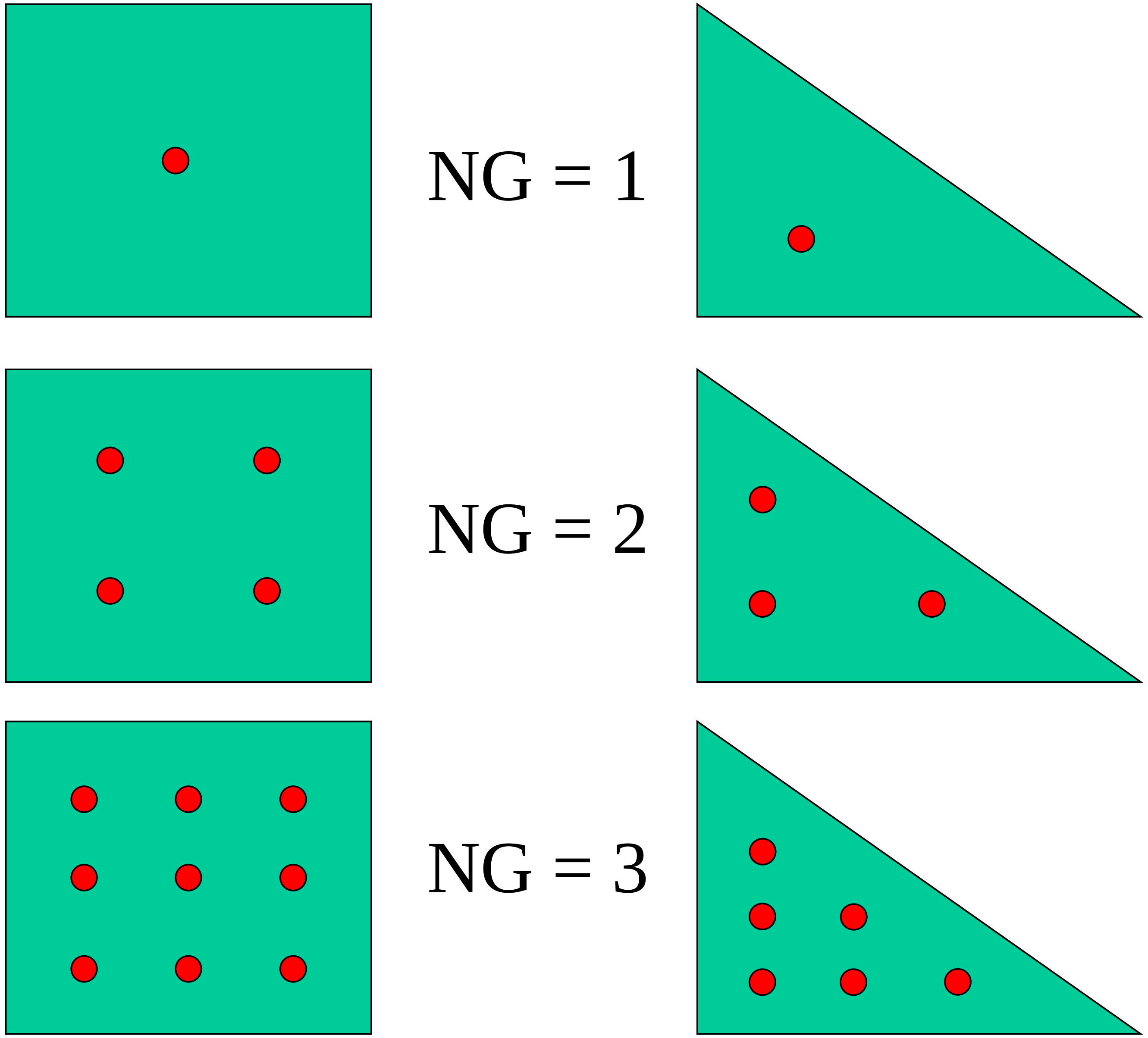

Integration of the thermal properties on the surface: Numerical method of Gauss

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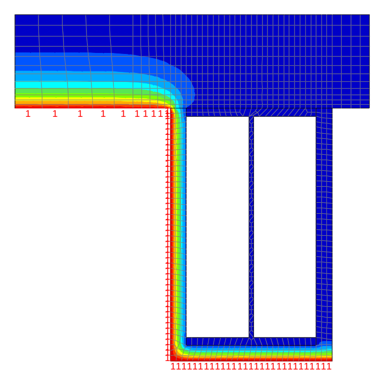
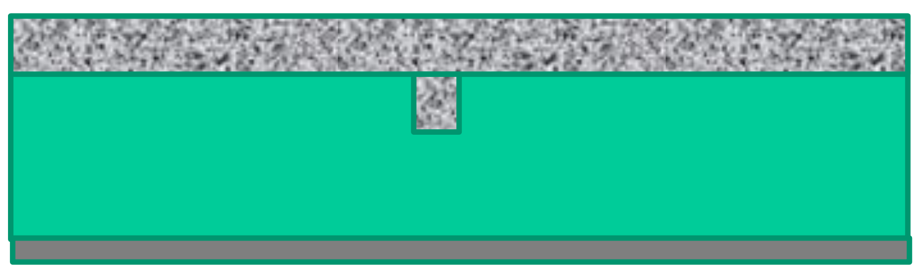
What is a cavity in SAFIR?
Definition: cavity = part of the model that does not contain solid, but influences the heat transfer in the model.

- ✓ Enclosed cavities



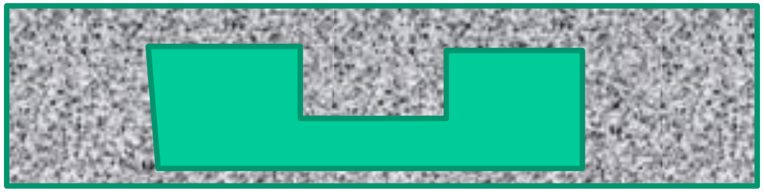
- ✓ Open cavities (don’t forget SYMVOID)



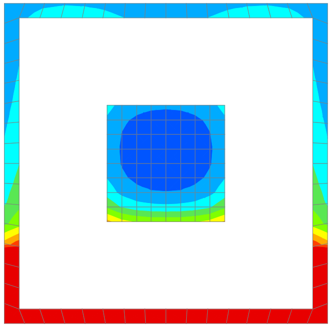
Limitation: only possible in 2D models, not in 3D

.Capabilities:

✓ Concave cavities

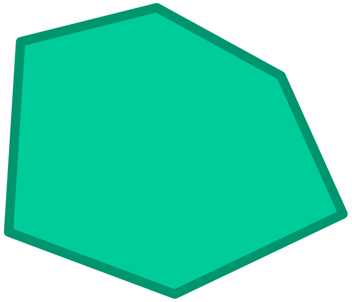


✓ Included objects



Heat transfer modes

1) Radiation in the cavity.

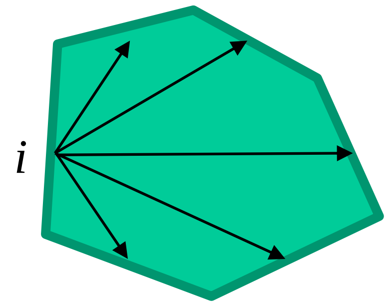


A cavity discretised by N = 6 facets

- Gaz in the cavity is taken as fully transparent (no absorption).
- Radiative temperature of each facet = temperature at mid length of the facet

For each facet *i*,

- The view factors to all facets *j* are computed: F_{ij} (this may take some time).
- The sum is computed $S = \sum_{j=1}^{N} F_{ij}$
- If $S \neq 1.00$ => all F_{ij} are divided by S (this ensures that no energy is created due to numerical errors in the computation of the view factors).



A cavity discretised by N = 6 facets

SAFIR message

```
On surface   1, Sum FiJ =  1.001
On surface   2, Sum FiJ =  1.001
On surface   3, Sum FiJ =  1.001
On surface   4, Sum FiJ =  1.000
```

$\Rightarrow$Classical equations of heat transfer by radiation.

Note:

Radiation = $f(T^4)$

=> The tangent matrix is not symmetrical.

=> The matrix is made symmetrical, thus not exact anymore.

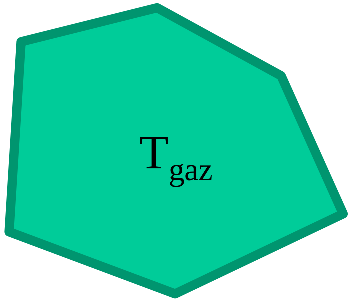
=> Convergence may be slower

=> Use smaller time steps

! Convergence is toward the true solution.

Heat transfer modes

2) Convection in the cavity.



A cavity discretised by N = 6 facets

HYPOTHESES:

- The viscosity of gas in the cavity is very high.
- The cavity is assumed to be small.

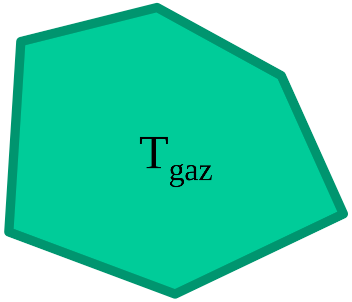
  => The temperature of gas is uniform in the cavity

- The volumetric heat ($c\rho$) of gas is negligible.
- The convection on the surface of the facets is linear: $q' = h_{non\ exposed\ surfaces}\,(T_{gas}\text{-}T_{facet})$

  => The temperature of the gas is the average of the temperatures on the facets.

Heat transfer modes

2) Convection in the cavity.



A cavity discretised by N = 6 facets

LIMITATIONS:

Gravity is not considered => The orientation of the cavity, for example vertical or horizontal, is not considered.
Air movements within the cavity are not considered.

=> Convection is considered in a simplified manner (but radiation is usually dominating).

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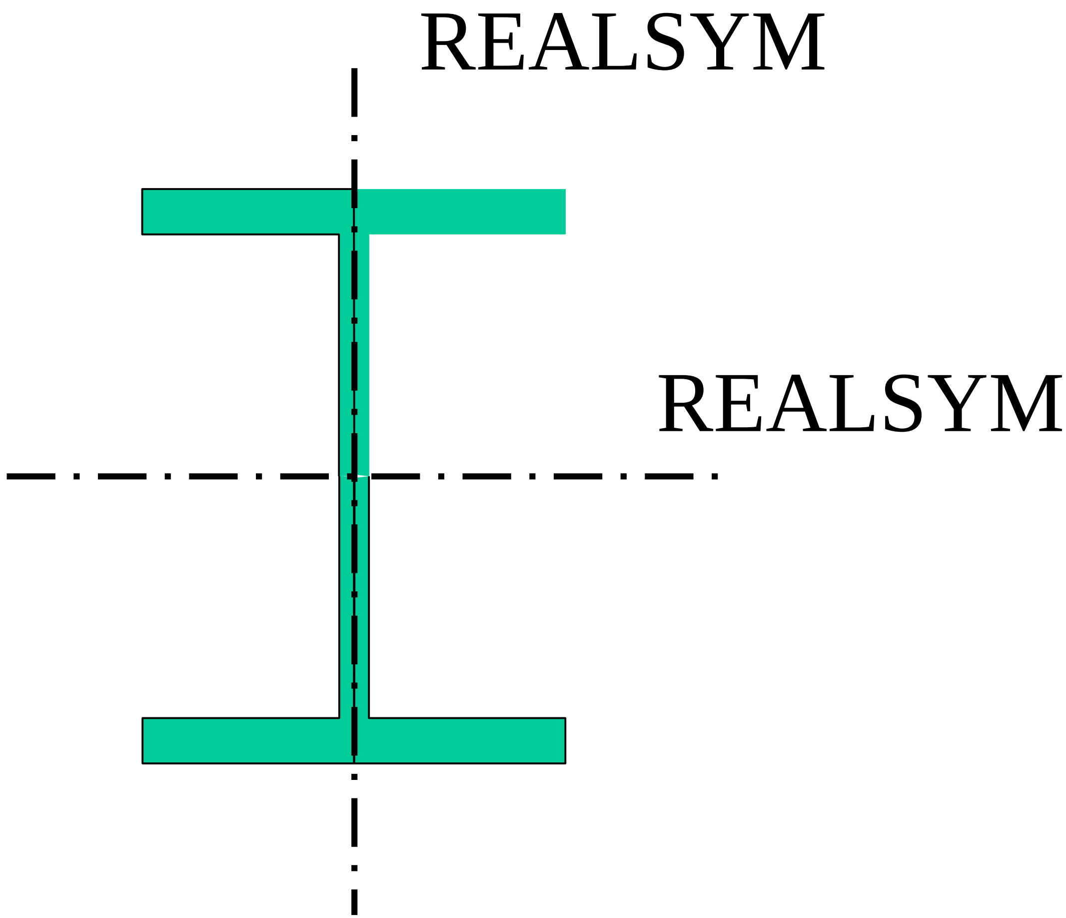
Symmetries

REALSYM:

- ✓ There is an axis of symmetry (for the geometry of the section and for the boundary conditions).
- ✓ In order to decrease the size of calculation, we model only ½ of the section.
- ✓ The section of each modelled "fiber" is reproduced on the other side of the axis of symmetry.

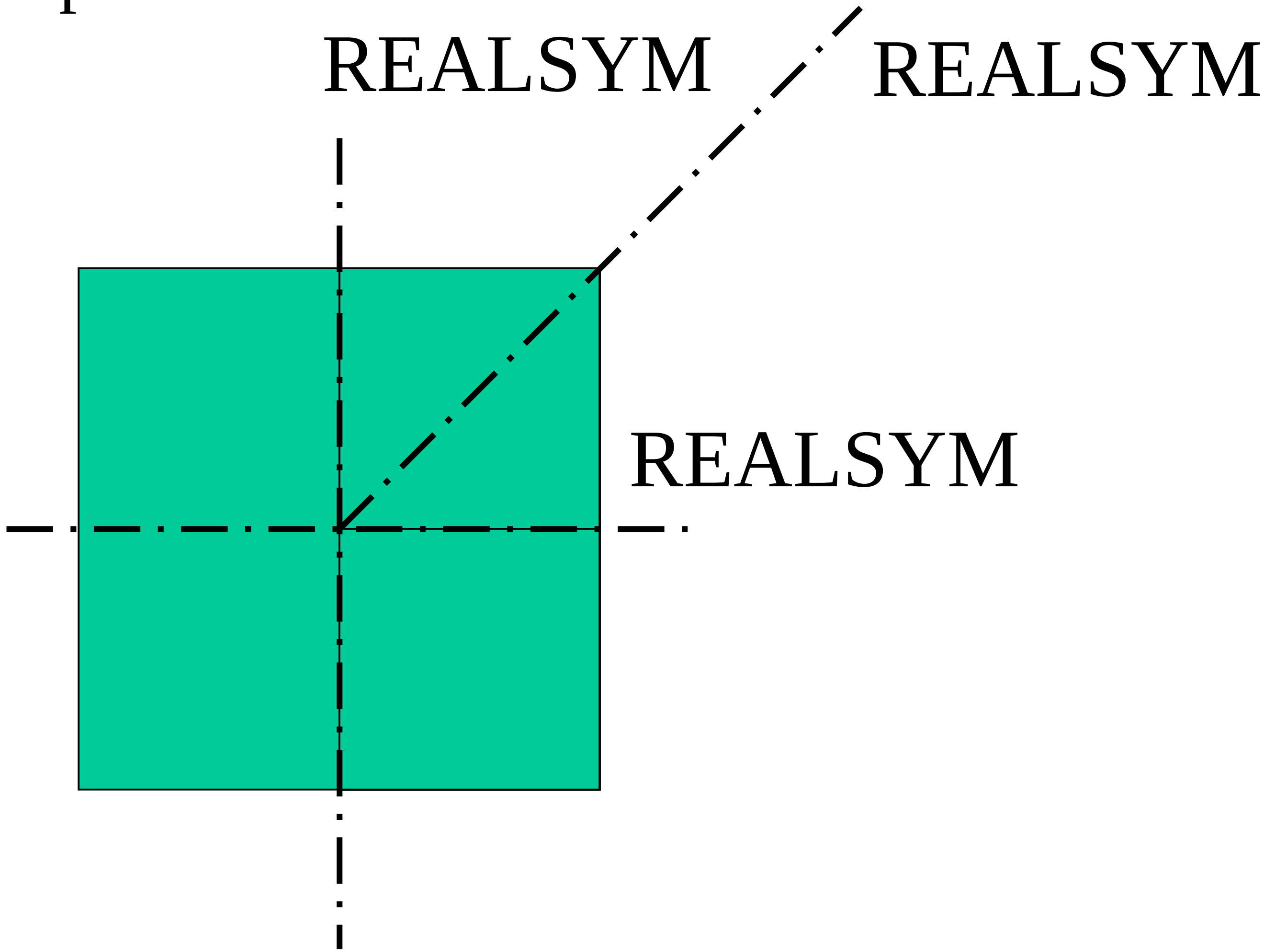
Symmetries

REALSYM: examples



Symmetries

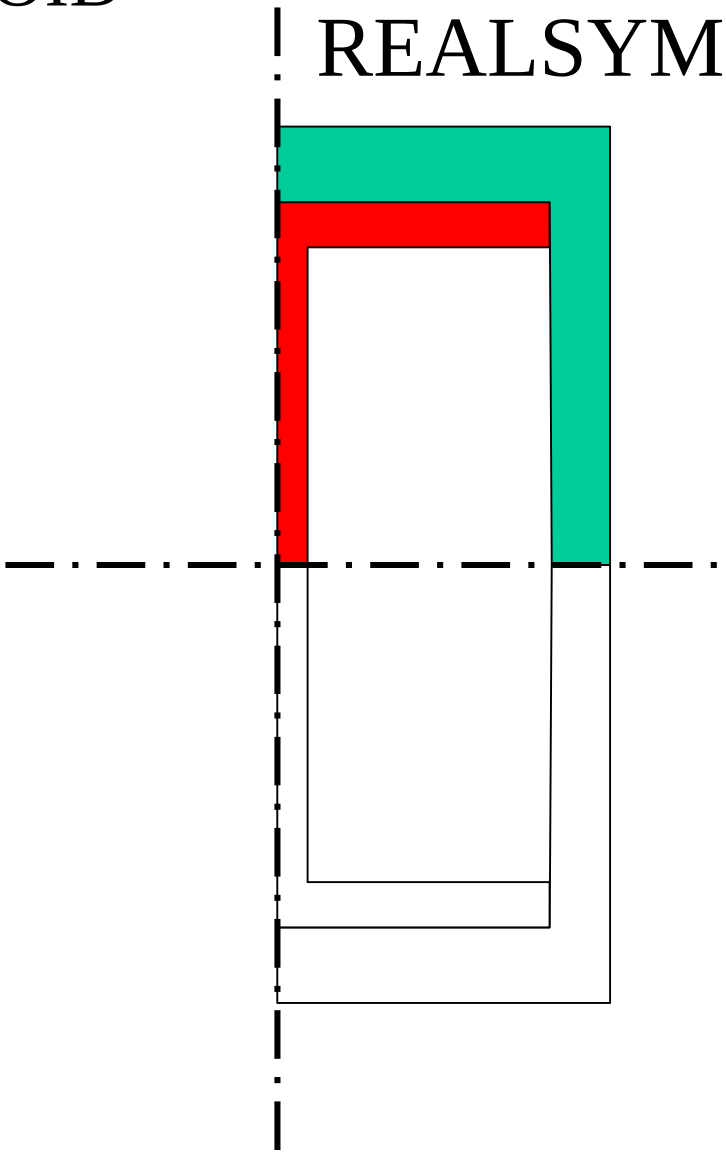
REALSYM: examples



Symmetries

SYMVOID

REALSYM



REALSYM

&

SYMVOID

(for calculation of the view factors in the cavity)

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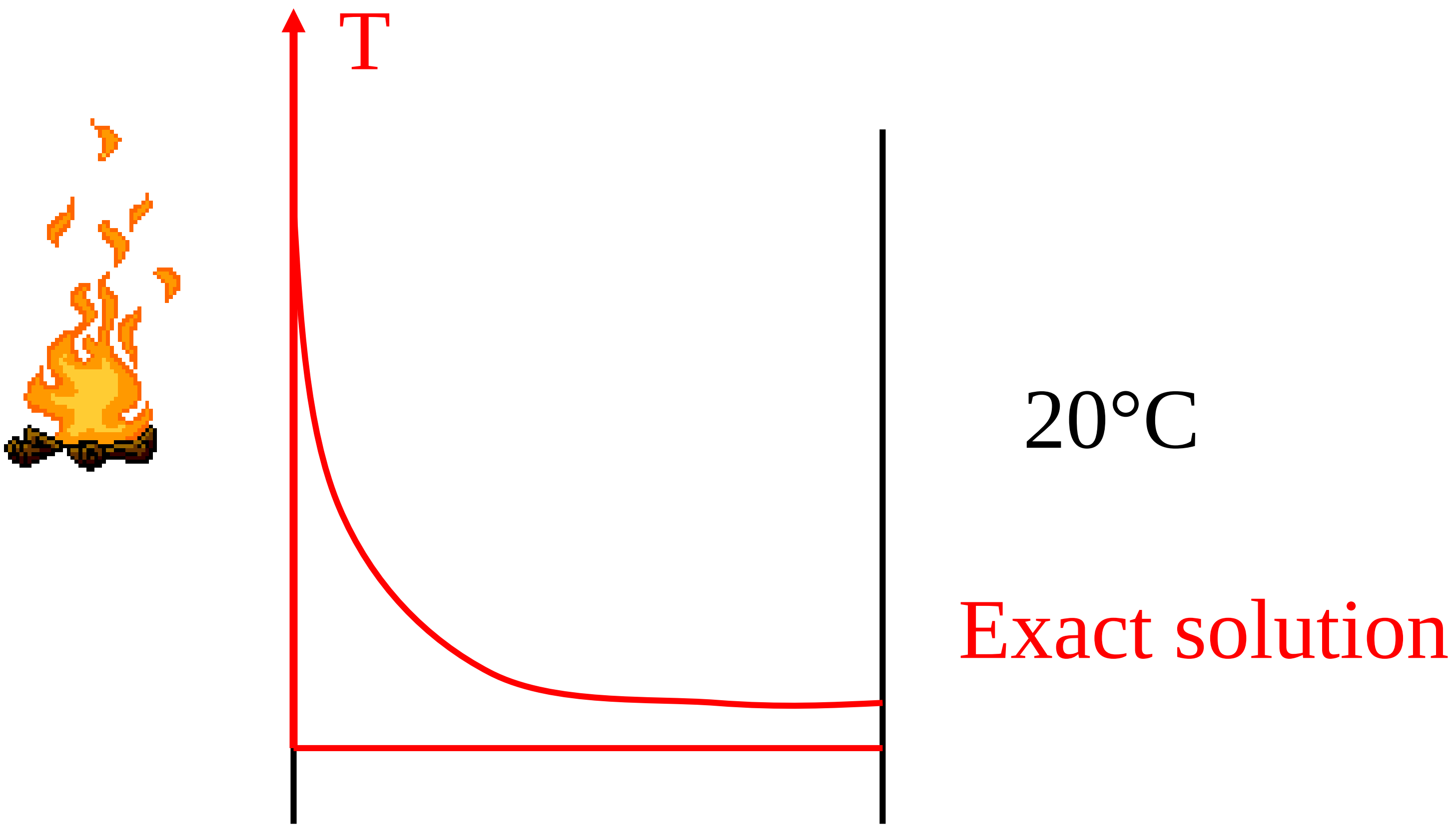
1) Free water – the evaporation is taken into account, but not the migration.

2) Perfect conductive contact between adjacents elements.

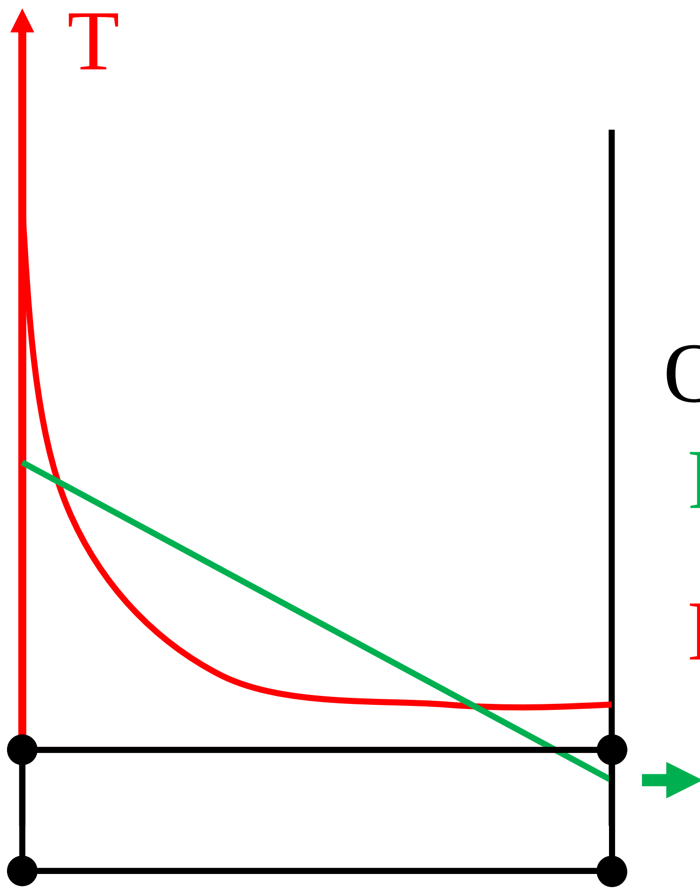
3) Fixed geometry (spalling! Can be taken into account, but not predicted, see advanced SAFIR course).

4) Isotropic materials :
   No influence of cracking in concrete)
   Note: timber is orthotropic.

5) Consequence of linear elements: possible skin effects (spatial oscillations)



A wall (uniaxial heat flow)

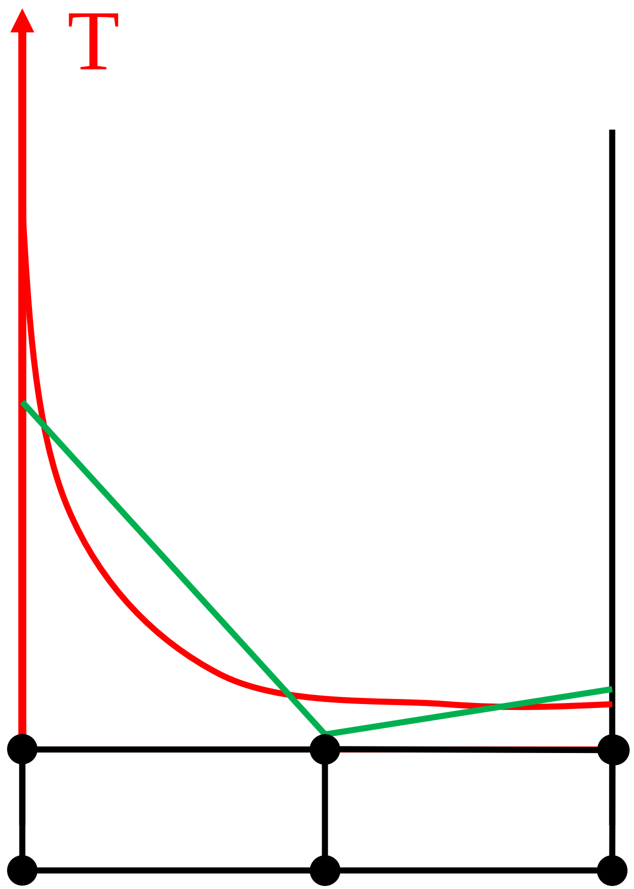


One finite element

F.E solution

Exact solution

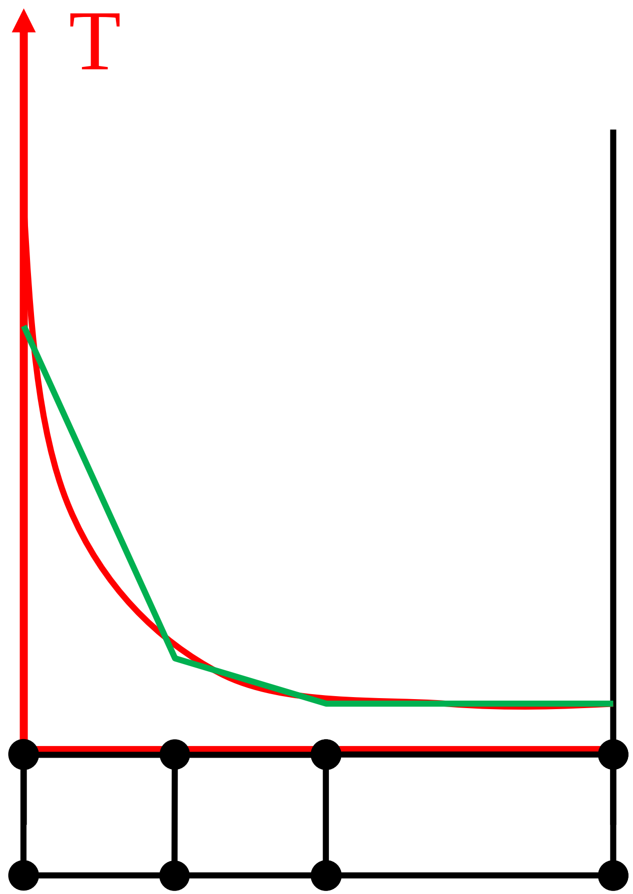
Cooling ?!?!?



2 finite elements

F.E solution

Exact solution

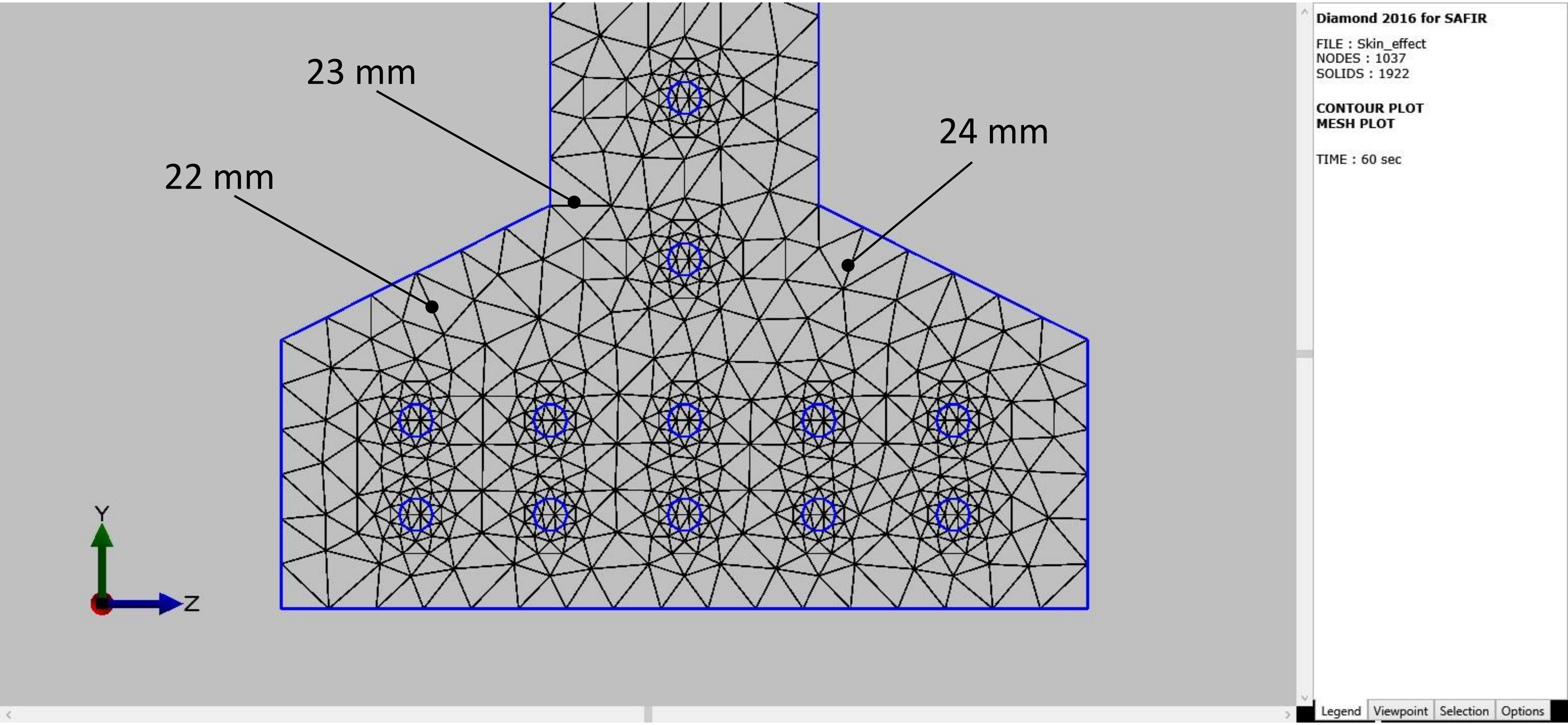


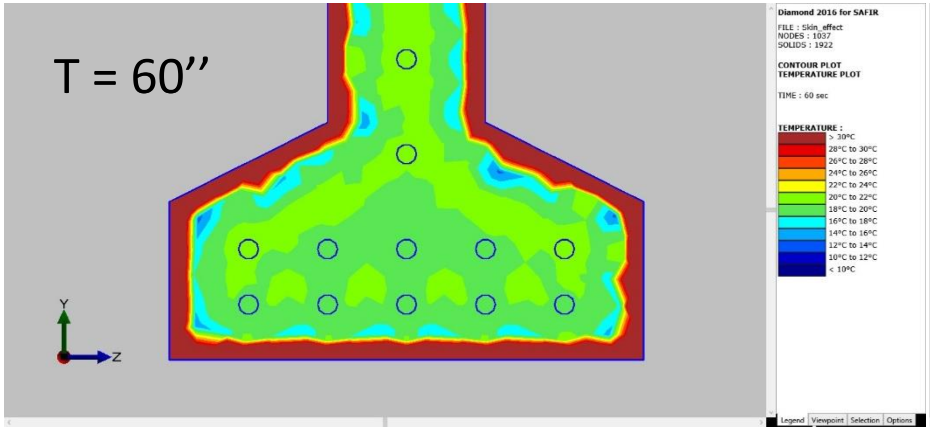
3 finite elements

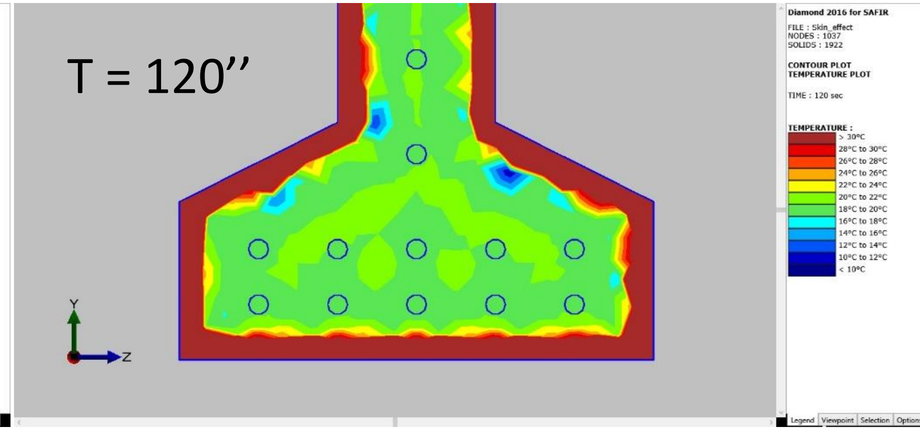
F.E solution

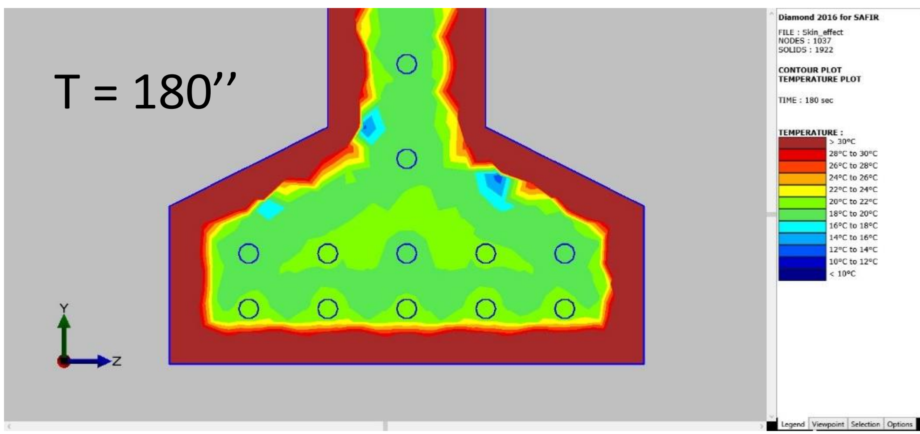
Exact solution

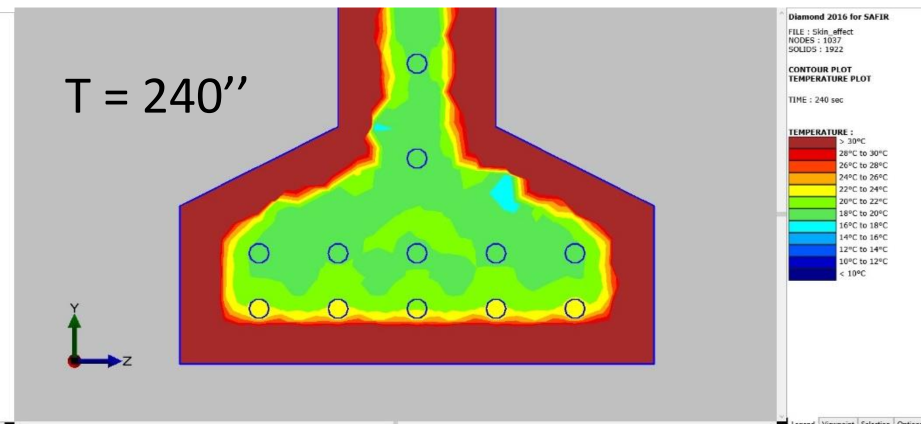
Example: a crude mesh in a prestressed section

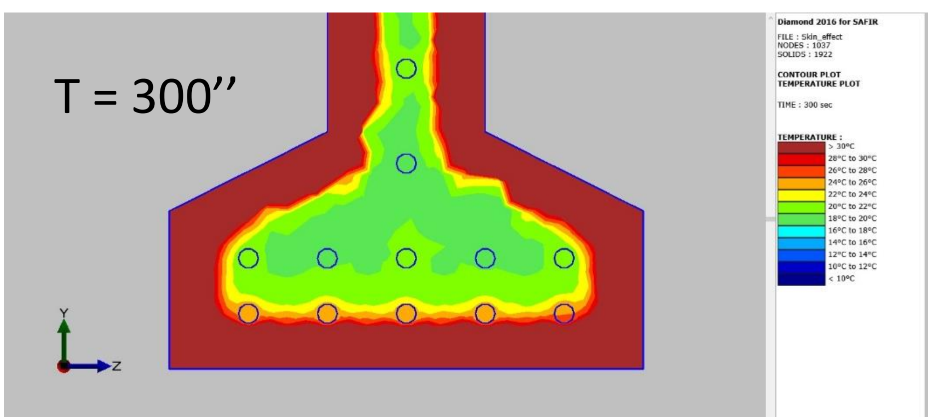


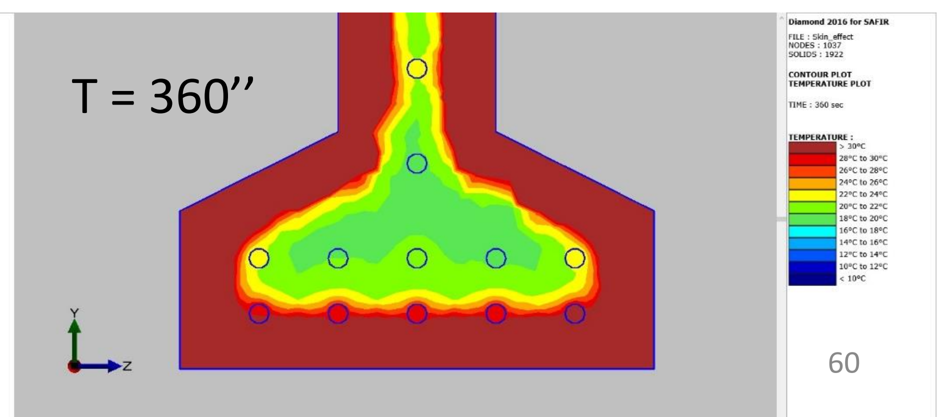

T = 60''
Y
Z
Diamond 2016 for SAFIR
FILE : Skin_effect
NODES : 1037
SOLIDS : 1922
CONTOUR PLOT
TEMPERATURE PLOT
TIME : 60 sec
TEMPERATURE :
> 30°C
28°C to 30°C
26°C to 28°C
24°C to 26°C
22°C to 24°C
20°C to 22°C
18°C to 20°C
16°C to 18°C
14°C to 16°C
12°C to 14°C
10°C to 12°C
< 10°C
Legend
Viewpoint
Selection
Options


T = 120''
Y
Z
Diamond 2016 for SAFIR
FILE : Skin_effect
NODES : 1037
SOLIDS : 1922
CONTOUR PLOT
TEMPERATURE PLOT
TIME : 120 sec
TEMPERATURE :
> 30°C
28°C to 30°C
26°C to 28°C
24°C to 26°C
22°C to 24°C
20°C to 22°C
18°C to 20°C
16°C to 18°C
14°C to 16°C
12°C to 14°C
10°C to 12°C
< 10°C
Legend
Viewpoint
Selection
Options


T = 180''
Y
Z
Diamond 2016 for SAFIR
FILE : Skin_effect
NODES : 1037
SOLIDS : 1922
CONTOUR PLOT
TEMPERATURE PLOT
TIME : 180 sec
TEMPERATURE :
> 30°C
28°C to 30°C
26°C to 28°C
24°C to 26°C
22°C to 24°C
20°C to 22°C
18°C to 20°C
16°C to 18°C
14°C to 16°C
12°C to 14°C
10°C to 12°C
< 10°C
Legend
Viewpoint
Selection
Options


T = 240''
Y
Z
Diamond 2016 for SAFIR
FILE : Skin_effect
NODES : 1037
SOLIDS : 1922
CONTOUR PLOT
TEMPERATURE PLOT
TIME : 240 sec
TEMPERATURE :
> 30°C
28°C to 30°C
26°C to 28°C
24°C to 26°C
22°C to 24°C
20°C to 22°C
18°C to 20°C
16°C to 18°C
14°C to 16°C
12°C to 14°C
10°C to 12°C
< 10°C
Legend
Viewpoint
Selection
Options


T = 300''
Y
Z
Diamond 2016 for SAFIR
FILE : Skin_effect
NODES : 1037
SOLIDS : 1922
CONTOUR PLOT
TEMPERATURE PLOT
TIME : 300 sec
TEMPERATURE :
> 30°C
28°C to 30°C
26°C to 28°C
24°C to 26°C
22°C to 24°C
20°C to 22°C
18°C to 20°C
16°C to 18°C
14°C to 16°C
12°C to 14°C
10°C to 12°C
< 10°C


T = 360''
Y
Z
Diamond 2016 for SAFIR
FILE : Skin_effect
NODES : 1037
SOLIDS : 1922
CONTOUR PLOT
TEMPERATURE PLOT
TIME : 360 sec
TEMPERATURE :
> 30°C
28°C to 30°C
26°C to 28°C
24°C to 26°C
22°C to 24°C
20°C to 22°C
18°C to 20°C
16°C to 18°C
14°C to 16°C
12°C to 14°C
10°C to 12°C
< 10°C

Solution:

The mesh must not be too crude

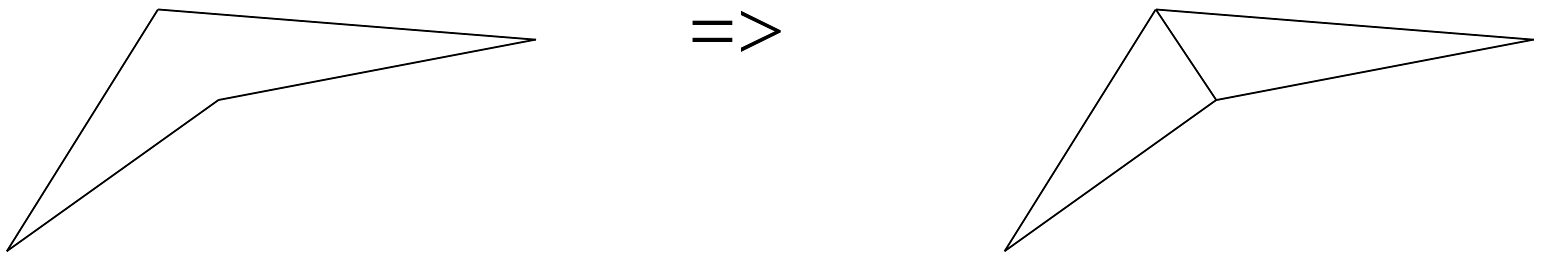
in the zones

in the direction

of non linear temperature gradients.

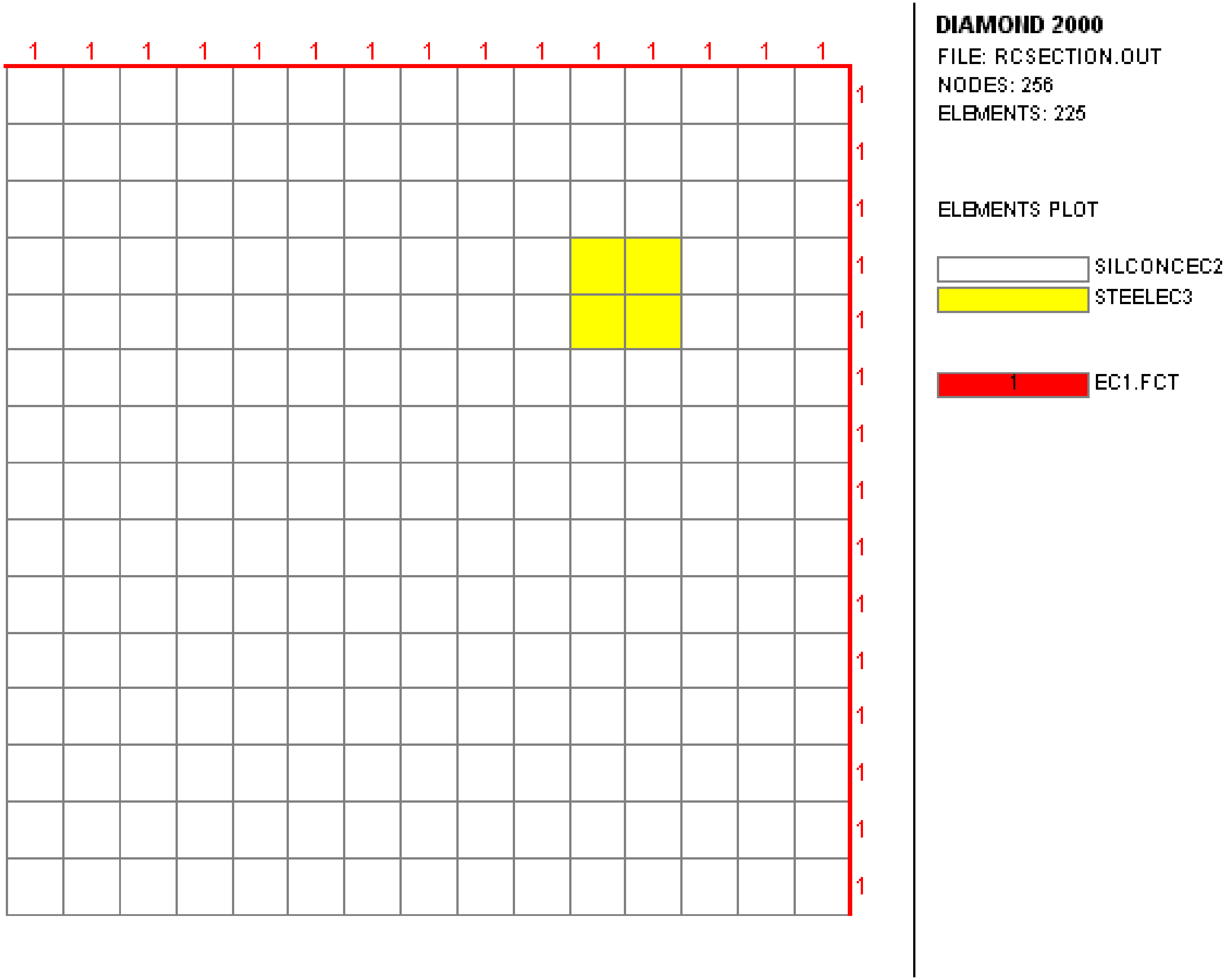
6) Concave elements are not acceptable.

If one is created by GID => cut it into 2 triangles



Basic theory of thermal analyses

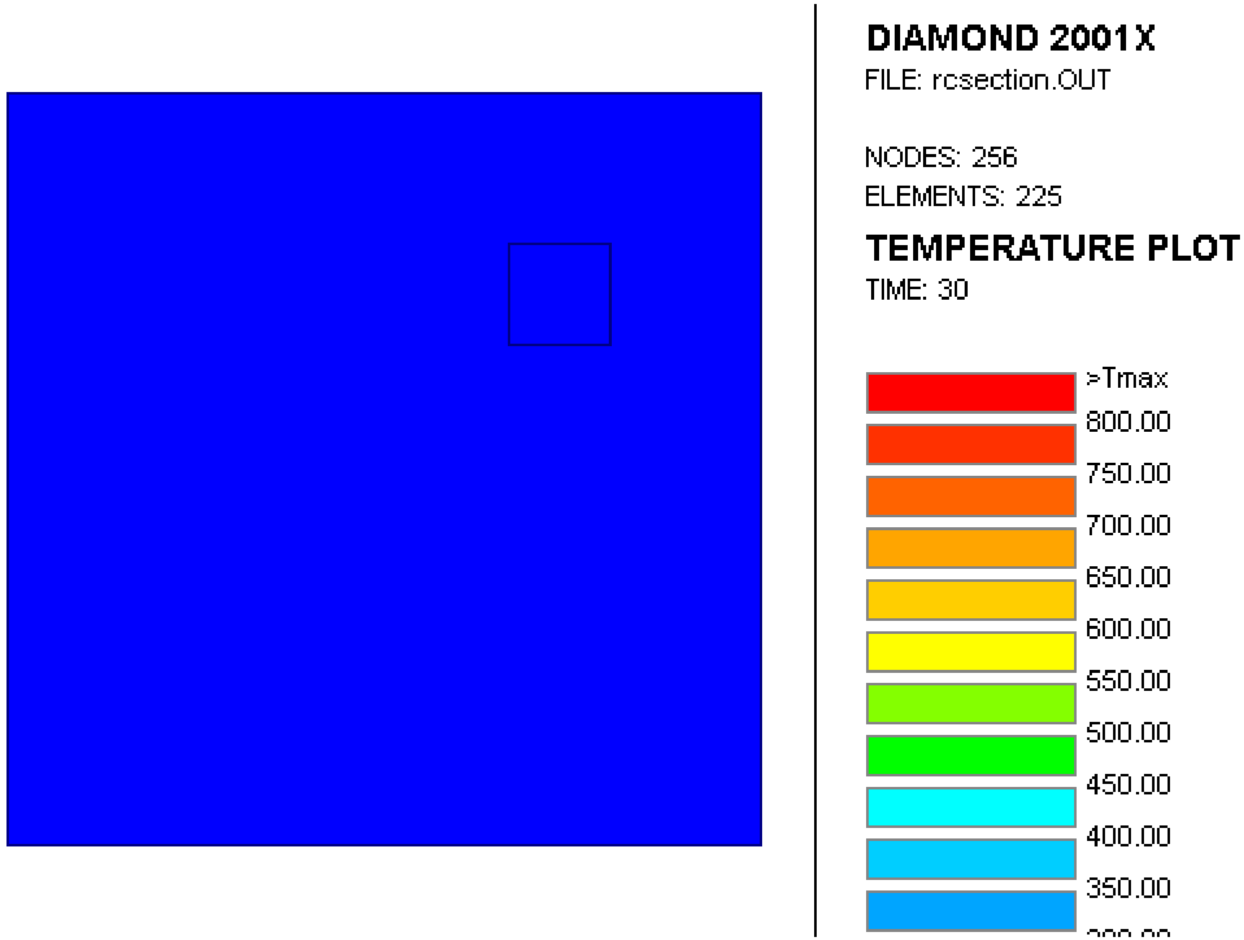
1) Different representation of the fire – boundary conditions
2) 2D or 3D discretization
3) The basic equations
4) The discretized field of temperatures
5) Material properties
6) Numerical integration on the surface
7) Cavities
8) Symmetries
9) Limitations
10) Examples

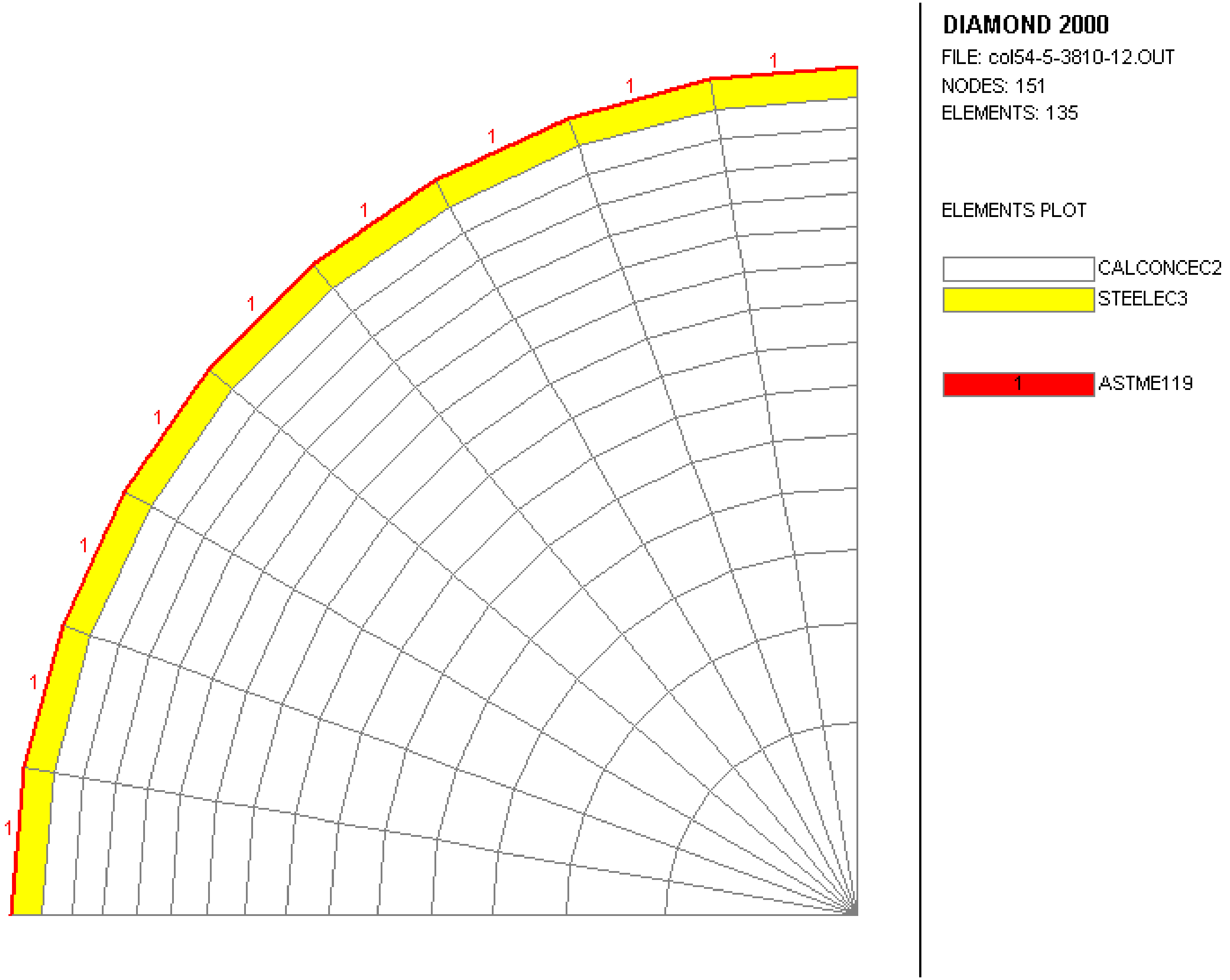


Example of a very simple discretization
¼ of a 30 x 30 cm² reinforced concrete section

The transient temperature distribution is evaluated.

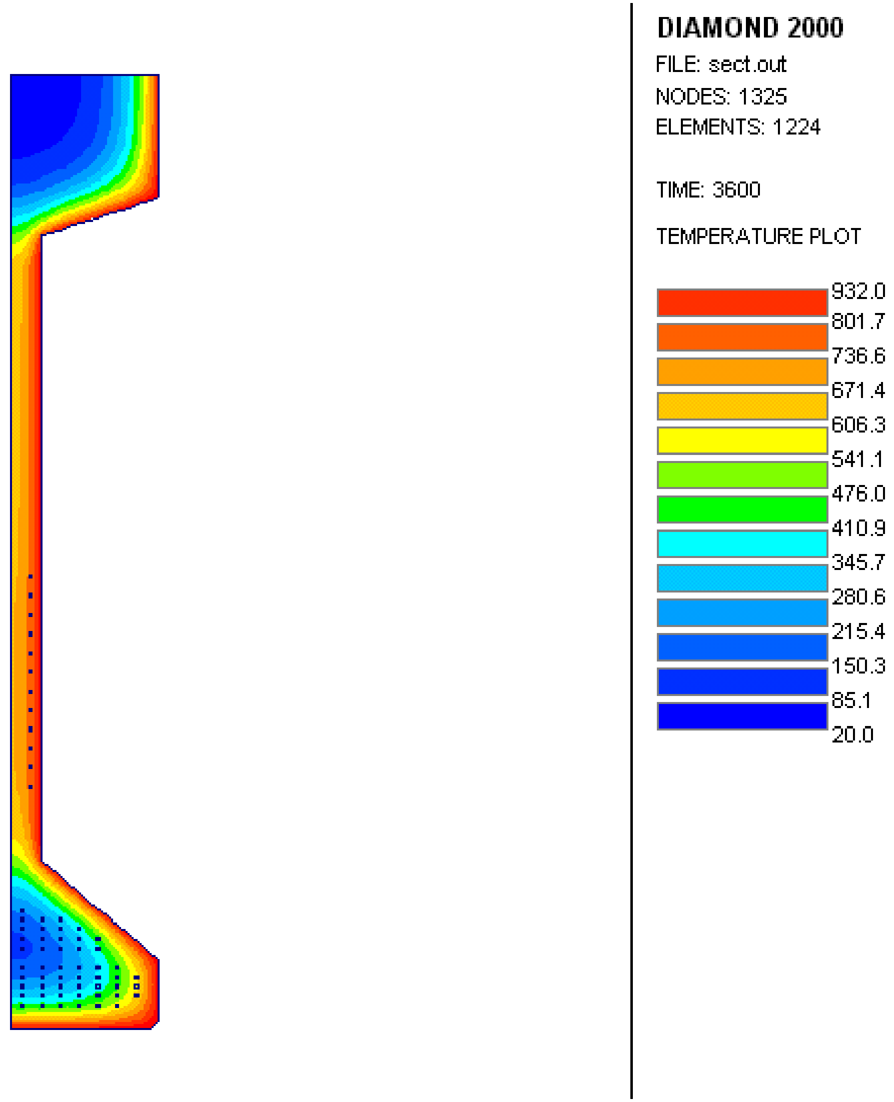
Here under a natural fire (peak temperature after 3600 sec).





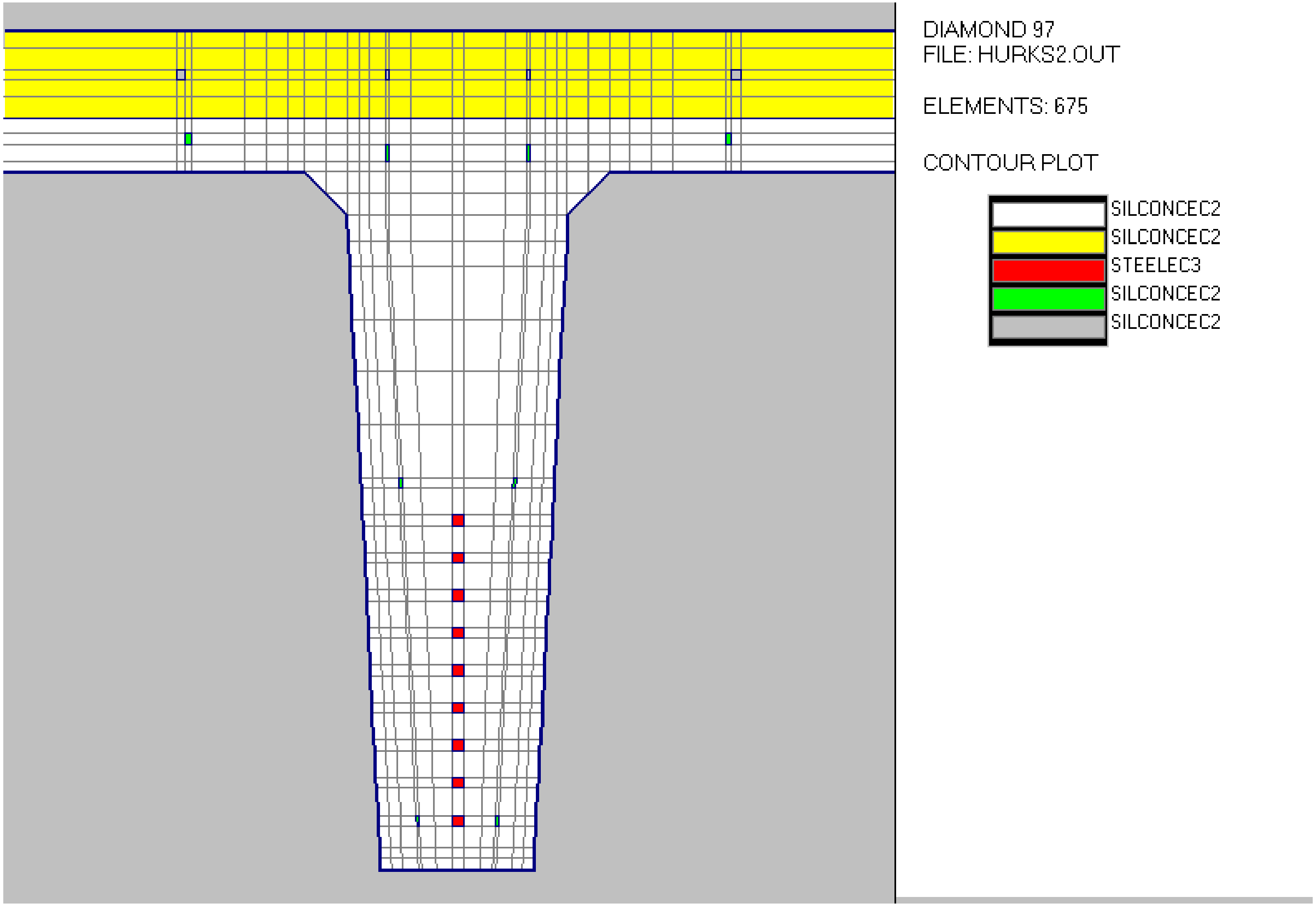
Concrete Filled Steel Section

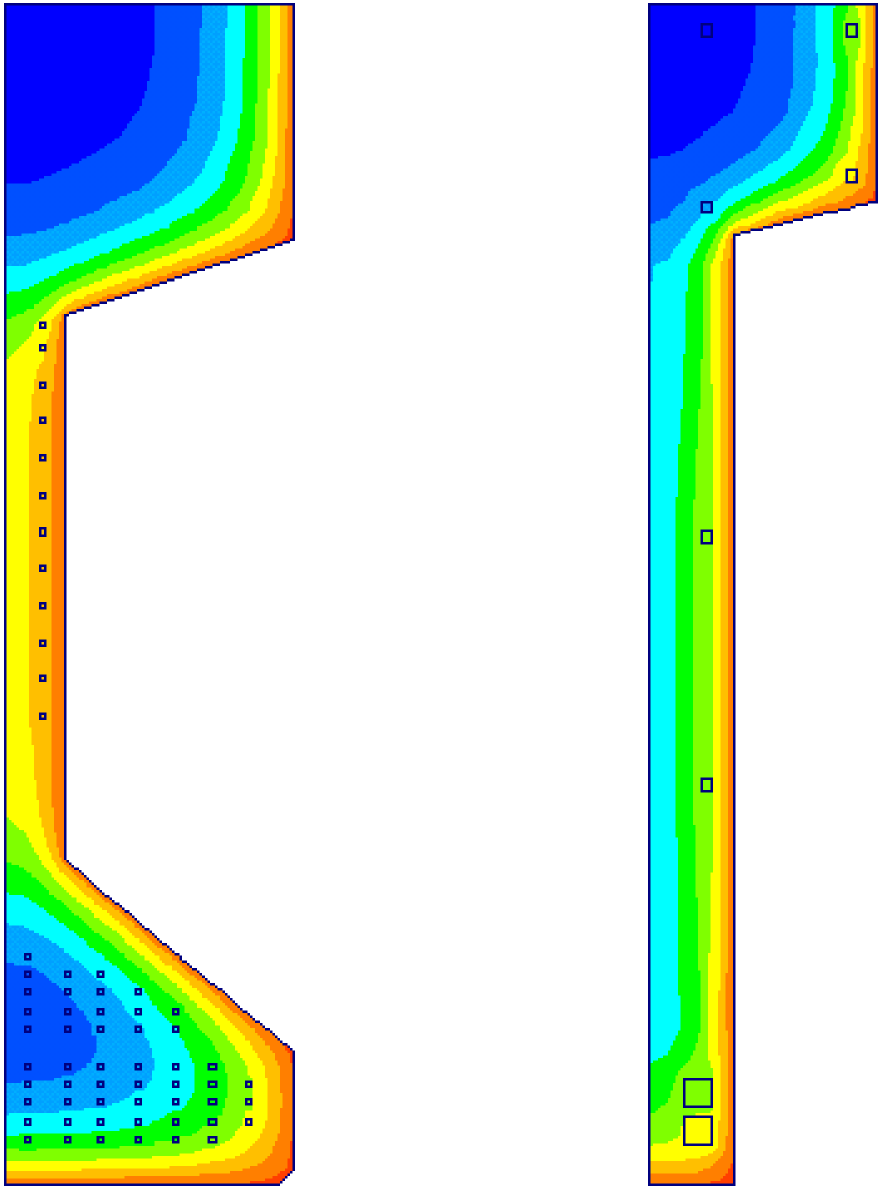
(*courtesy N.R.C.* Ottawa)

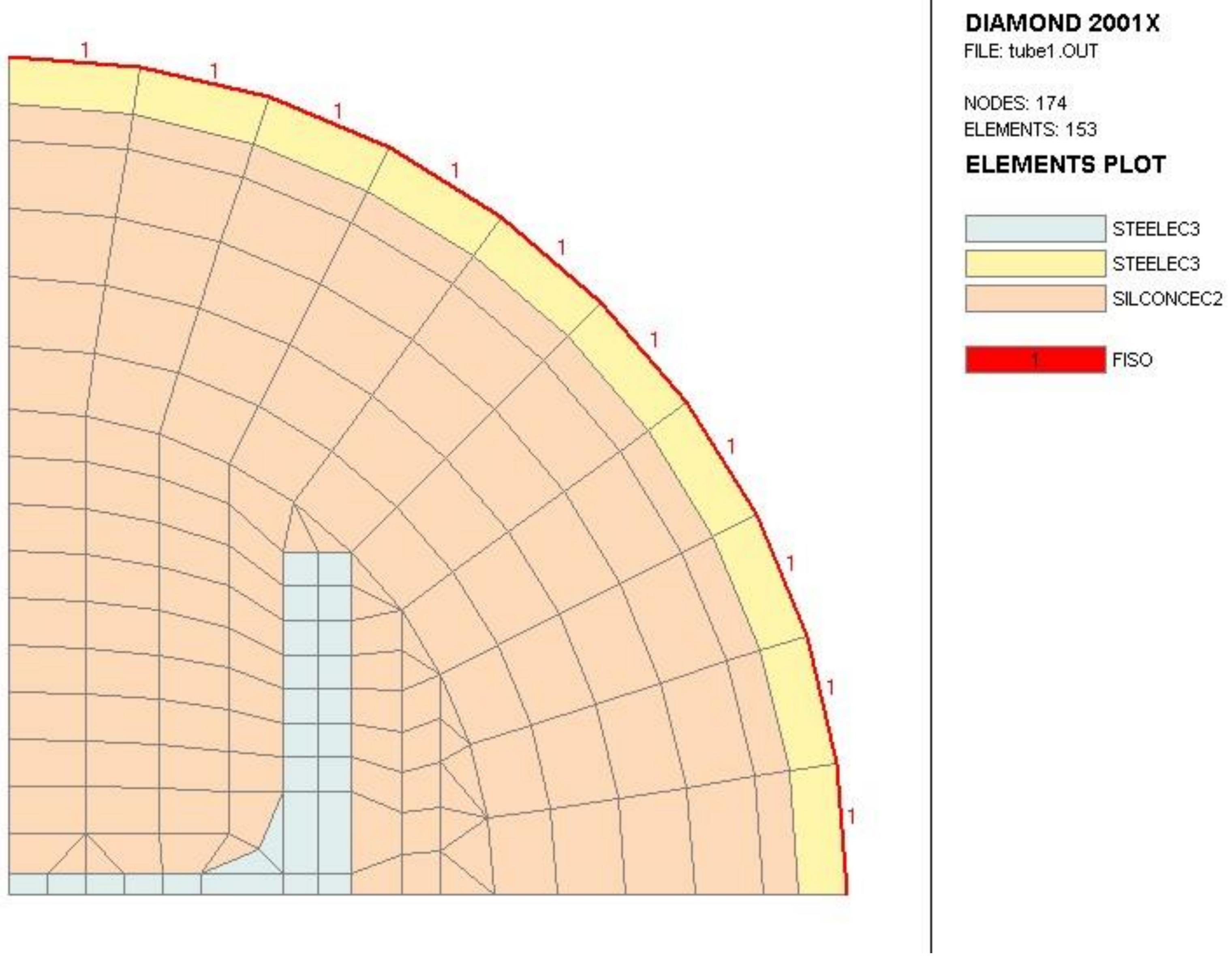


Prestressed concrete section

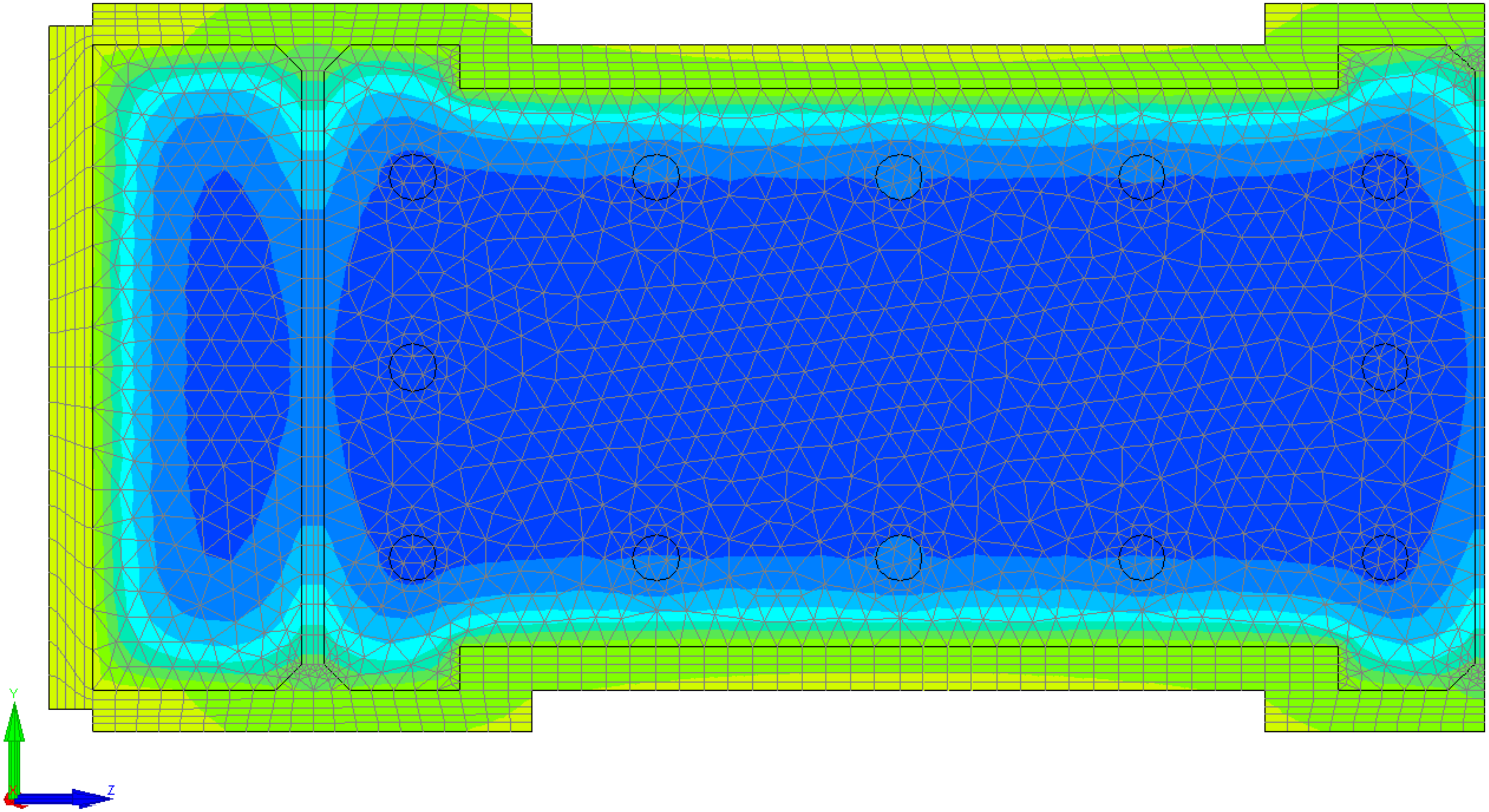
TT prestressed beam



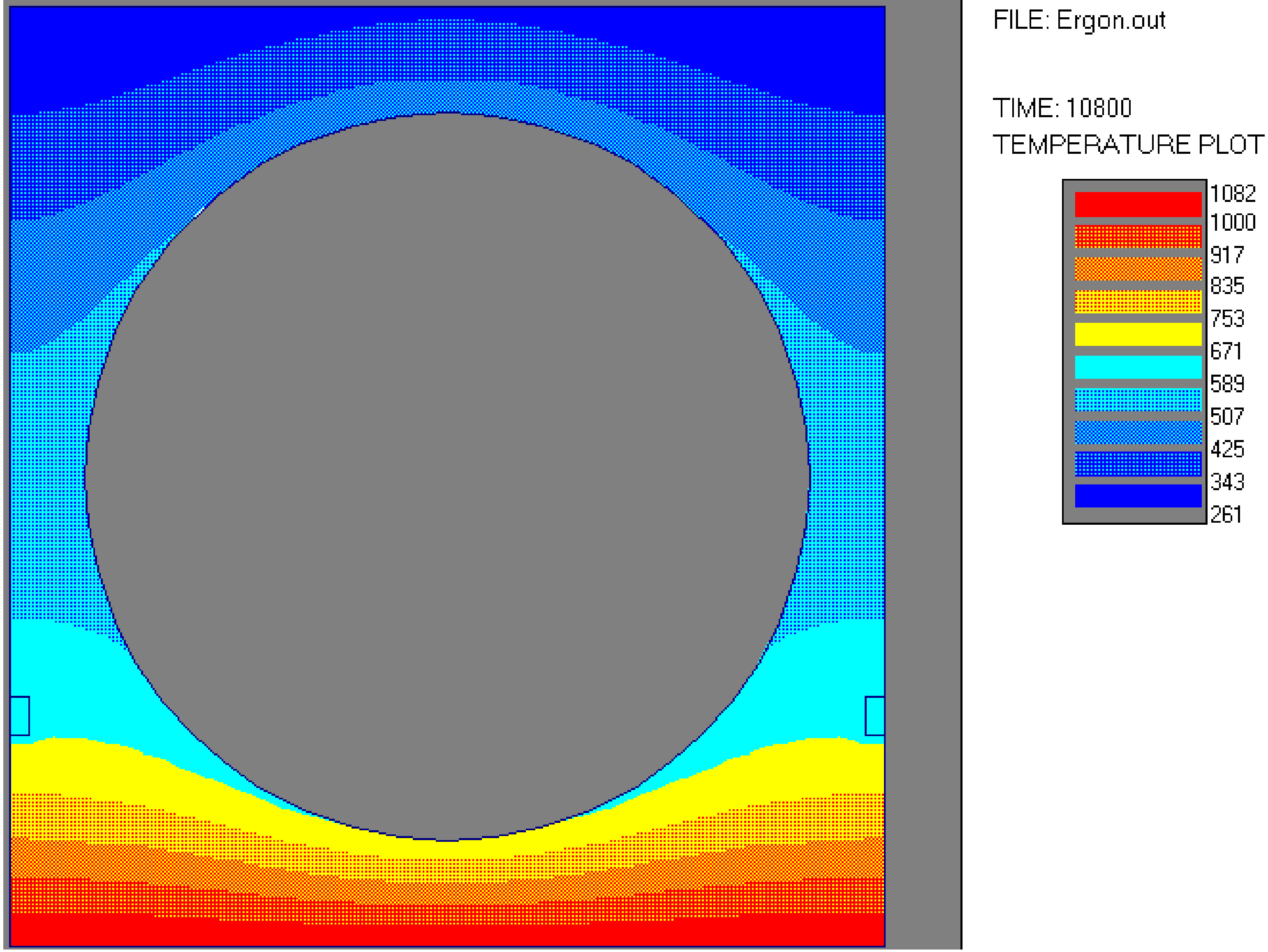




Steel H section in a steel tube filled with concrete

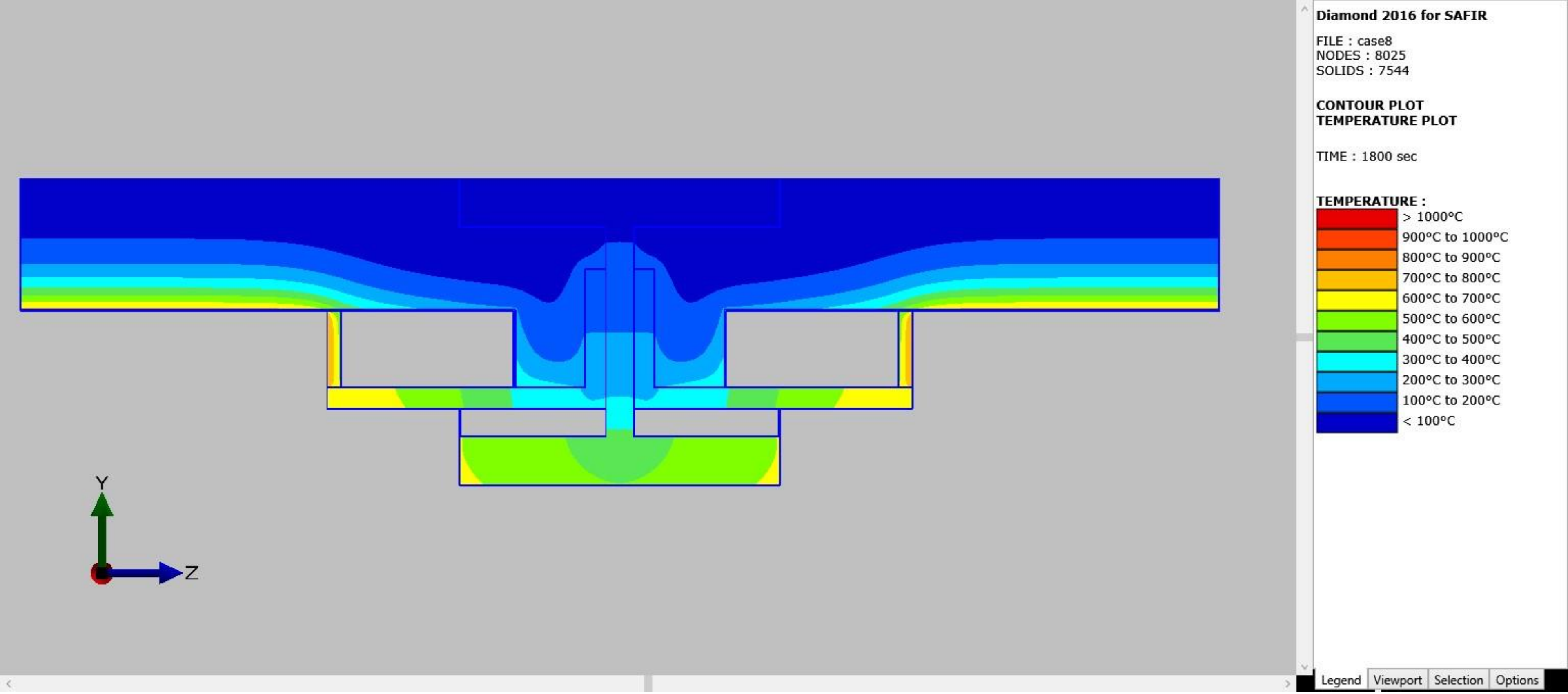


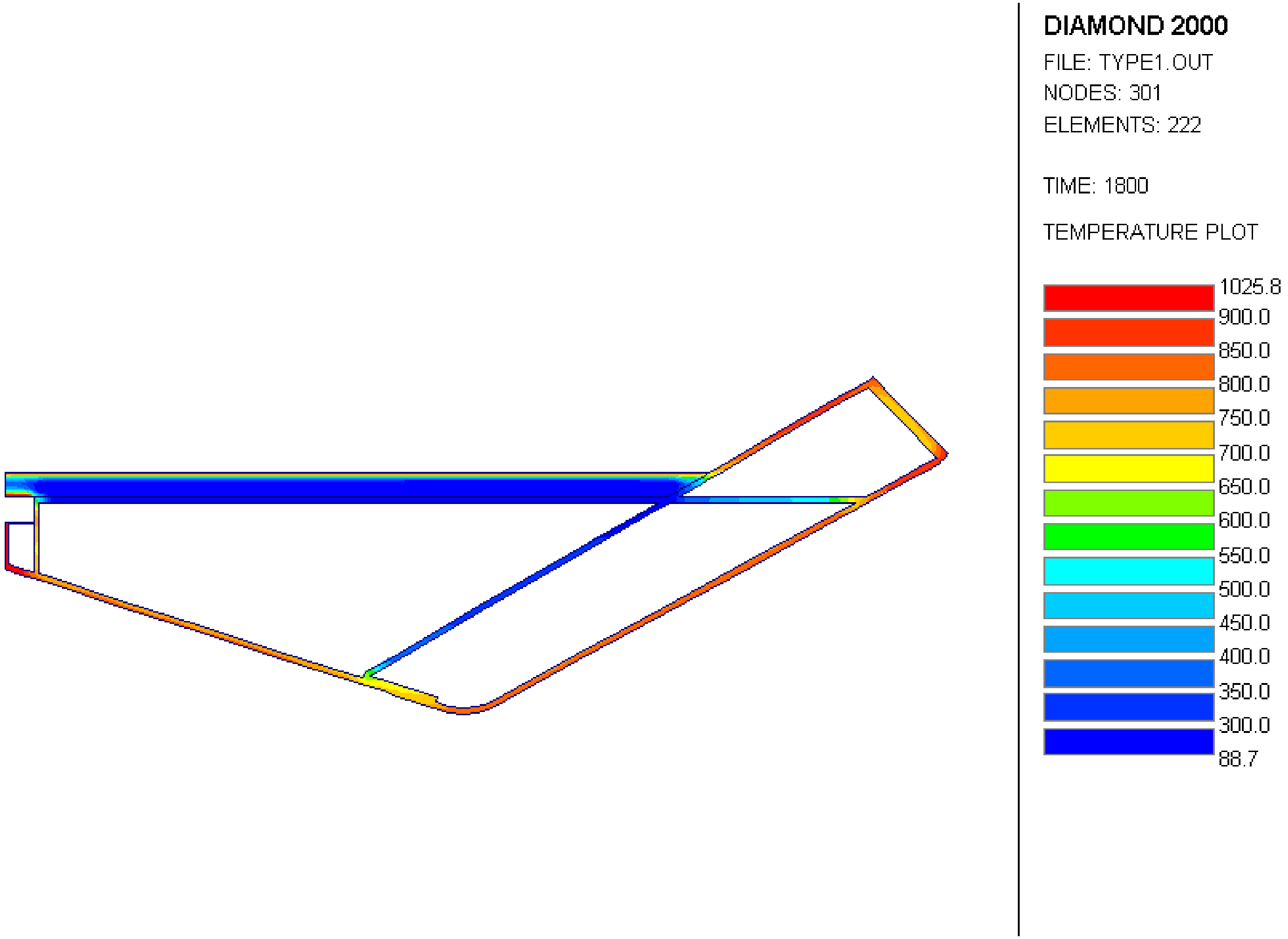
Composite steel-concrete columns (1/2)
Courtesy: Technum



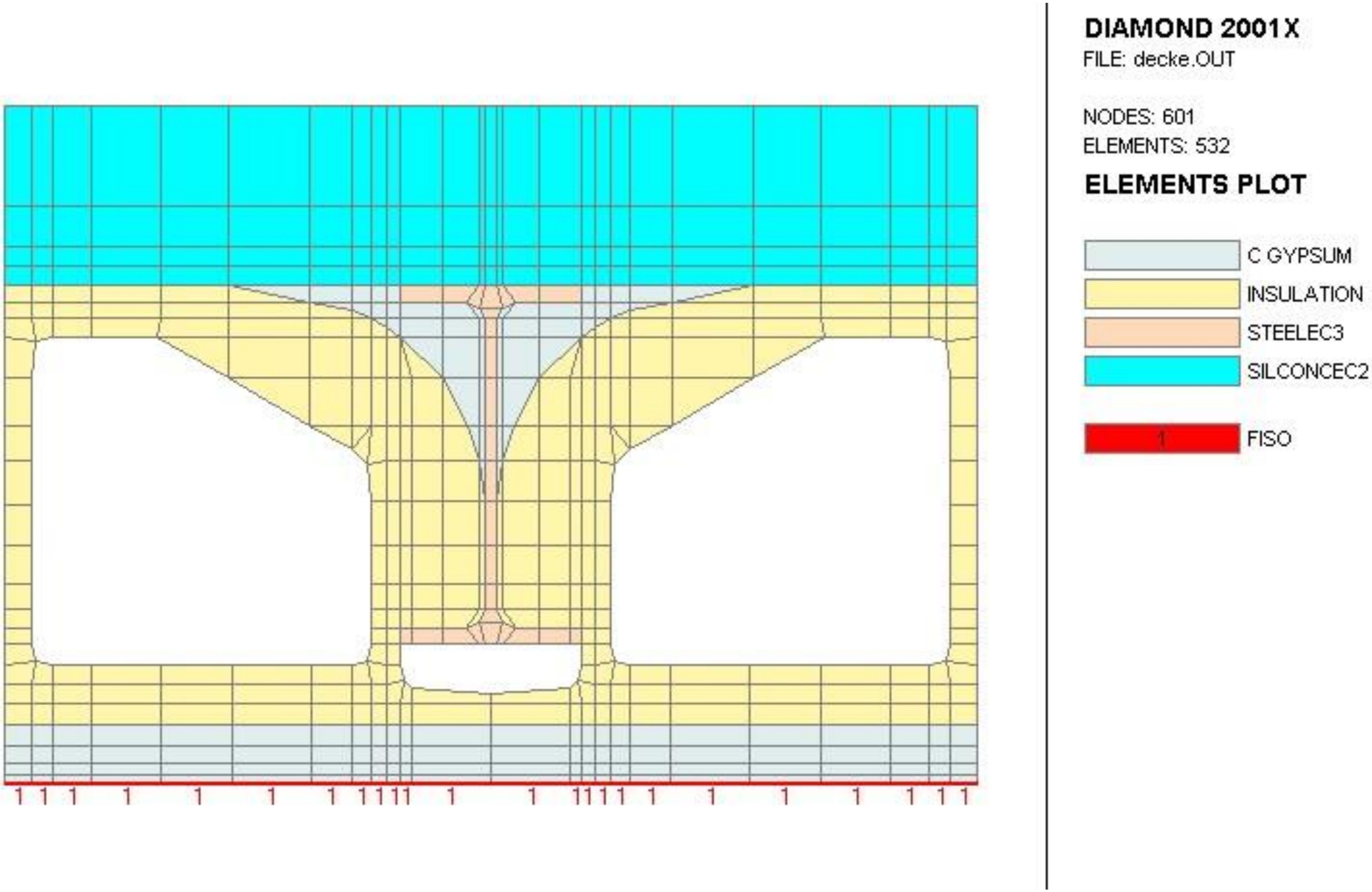
Radiation in the cavities is taken into account

Concrete hollow core slab

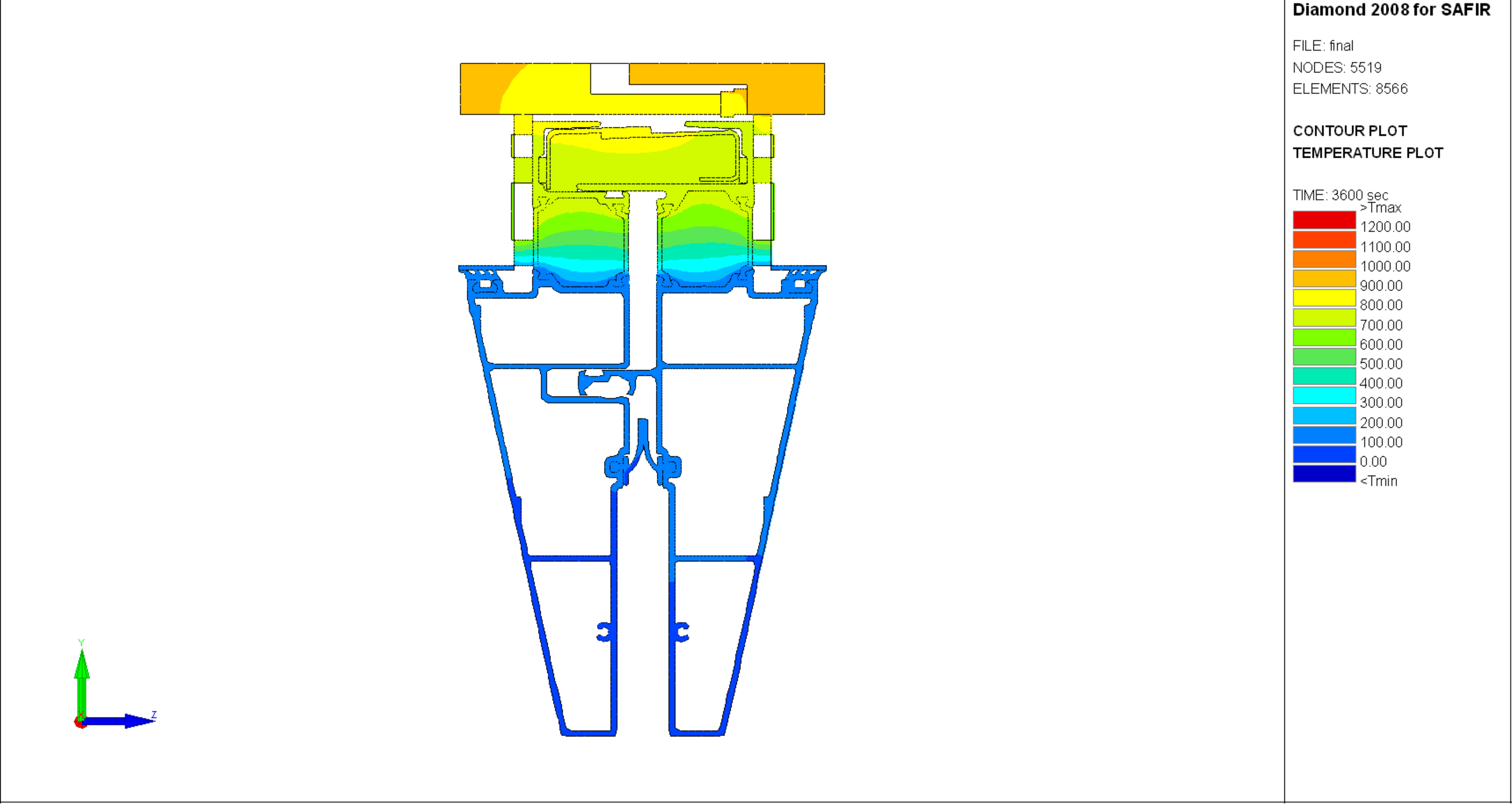

Diamond 2016 for SAFIR
FILE : case8
NODES : 8025
SOLIDS : 7544
CONTOUR PLOT
TEMPERATURE PLOT
TIME : 1800 sec
TEMPERATURE :
> 1000°C
900°C to 1000°C
800°C to 900°C
700°C to 800°C
600°C to 700°C
500°C to 600°C
400°C to 500°C
300°C to 400°C
200°C to 300°C
100°C to 200°C
< 100°C
Y
Z
Legend
Viewport
Selection
Options



T.G.V. railway station in Liege (courtesy Bureau Greisch). Main steel beam with concrete slab.

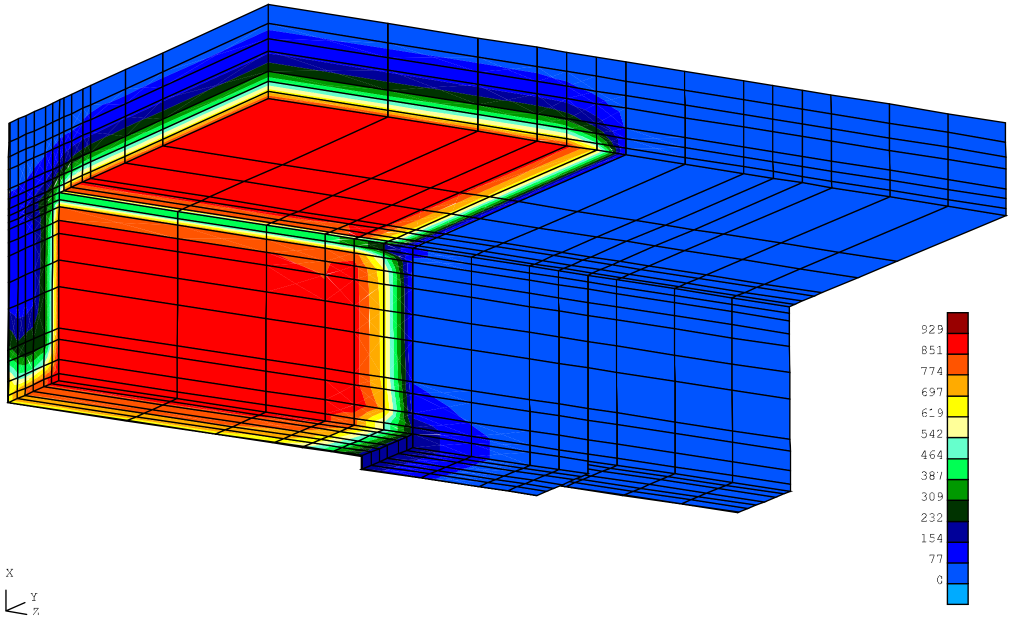


Old floor system; steel I beams and precast voussoirs
Courtesy: Lenz Weber, Frankfurt

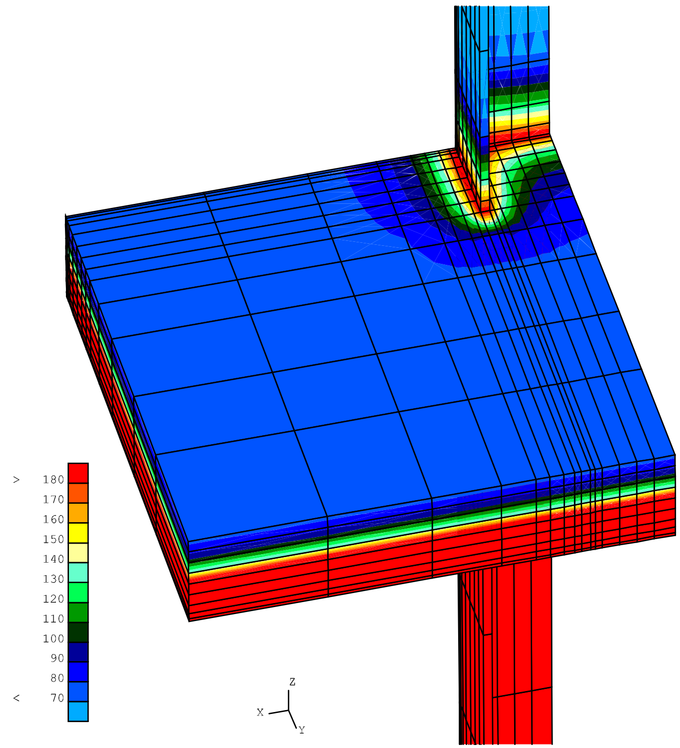


Window frame (courtesy: Permasteelisa)

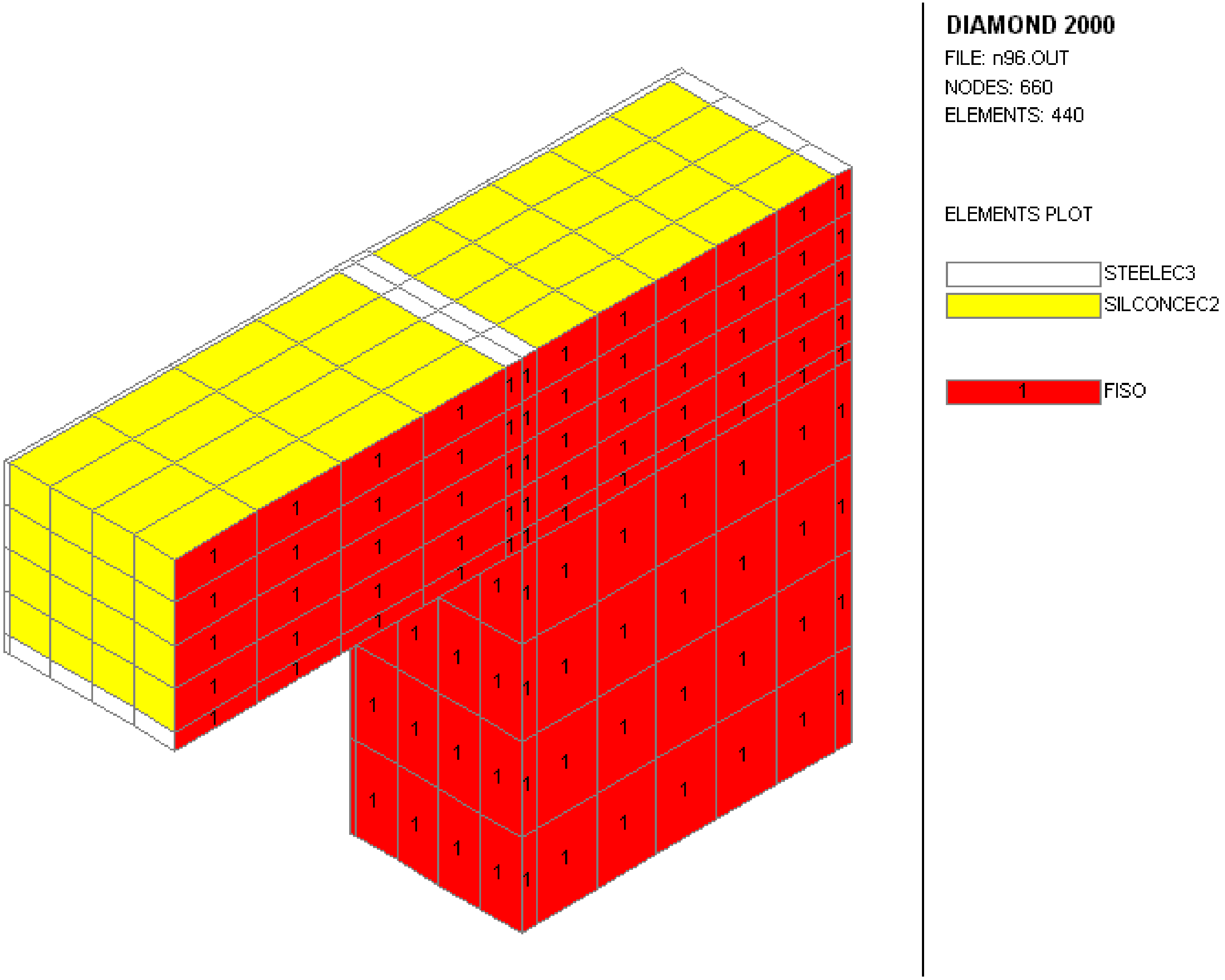
Composite beam partly heated



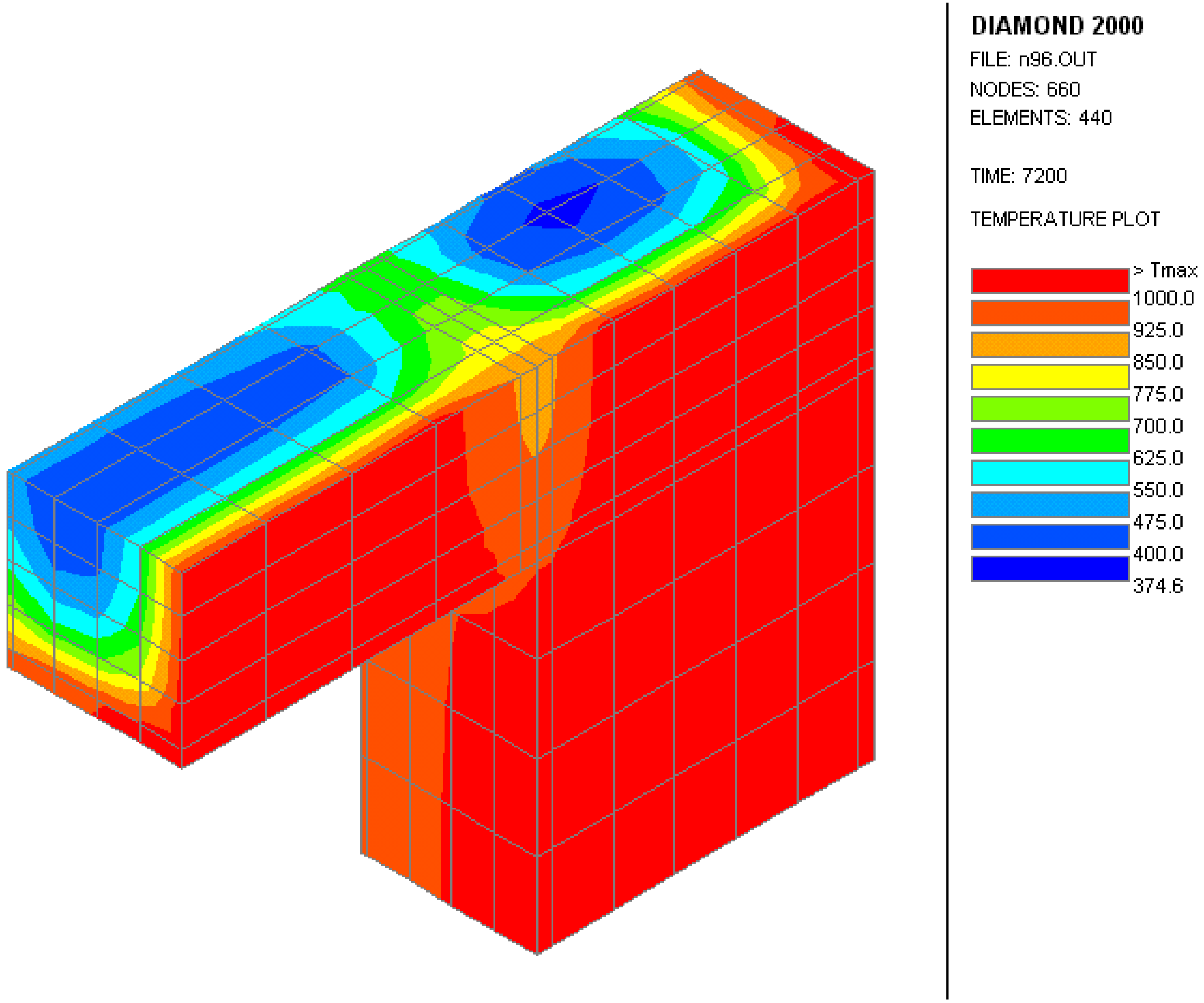
Steel column through a concrete slab



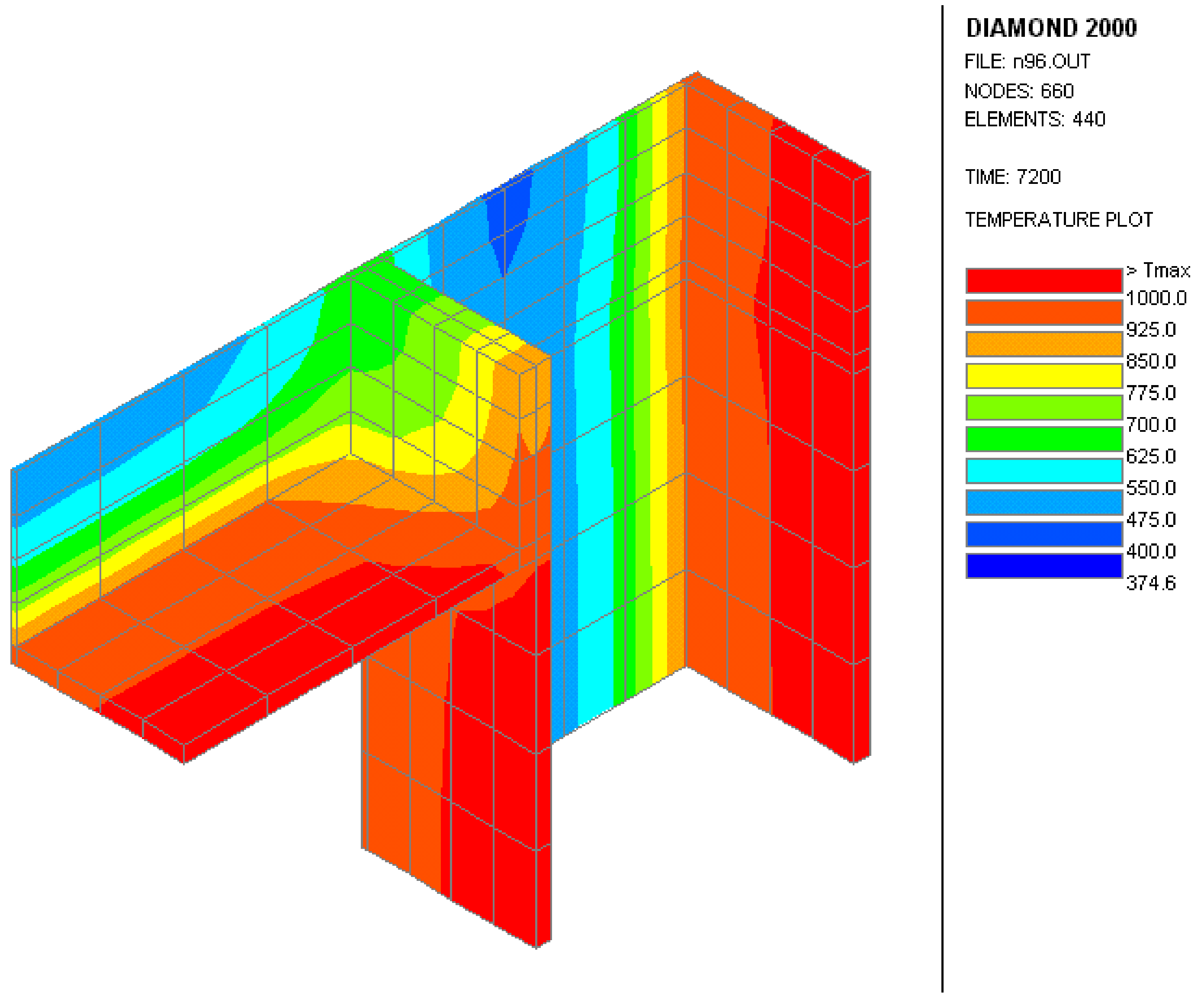
3D examples



Composite steel-concrete joint Discretisation

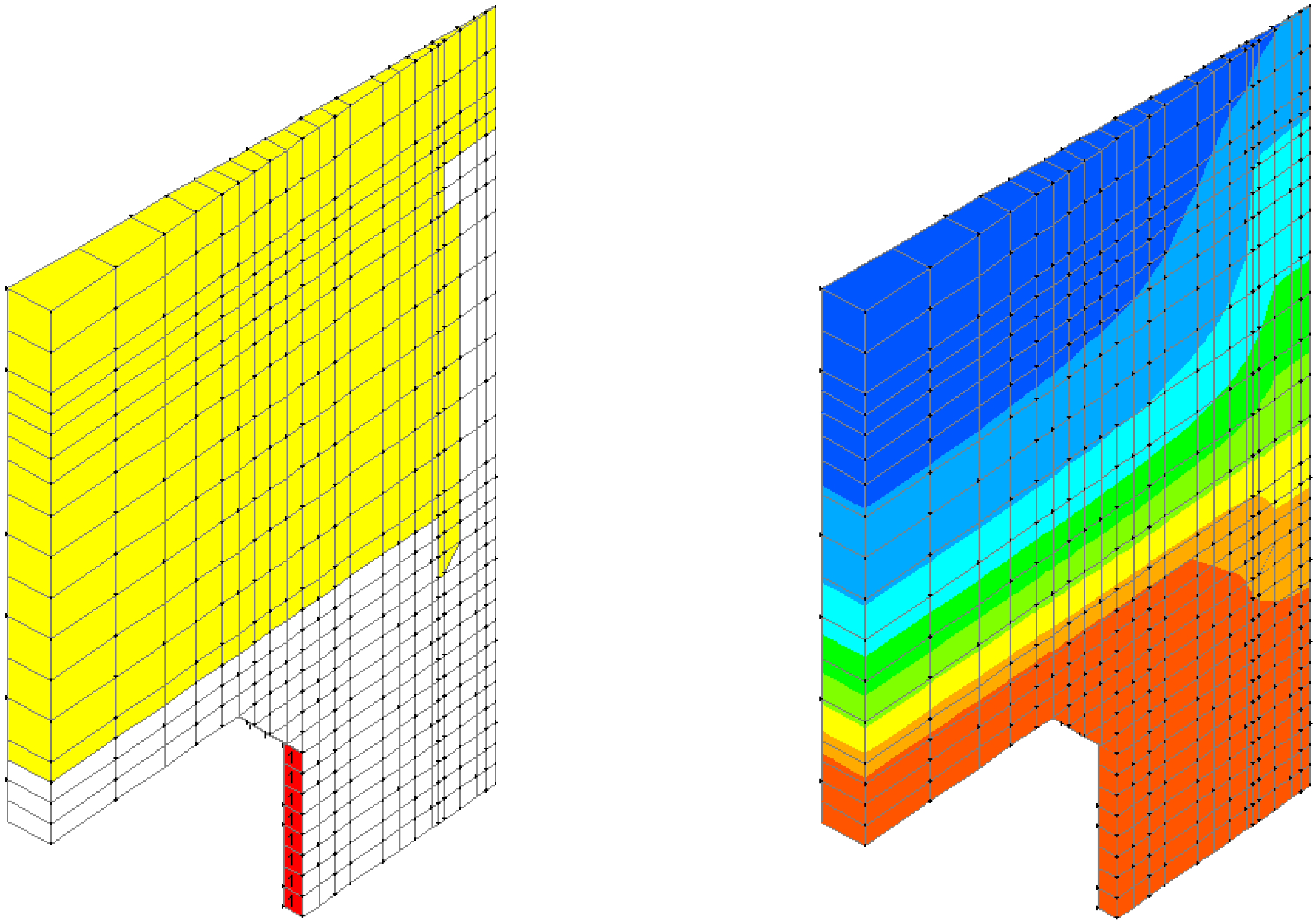


Composite steel-concrete joint
Temperatures on the surface



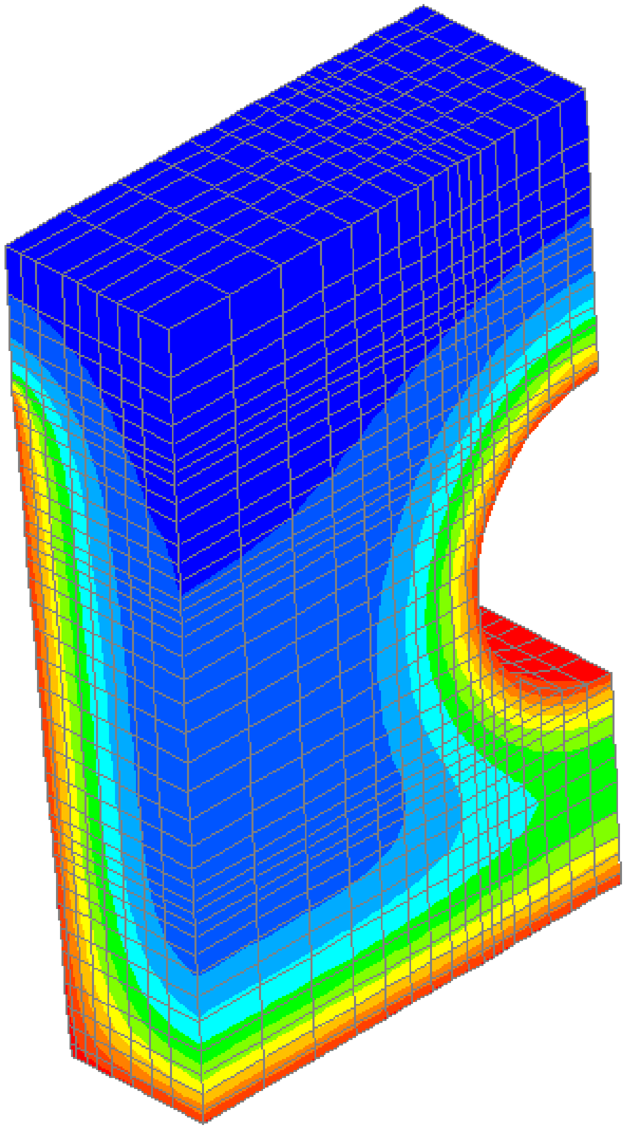
Composite steel-concrete joint

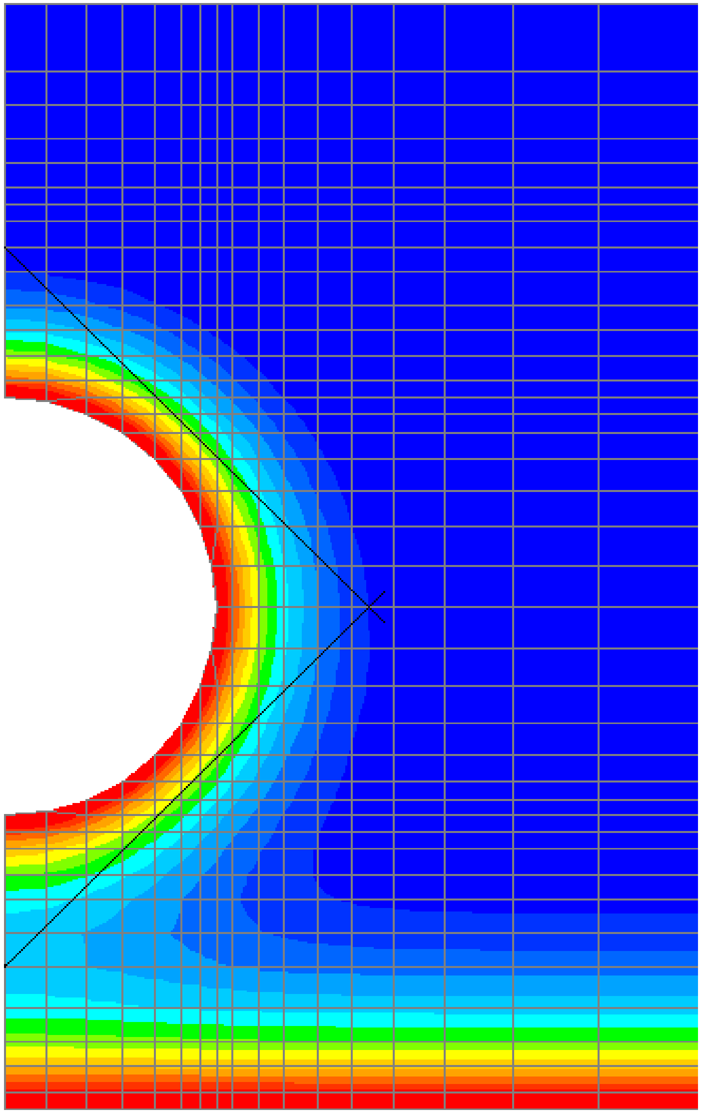
Temperatures on the steel elements (concrete is transparent)



Project Team EN 1994-1-2 (Eurocode 4)

Steel stud on a thick plate (axi-symetric problem)





Concrete beam (courtesy *Halfkann & Kirchner*)

Transmission of the shear force around the holes

Thank you

For any further information please contact:
safir@uliege.be

Jean-Marc Franssen & Thomas Gernay

LIÈGE université

JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING