SAFIR

A software for modelling the behaviour of structure subjected to the fire

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SAFIR

Introduction

Basic theory of thermal calculations

Three steps in the structural fire design:

1. *Define the fire (not made by SAFIR).*
2. *Calculate the temperatures in the structure.*
3. *Calculate the mechanical behaviour.*

Step 1

Define the fire (that will then be taken as a data by SAFIR)

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Option 1: a design time-temperature curve: $T_g = f(t)$

- 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.

Heat flux linked to a T_g-t curve: $q^{\bullet} = h\left(T_g - T_S\right) + \sigma\,\varepsilon\left(T_g^4 - T_S^4\right)$

Option 1: a design time-temperature curve: $T_g = f(t)$

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

h: (coefficient of convection) introduced in the data as a property of the material of each F.E. (one value for exposed surfaces and one value for unexposed surfaces).

ε: (emissivity) introduced in the data as a property of the material of each F.E.

σ: Stefan Boltzman constant.

T_g: gas temperature applied to the surfaces of the F.E.

T_S: surface temperature (calculated by SAFIR) 6

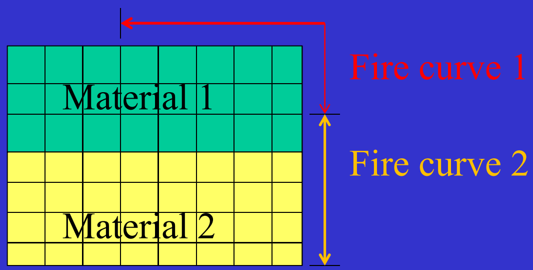
Option 1: a design time-temperature curve: $T_g = f(t)$

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

A structure:

✓ may contain a finite number of different materials and

✓ be subjected to a finite number of T-t curves



Option 1: a design time-temperature curve: $T_g = f(t)$

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

Note:

If a surface is in contact with air at ambiant temperature, then a T-t curve MUST be applied (in which T_g is constant and equal, for example, to 20°C).

T_S will be calculated by SAFIR and will not remain equal to 20°C.

Option 1: a design time-temperature curve: $T_g = f(t)$

Concave shapes

If the hot air, or the gaz, is fully dark, then the heated perimeter is the blue line. => The T-t curve can be applied directly on the whole perimeter.

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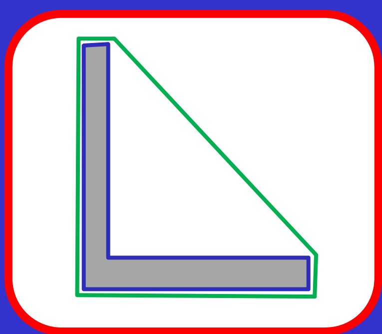
Option 1: a design time-temperature curve: $T_g = f(t)$

If the hot air, or the gaz, is fully transparent, and the heating is mainly from far walls or far flames, then the amount of radiation energy that cross the green surface cannot have increased when it reaches the blue perimeter.



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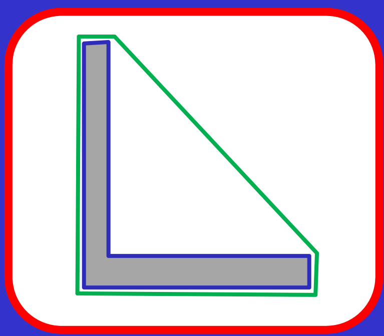
Option 1: a design time-temperature curve: $T_g = f(t)$

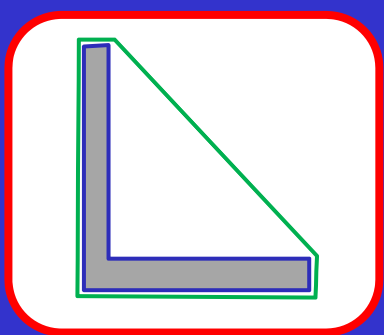
In simple calculation models, the green perimeter is taken into account. It thus introduces a slight approximation on the convection term.



Option 1: a design time-temperature curve: $T_g = f(t)$

In generalcalculation models, two solutions are possible:

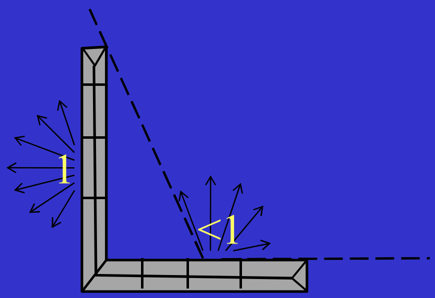
1) Multiply for the whole section *h* and ε by the ratio between the green and the blue surface (k_{shadow} = green/blue).



Option 1: a design time-temperature curve: $T_g = f(t)$

In generalcalculation models, two solutions are possible:

2) Multiply *h* and *e* by the view factor V_i between the surface of the surface *i* and the « fire angle ». This view factor is equal to 1.0 for convex parts.



Option 1: a design time-temperature curve: $T_g = f(t)$

In generalcalculation models, two solutions are possible:

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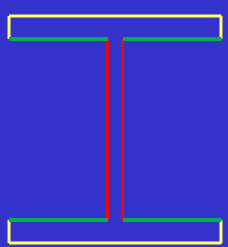
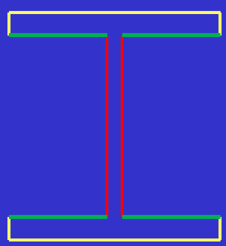


Note: a surface *i* can be defined for each F.E., or for a group of F.E. Example: the web and the interior of the flanges in an H or I section

Option 1: a design time-temperature curve: $T_g = f(t)$

In generalcalculation models, two solutions are possible:

2) Multiply *h* and *e* by the view factor V_i between the surface of the F.E. and the « fire angle ». This view factor is equal to 1.0 for convex parts.



Note: it can be verified that

$$\sum_i V_i \, L_i = \text{perimeter} \times k_{shadow}$$

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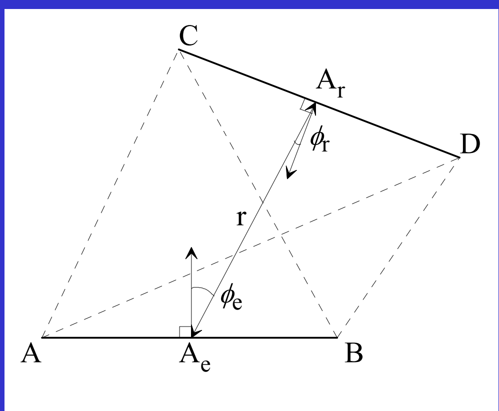
How to calculate a view factor (in 2D)?



$$V_{r,e} = \frac{\left|\overline{AC} + \overline{BD} - \overline{AD} - \overline{BC}\right|}{2\overline{CD}}$$

r: receiving surface
e: emitting surface

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Example of a tool for determining Temperature-time curve:

OZone

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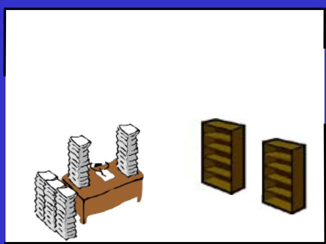
OZone V2.0.XX

Fire phases and associated model
The compartment.



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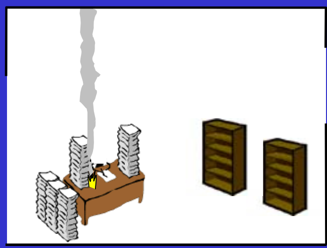
OZone V2.0.XX

Fire phases and associated model
The fire starts.



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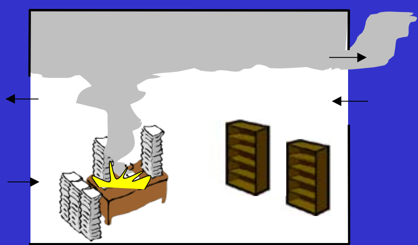
OZone V2.0.XX

Fire phases and associated model
Stratification in 2 zones.



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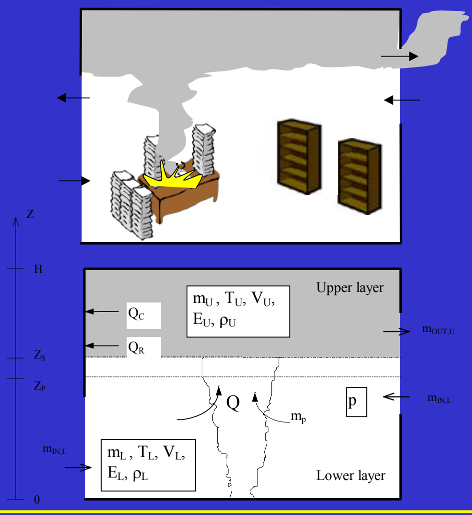
OZone V2.0.XX

Fire phases and associated model
2 zones model.



The position of the interface layer changes during the fire.

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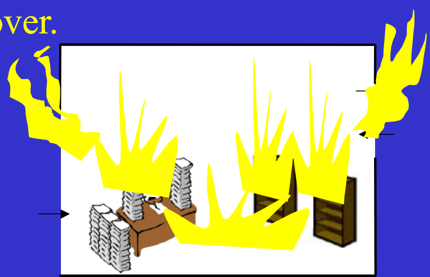
OZone V2.0.XX

Fire phases and associated model
Flash over.



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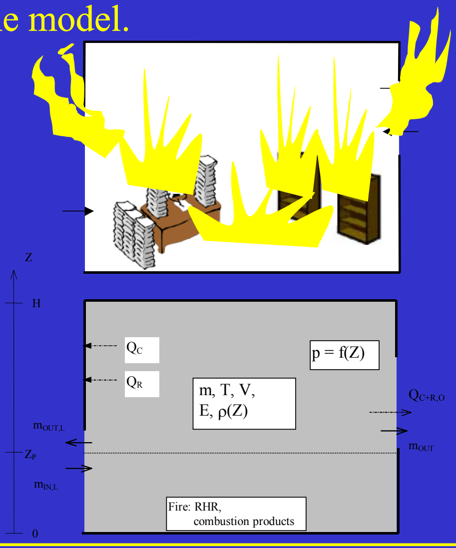
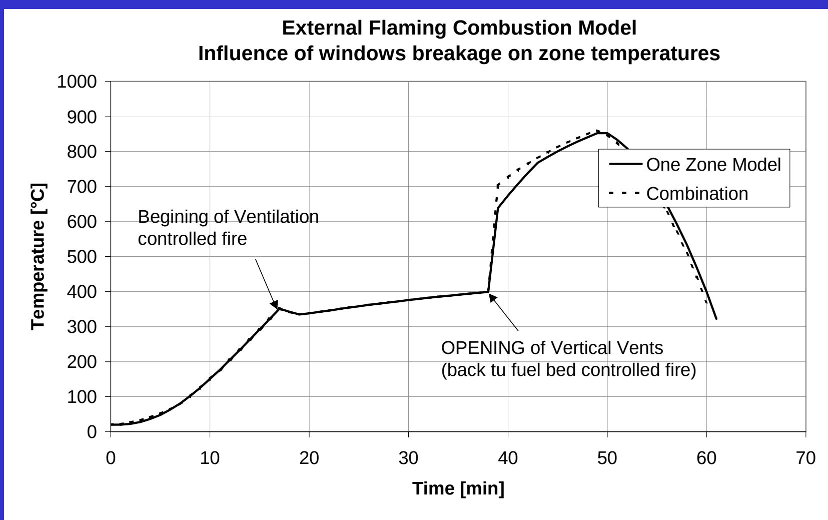
OZone V2.0.XX

Fire phases and associated model
1 zone model.



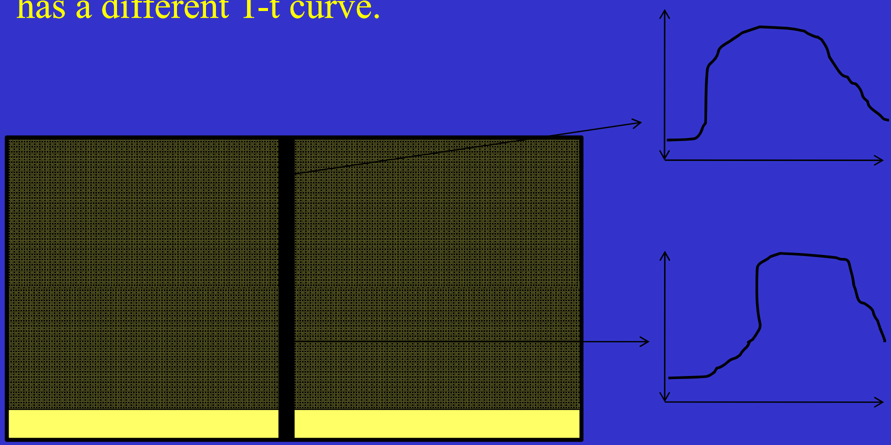
OZone V2.0.XX

Result to be used by SAFIR : the time-temperature curve



The position of the interface layer changes during the fire.

Consequence: each vertical position of a column or a wall has a different T-t curve.



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Option 2: a flux at the boundary

$$\boxed{\dot{q} = f(t)}$$

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

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

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

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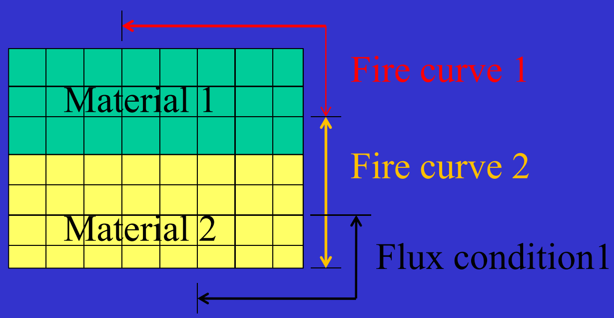
Option 2: a flux at the boundary

A structure may be subjected to
- ✓ a finite number of FLUX conditions and
- ✓ a finite number of T-t curves



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Option 3: a flux defined by the local fire model of EN 1991-1-2 (Hasemi's model).

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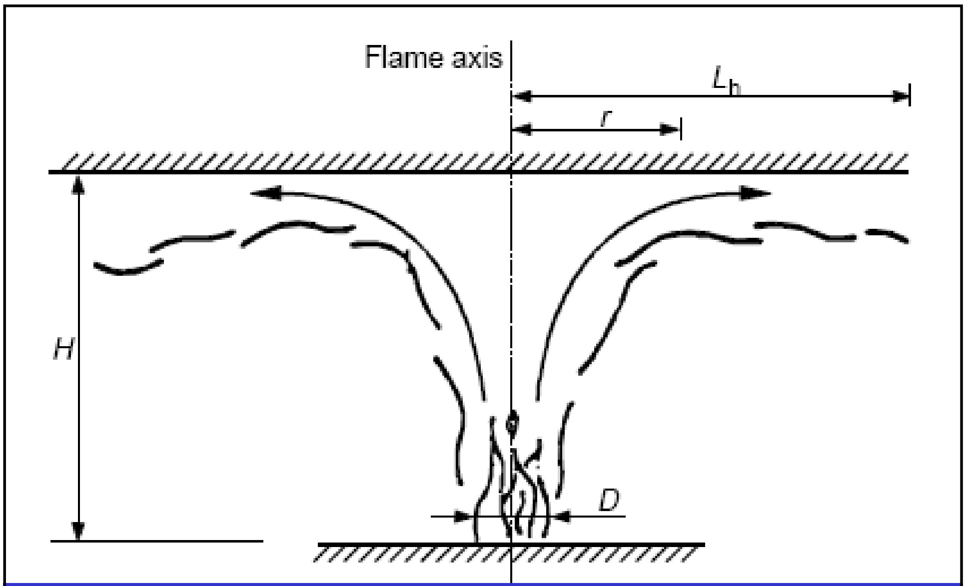
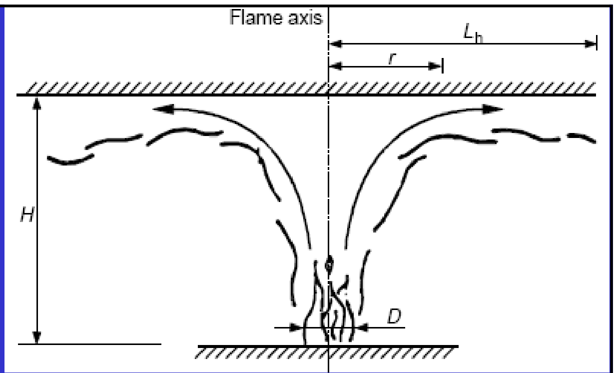


Localised fire model of Hasemi (based on experimental tests) introduced in EN 1991-1-2

Basic equations of the model



$$Q_H^* = Q / (1{,}11 \cdot 10^6 \cdot H^{2{,}5})$$

$$L_h = \left(2{,}9\ H\ (Q_H^*)^{0{,}33}\right) - H$$

$$Q_D^* = Q / (1{,}11 \cdot 10^6 \cdot D^{2{,}5})$$

$$z' = 2{,}4\ D\left(Q_D^{*\,2/5} - Q_D^{*\,2/3}\right) \quad \text{when} \quad Q_D^* < 1{,}0$$

$$z' = 2{,}4\ D\left(1{,}0 - Q_D^{*\,2/5}\right) \quad \text{when} \quad Q_D^* \geq 1{,}0$$

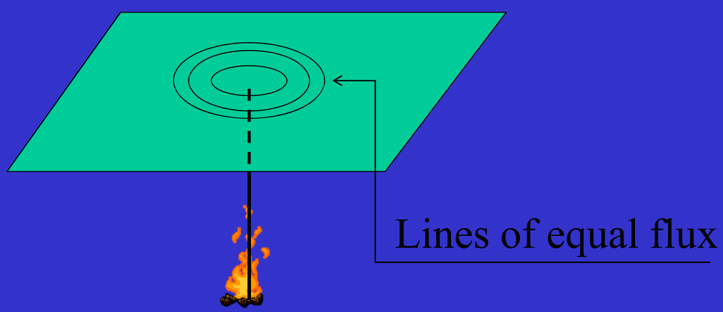
Vertical position of the virtual heat source

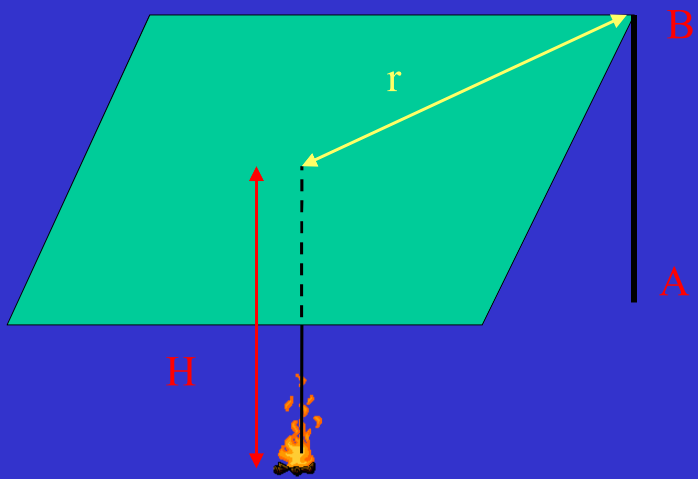
$$y = \frac{r + H + z'}{L_h + H + z'}$$

$\dot{h} = 100\ 000$	if $y \leq 0{,}30$
$\dot{h} = 136\ 300$ to $121\ 000\ y$	if $0{,}30 < y < 1{,}0$
$\dot{h} = 15\ 000\ y^{3{,}7}$	if $y \geq 1{,}0$

In short:

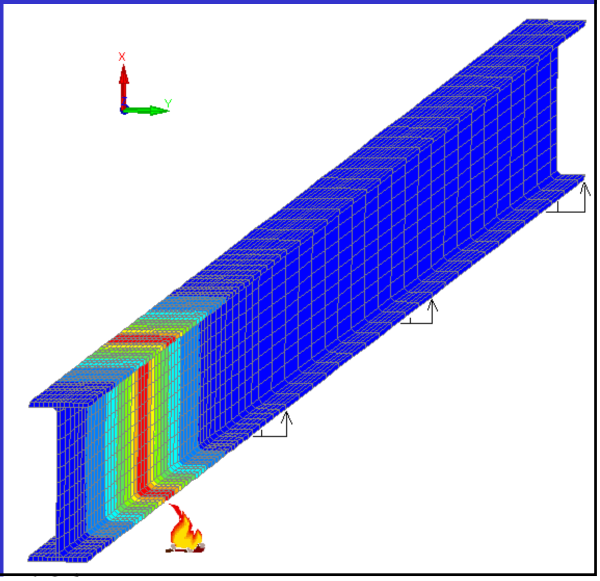
Flux received **at the ceiling** by the structure is function of:
- Characteristics of the fire (Q, D)
- Vertical distance between the fire and the ceiling (H)
- Horizontal distance between the fire and the point considered (r).





All points of the column AB will received the same flux (in fact, the one calculated at point B).

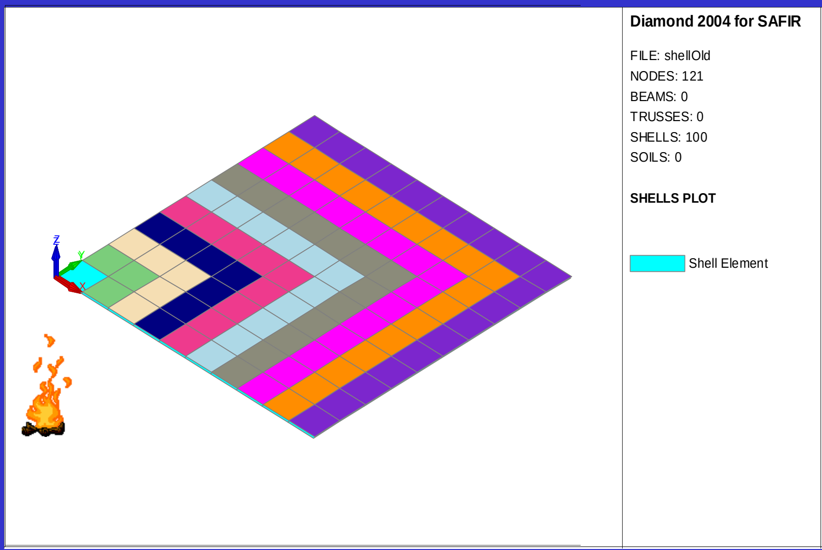
A full 3D thermal analysis of the complete structure based on 3D solid elements would be too expensive.



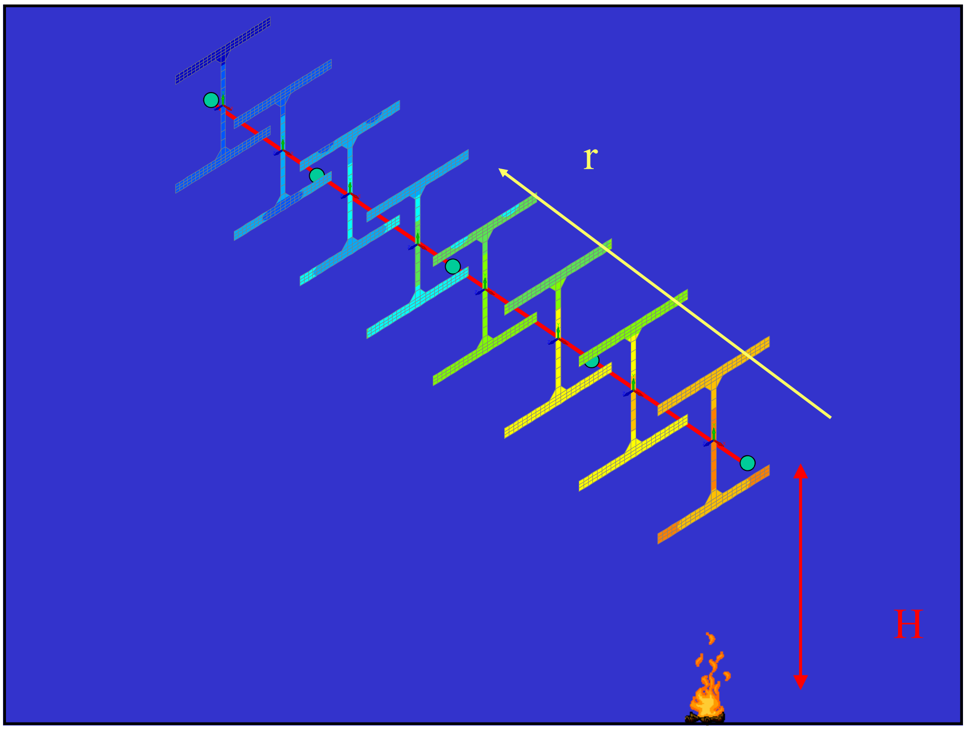
First solution used (historically): define some bands of elements with different boundary conditions.

• time consuming for the user.

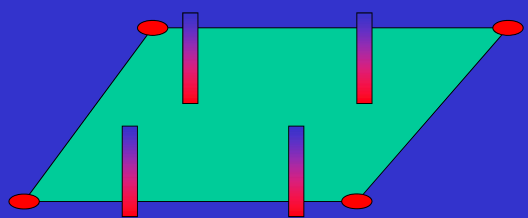
• spurious stresses.



Principle of the solution used now: in the BEAM section types that are heated by the HASEMI fire, a 2D thermal analysis is performed in each longitudinal integration point.



Principle of the solution used now : in the SHELL section types that are heated by the HASEMI fire, a 1D thermal analysis is performed in each of the 4 integration points in the plane of each shell element.



Note: it is possible to have in the same structure, sections that are:

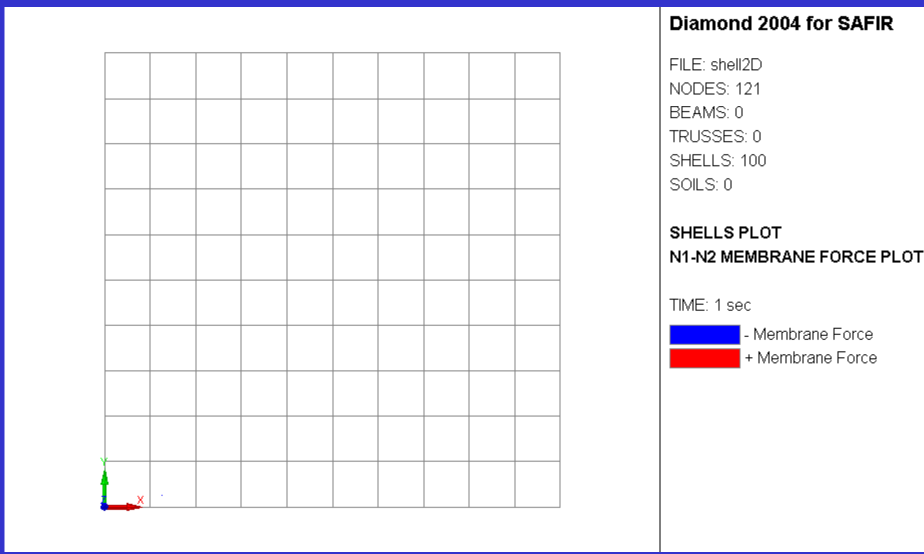
- heated by Hasemi fires,
- heated by $T_g = f(t)$ fires,
- not heated.

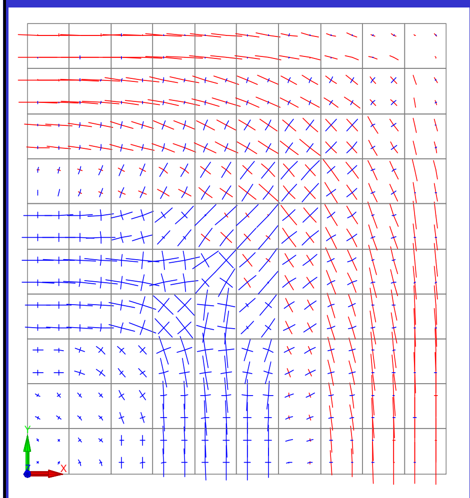
Note: the input file describing the structure for the mechanical analysis must be present before starting the thermal analyses (in order to allow computing *r* in every P.o.I.).

Note: gravity MUST be in the direction:
-Z for 3D structures;
-Y for 2D structures.

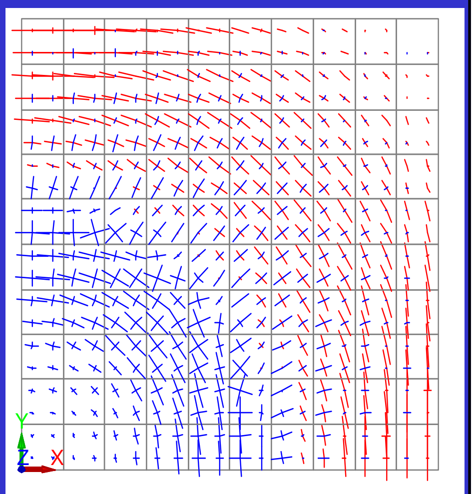
In SAFIR, the file "*hasemi.txt*" describes the local fire(s).
It has to be present in the same folder as the input files.

Application



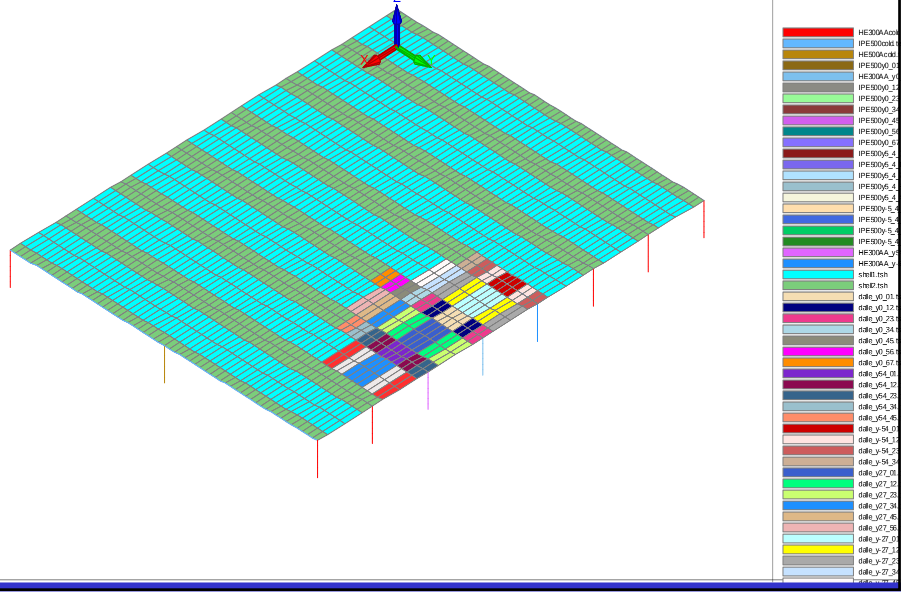


Temperature per zone

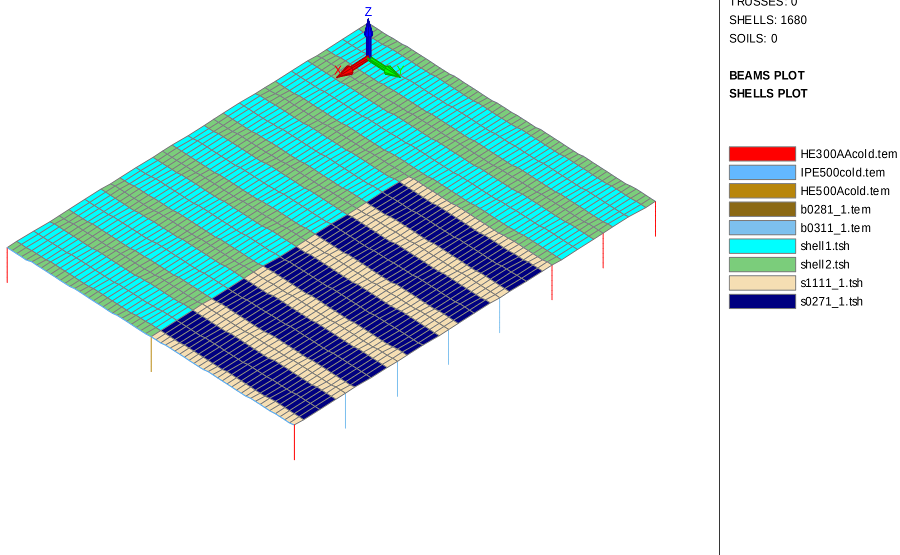


Continuous distribution

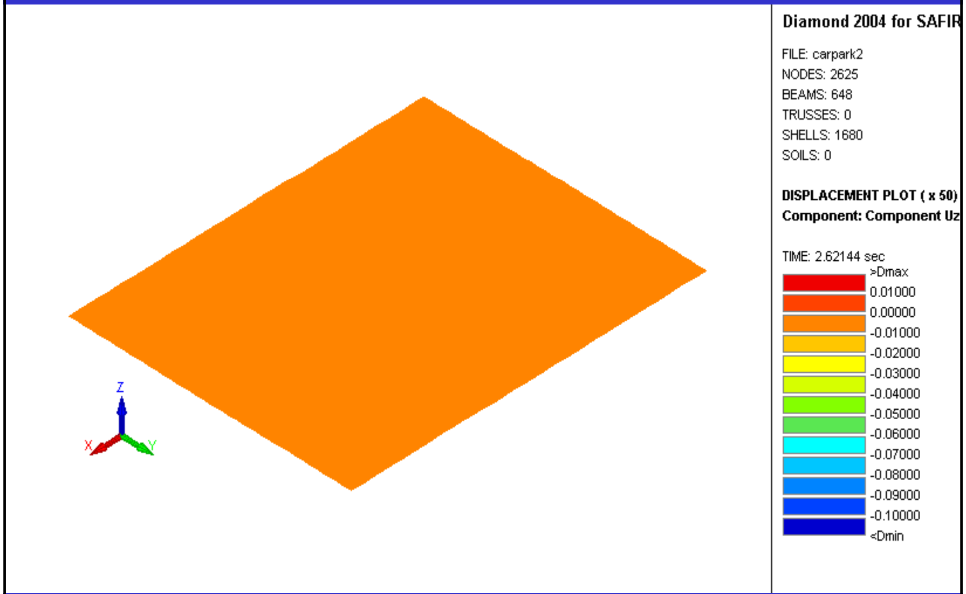
The old way of modelling a car park subjected to a local fire.



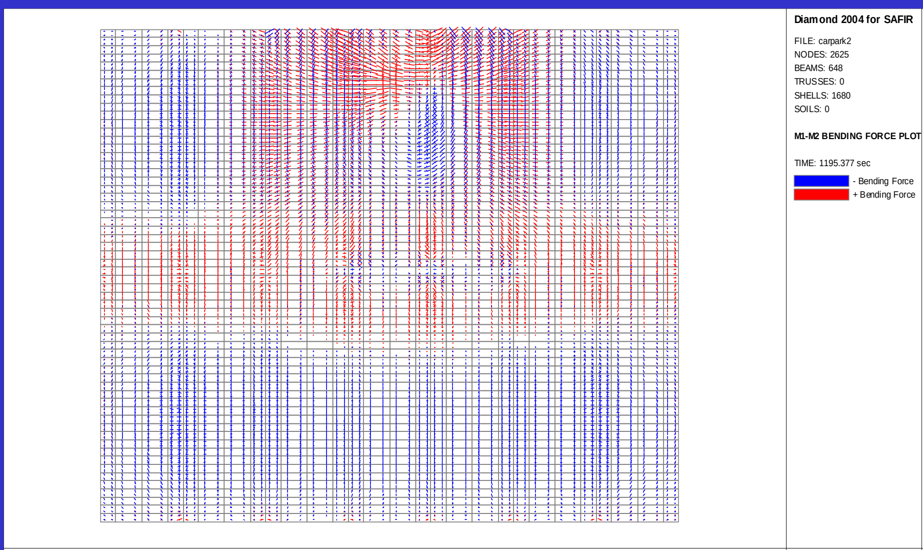
The new way of modelling a car park subjected to a local fire.



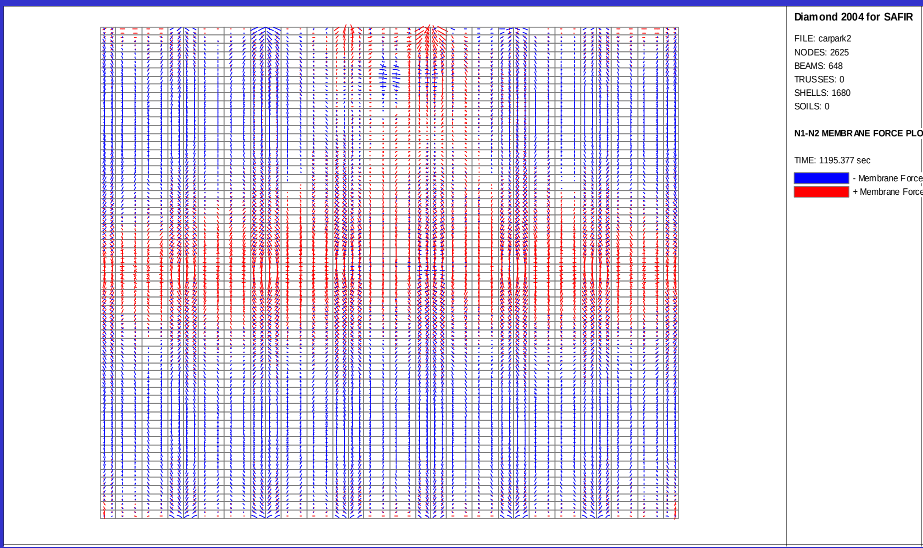
The displacement field is continuous (but this is "easy")

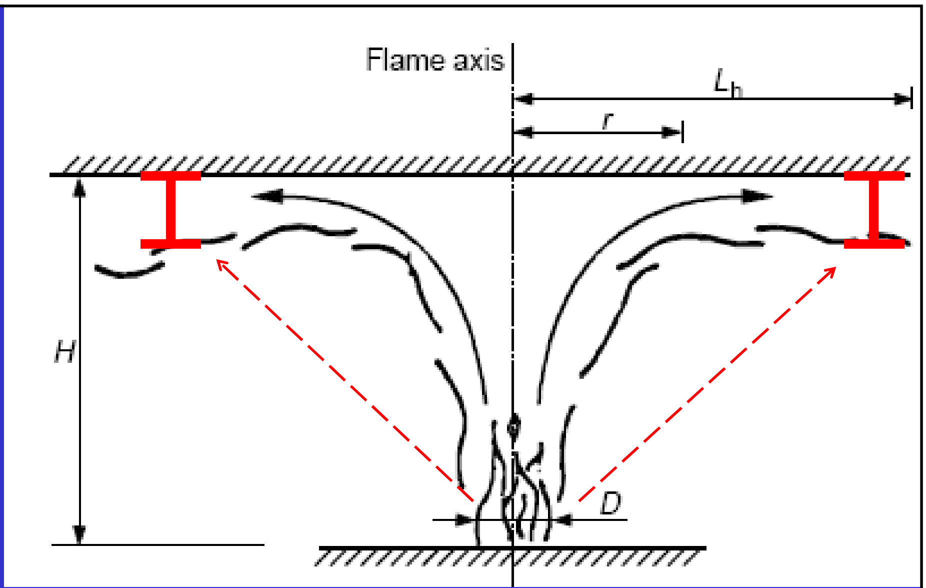


The field of moments is also continuous (this is not "easy")



The field of membrane forces is also continuous (not "easy")





Note: the information about the direction of the fire source is not in the model

Link between thermal and mechanical analyses

The type of model used for the thermal analysis depends on the type of model that will be used in the subsequent mechanical analysis.

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Link between thermal and mechanical analyses

Temperature field		Mechanical model
3D F.E.	=>	Simple calculation model
<u>2D F.E.</u>	=>	<u>Beam F.E. (2D or 3D)</u>
1D F.E. or local Hasemi fire model	=>	Shell F.E. (3D)
Simple calculation model	=>	Truss F.E. (2D or 3D)

This presentation

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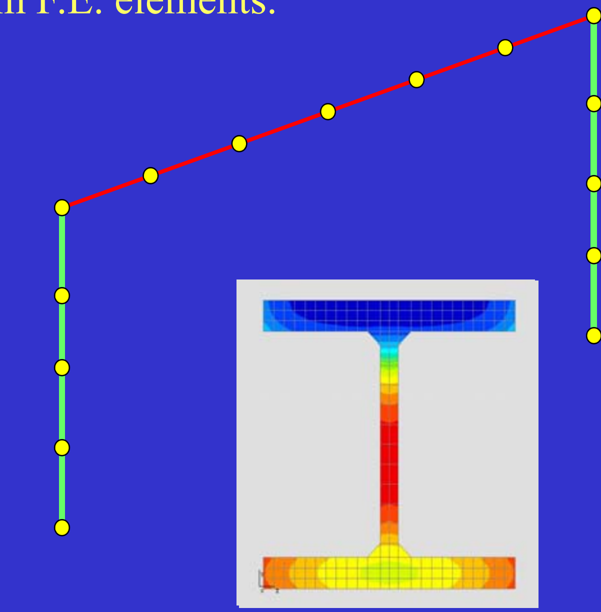
General principle of a mechanical analysis based on beam F.E. elements.



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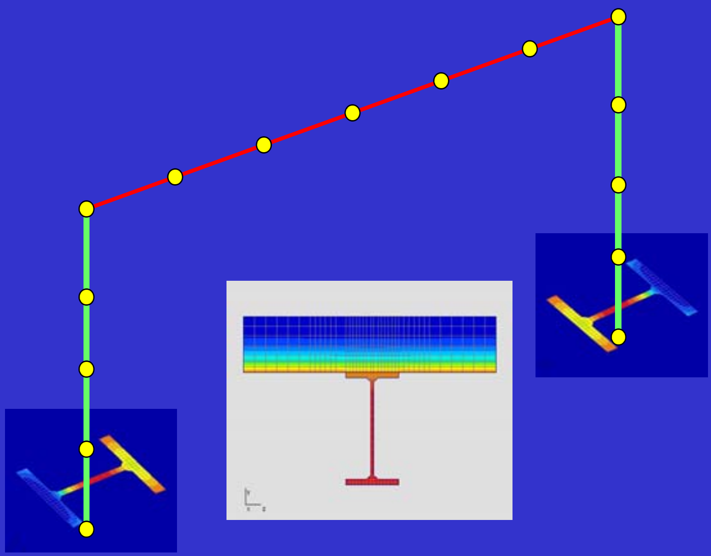

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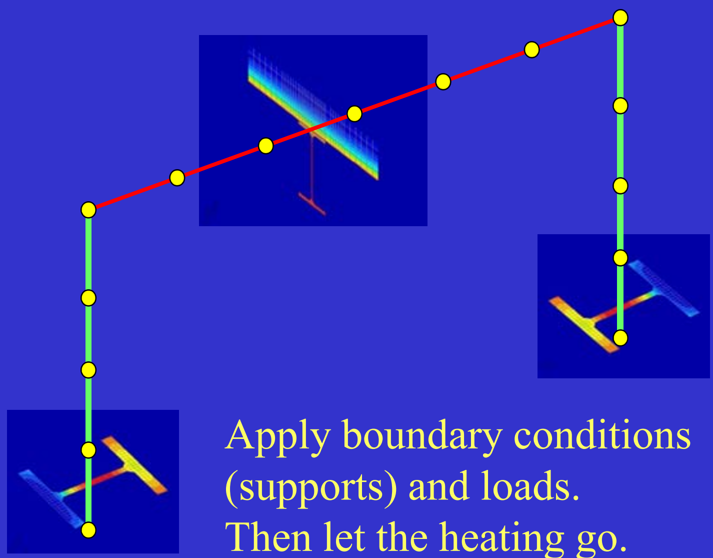

Apply boundary conditions (supports) and loads.
Then let the heating go.

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Organisation of the files for a typical calculation
- one thermal calculation for each section type
- One structural calculation for a structure that may contain several section types.

Note: one new section type if:

- the geometry of the section is different,
- the fire curve is different,
- the thermal properties are different,
- the mechanical properties are different.

Note: in this case, it is possible to copy the results of the thermal calculation in a file with a new name.

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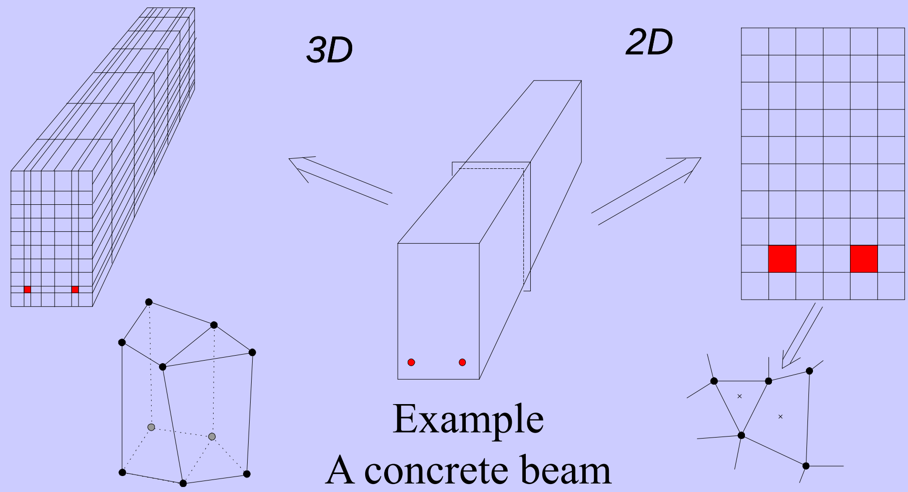
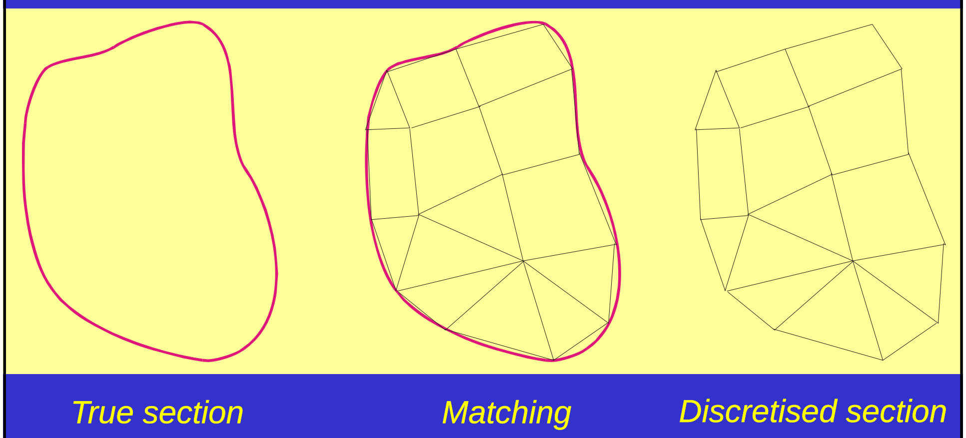
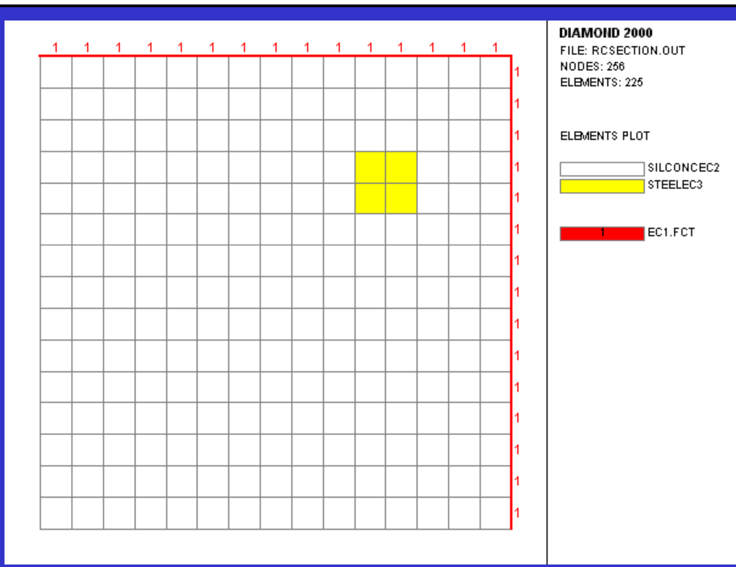
Step 2. Thermal Calculation - discretisation of the structure



Step 2. Thermal response : discretisation of the structure

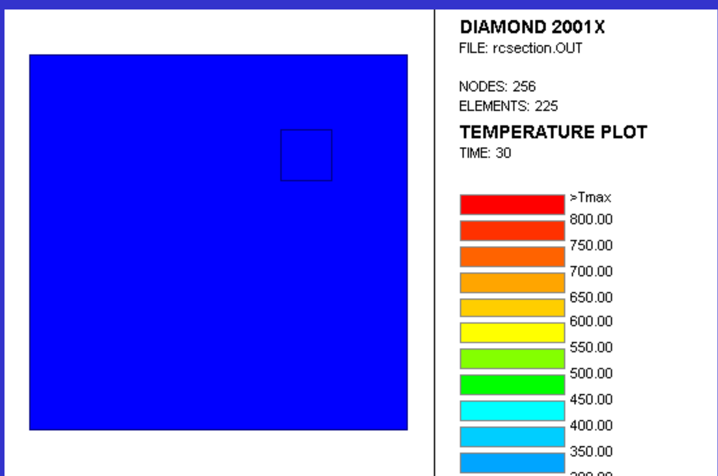


⇒The discretised section is an approximation of the real section



Example of a very simple discretisation
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).



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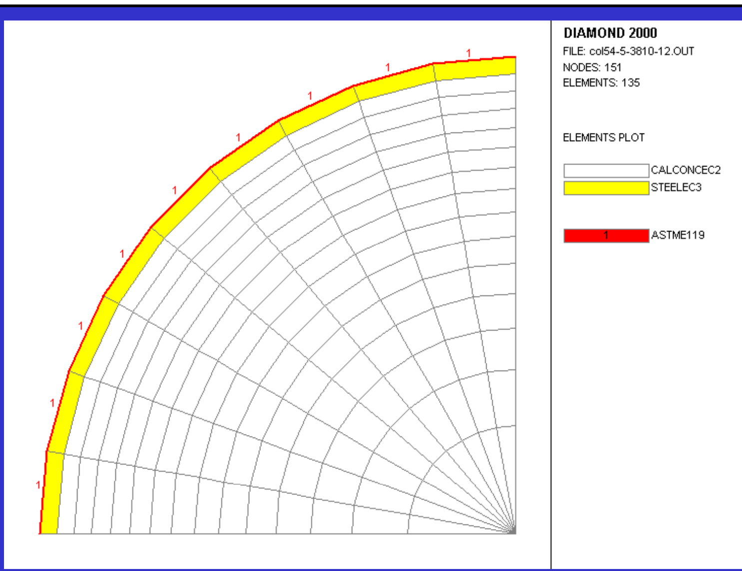

Concrete Filled Steel Section
(*courtesy N.R.C.* Ottawa)

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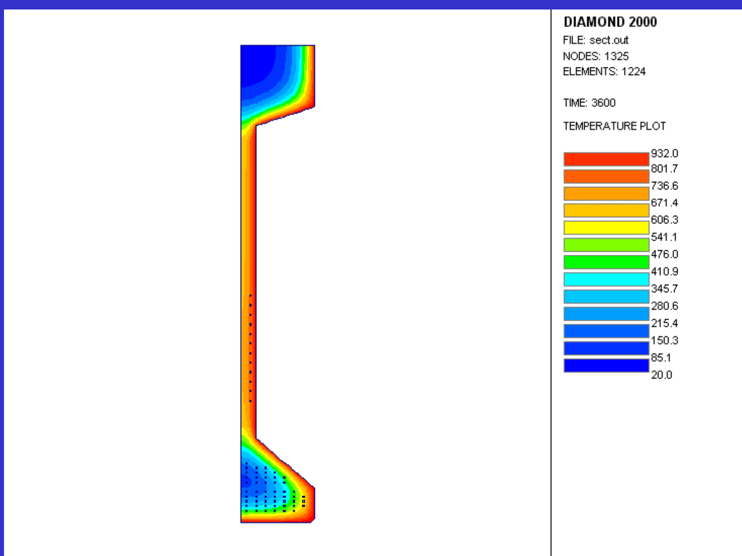

Prestressed concrete section

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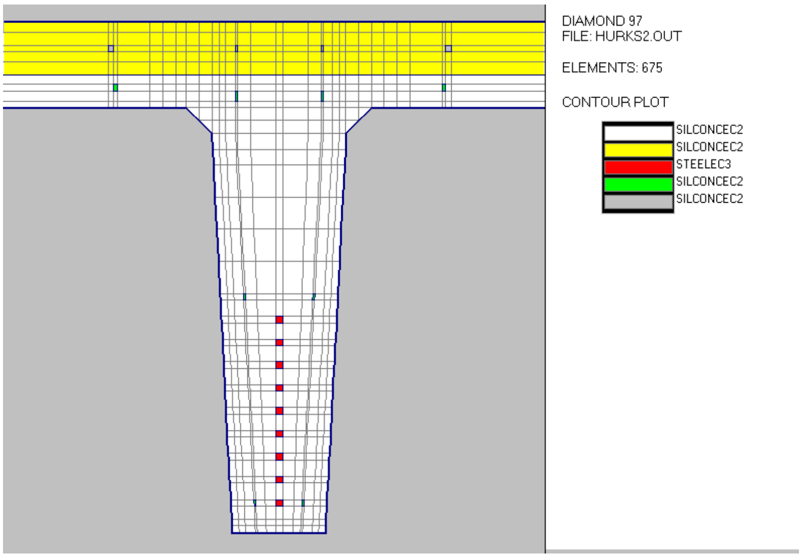
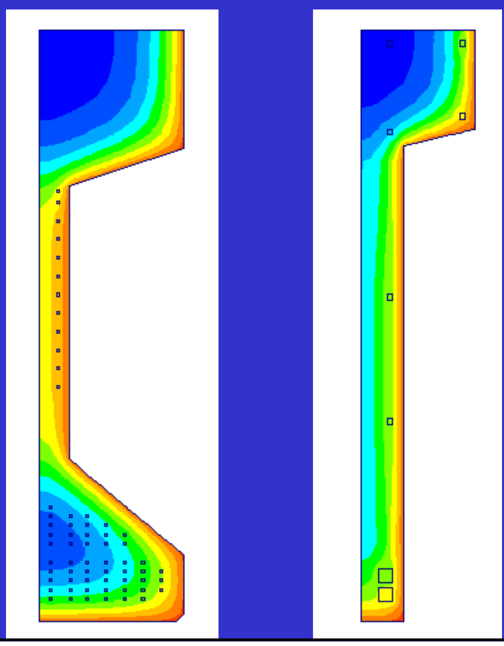
TT prestressed beam





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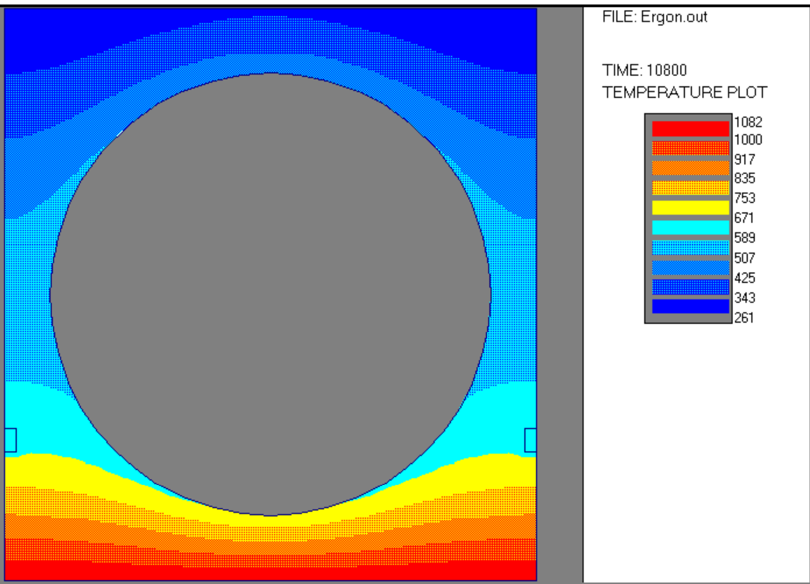

Radiation in the cavities is taken into account
Concrete hollow core slab

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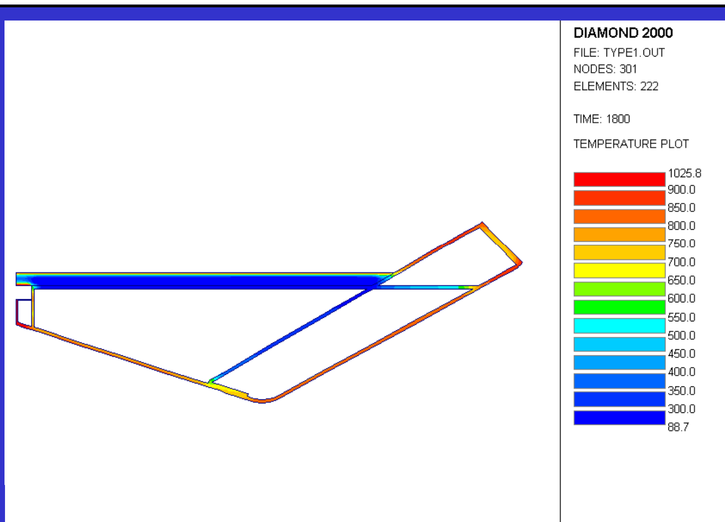

T.G.V. railway station in Liege (courtesy Bureau Greisch).
Main steel beam with concrete slab.

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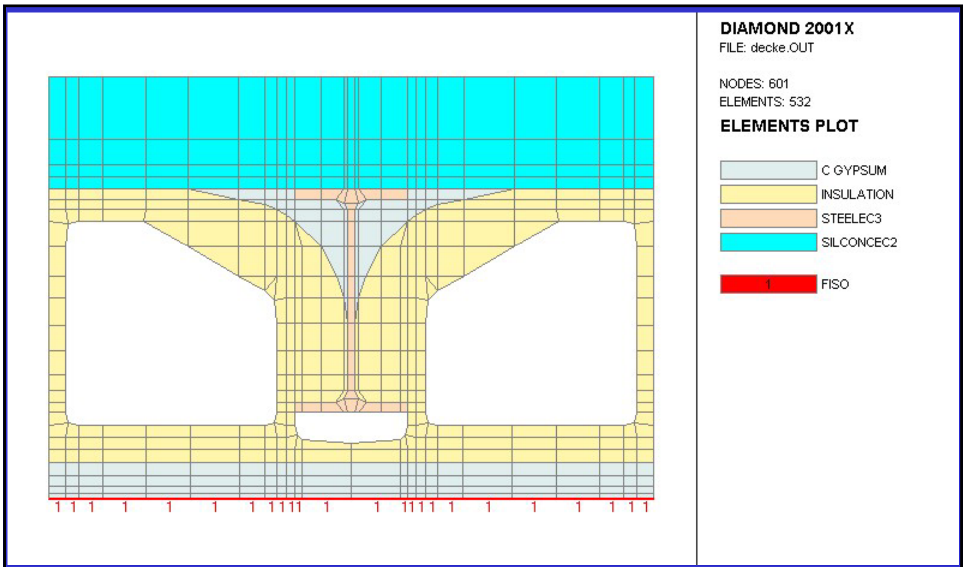

Old floor system; steel I beams and precast voussoirs
Courtesy: Lenz Weber, Frankfurt

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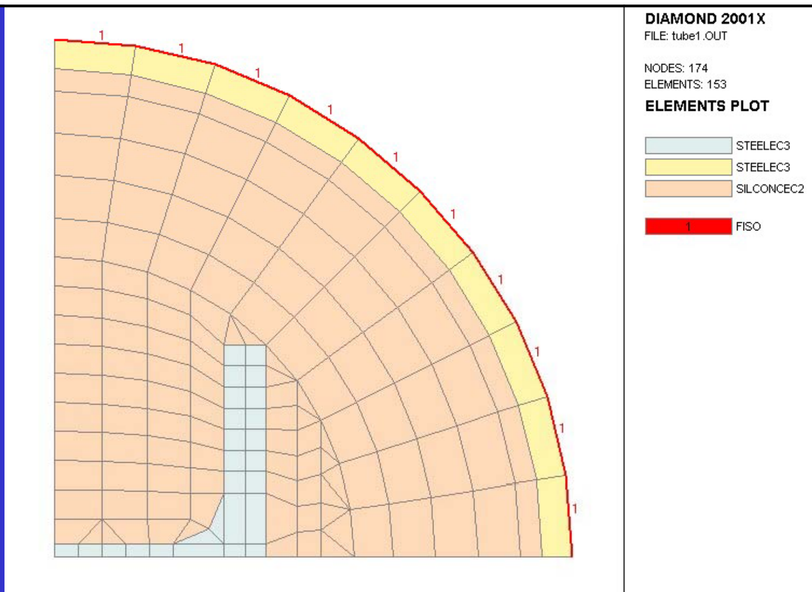
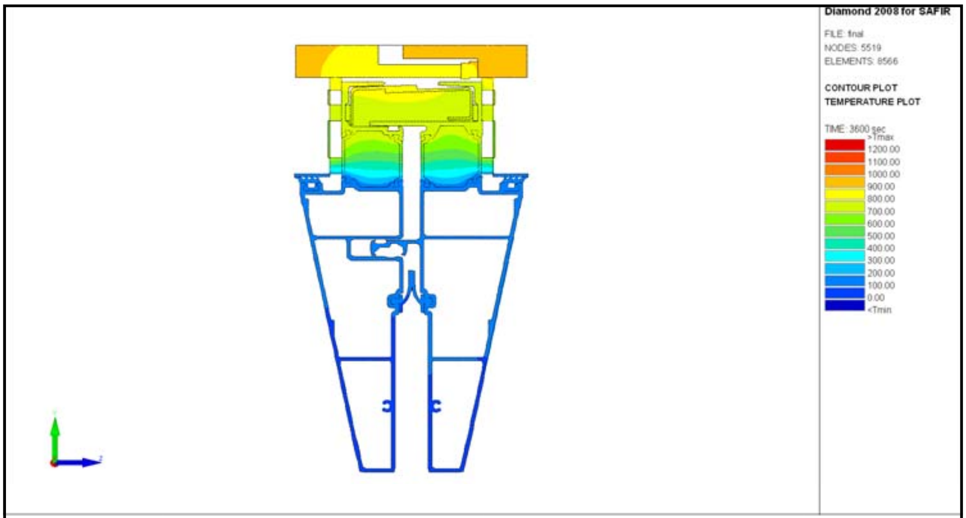


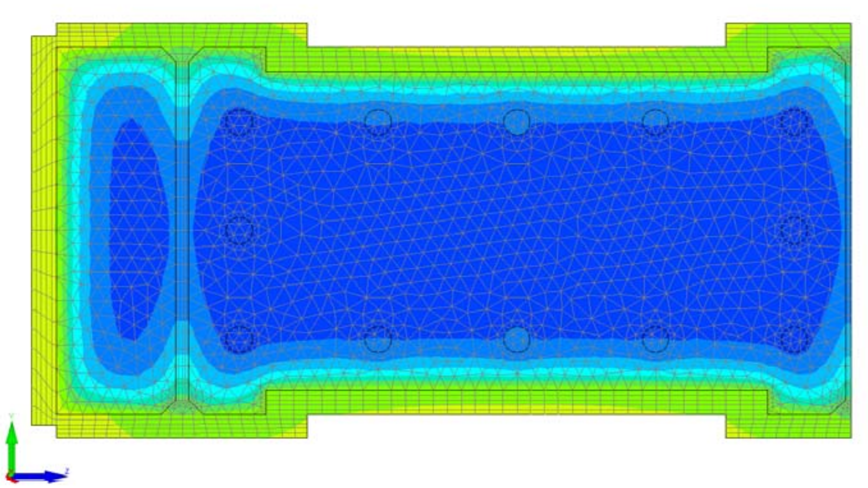
Steel H section in a steel tube filled with concrete

66



Window frame (courtesy: Permasteelisa)

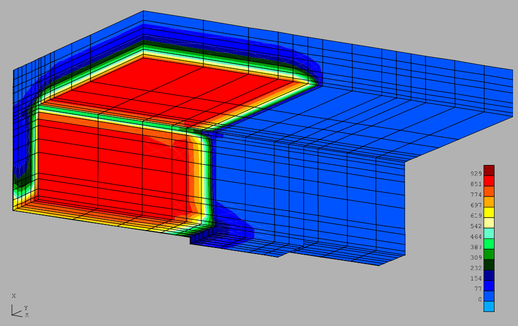
67



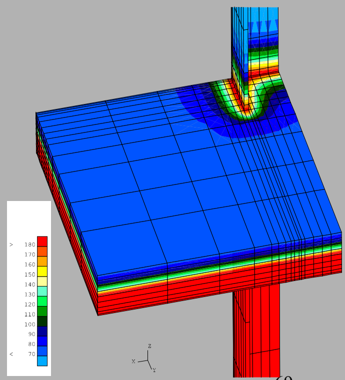
Composite steel-concrete columns (1/2)
Courtesy: Technum

68

Composite beam partly heated

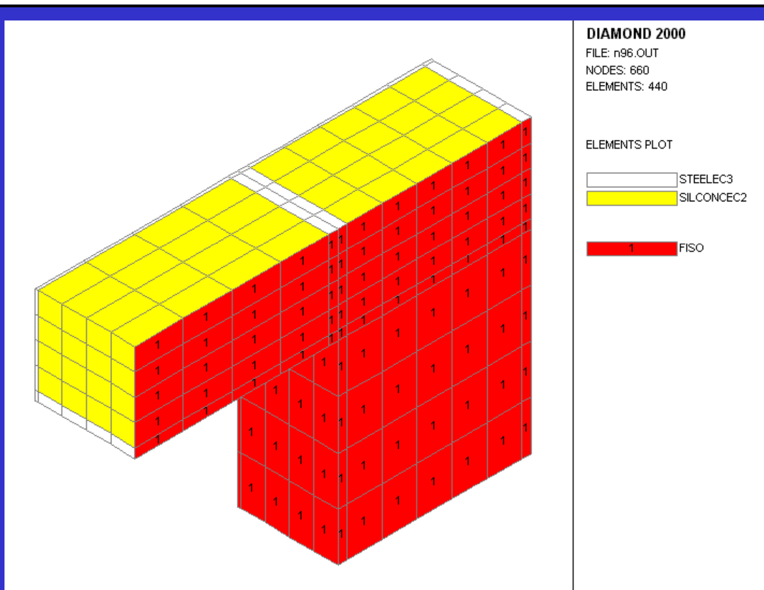


Steel column through a concrete slab



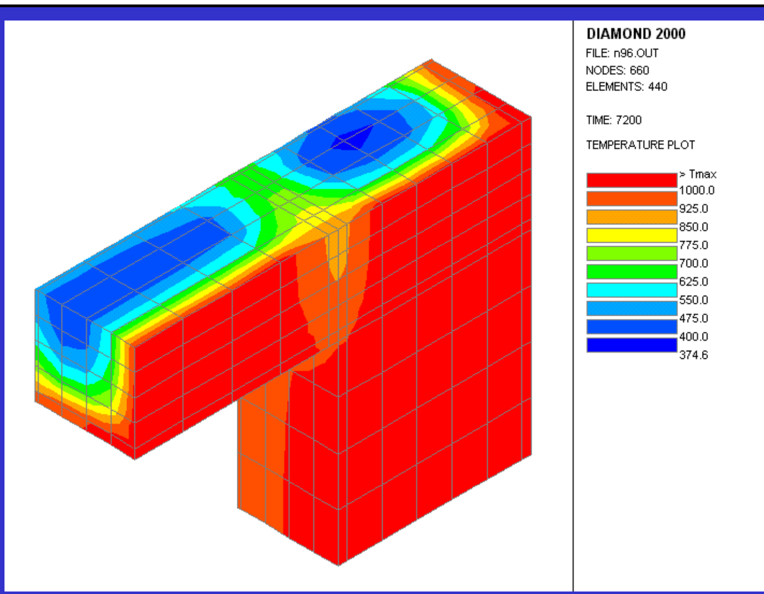
3D examples

69



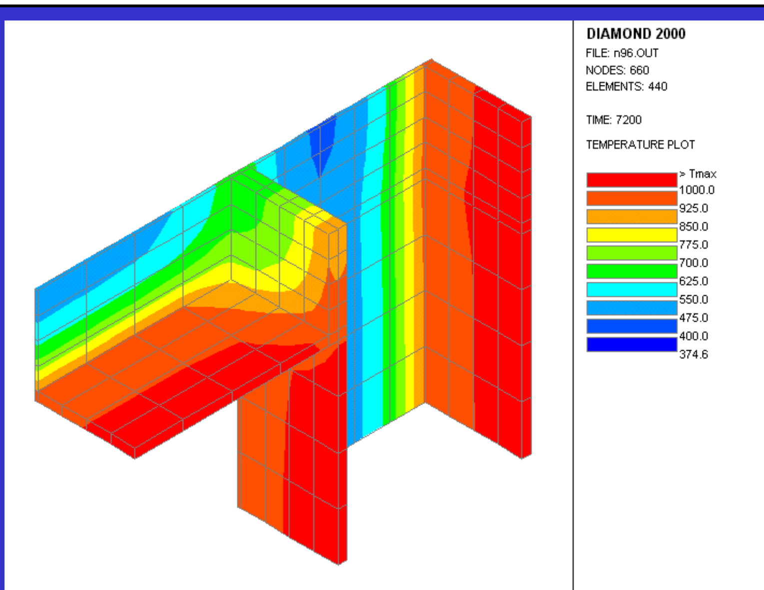
Composite steel-concrete joint
Discretisation

70

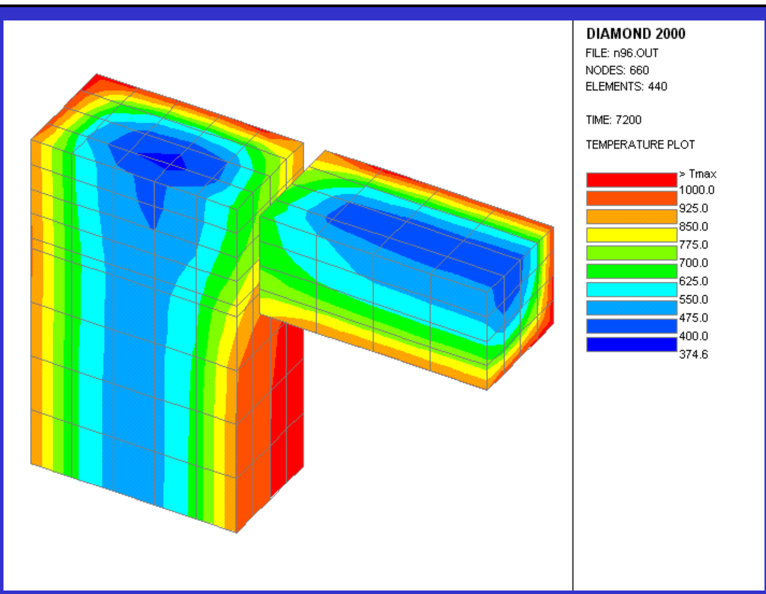


Composite steel-concrete joint
Temperatures on the surface

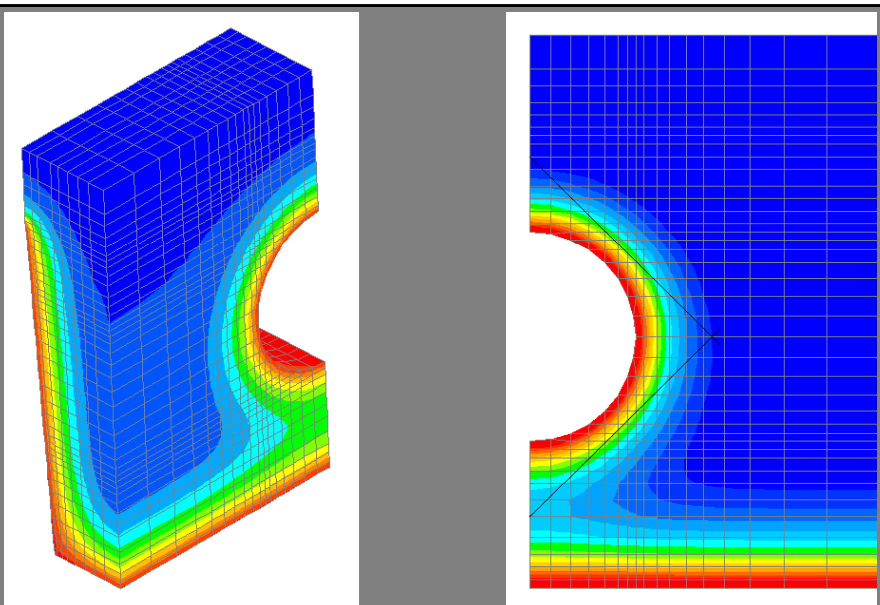
71



Composite steel-concrete joint
Temperatures on the steel elements (concrete is transparent)



Composite steel-concrete joint
Temperatures on the concrete elements (steel transparent)



Concrete beam (courtesy *Halfkann & Kirchner*)
Transmission of the shear force around the holes

74

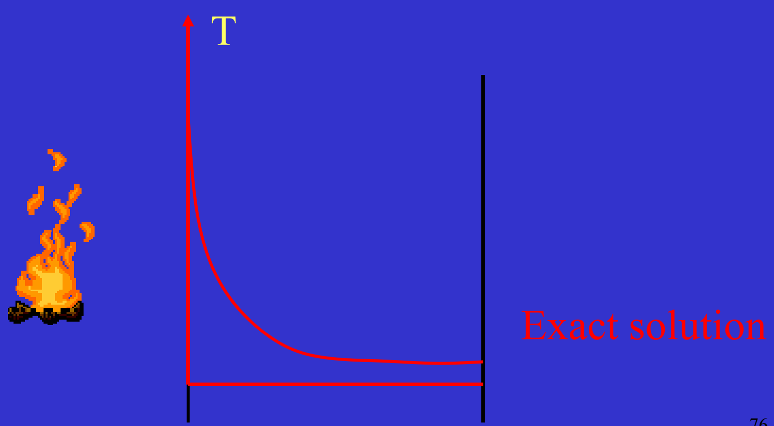
Step 2. Thermal response : limitations

- Free water – the evaporation is taken into account, but not the migration.
- Internal cavities only in 2D sections.
- Perfect conductive contact between the materials.
- Fixed geometry (spalling! Now taken into account, but not predicted, see advanced SAFIR course).
- Isotropic materials (no influence of cracking in concrete. Now orthotropic timber is considered).

Step 2. Thermal response : limitations

Linear elements.

Consequence: possible skin effects (spatial oscillations)



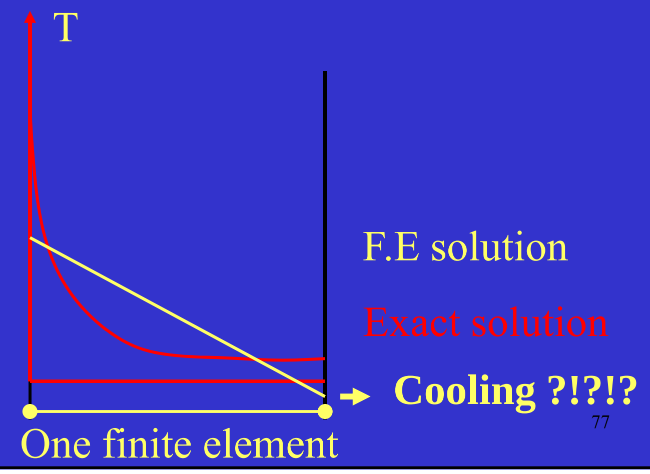
A wall (uniaxial heat flow)

76

Step 2. Thermal response : limitations

Linear elements.

Consequence: possible skin effects (spatial oscillations)

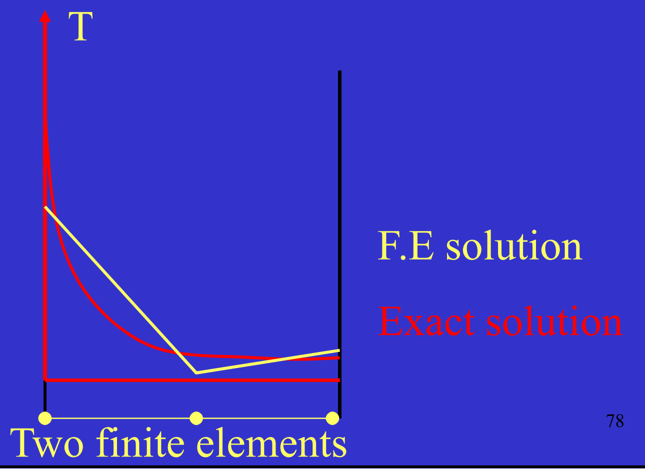


77

Step 2. Thermal response : limitations

Linear elements.

Consequence: possible skin effects (spatial oscillations)

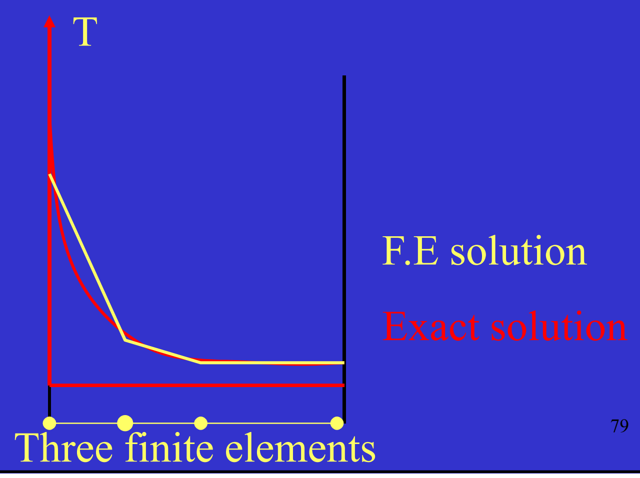


78

Step 2. Thermal response : limitations

Linear elements.

Consequence: possible skin effects (spatial oscillations)



Step 2. Thermal response : limitations

Linear elements.

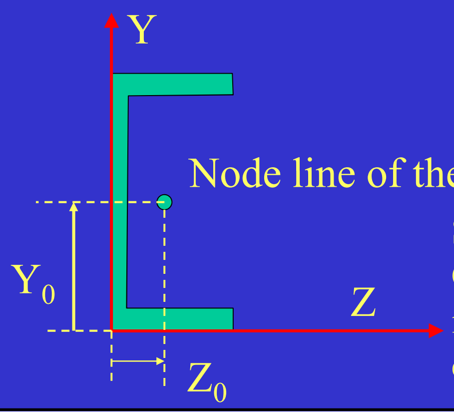
Consequence: possible skin effects (spatial oscillations)

Solution:

The mesh must not be too crude
in the zones
and in the direction
of non linear temperature gradients.

Structure of the input file for thermal analyses

```
NODELINE     Y0   Z0
YC_ZC        Yc   Zc
```

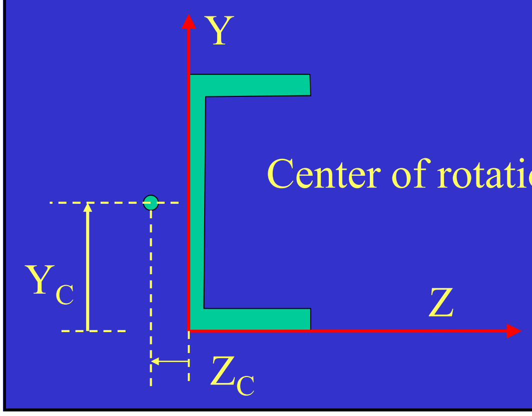


Node line of the structural analysis

Sytem of coordinates. Chosen to allow easy introduction of the node coordinates

Structure of the input file for thermal analyses

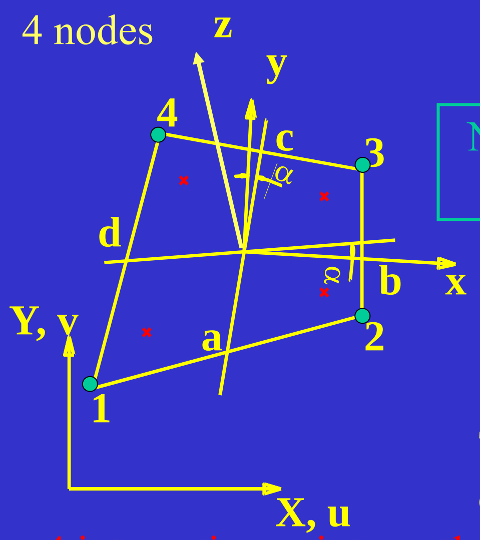
```
NODELINE     Y0   Z0
YC_ZC        Yc   Zc
```



Center of rotation (structural analysis)

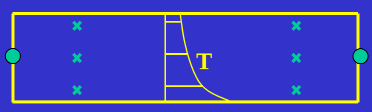
The Shell Finite Element

4 nodes



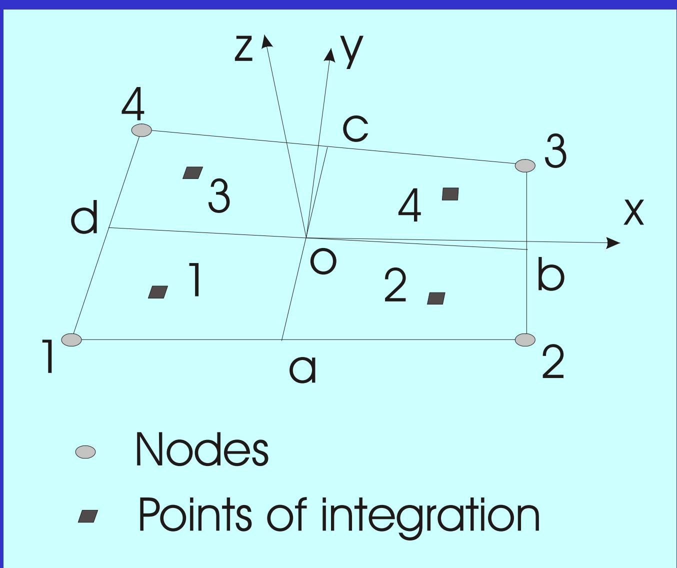
Uniform thickness

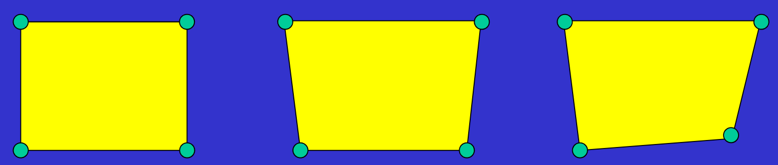
NG integration points on the thickness



T varies on the thickness, does not vary in the plane

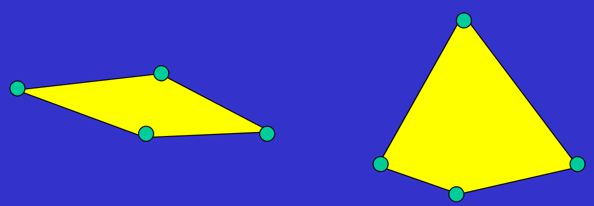
4 integration points on the surface



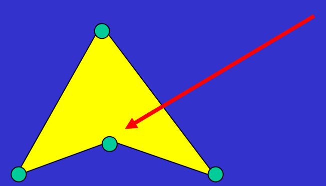


GEOMETRIES OK

NB: The 4 nodes need not be in the same plane
(still, it is preferable not to distort too much out of plane)



GEOMETRIES not recommended



GEOMETRY not accepted

6 D.o.F. at each node of the shell elements:
3 translations and 3 rotations.

⇒One node can be used:

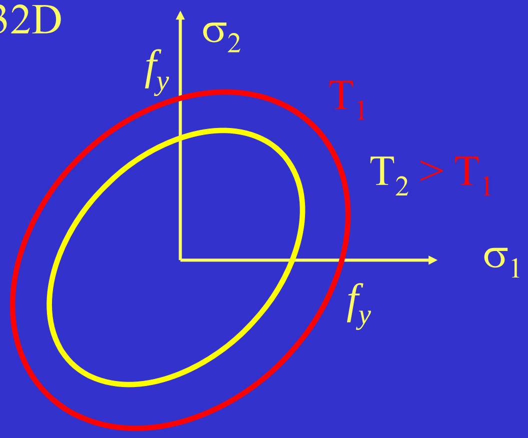
- as the end node of a 3D beam element and
- as the node of a shell element and
- as the node of a truss element.

Membrane behaviour (steel plates): NG = 2
Flexural behaviour (concrete slabs): NG ↑↑ (max. = 10)

Materials:

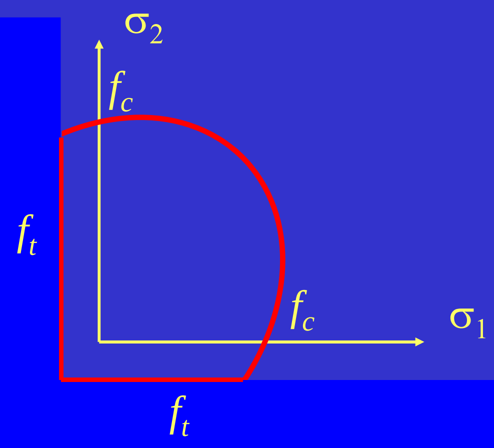
STEELEC32D (very stable)
SILCONC2D & CALCONC2D (not so stable)
+ rebars (STEELEC2)

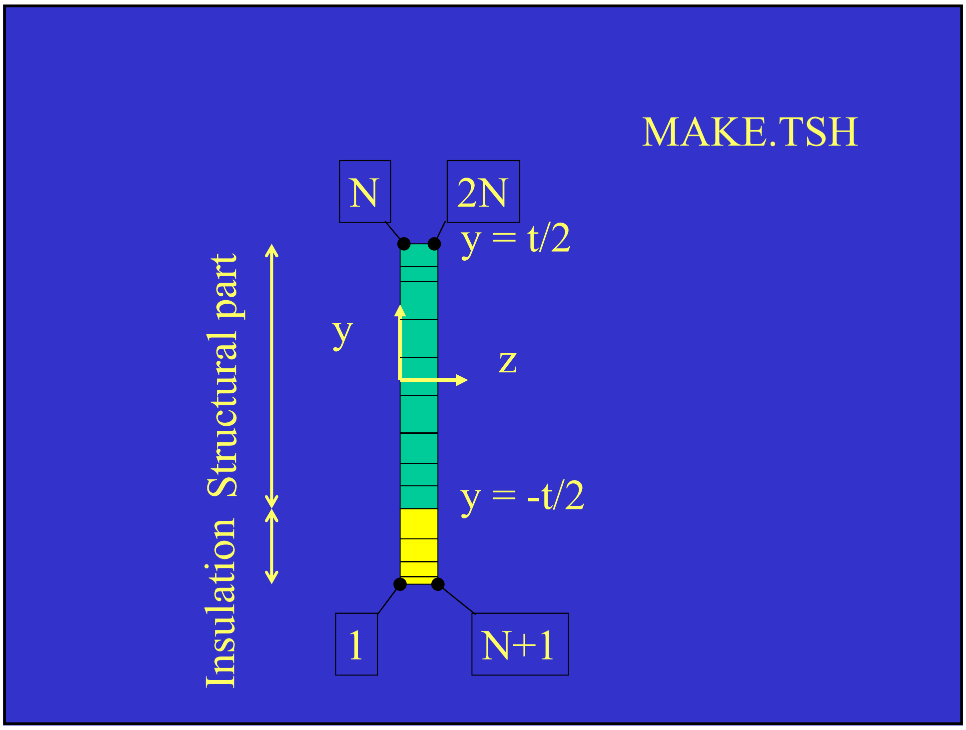
STEELEC32D

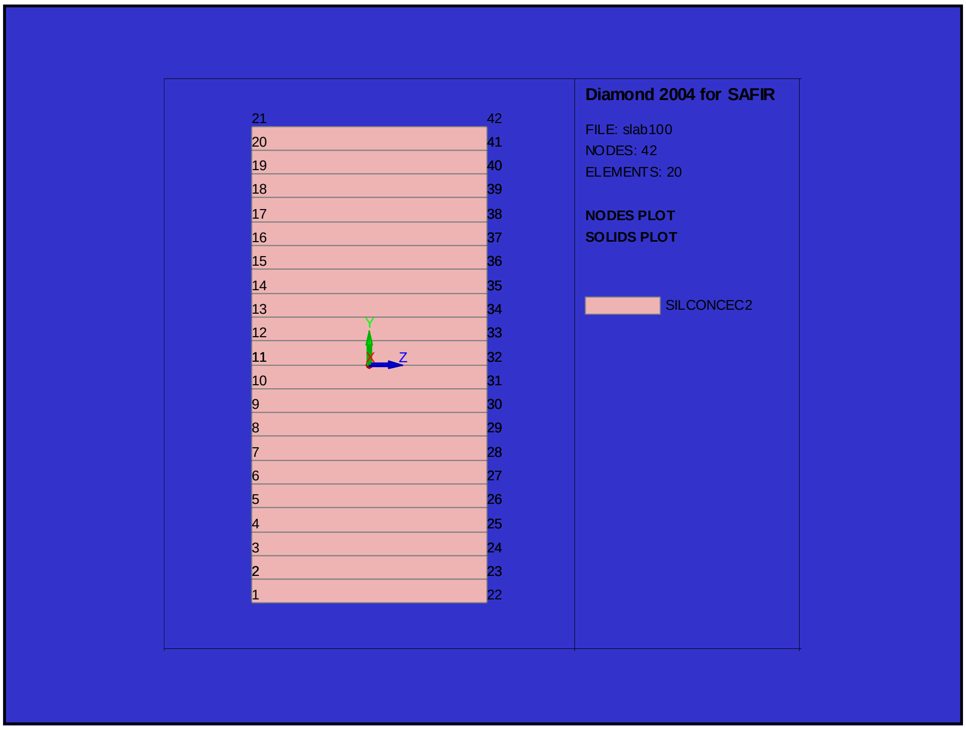


- Associated plasticity
- Von Misses yield surface
- Isotropic hardening (same laws as EN 1993-1-2)

SILCONC2D and CALCONC2D




MAKE.TSH
N
2N
y = t/2
y
z
y = -t/2
Insulation Structural part
1
N+1

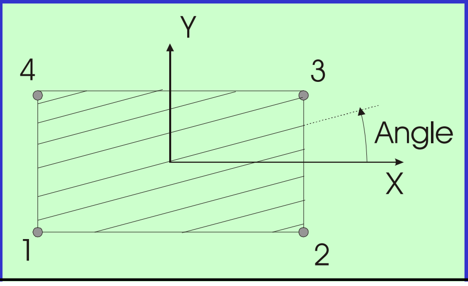

Diamond 2004 for SAFIR
FILE: slab100
NODES: 42
ELEMENTS: 20
NODES PLOT
SOLIDS PLOT
SILCONCEC2
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
42
41
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
Y
Z

Different layers of rebars can be present in the element. The rebar layers are horizontal (i.e. parallel to the local **x, y** plane). The rebars are uniformly distributed (layered rebars). Each layer is defined by:

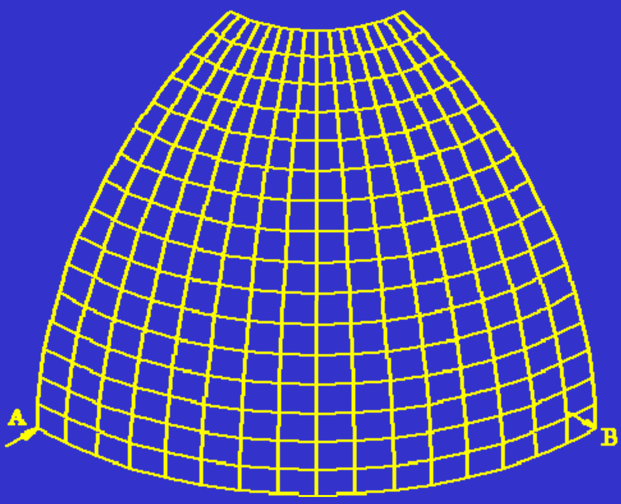
- it's local vertical coordinate **z** in the element (this level must not necessarily coincide neither with the position of a point of integration on the thickness, nor with a position where the temperature has been calculated. Linear interpolations are made);
- it's cross section per unit length of width (m^2/m for example);
- it's material number; and
- the angle between the direction of the rebars and the local **x** axis..

Assumptions for rebar elements are:

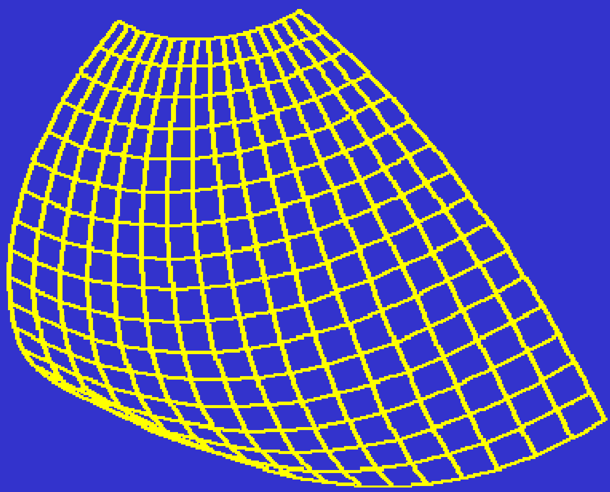
- the cross section of the rebar is not subtracted from the plane section of the element. This means that, in a reinforced concrete slab, steel and concrete are supposed to be simultaneously present at the location of the bars,
- the bars resist only axial direction actions. This means that a mesh of perpendicular rebars does not resist shear by itself.



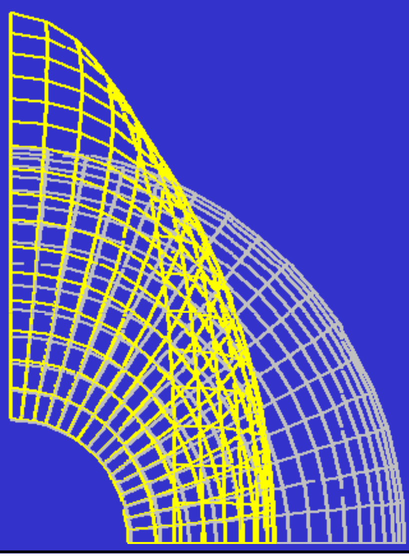
Hemispherical Shell



Deformed Hemispherical Shell

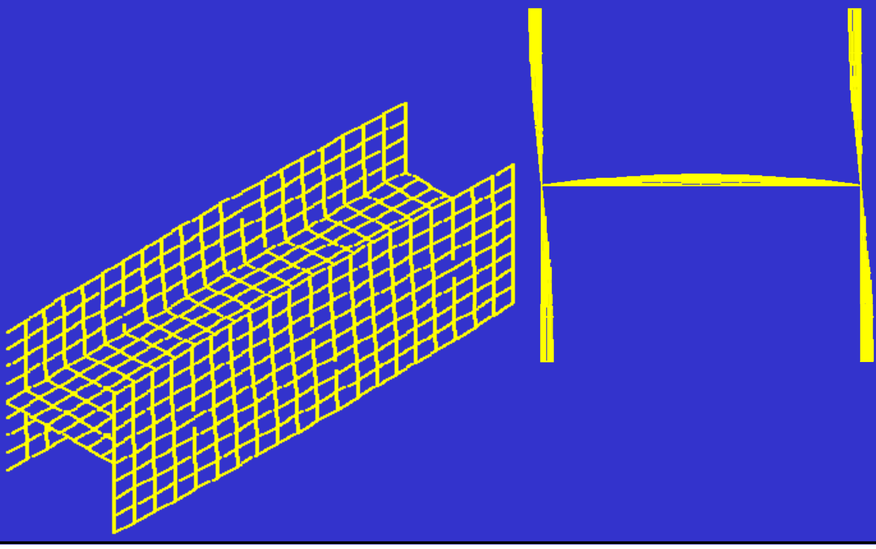


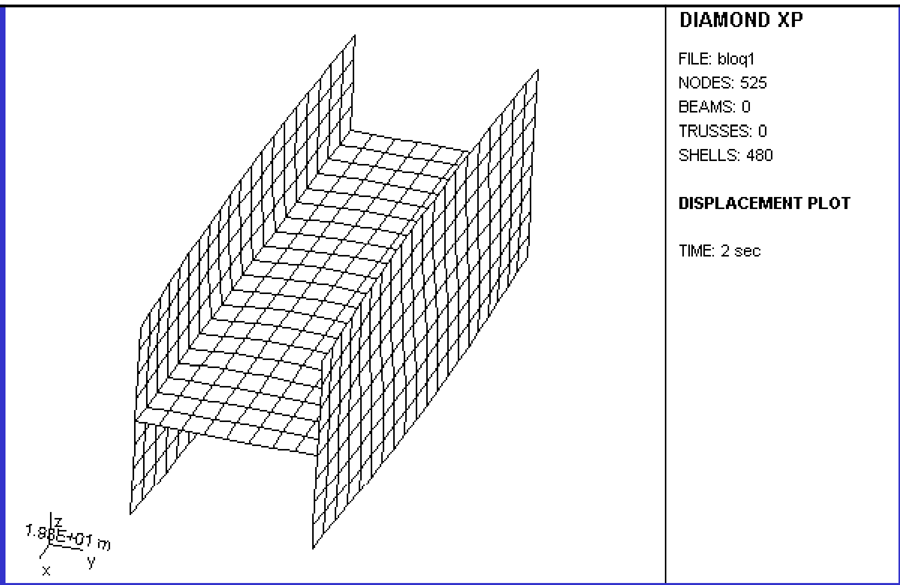
Initial Geometry and Deformed



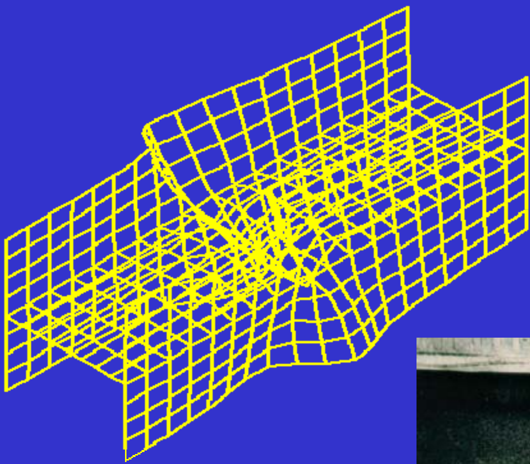
HE 300 AA+

Initial geometry





Heating and shortening
(no amplification of the displacements in this animation)



Thank you.