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

*Course by*

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# *Basic theory of the shell F.E.*

1) Degrees of freedom and local axes
2) Numerical integration
3) Material properties
4) Temperature distribution
5) Orientation of the rebars
6) Spurious modes
7) Output
8) Examples

# 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.*

1) Degrees of freedom and local axes
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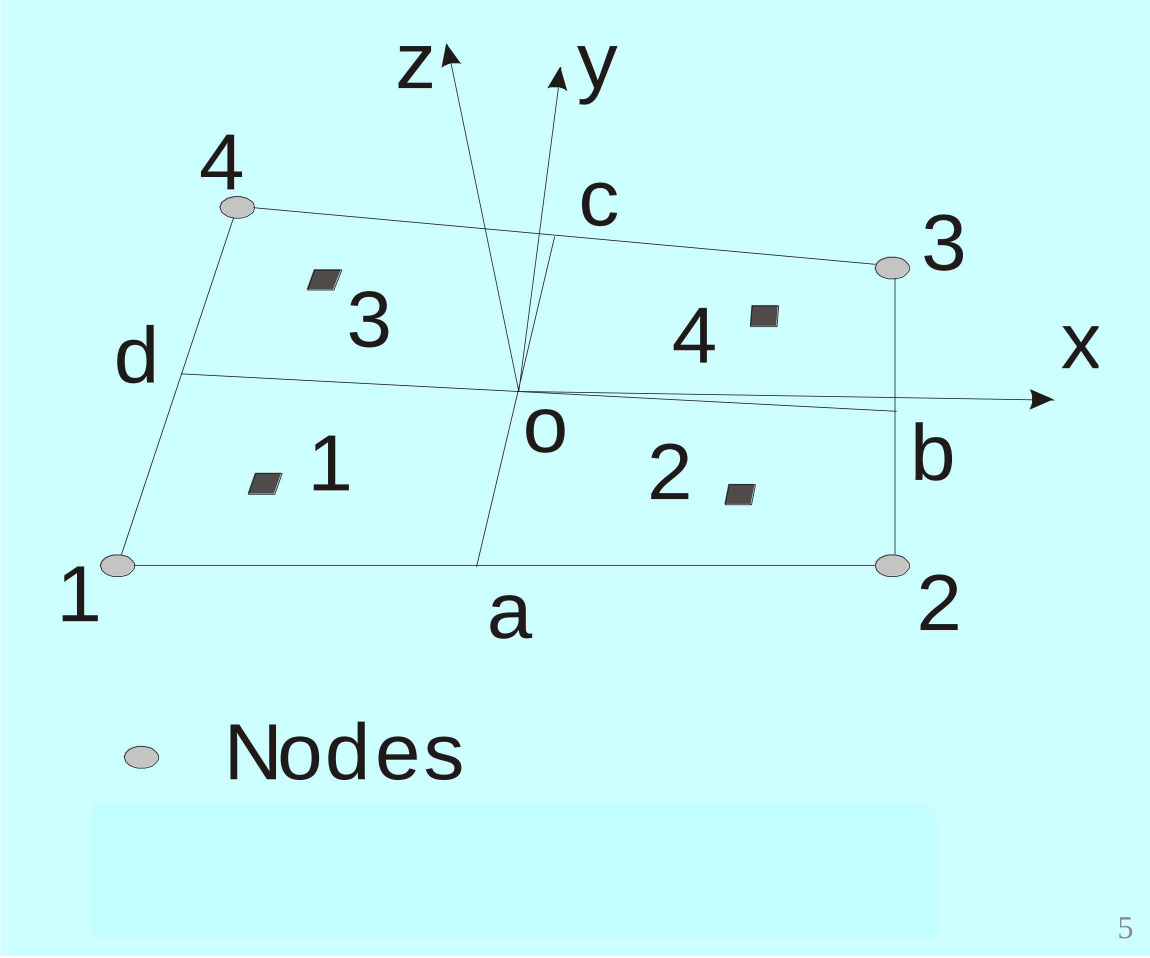
The shell finite element

✓ 4 nodes

✓ Uniform thickness



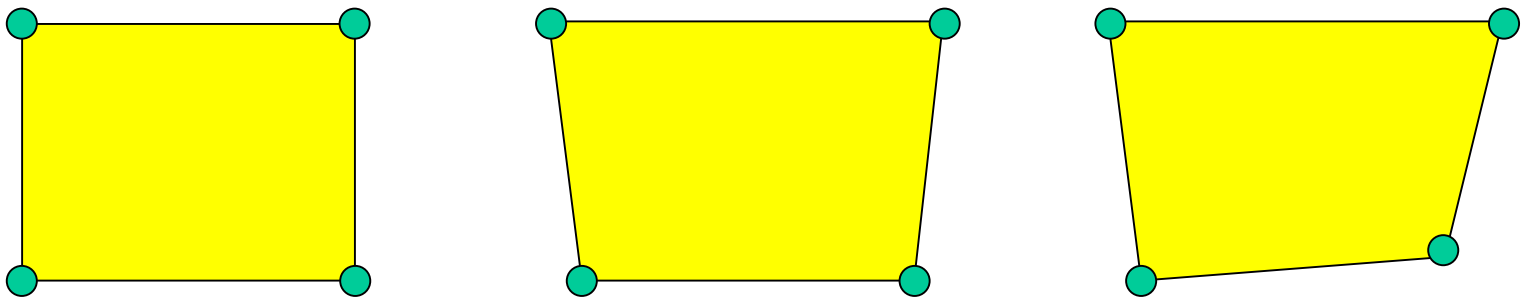
6 D.o.F. at each node of the shell elements:

3 translations

3 rotations.

$\Rightarrow$One node of the structure can be used:

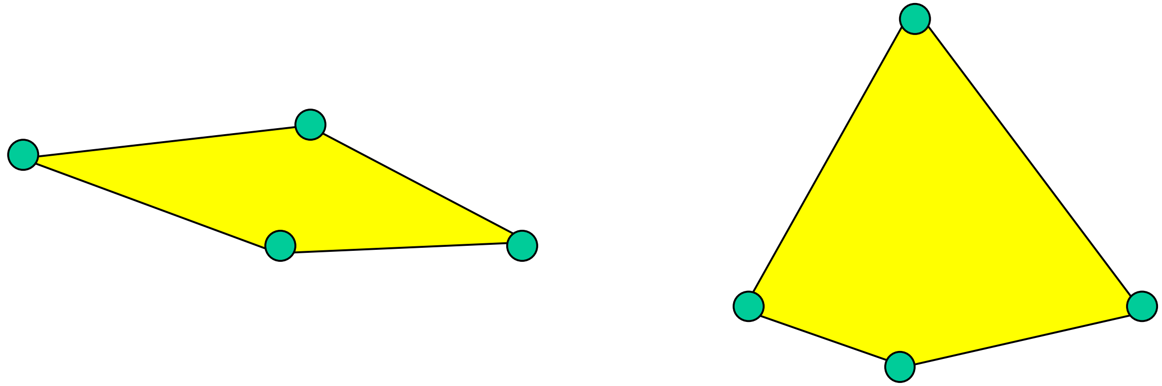
- as the end node of a 3D beam element and
- as the node of a shell element and
- as the node of a truss element.



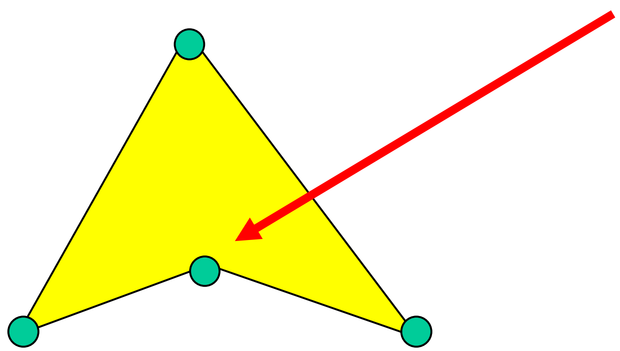
GEOMETRIES OK

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

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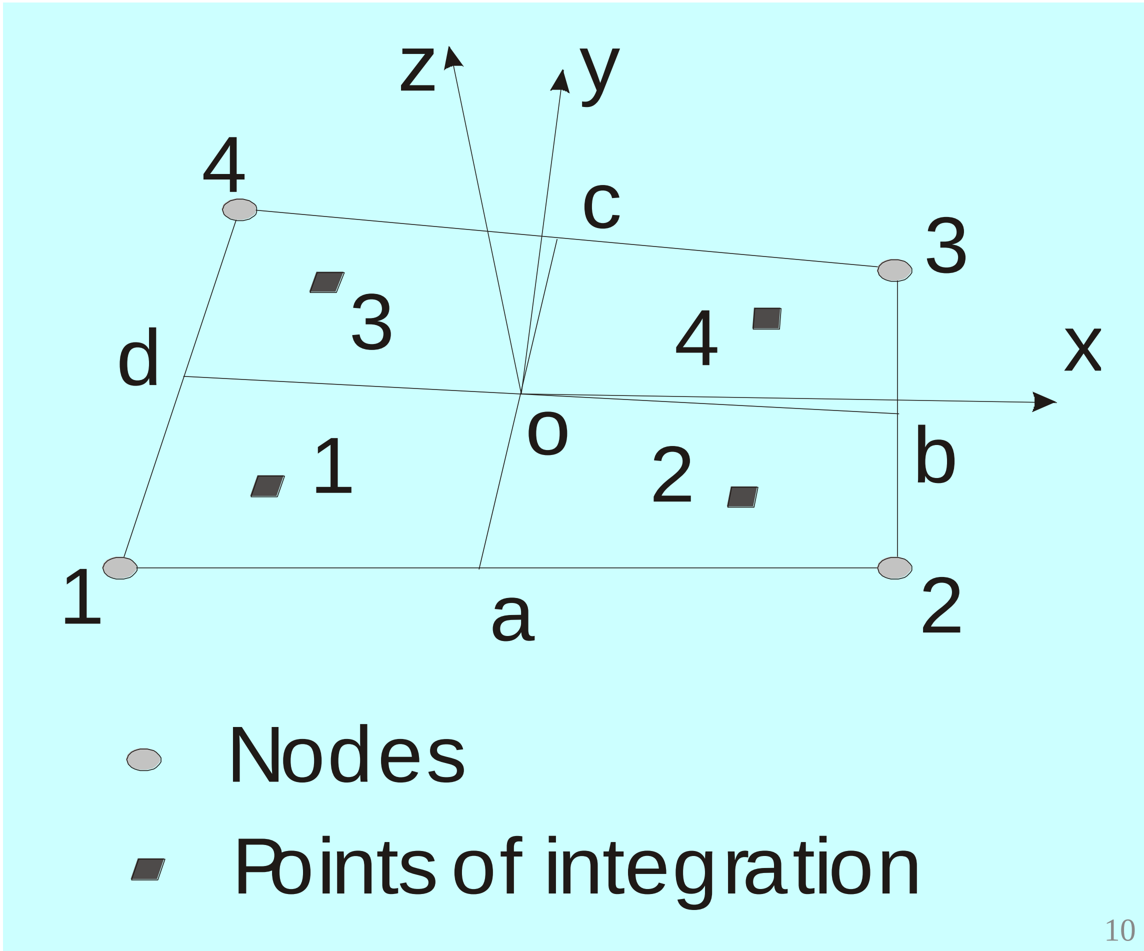
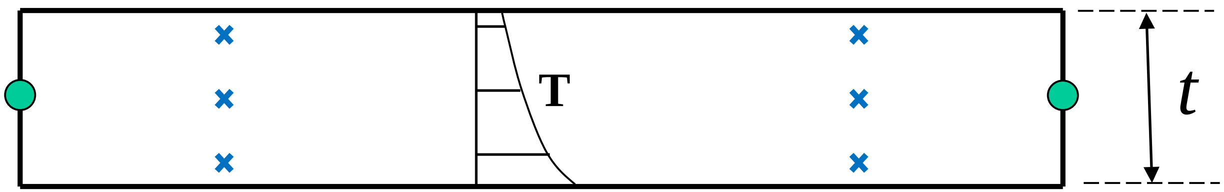
The shell finite element

- ✓ 4 nodes
- ✓ Uniform thickness
- ✓ 4 points of integration on the thickness



# The Shell Finite Element

NG integration points on the thickness *t*
NG is chosen by the user, from 2 to 10.
Here, NG = 3

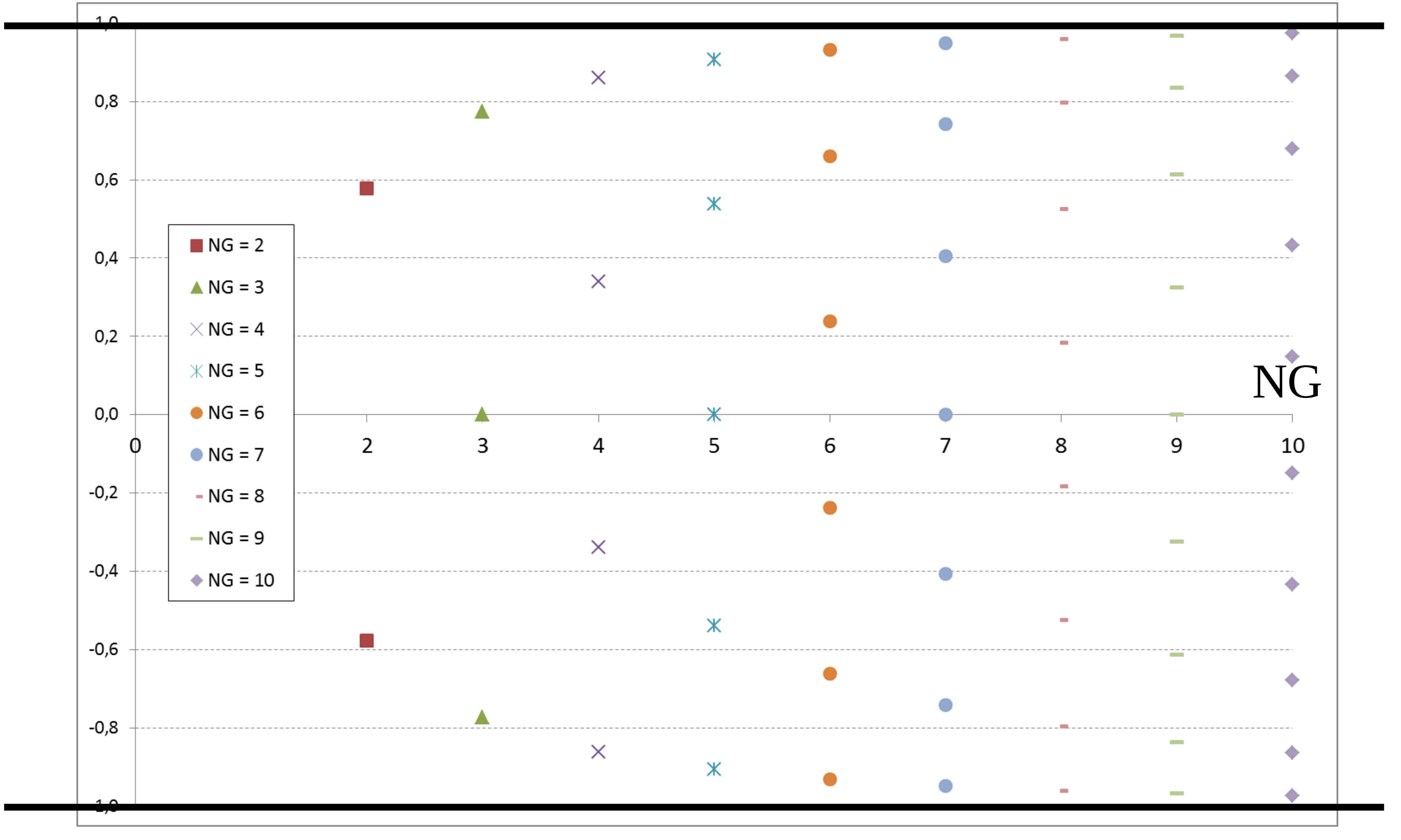



The temperature T varies on the thickness of the element.

T does not vary in the plane of the element,
except for localized fires (HASEMI, LOCAFI or CFD-SAFIR interaction).

Membrane behavior (steel plates): NG = 2

Flexural behavior (concrete slabs): NG ↑↑ (max. = 10)




Position of the integration points on the thickness

1) Degrees of freedom and local axes
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Materials:

- Matrix of the element

  STEELEC32D (plane stress, very stable)

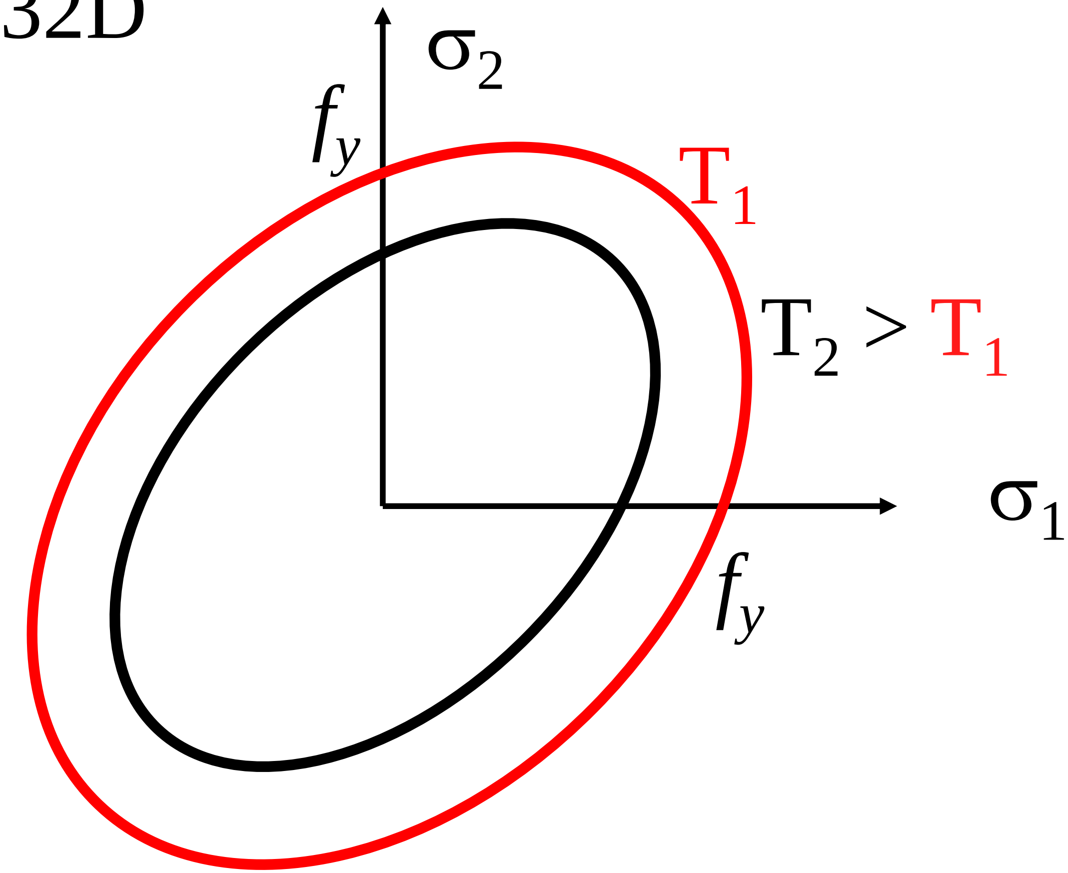
  SILCOETC2D & CALCOETC2D (plane stress, stable)

  $\nu$ $f_c$ $f_t$ 0.0025 0.25 0.19 0.3 4000.

- Eventual rebars

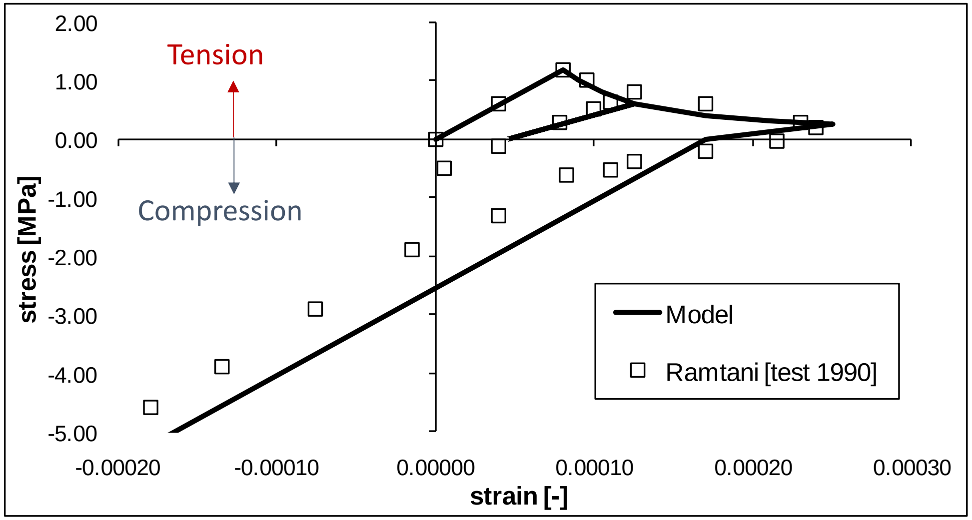
  STEELEC2EN (uniaxial)

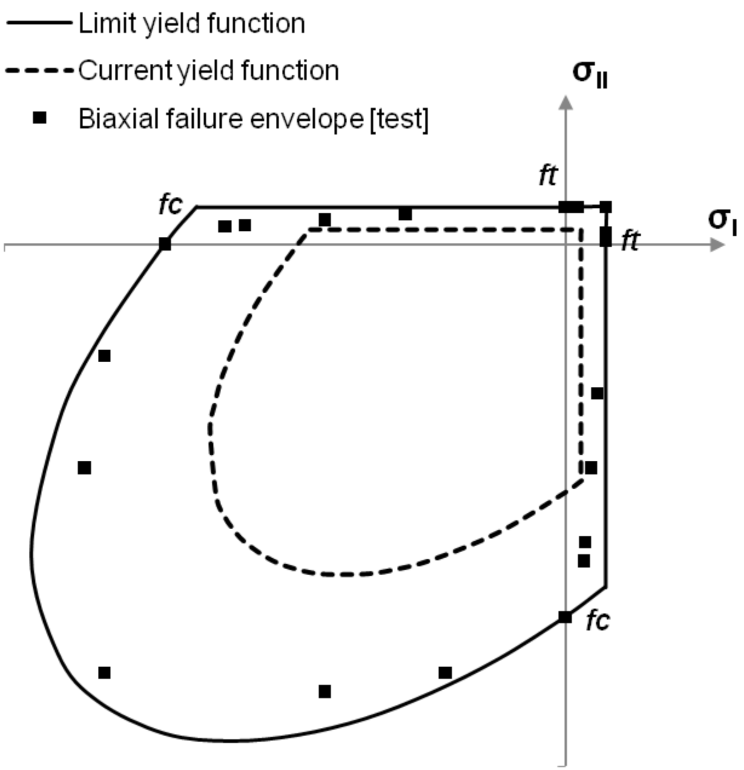
# STEELEC32D




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

# SILCOETC2D & CALCOETC2D




- Plastic-Damage model
- Multi-surface yield criterion: Drucker Prager - Rankine
- Damage tensor with crack closure

1) Degrees of freedom and local axes
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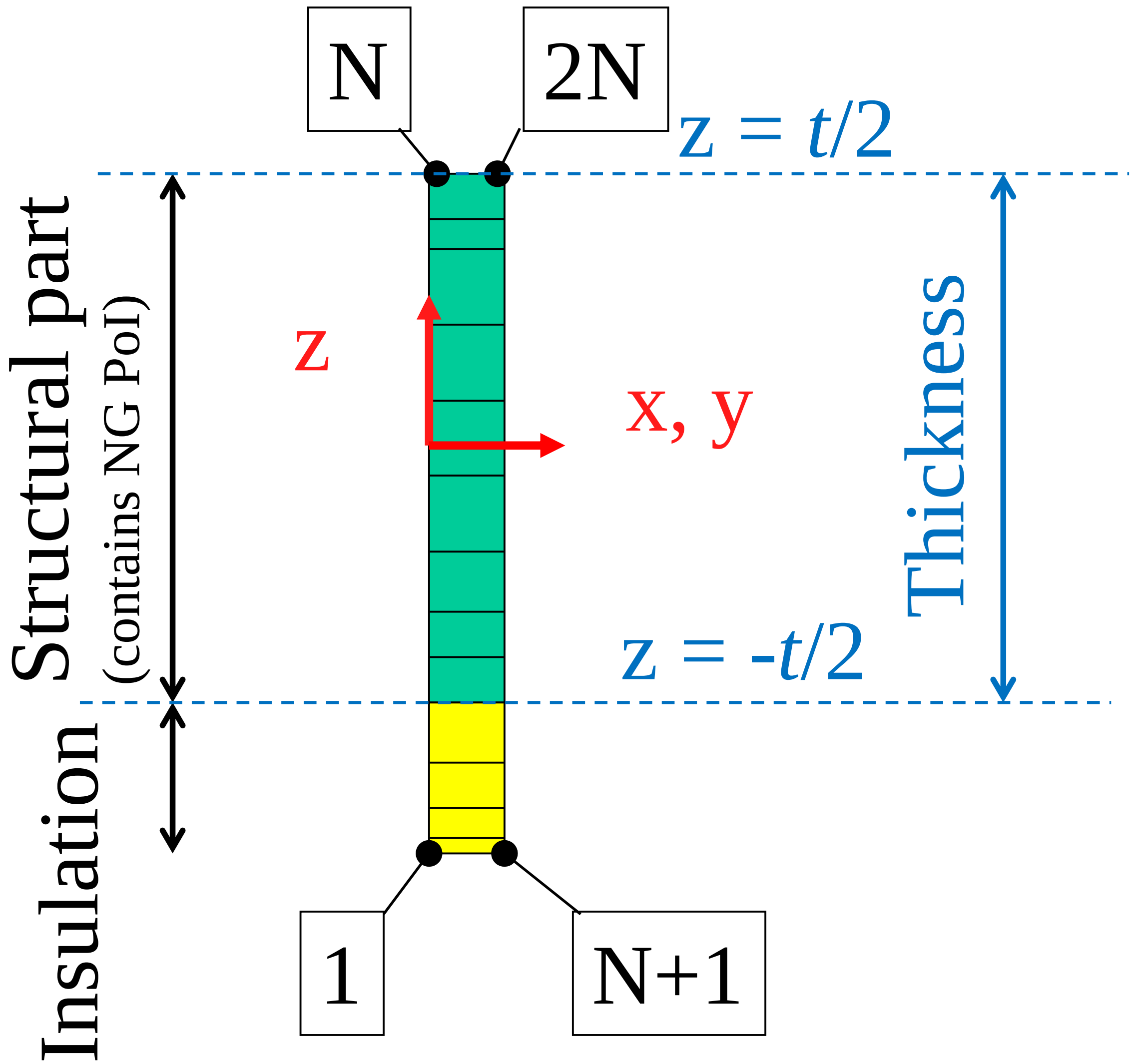
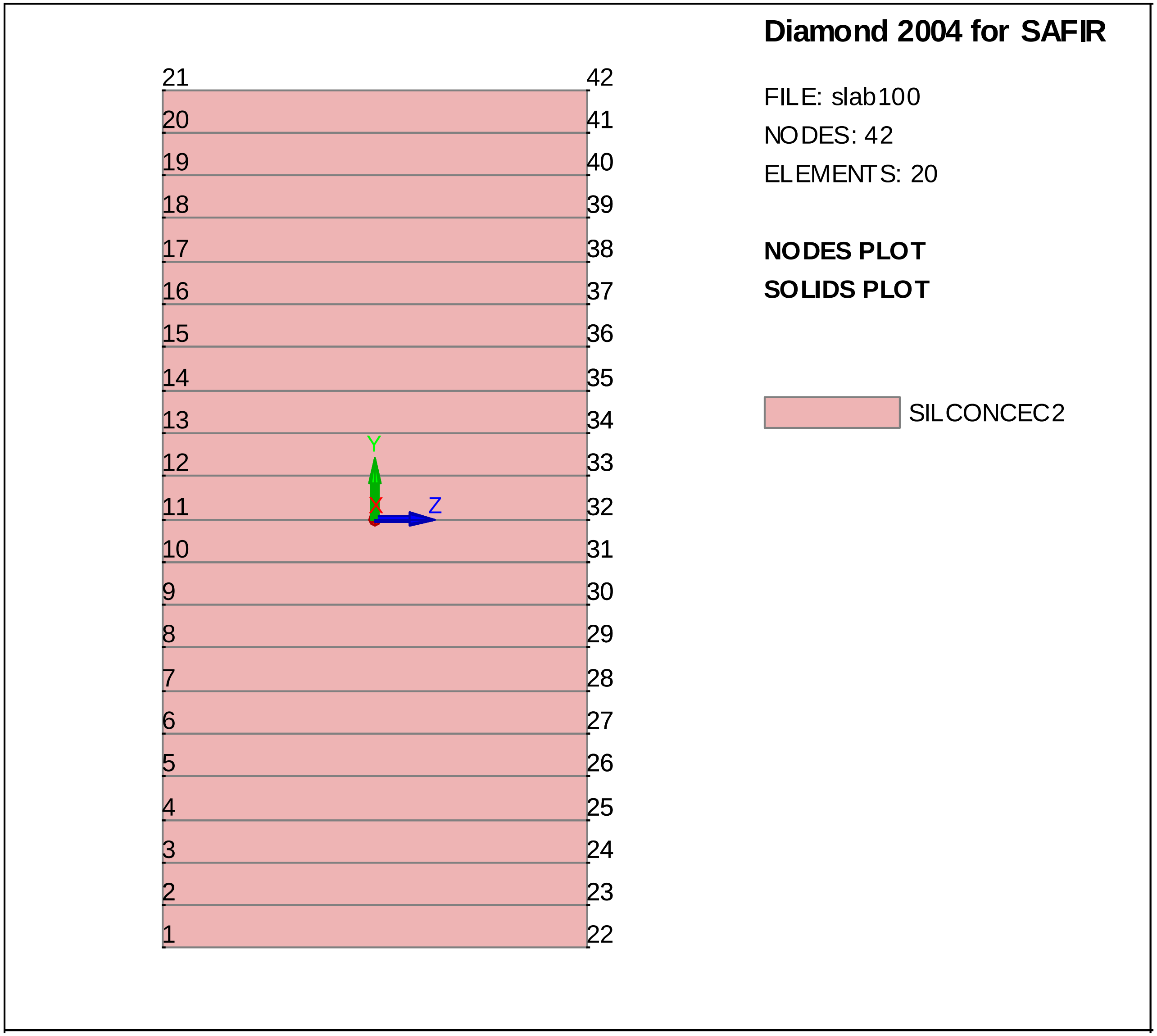
# Temperature distribution: 1D (2D)

Command MAKE.TSH will write the temperatures in a file « filename.tsh ».






Example of a mesh for a shell element without thermal protection.
Note: the width of the model is not relevant.

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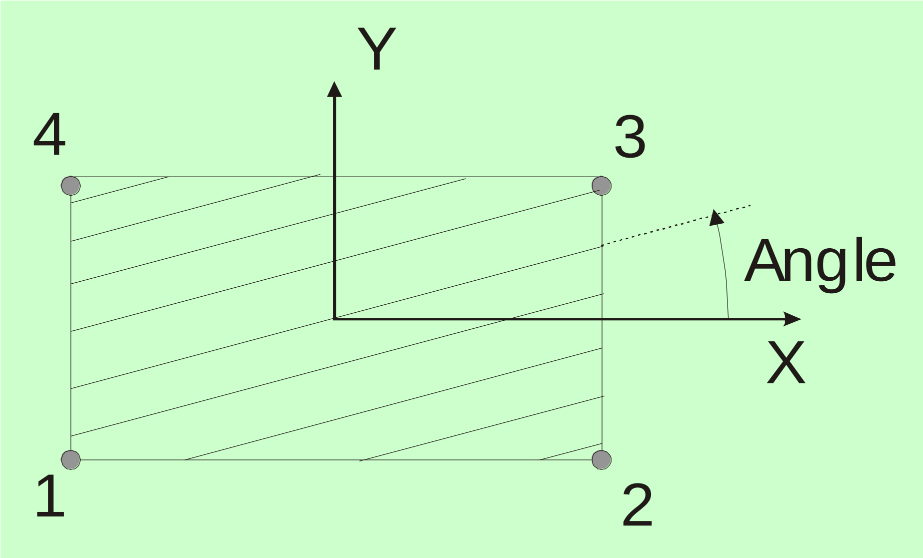
Different layers of rebars can be present in the element. The rebar layers are horizontal (i.e. parallel to the local **x, y** plane). The rebars are uniformly distributed (layered rebars). Each layer is defined by:

- 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.



In fact, for each bar layer, there are two methods
to give the orientation of the bars in the plane of the element.

**<u>Method 1</u>: with respect to the local system of coordinates of each element.**

**1 card.**

- "ANGLE"
- **angle** Angle in degrees between the local x axis and the layer of rebars, see Figure in which the bars of the layer are represented by doted lines. This angle cannot be smaller than -180°.

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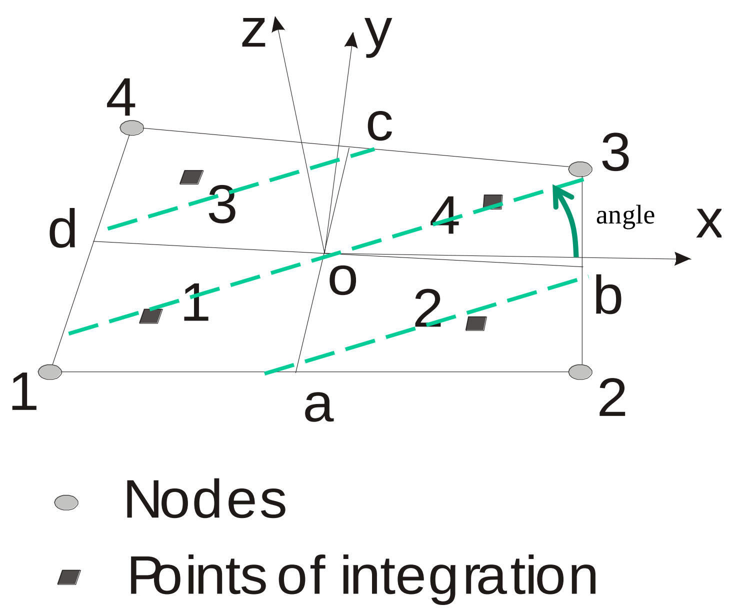
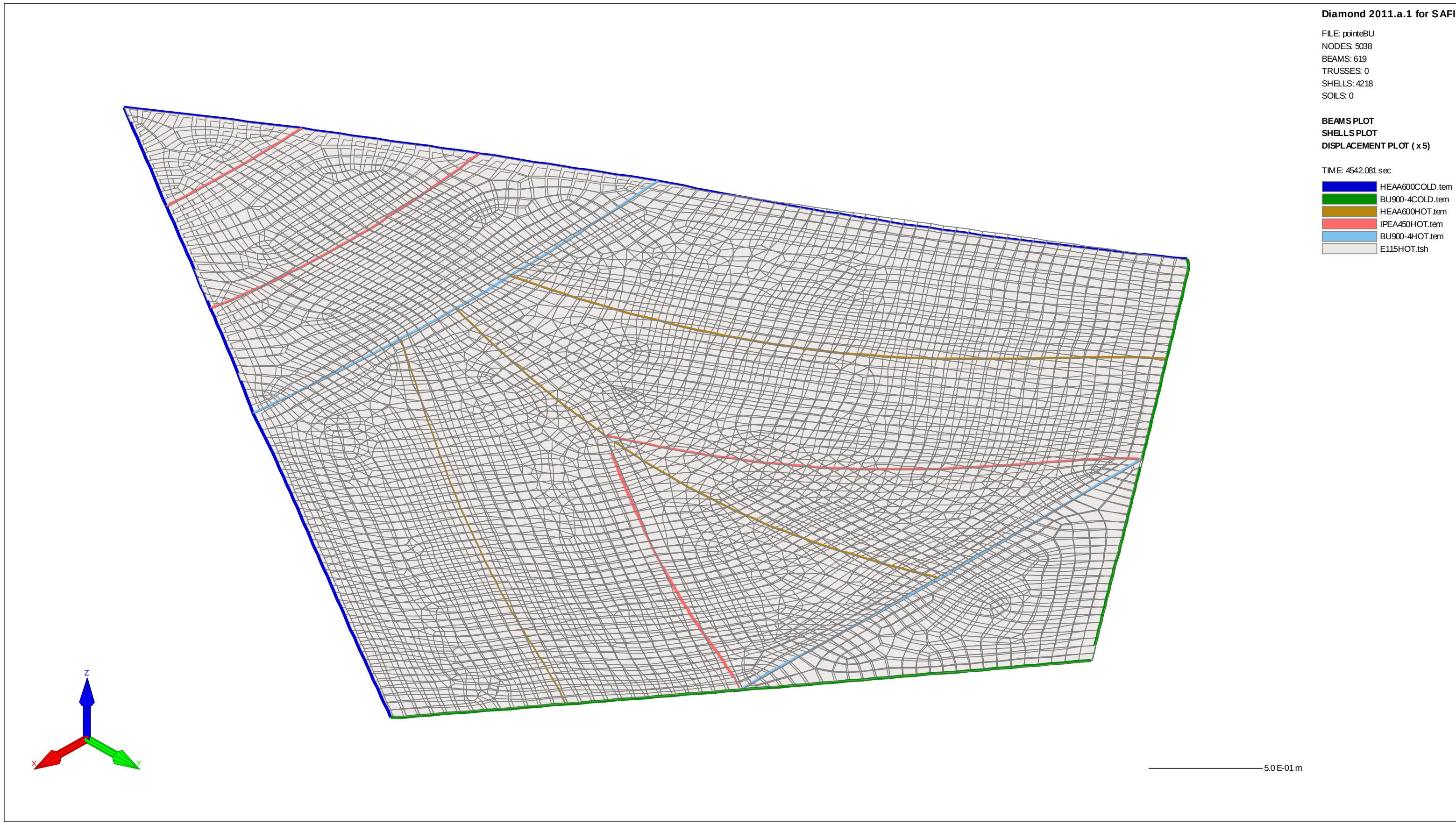


This method is not appropriate in unstructured meshes because the local system of coordinates is different in all elements.




Japan Tobacco Intl, Geneva
Model: Ingeni (courtesy Lorenzo Lelli)

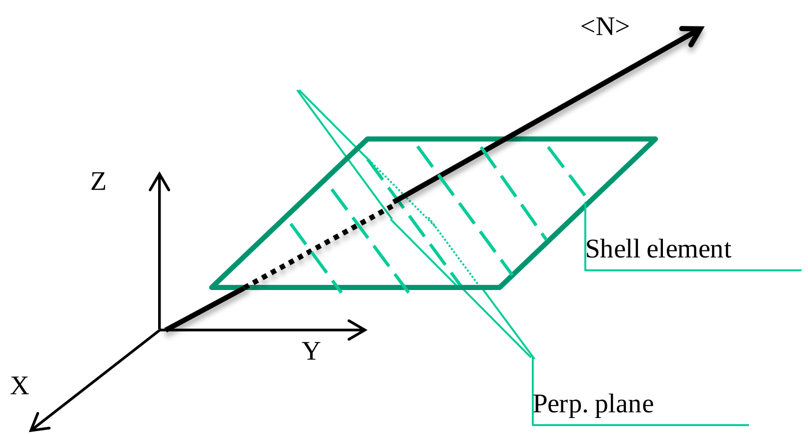
**<u>Method 2</u>: with respect to the global system of coordinates of the structure.**
**1 card.**
- "NORMAL"
- $N_1$
- $N_2$
- $N_3$

< $N_1$ ; $N_2$ ; $N_3$ > is a vector in the global system of coordinates of the structure. The norm of the vector does not have to be 1.

This vector is used to define the position of the bar layers in the shell elements with respect to the global system of coordinates according to the following technique, see Figure.

The bars have the orientation of the line which is the intersection between the shell element and a plane that is perpendicular to the normal.

If the norm of the vector is 0, then the orientation of this bar layer is perpendicular, in each element, to the previous bar layer (not possible for bar layer 1).



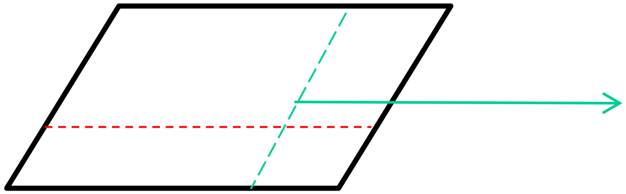


**Figure 3: bars in a plate.
Use method 2 if the
mesh is unstructured**

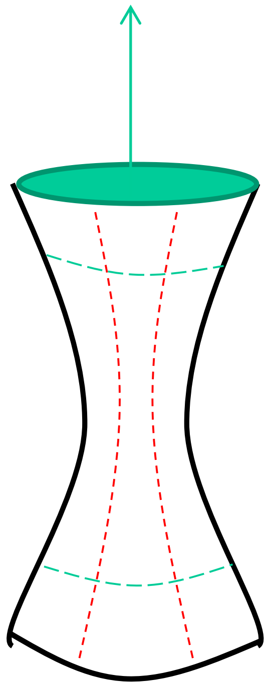


**Figure 4: bars in a hyperbolic paraboloid**

**Method 2**

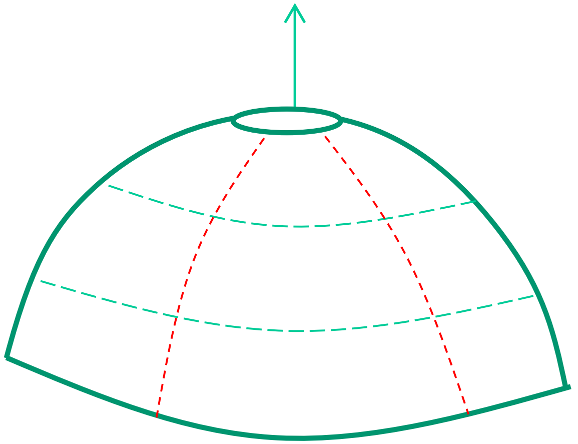


**Figure 5: bars in a dome**

**Method 2**

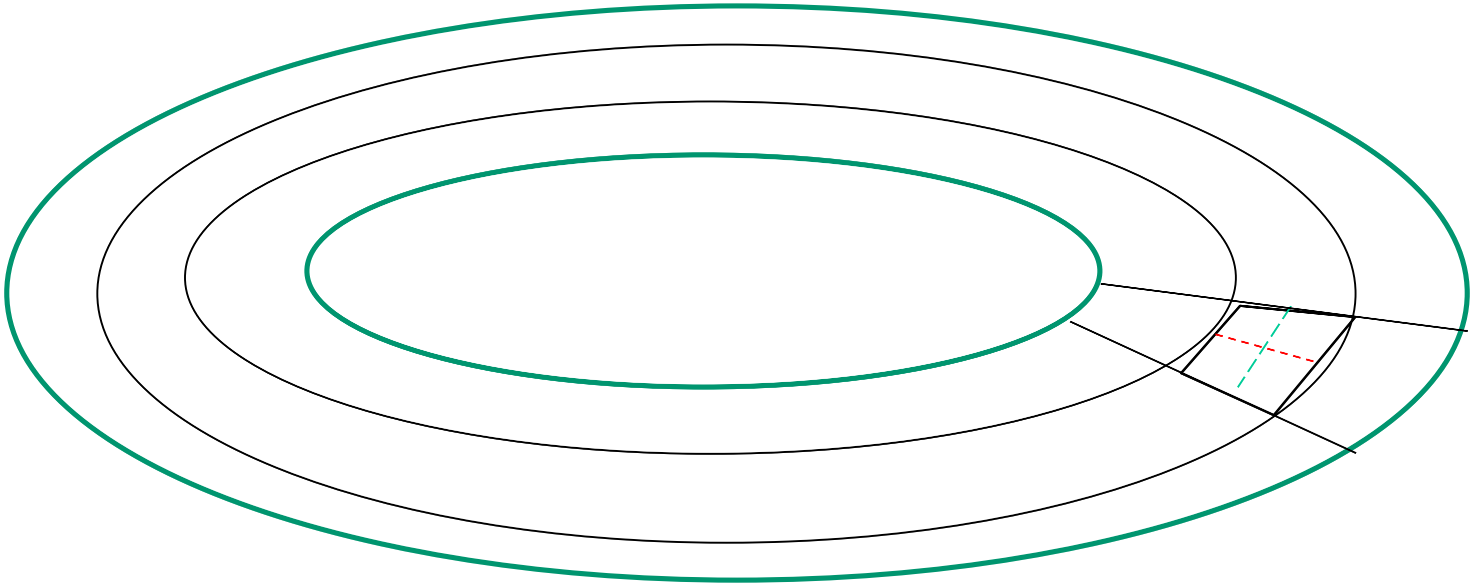


**Figure 6: bars in a circular ring**

**Method 1**

ACKNOWLEDGEMENT
DEVELOPMENT OF THE SECOND METHOD HAS BEEN SUPPORTED BY « HOLMES FIRE »

The information about the re-bars of the shells (section, vertical position, orientation, number of the material) have to be entered by the user at the beginning of the file xxx.TSH that gives the temperatures for the relevant section type.

```
10 cm thick slab                         ! Comment lines
2 layers of re-bars
                                         ! 1 blank line
 THICKNESS     0.10     meters           ! General information
  MATERIAL     1
    REBARS     2        layers


  MATERIAL     2                         ! Bar layer 1
   SECTION     257e-6   m²/m
     LEVEL    -0.030    m
     ANGLE     0.       degree


  MATERIAL     2                         ! Bar layer 2
   SECTION     257e-6   m²/m
     LEVEL    -0.025    m
     ANGLE     90.      degrees


         HOT
```

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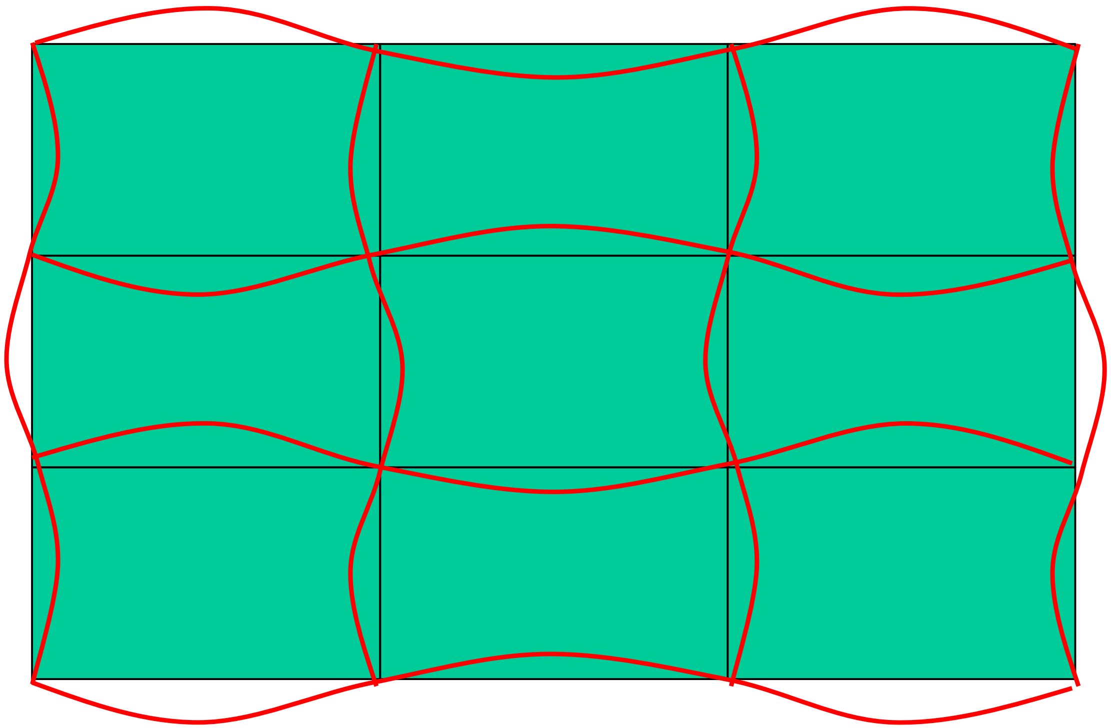
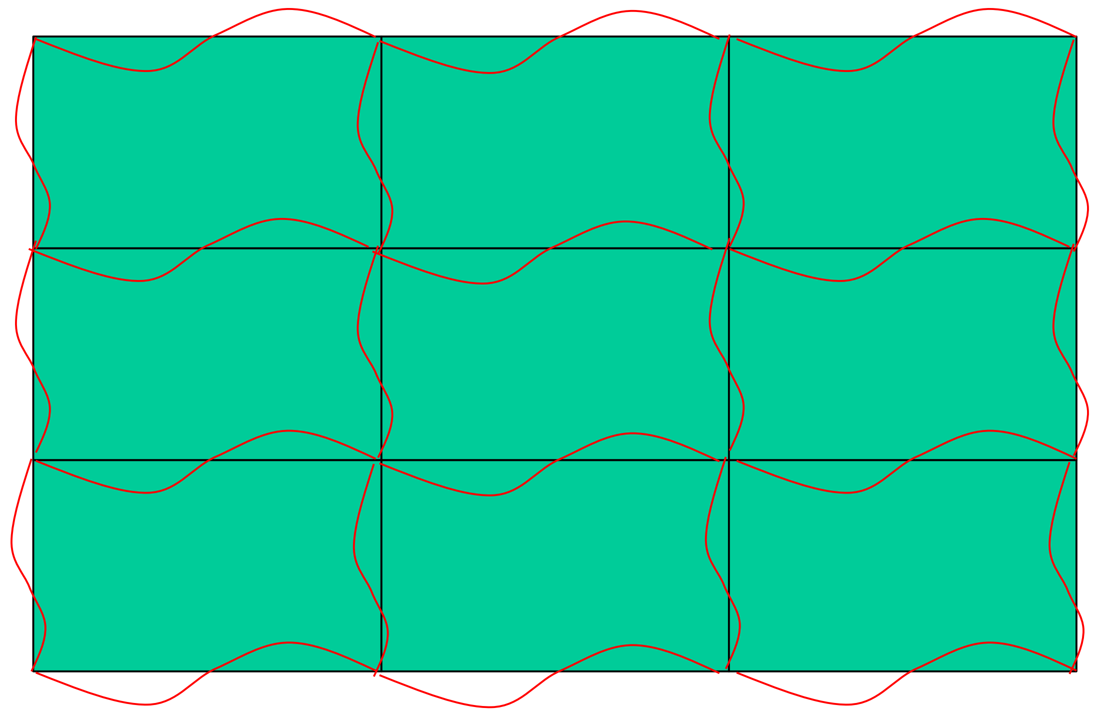
# Possibility of spurious mode 1 in perfectly regular meshes



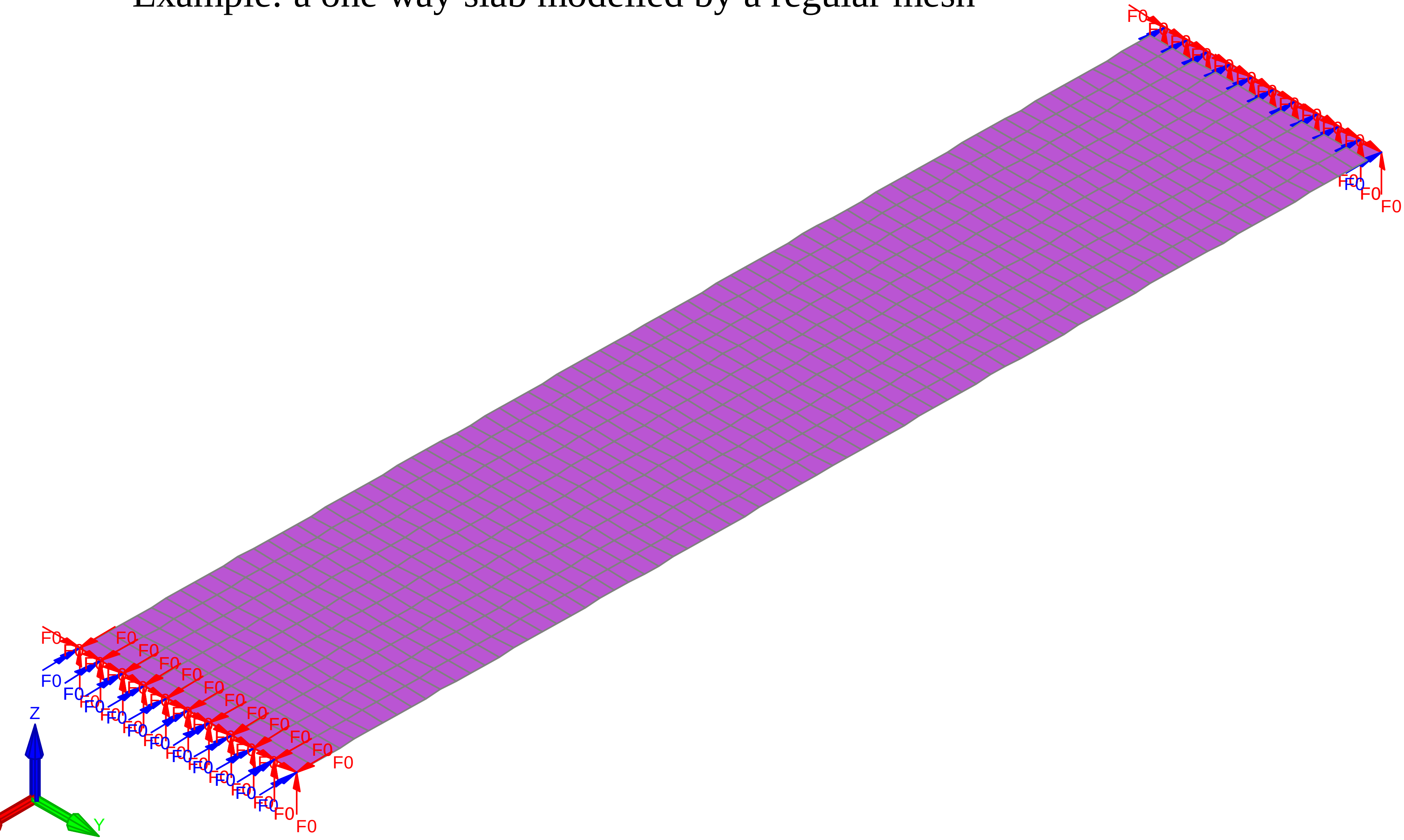
Deformation with no energy activated in the four PoI of each element

# Possibility of spurious mode 2 in perfectly regular meshes

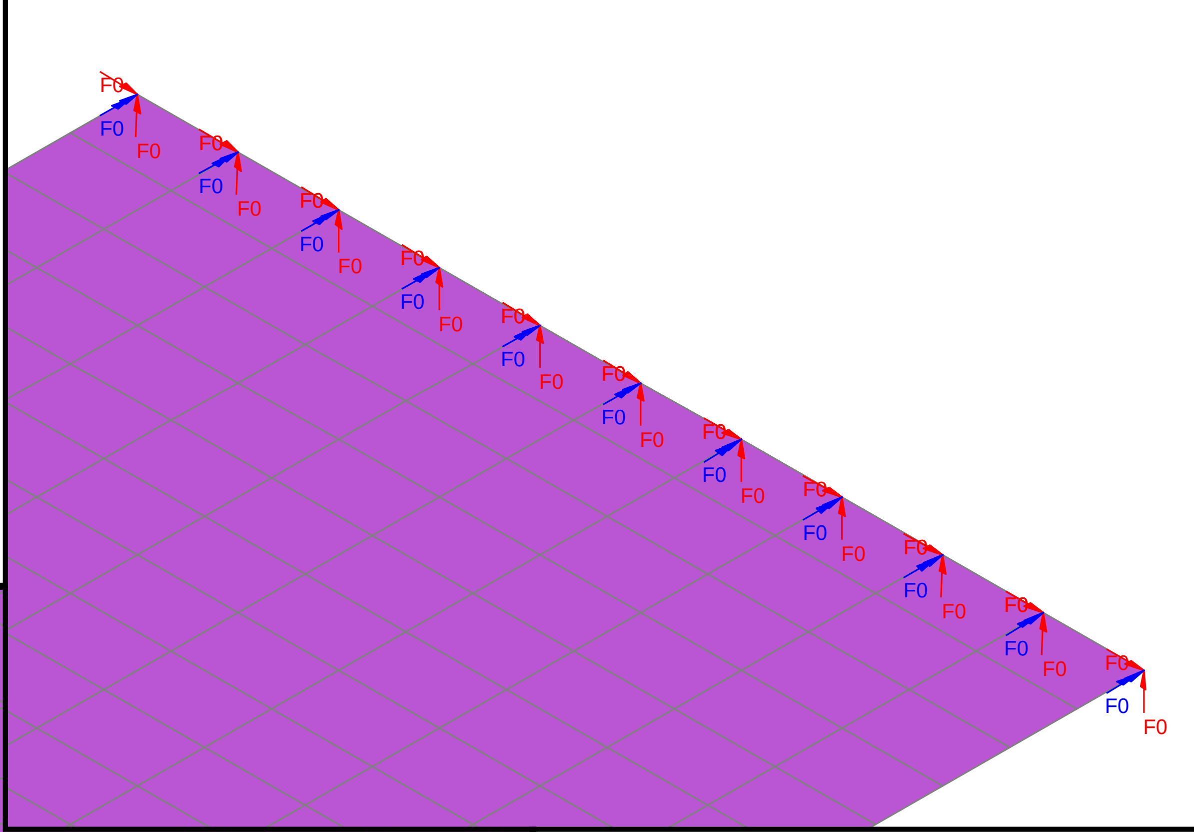


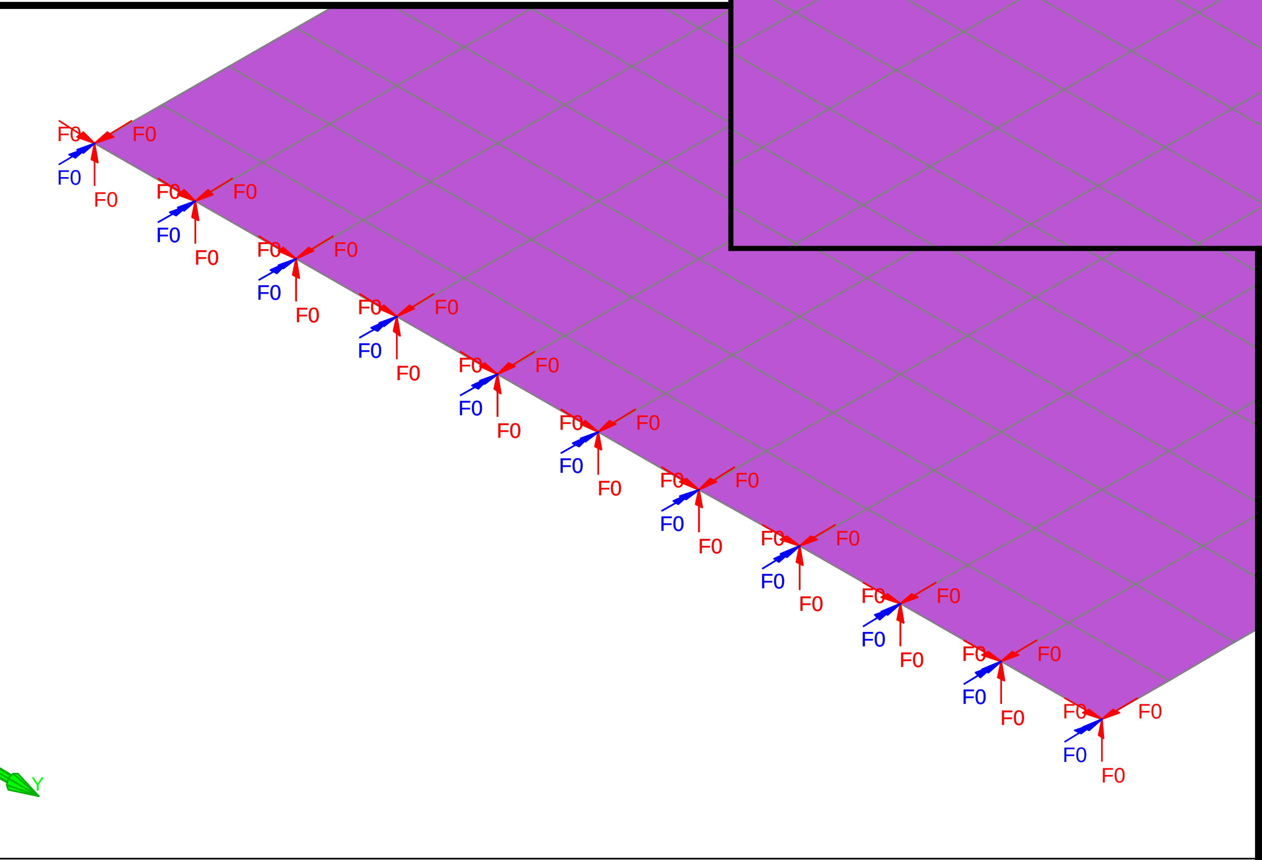
Deformation with no energy activated in the four PoI of each element

Example: a one way slab modelled by a regular mesh

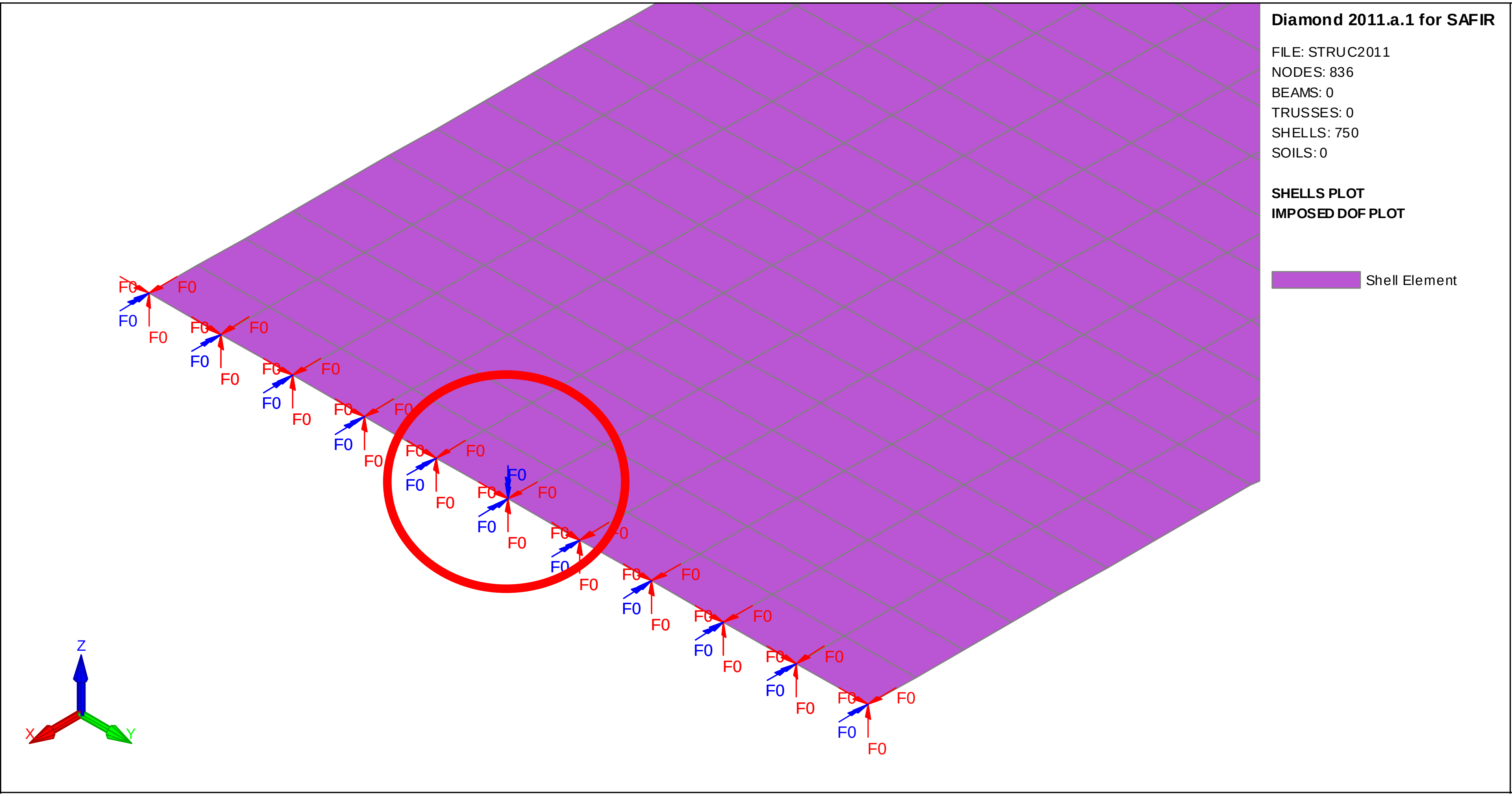


The model will not run with this regular mesh and these boundary condition



# One possible solution



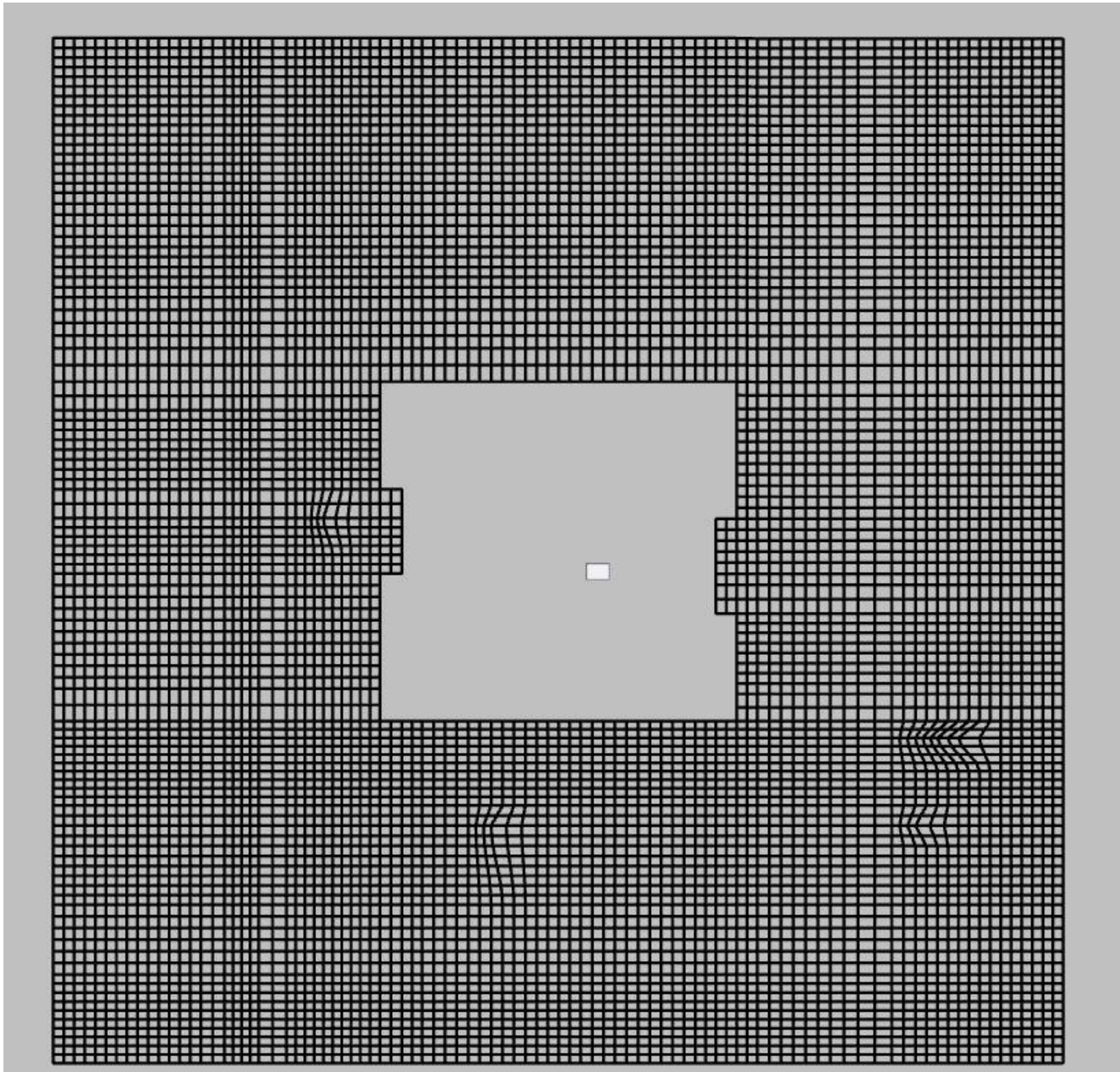
# In this concrete slab, the mesh is « nearly » regular.

The model will run even if no rotation around z is fixed.

Yet, the rotations around z of all nodes increase as 0, +0.1, -0.2, +0.4, -0.8, until several radians !

This indicates a very low stiffness against spurious mode 2

Fixing the rotation around z at one node keeps all rotations more realistic.



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# What can be printed about the material behavior?

`PRNSIGMASH      1`

Strains and Stresses
- in the material of the shell [N/mm²]
- in the material of the eventual re-bars

`PRNSIGMASH`

is equivalent to

`PRNSIGMASH` in all shell elements

SHELL: 1, SURF: 1, THICK: 1 ex: -0.000002 ey: 0.000011 exy: 0.000000
SHELL: 1, SURF: 1, THICK: 1 Sx: 0.30 Sy: 2.40 Sxy: -0.04
SHELL: 1, SURF: 1, THICK: 2 ex: -0.000002 ey: 0.000011 exy: -0.000001
SHELL: 1, SURF: 1, THICK: 2 Sx: 0.28 Sy: 2.29 Sxy: -0.04
SHELL: 1, SURF: 1, THICK: 3 ex: -0.000002 ey: 0.000010 exy: -0.000001
SHELL: 1, SURF: 1, THICK: 3 Sx: 0.26 Sy: 2.11 Sxy: -0.05
SHELL: 1, SURF: 1, THICK: 4 ex: -0.000001 ey: 0.000009 exy: -0.000001
SHELL: 1, SURF: 1, THICK: 4 Sx: 0.22 Sy: 1.88 Sxy: -0.06
SHELL: 1, SURF: 1, THICK: 5 ex: -0.000001 ey: 0.000008 exy: -0.000001
SHELL: 1, SURF: 1, THICK: 5 Sx: 0.18 Sy: 1.64 Sxy: -0.07
SHELL: 1, SURF: 1, THICK: 6 ex: -0.000001 ey: 0.000007 exy: -0.000001
SHELL: 1, SURF: 1, THICK: 6 Sx: 0.14 Sy: 1.41 Sxy: -0.08

# What can be printed about the material behavior?

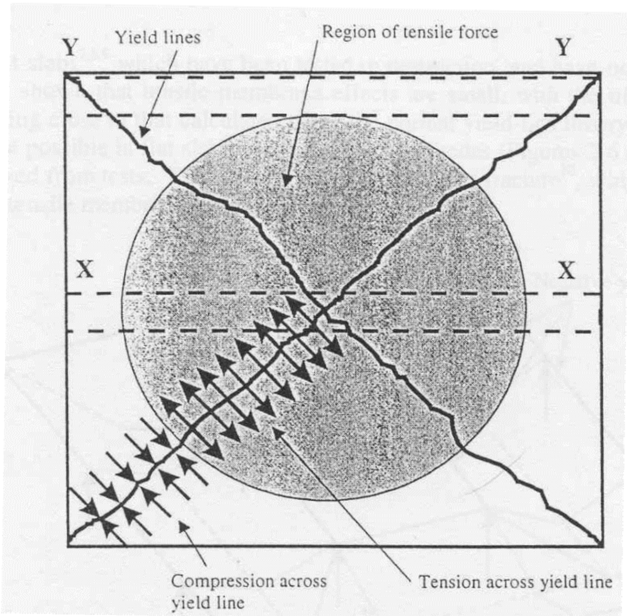
PRNNXSHELL

$N_x$, $N_y$, $N_{xy}$ [in kN/m] + $N_1$, $N_2$ and $\alpha$ (with respect to the local axis *x*)
in the 4 integr. pts in the plane, for all shell elements

$$N_x = \int_{-t/2}^{t/2} \sigma_{xx}\, dt + \sum_{bars} \sigma_{x,i} A_i$$

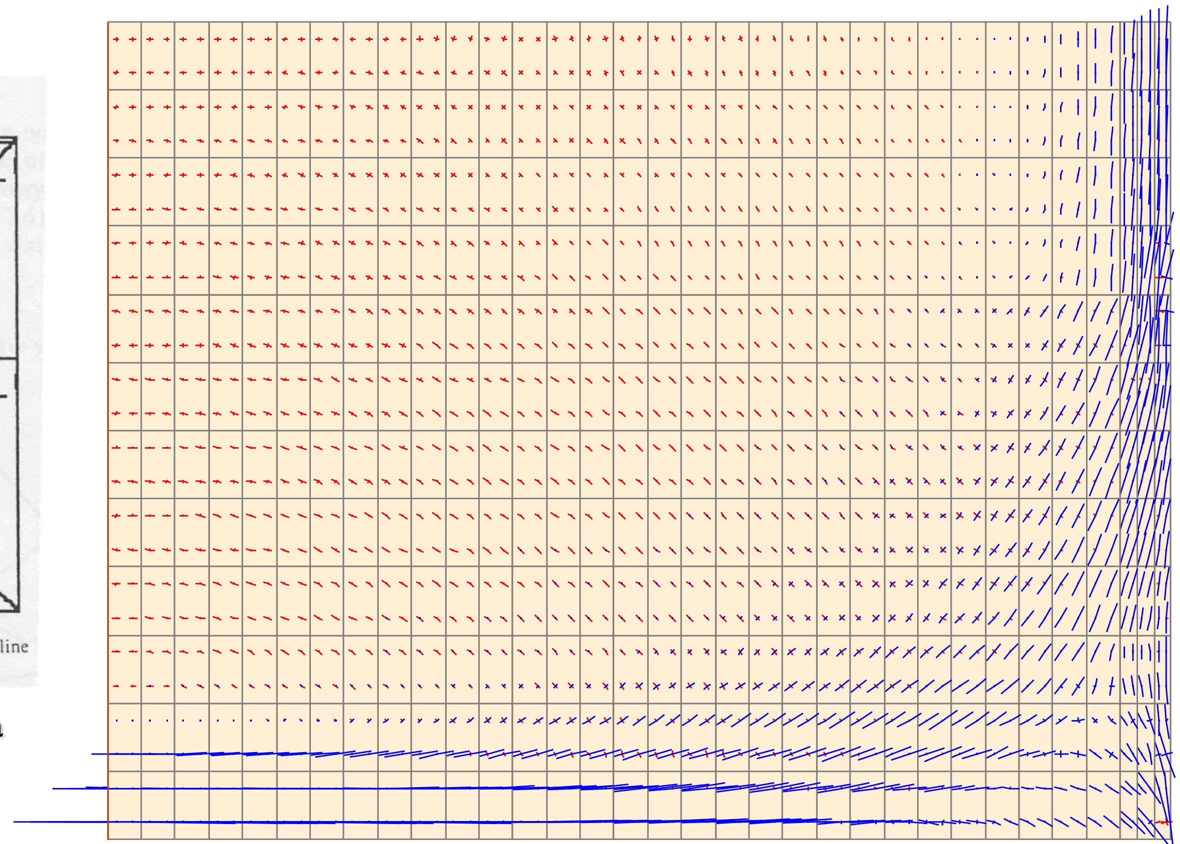
# Membrane action in a concrete slab

**Membrane stresses**



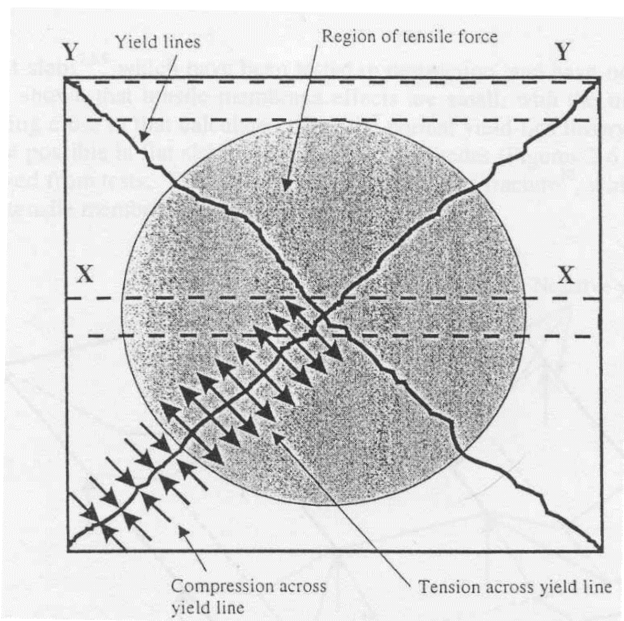

**In-plane membranes forces in a slab with no in-plane restraint**

**C. Bailey (2000)**



# Membrane action in a concrete slab

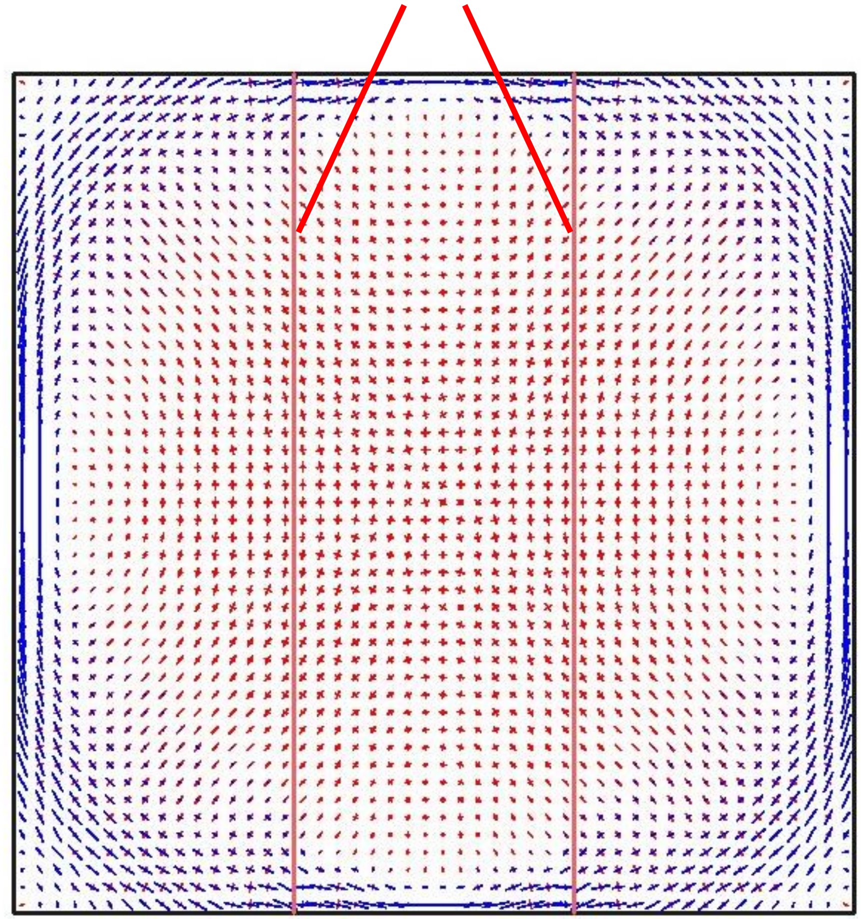
## ***Membrane stresses***




**In-plane membranes forces in a slab with no in-plane restraint**

**C. Bailey (2000)**

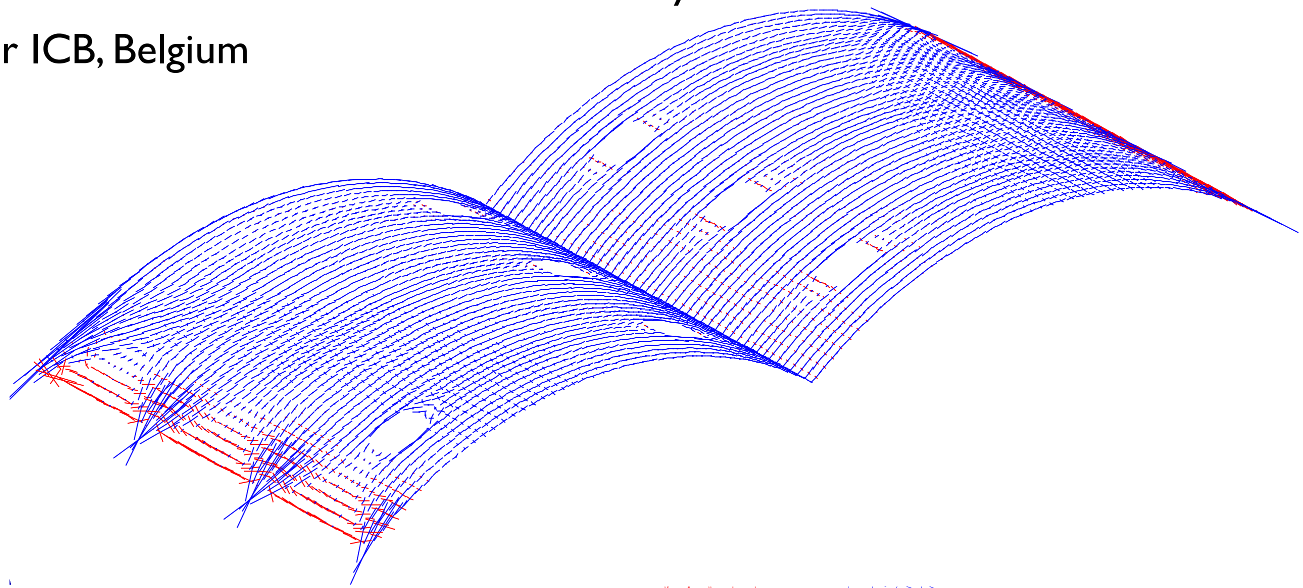
**Unprotected beams**



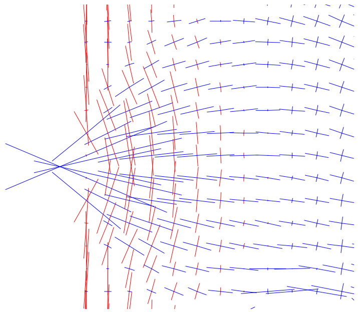
# Membrane forces in a shell

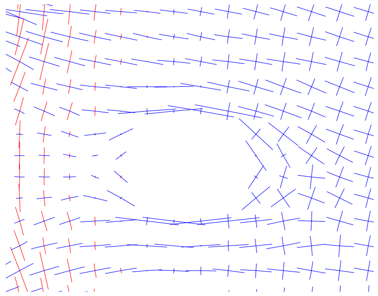
3D mechanical calculation – Structural fire analysis of an arched reinforced concrete roof

Study for ICB, Belgium



Plot of the membrane forces in the concrete shells





| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHELL: | 1 | Surf: 1 | Nx: | 2.12 | Ny: | 18.83 | Nxy: | -0.72 | N1: | 18.86 | N2: | 2.09 | angle: | -87.5° |
| SHELL: | 1 | Surf: 2 | Nx: | 2.32 | Ny: | 19.54 | Nxy: | -0.92 | N1: | 19.59 | N2: | 2.27 | angle: | -86.9° |
| SHELL: | 1 | Surf: 3 | Nx: | -0.81 | Ny: | 18.01 | Nxy: | -0.80 | N1: | 18.04 | N2: | -0.85 | angle: | -87.6° |
| SHELL: | 1 | Surf: 4 | Nx: | -0.62 | Ny: | 18.71 | Nxy: | -1.00 | N1: | 18.77 | N2: | -0.67 | angle: | -87.0° |
| SHELL: | 2 | Surf: 1 | Nx: | 2.31 | Ny: | 20.33 | Nxy: | -1.75 | N1: | 20.49 | N2: | 2.15 | angle: | -84.5° |
| SHELL: | 2 | Surf: 2 | Nx: | 2.78 | Ny: | 21.97 | Nxy: | -2.97 | N1: | 22.42 | N2: | 2.33 | angle: | -81.4° |
| SHELL: | 2 | Surf: 3 | Nx: | -0.94 | Ny: | 19.42 | Nxy: | -1.86 | N1: | 19.58 | N2: | -1.11 | angle: | -84.8° |
| SHELL: | 2 | Surf: 4 | Nx: | -0.48 | Ny: | 21.06 | Nxy: | -3.08 | N1: | 21.49 | N2: | -0.91 | angle: | -82.0° |

# What can be printed about the material behavior?

`PRNMXSHELL`

$M_x$, $M_y$, $M_{xy}$ [in kNm/m] + $M_1$, $M_2$ and $\alpha$
in the 4 integr. pts in the plane, for all shell elements

$$M_x = \int_{-t/2}^{t/2} \sigma_{xx}\, z\, dz + \sum_{nbars} \sigma_{x,i}\, z_i\, A_i$$

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHELL: | 1 | Surf: 1 | Mx: | 0.00 | My: | -0.01 | Mxy: | 0.00 | M1: | 0.00 | M2: | -0.01 | angle: | -3.2° |
| SHELL: | 1 | Surf: 2 | Mx: | 0.00 | My: | -0.01 | Mxy: | 0.00 | M1: | 0.00 | M2: | -0.01 | angle: | -3.7° |
| SHELL: | 1 | Surf: 3 | Mx: | 0.00 | My: | 0.00 | Mxy: | 0.00 | M1: | 0.00 | M2: | 0.00 | angle: | -9.5° |
| SHELL: | 1 | Surf: 4 | Mx: | 0.00 | My: | 0.00 | Mxy: | 0.00 | M1: | 0.00 | M2: | 0.00 | angle: | -9.3° |
| SHELL: | 2 | Surf: 1 | Mx: | 0.00 | My: | -0.01 | Mxy: | 0.00 | M1: | 0.00 | M2: | -0.01 | angle: | -3.7° |
| SHELL: | 2 | Surf: 2 | Mx: | 0.00 | My: | -0.01 | Mxy: | 0.00 | M1: | 0.00 | M2: | -0.01 | angle: | -3.7° |
| SHELL: | 2 | Surf: 3 | Mx: | 0.00 | My: | 0.00 | Mxy: | 0.00 | M1: | 0.00 | M2: | 0.00 | angle: | -8.7° |
| SHELL: | 2 | Surf: 4 | Mx: | 0.00 | My: | 0.00 | Mxy: | 0.00 | M1: | 0.00 | M2: | 0.00 | angle: | -7.3° |
| SHELL: | 3 | Surf: 1 | Mx: | -0.01 | My: | -0.01 | Mxy: | 0.00 | M1: | -0.01 | M2: | -0.01 | angle: | -0.8° |
| SHELL: | 3 | Surf: 2 | Mx: | -0.01 | My: | -0.01 | Mxy: | 0.00 | M1: | -0.01 | M2: | -0.01 | angle: | 0.0° |
| SHELL: | 3 | Surf: 3 | Mx: | 0.00 | My: | 0.00 | Mxy: | 0.00 | M1: | 0.00 | M2: | 0.00 | angle: | -10.3° |
| SHELL: | 3 | Surf: 4 | Mx: | 0.00 | My: | 0.00 | Mxy: | 0.00 | M1: | 0.00 | M2: | 0.00 | angle: | -6.2° |

# What can be printed about the material behavior?

PRNEASHELL

$$\frac{E\,t}{1-\nu^2}$$

$EA_x$, $EA_y$
in the 4 integr. pts in the plane, for all shell elements

PRNEISHELL

$$\frac{E\,t^3}{12\left(1-\nu^2\right)}$$

$EI_x$, $EI_y$
in the 4 integr. pts in the plane, for all shell elements

**STIFFNESS IN THE SHELL ELEMENTS.**

**------------------------------**

| ELEM | NG | EAx | EAy | EIx | EIy |
|---|---|---|---|---|---|
| - | - | kN/m | kN/m | $kNm^2/m$ | $kNm^2/m$ |
| 1 | 1 | 2438151. | 2438151. | 23. | 23. |
| 1 | 2 | 2438151. | 2438151. | 23. | 23. |
| 1 | 3 | 2438151. | 2438151. | 23. | 23. |
| 1 | 4 | 2438151. | 2438151. | 23. | 23. |
| 2 | 1 | 2438151. | 2438151. | 23. | 23. |
| 2 | 2 | 2438151. | 2438151. | 23. | 23. |
| 2 | 3 | 2438151. | 2438151. | 23. | 23. |
| 2 | 4 | 2438151. | 2438151. | 23. | 23. |

1) Degrees of freedom and local axes

2) Numerical integration

3) Material properties

4) Temperature distribution

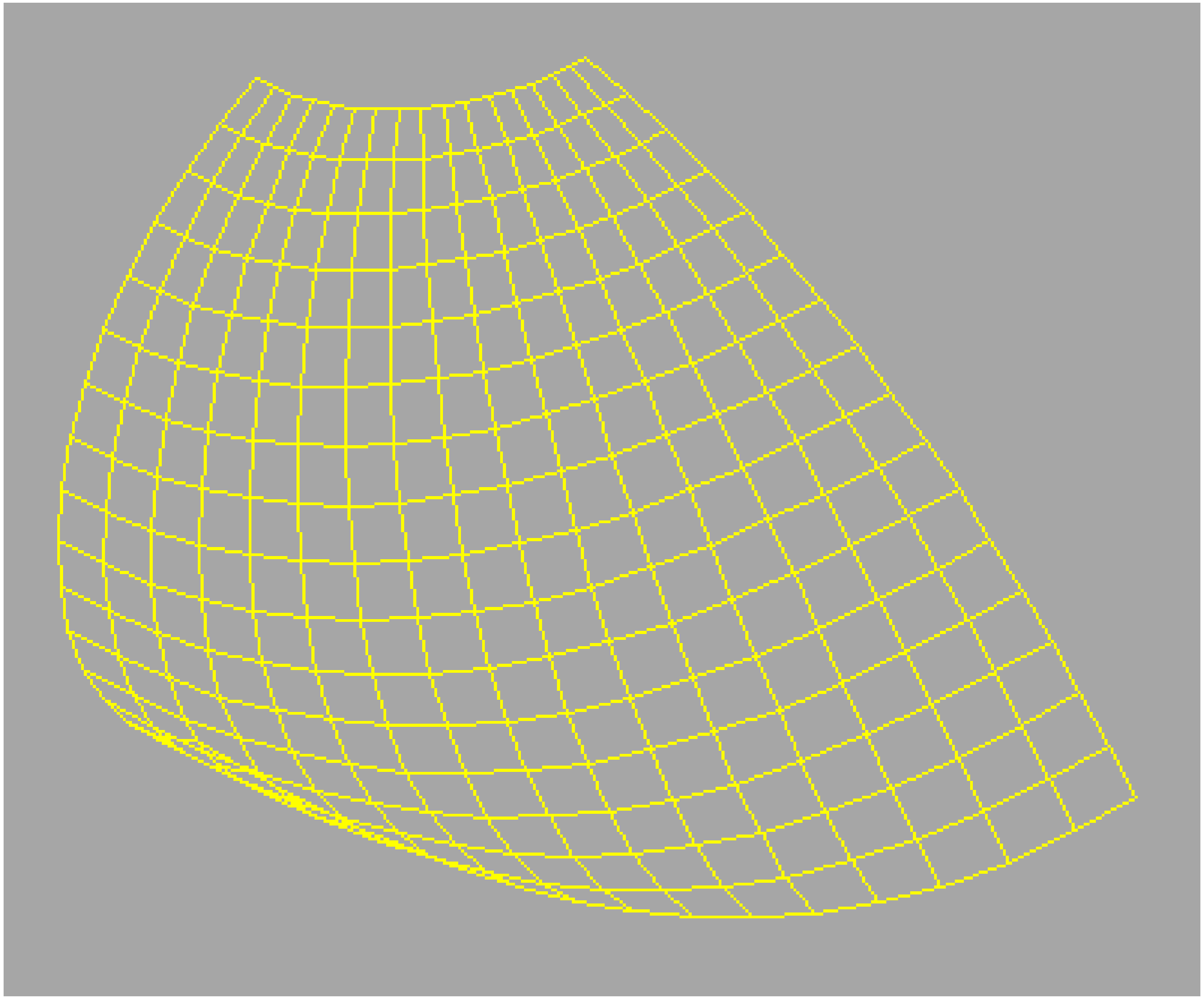
5) Orientation of the rebars

6) Spurious modes

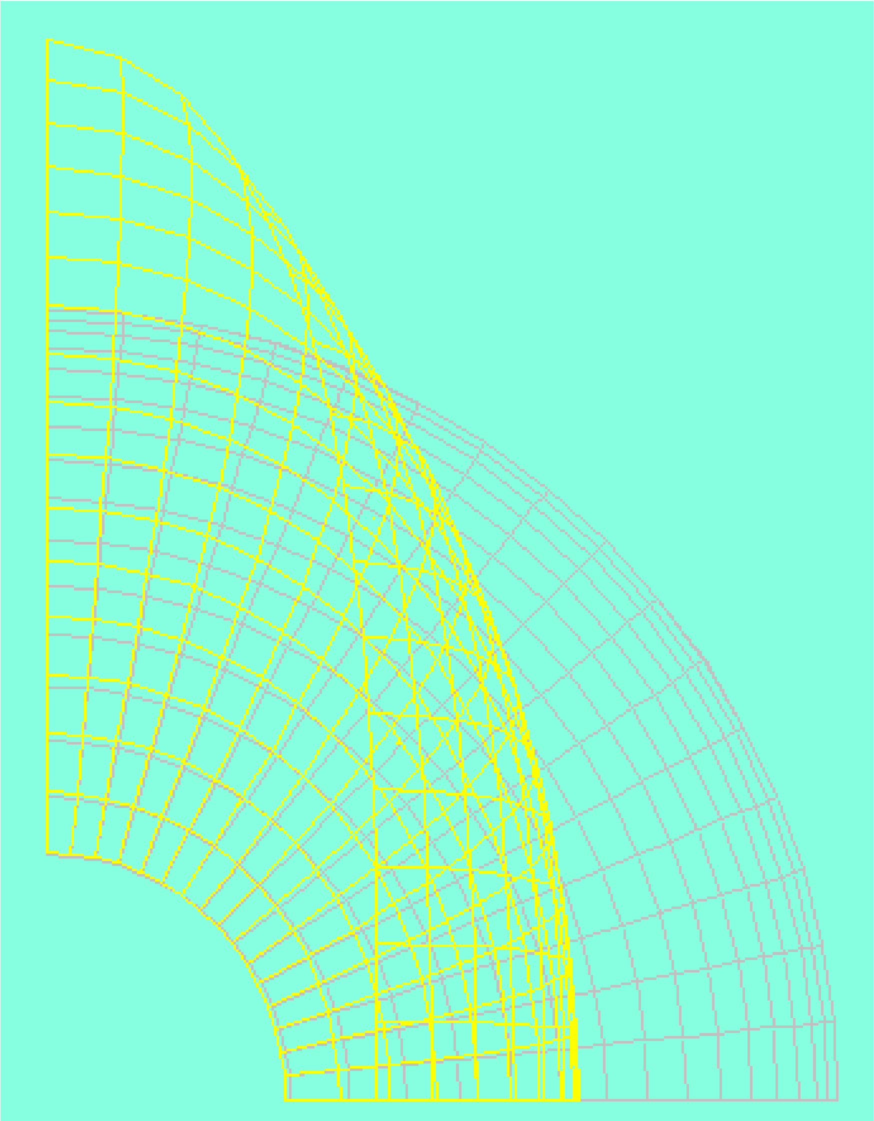
7) Output

8) Examples

# Deformed Hemispherical Shell

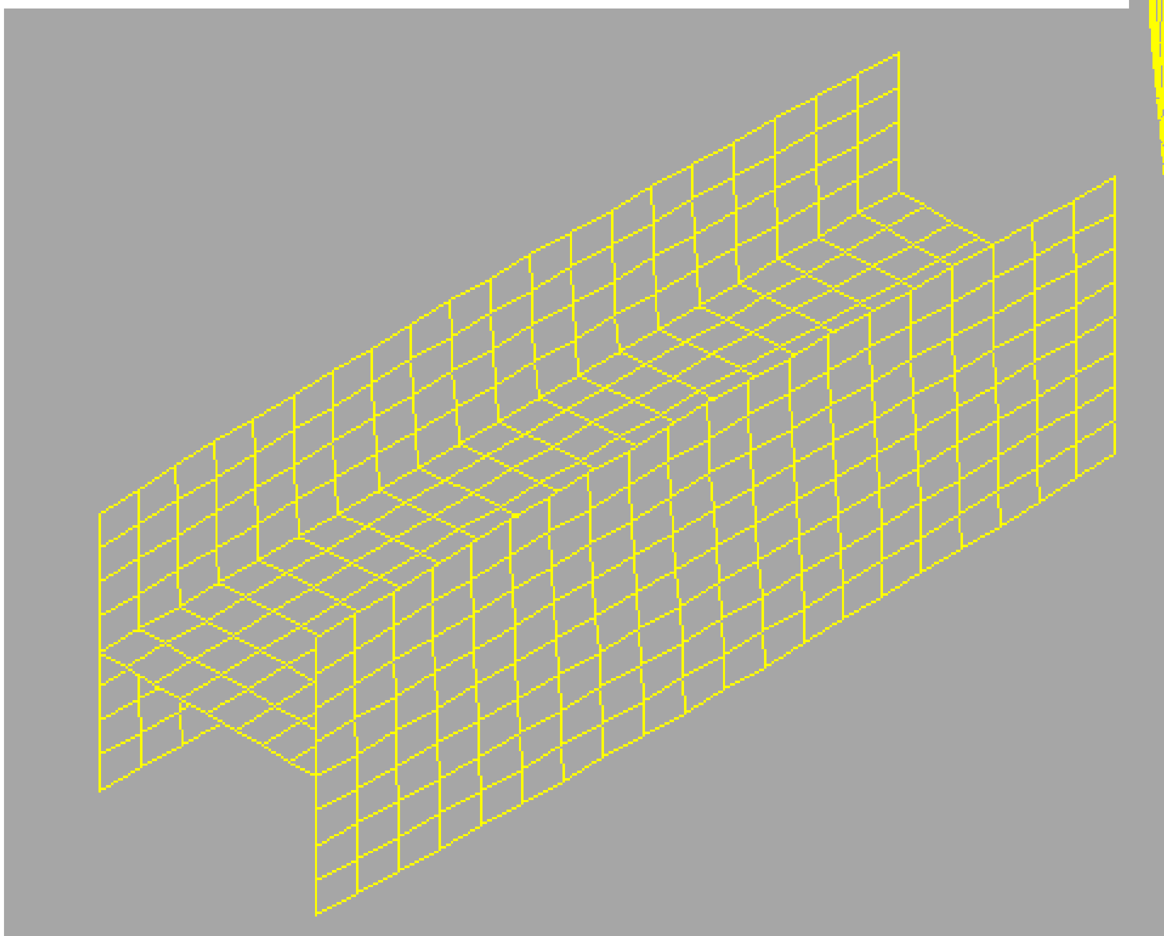


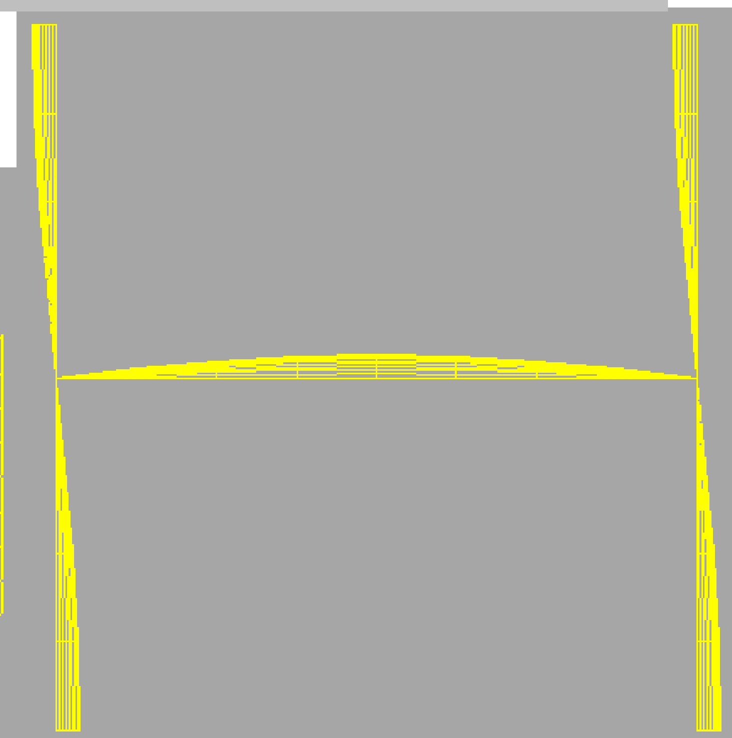
# Initial Geometry and Deformed

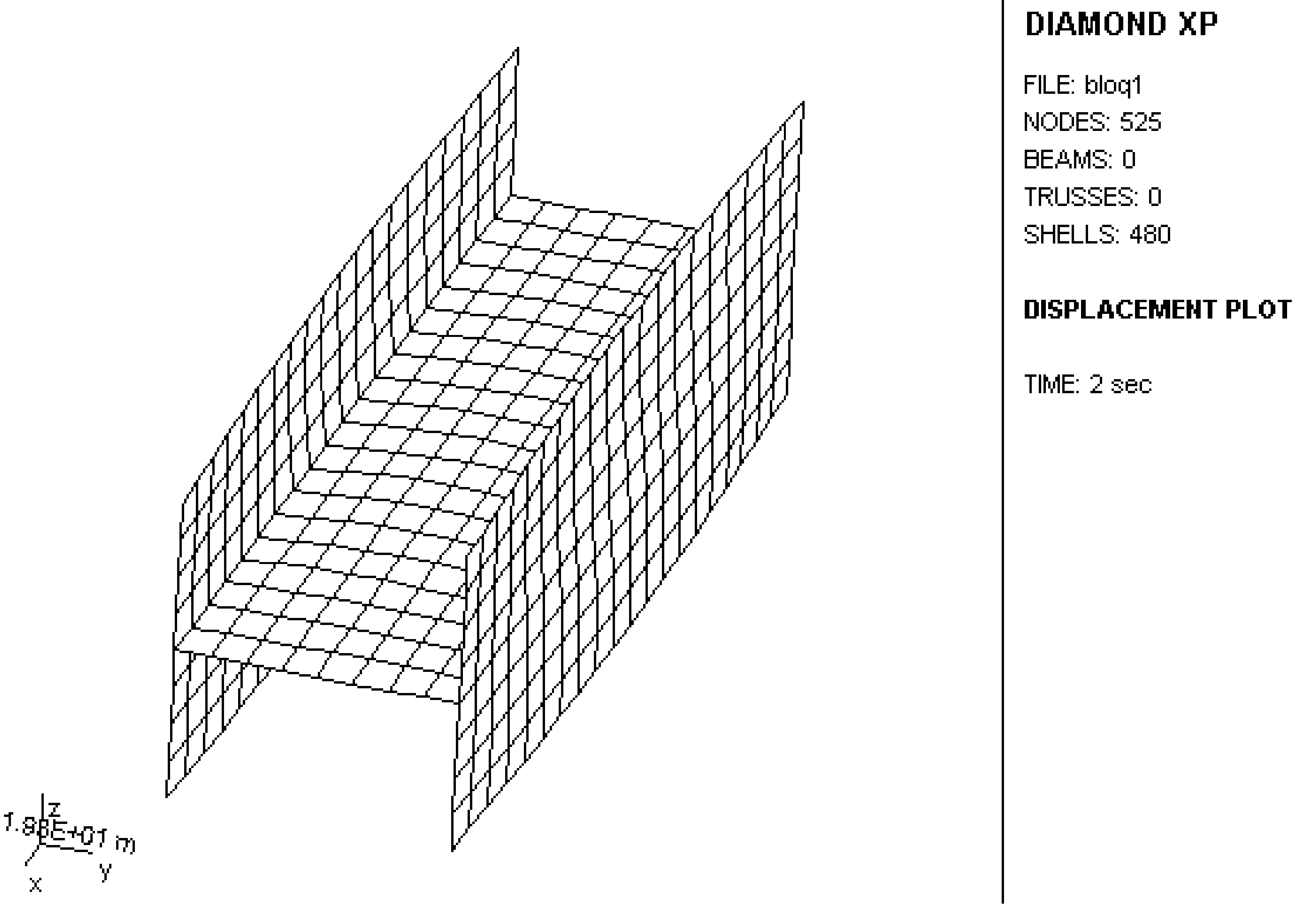


# HE 300 AA+

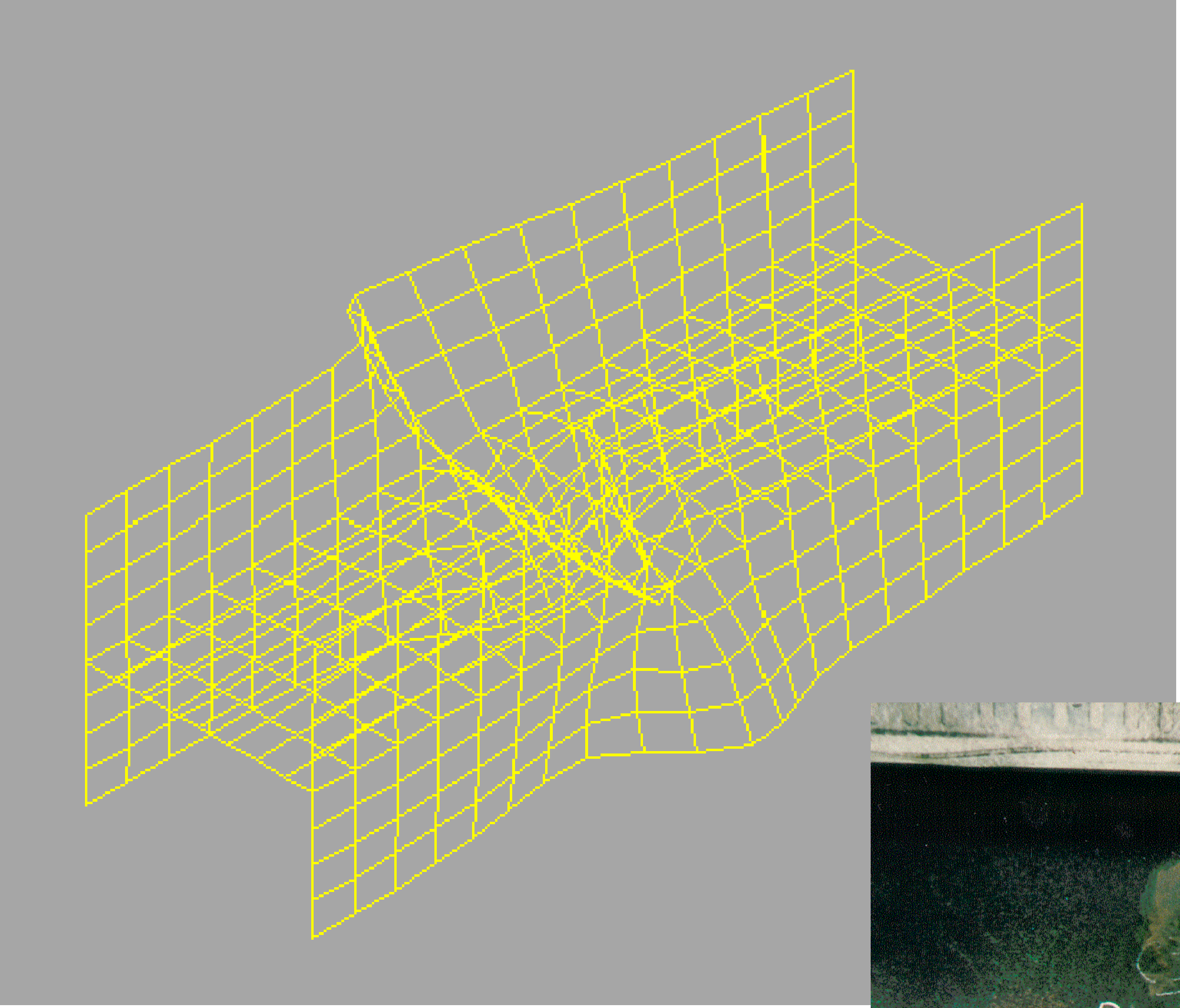
# Initial geometry








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

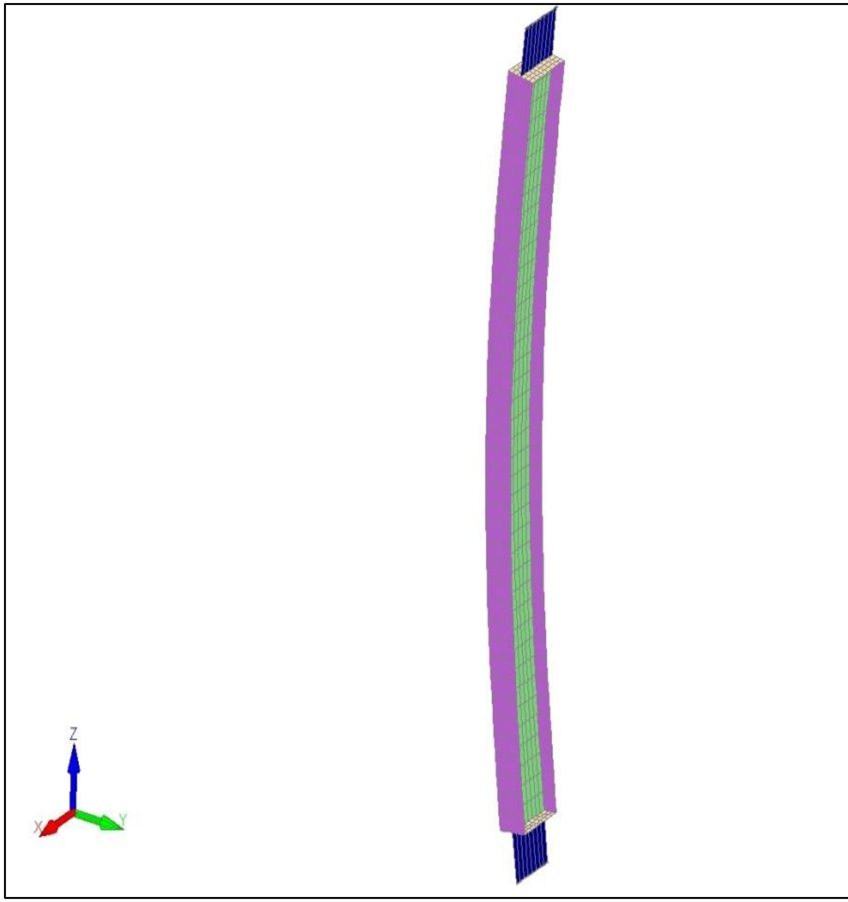



PB5
SB6E

# Numerical simulations vs. Experimental tests

- FIDESC4 Test No 1

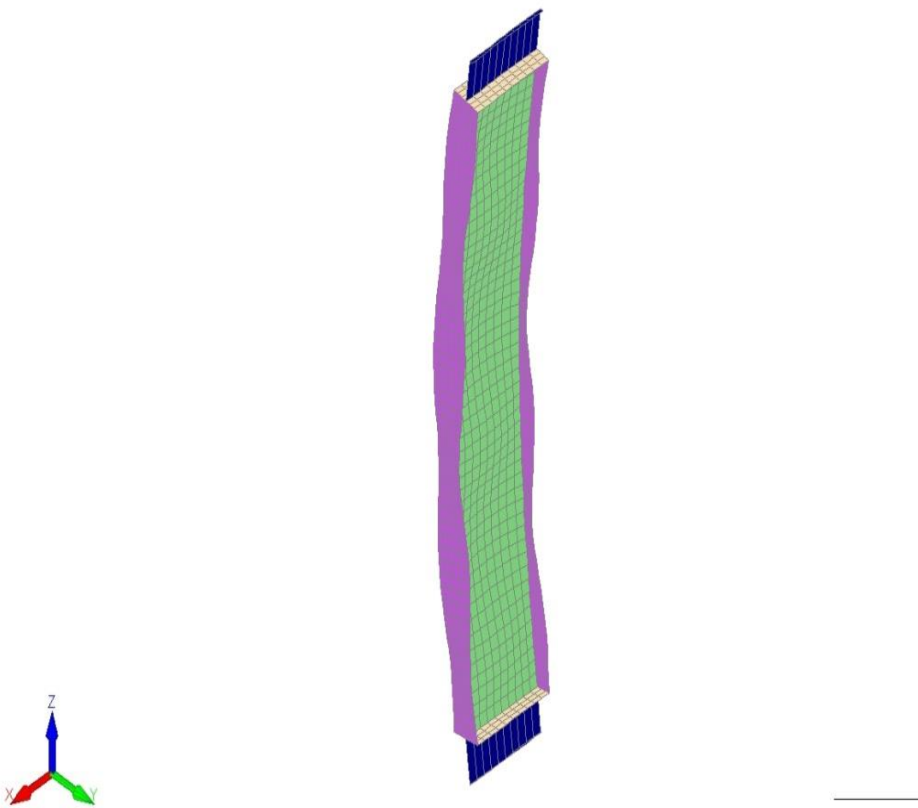
| Failure Temperature - SAFIR [°C] | Failure Temperature - TEST [°C] |
|---|---|
| 571,5 | 610 |




# Numerical simulations vs. Experimental tests

- FISDESC4 Test No 4

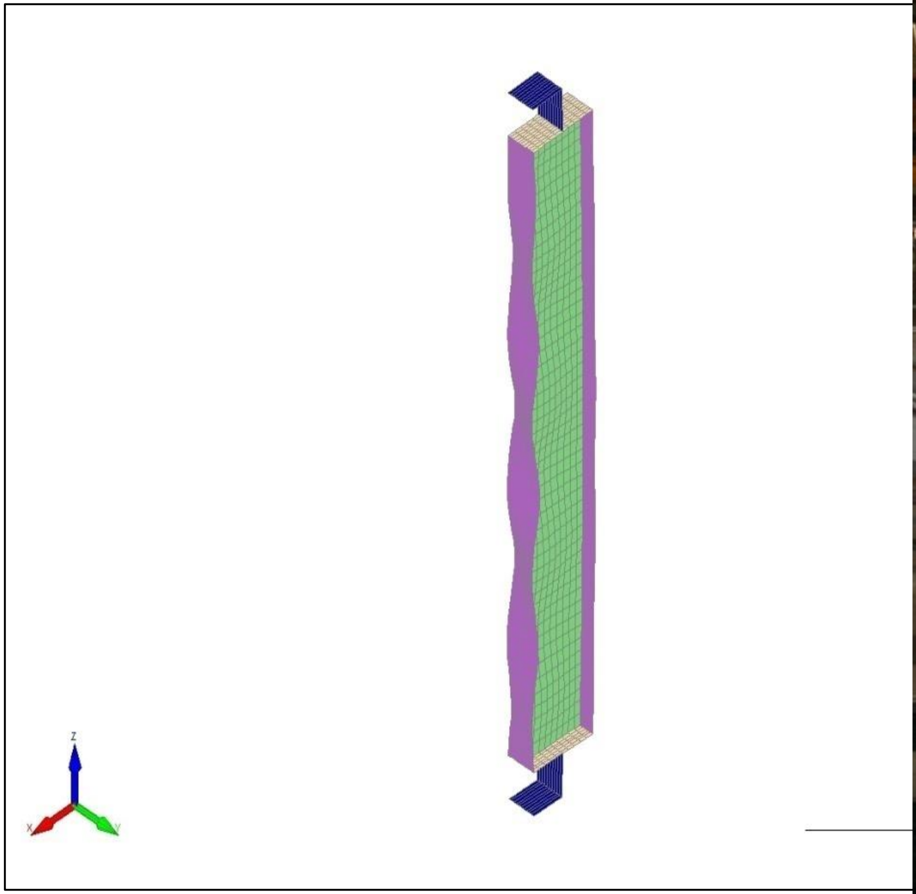
| Failure Temperature - SAFIR [°C] | Failure Temperature - TEST [°C] |
|---|---|
| 459 | 452 |




# Numerical simulations vs. Experimental tests

- FISDESC4 Test No 6

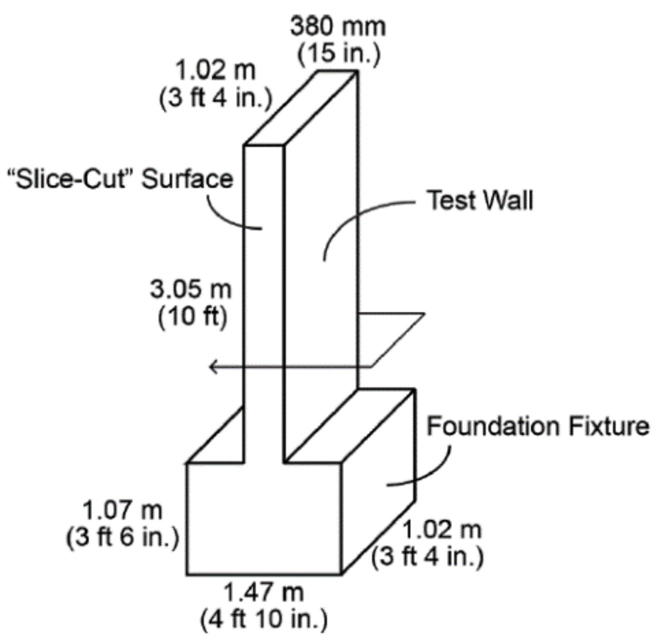
| Failure Temperature - SAFIR [°C] | Failure Temperature - TEST [°C] |
|---|---|
| 531 (cf. stif+) | 530 |

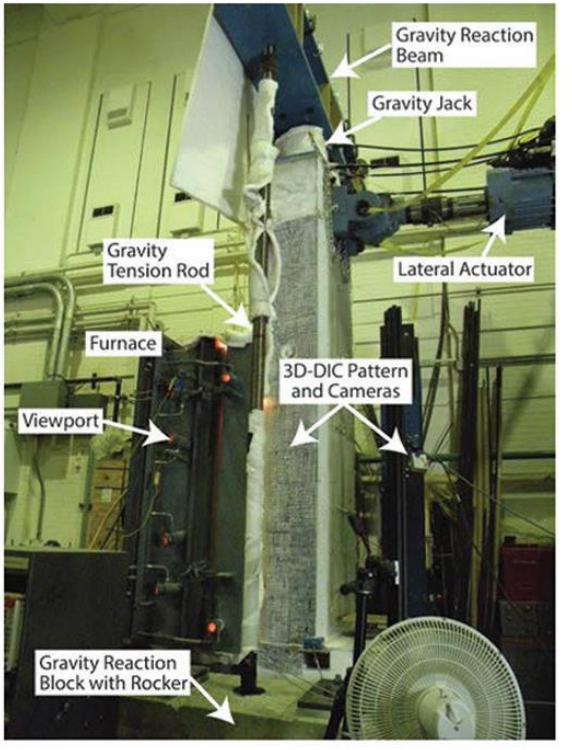



# Numerical simulations vs. Experimental tests

Test campaign from Notre Dame University

- **Fixed-free RC wall** made of calcareous concrete with $f_c$ 47.1 Mpa
- Test procedure:
  1. **Axial load** of 2400 kN applied at the top
  2. Initial **transverse load** of 36 kN, toward furnace, applied near top
  3. **ASTM E119 fire** starts, **applied on one side** from base to mid-height
  4. **Transverse load stepwise increased** by 22 kN every 2h – test duration 10h

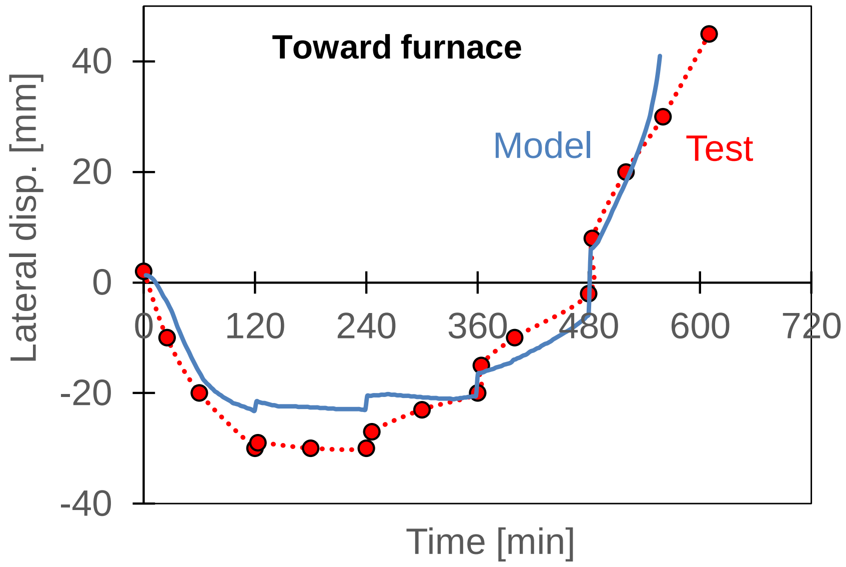


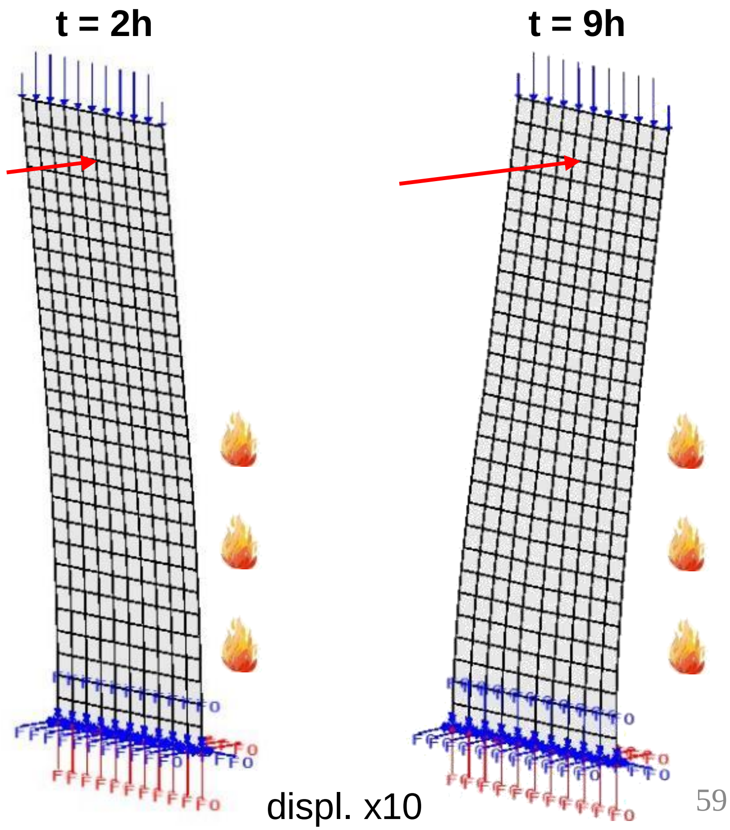



# Numerical simulations vs. Experimental tests

Numerical simulation in SAFIR[1] using the **Shell FE** with multiaxial concrete model

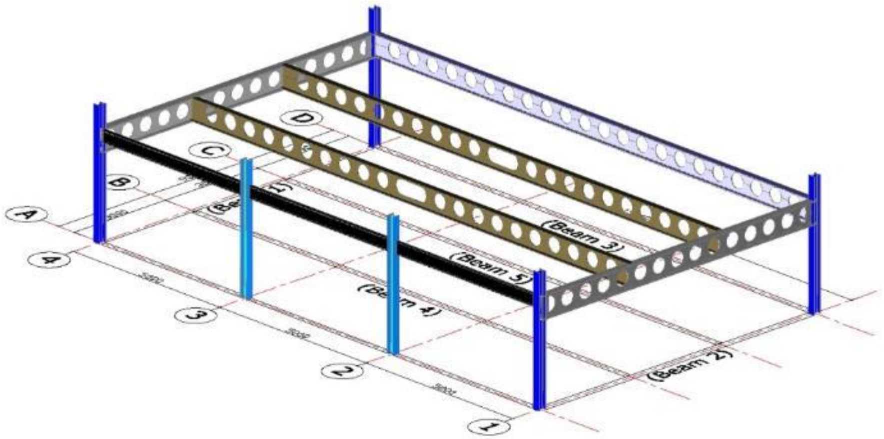
- First, **thermal gradient effect** prevails → moves opposite to the furnace
- Then, **curvature reversal** is captured. Complex combination of:
  - Thermal bowing: bend away from the heat source
  - Transverse load (increased stepwise): bend toward the heat source
  - Transient creep strain on the heated face: bend toward the heat source
  - Shift of neutral axis (affects load eccentricity): bend toward the heat source



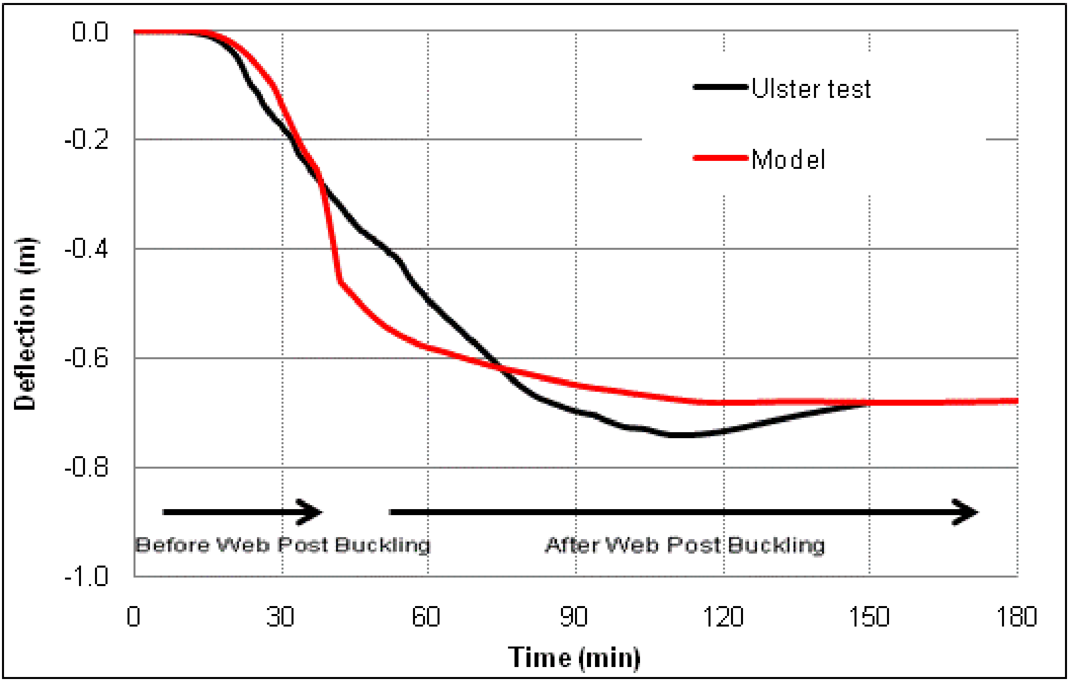



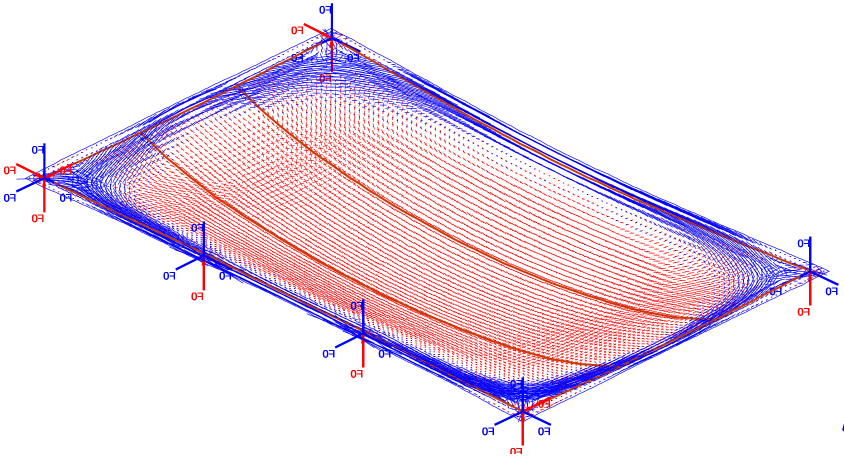

[1]Gernay T, Franssen, JM. (2015) *Fire Safety Journal*.

# Numerical simulations vs. Experimental tests

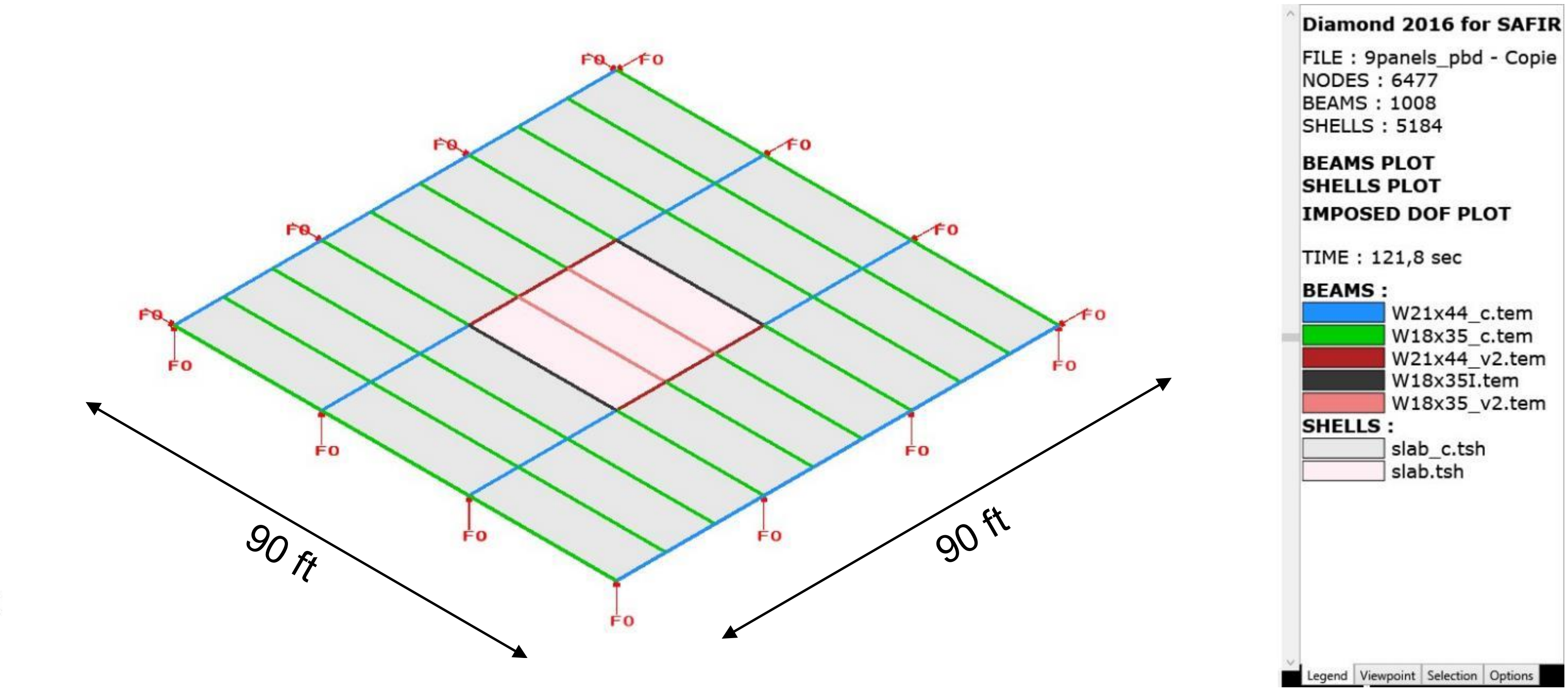



# Numerical simulations vs. Experimental tests

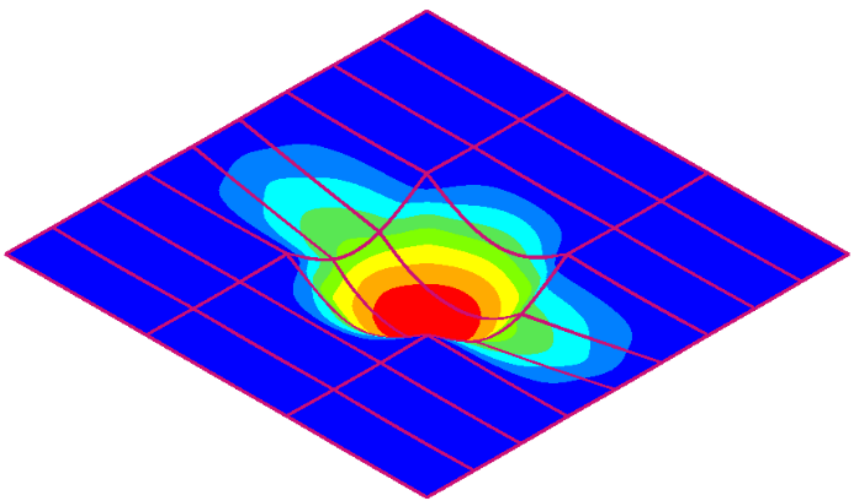


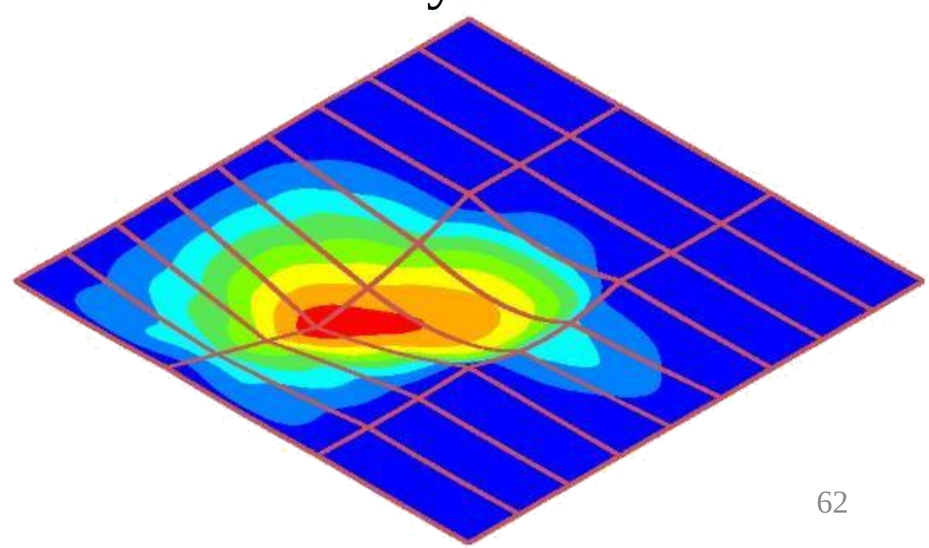
tension compression




Fire in central bay



Fire in central bay after column loss



# *Thank you*

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LIÈGE université

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WHITING SCHOOL
of ENGINEERING