

SAFIR[®]

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

Course by

Jean Marc Franssen & Thomas Gernay



Basic theory of beam F.E.

- 1) Local system of coordinates
- 2) Degrees of freedom
- 3) The basic equations
- 4) Material properties
- 5) Numerical integration on the length
- 6) Numerical integration on the surface
- 7) Stiffness in torsion
- 8) Examples

Three steps in the structural fire design:

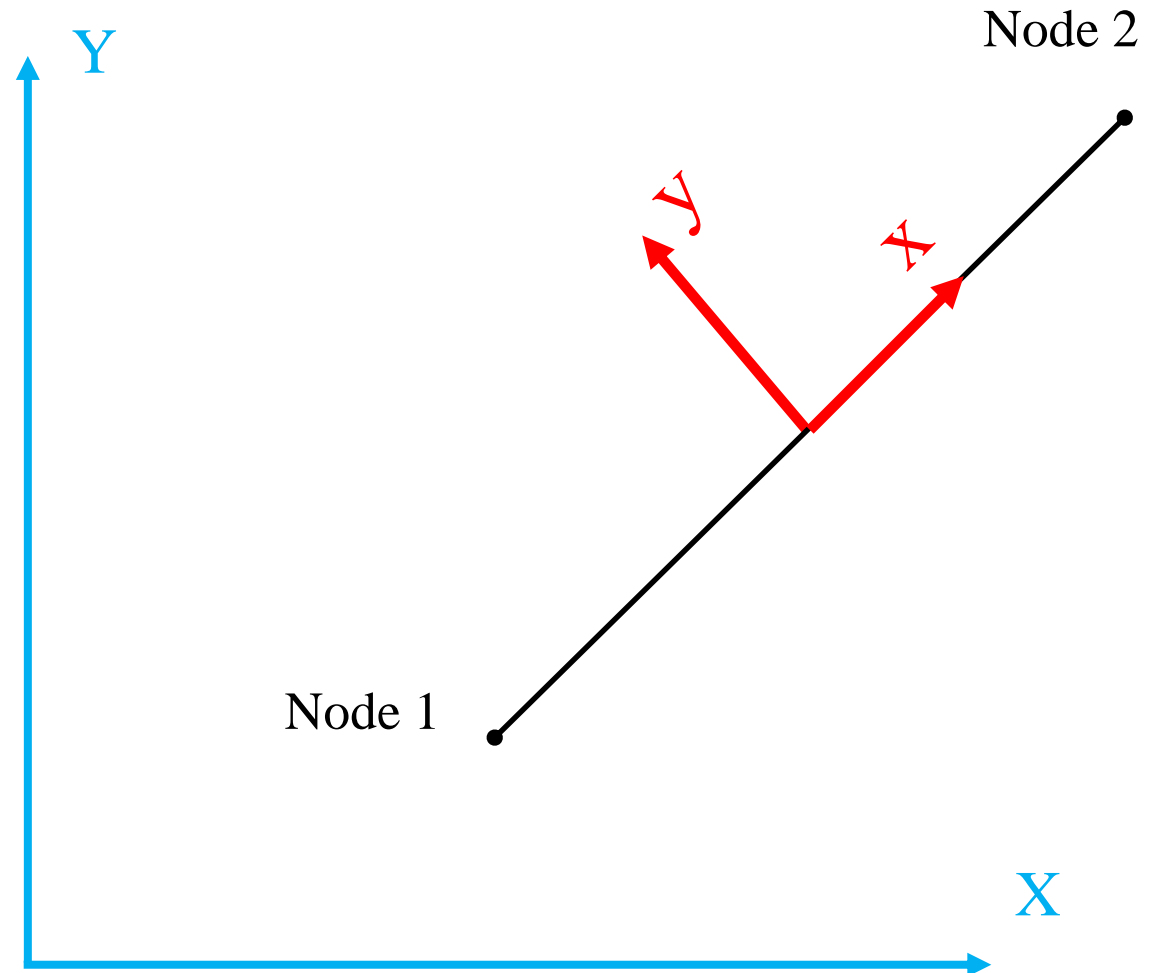
- 1. Define the fire (not made by SAFIR).*
- 2. Calculate the temperatures in the structure.*
- 3. Calculate the mechanical behaviour.*

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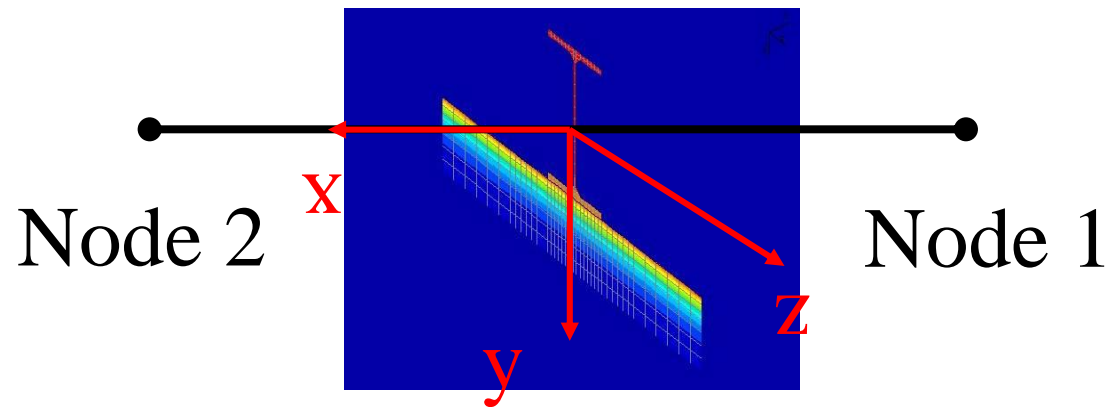
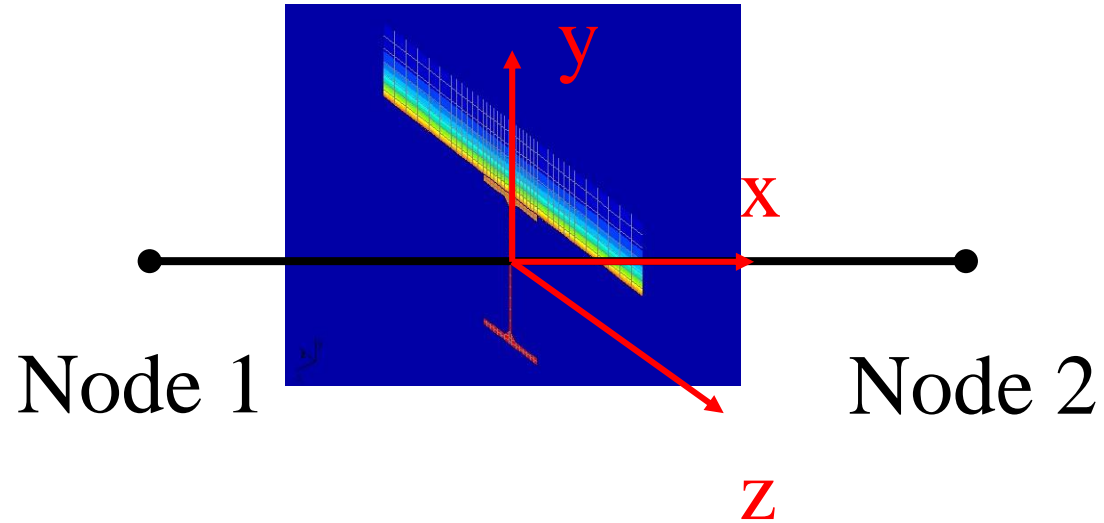
2D beam finite element

Global system of coordinates (of the structure)

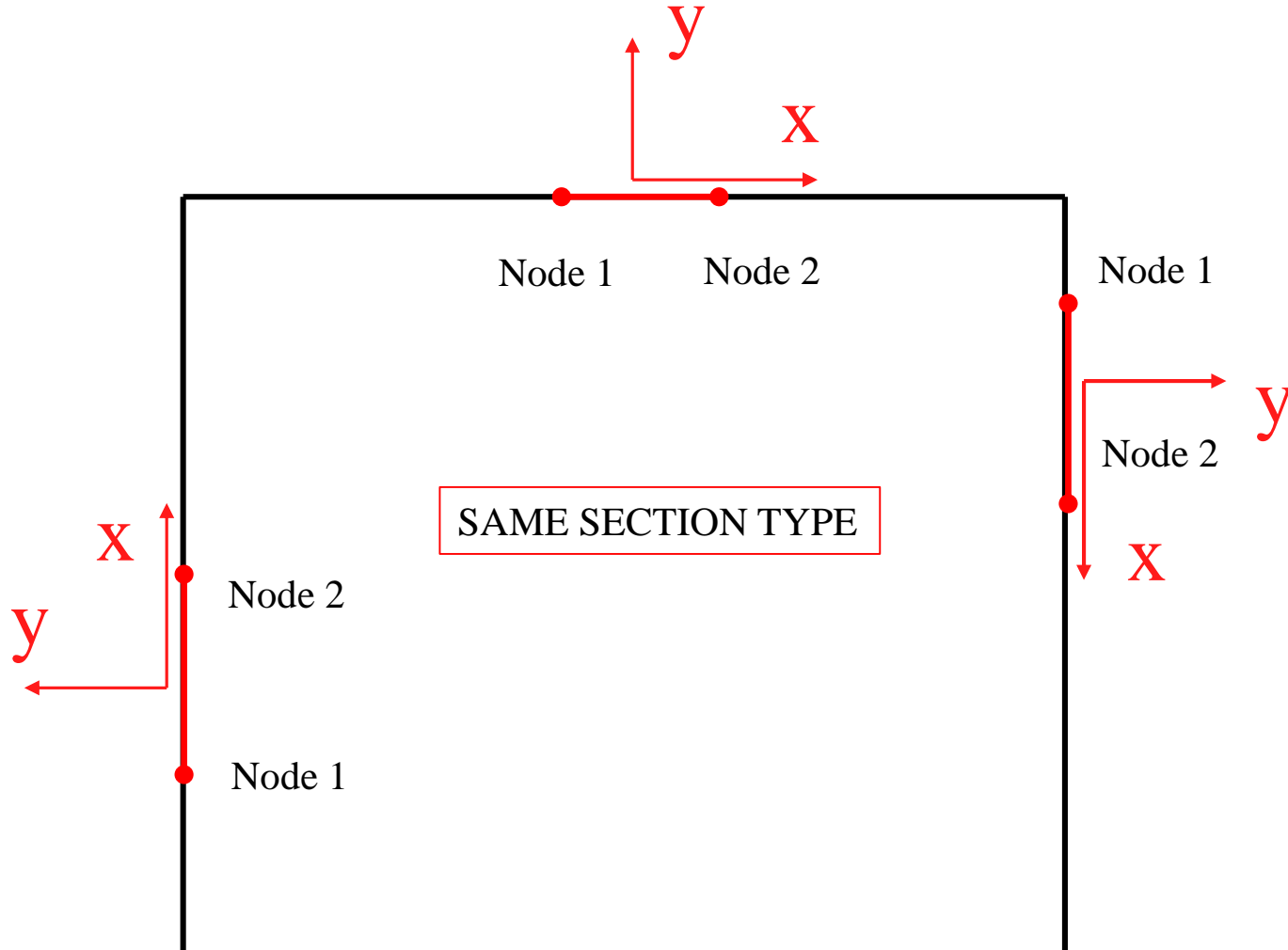
Local system of coordinates (of each beam)



Why is the local SoC important?



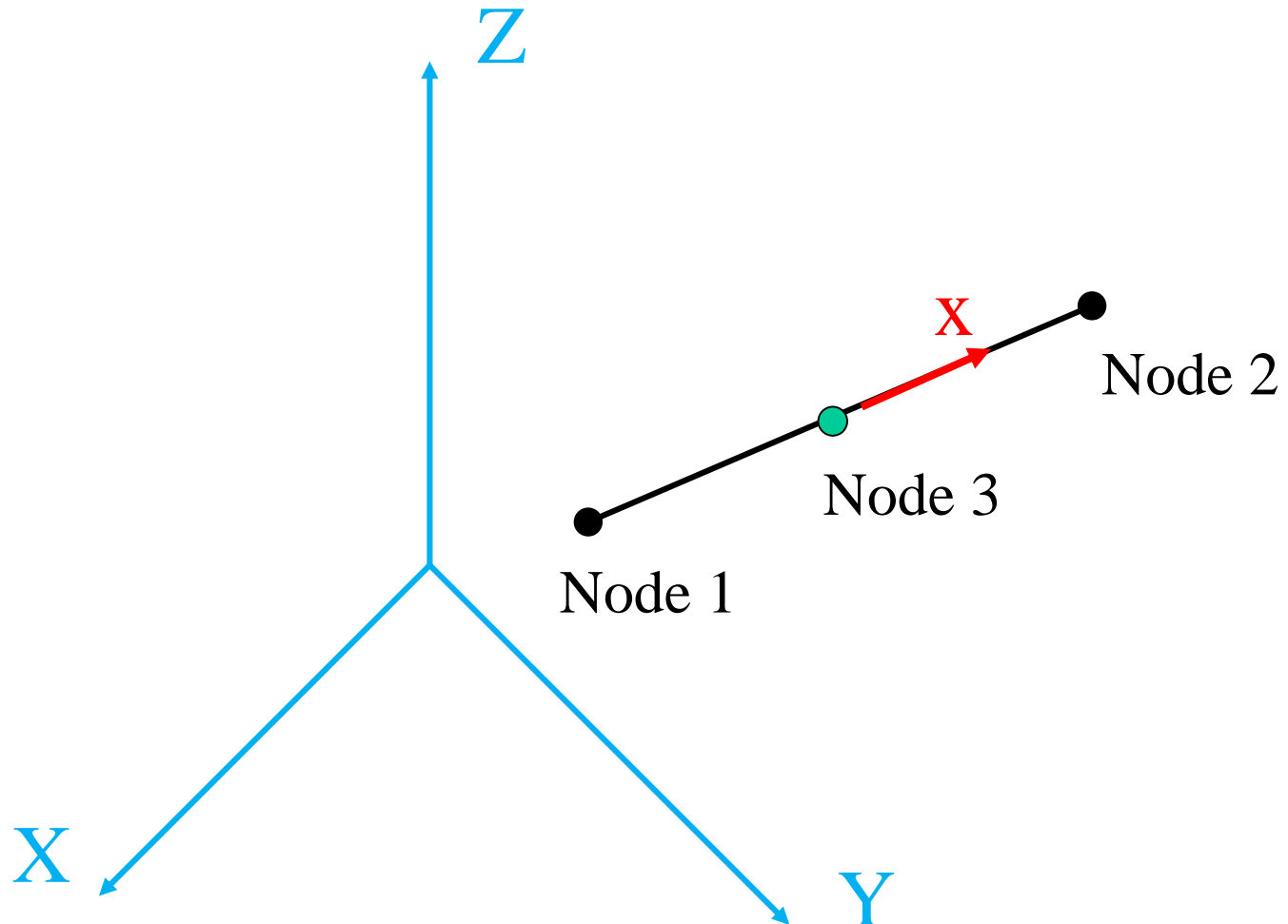
Example: a simple 2D frame.



The same section type can be used because the unexposed side of the section (positive values of y) is correctly located toward the outside.

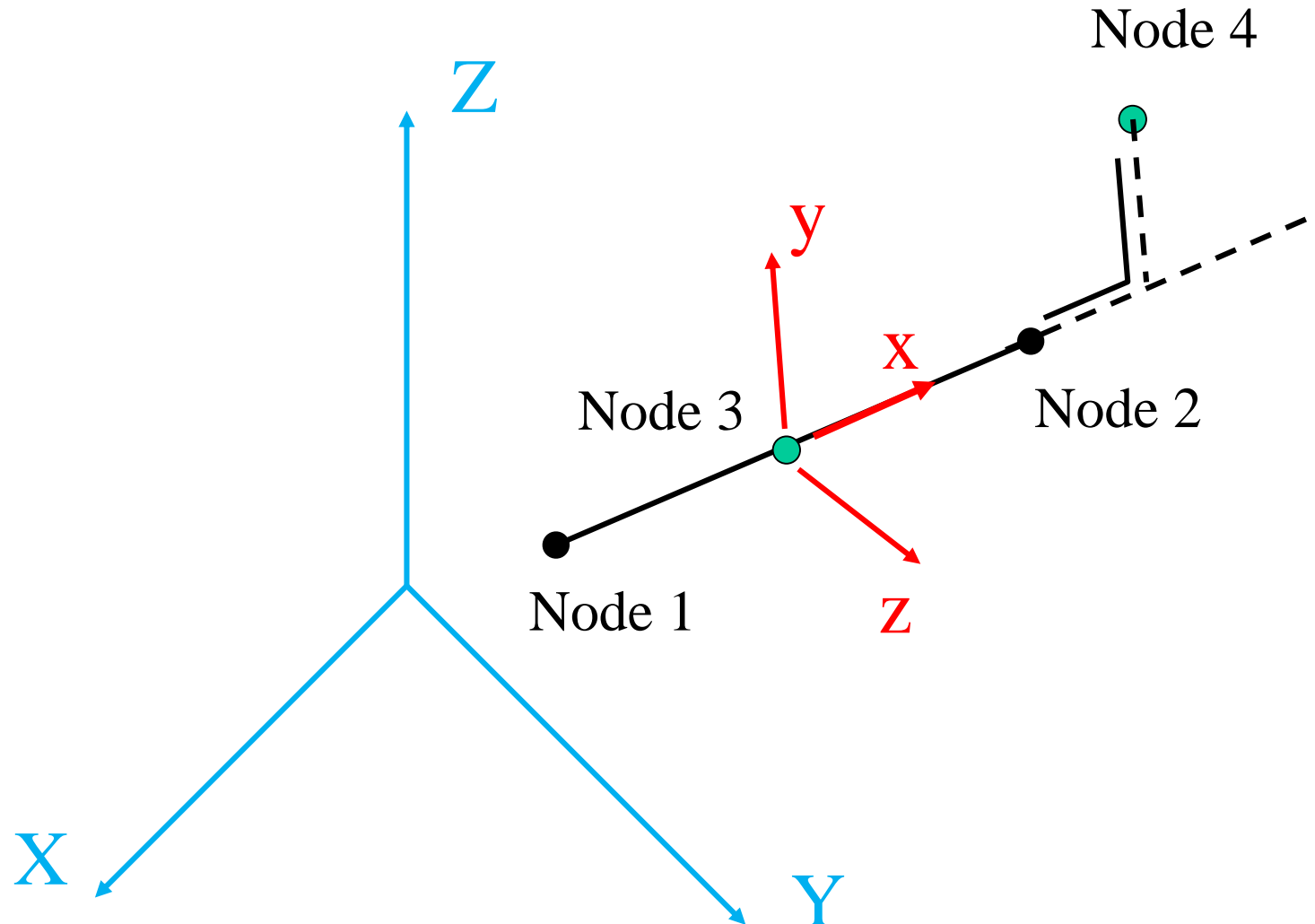
This would not be the case if the elements in the right hand column would have their nodes from bottom to top.

3D beam finite element



In which direction is pointing **y**?

3D beam finite element

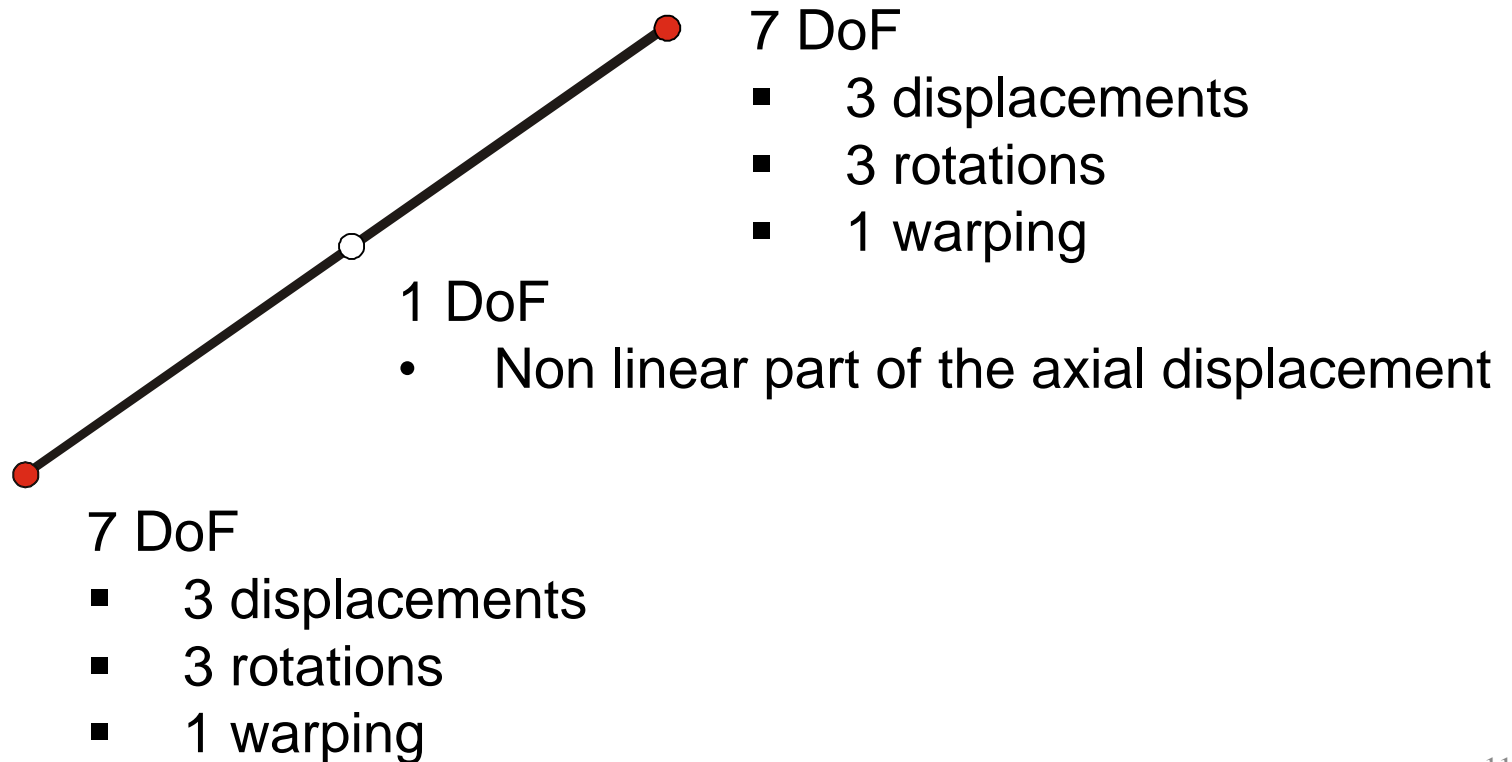


y is in the plane defined by nodes 1, 2 and 4,
in the direction from axis x to node 4.

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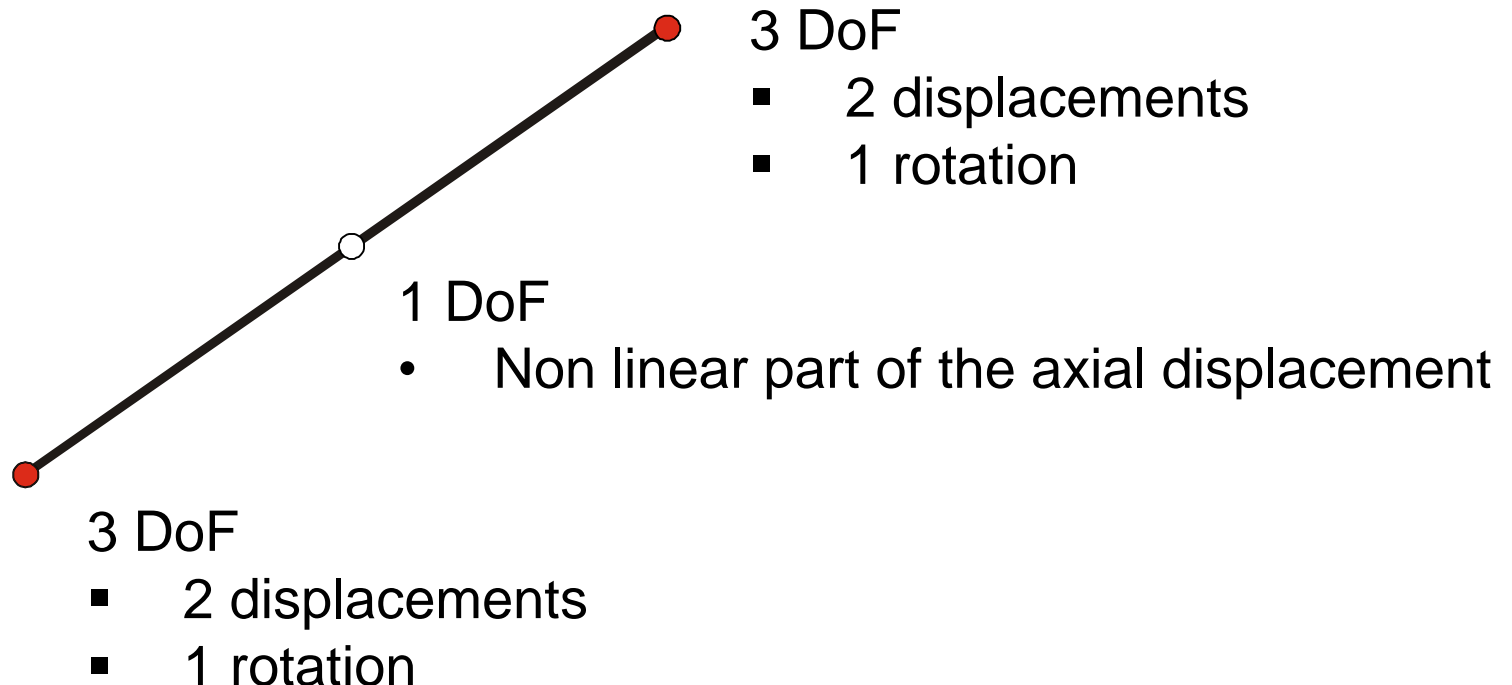
One 3D beam finite element

- Prismatic.
- Straight in the initial configuration.

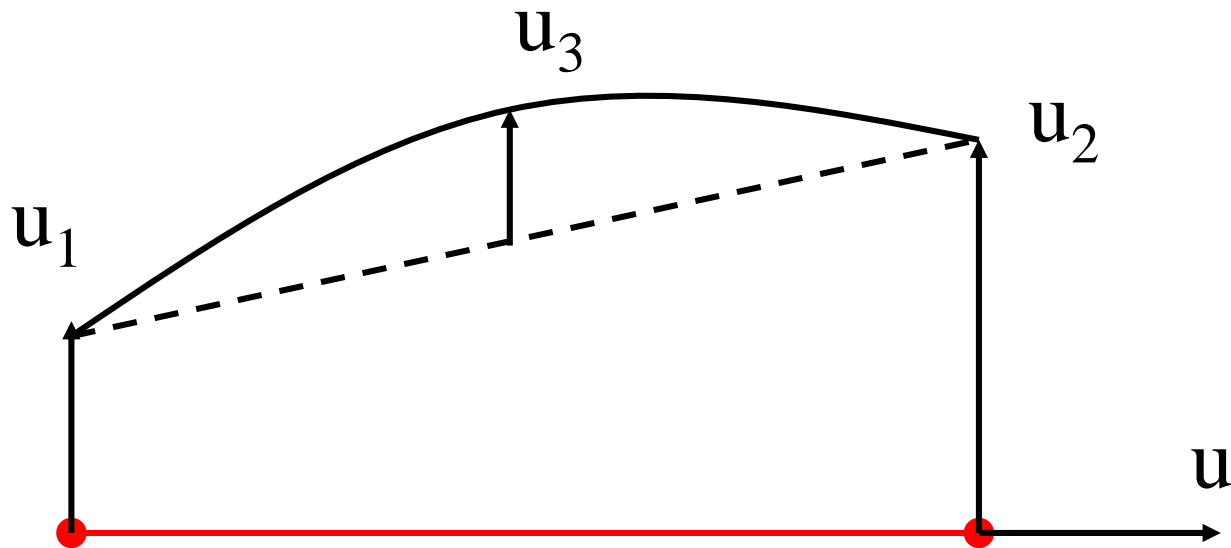


One 2D beam finite element

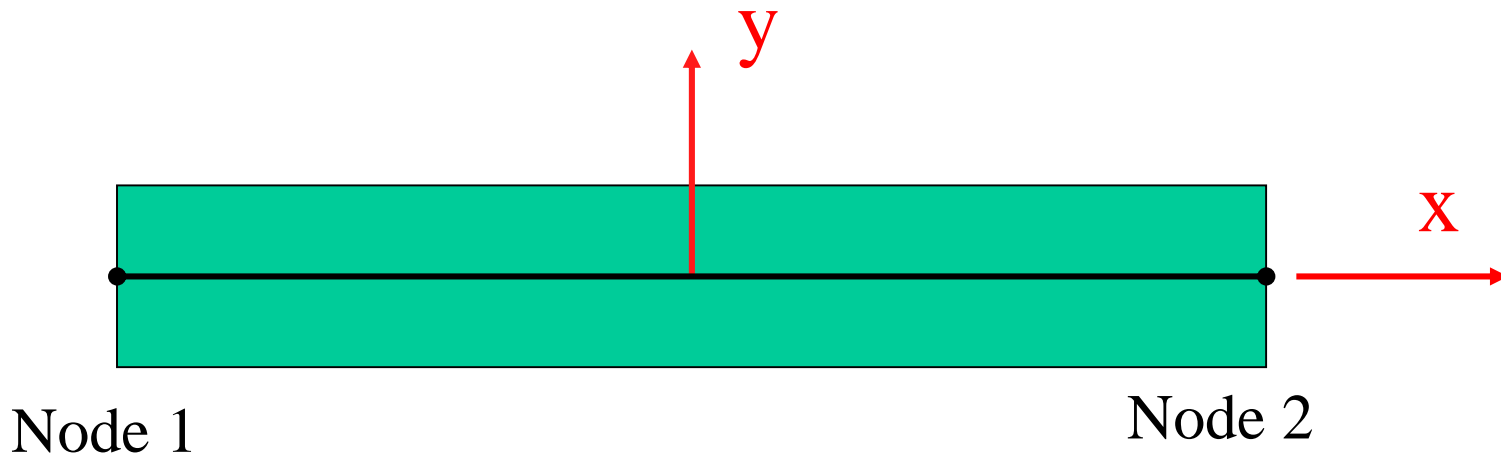
- Prismatic.
- Straight in the initial configuration.



The central node bears the non linear component of the axial displacement.



Why ????



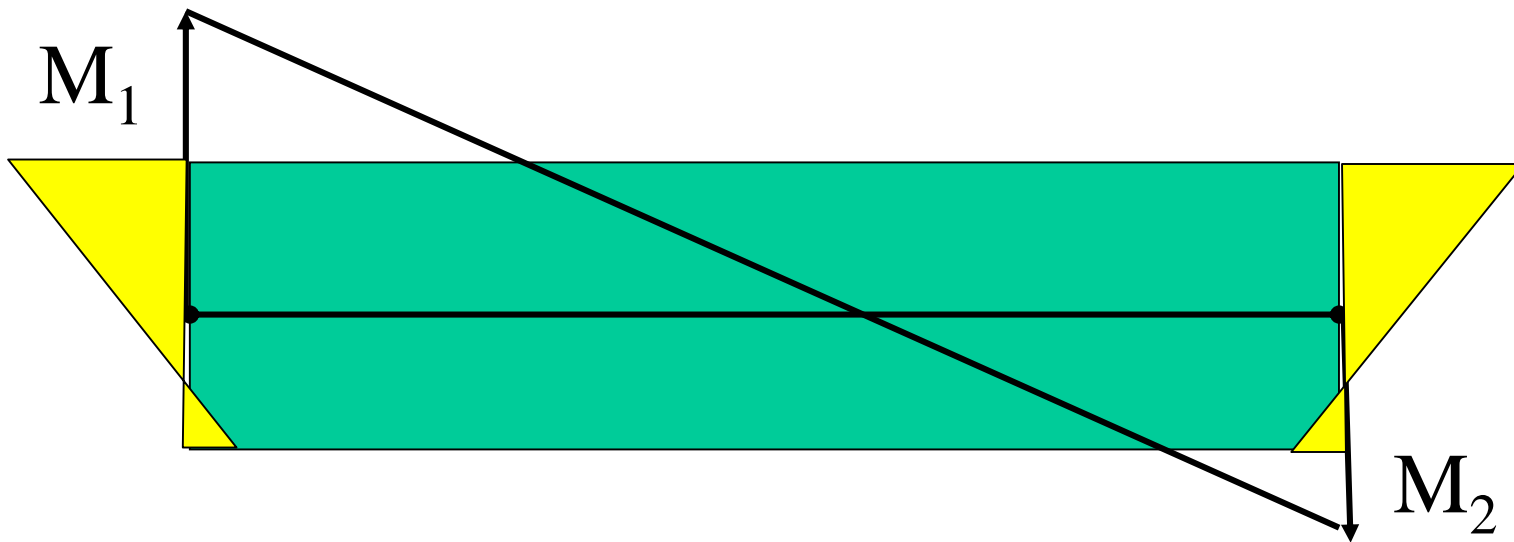
With only 2 nodes, the axial displacement u of the node line can only be a linear function of x .

\Rightarrow On the node line ($y = 0$), the strain du/dx can only be constant.

\Rightarrow This leads to too stiff elements.

Example: linear bending moment in a section that is not symmetrical.

The strain at mid-level is not constant, but a beam F.E. with 2 nodes cannot represent this.

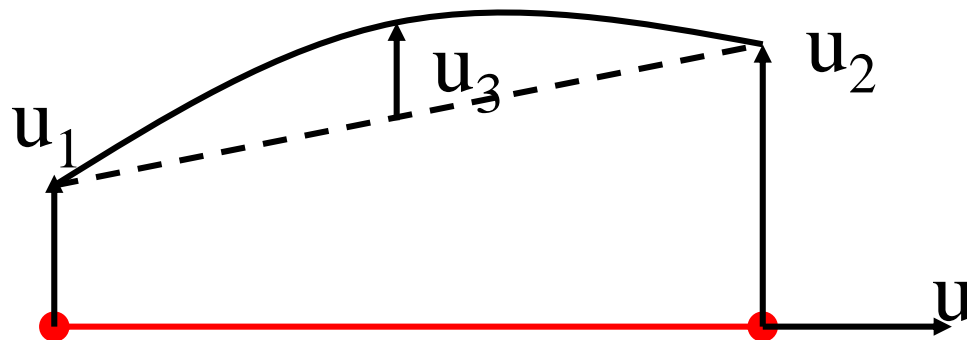


It is desirable to have a strain that varies along the node line.
This is possible if the axial displacement is $f(x^2)$.
An additional DoF is needed. It is supported by the central node.

Note that the effect of the central node has nothing to do with:

- Large displacements
- Effects of fire

This central node is not required in elastic elements (the strain is not used).



Elements in which u_3 is 0 during the simulation don't have much plasticity. Elements in which u_3 starts to increase during the simulation are those where a lot of plasticity develops

Transmission of warping between adjacent elements?

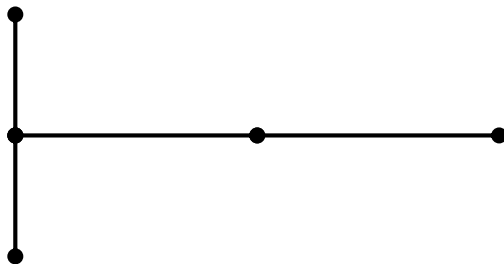
✓ In continuous elements: yes



✓ At joints: no

⇒ either fix the warping to 0 at the common node.

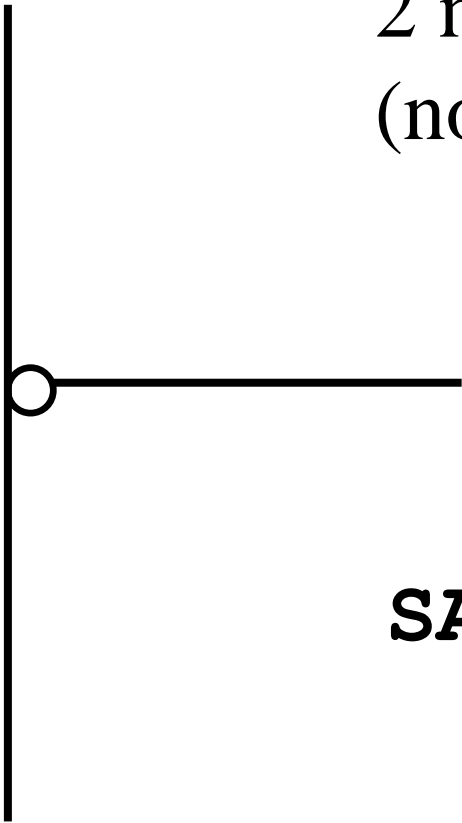
⇒ or use the RELAX command to release the warping ($w = 0$)
at the end of some elements.



Internal hinges

First solution used historically

2 nodes at the same location
(node i and node j)



SAME	i	j	YES	YES	NO
			X	Y	θ

This solution has 2 drawbacks:

- 1) The linked DoF's are parallel to the global system of coordinates
=> Not applicable for diagonals in 3D models
- 1) The linked DoF's don't follow the elements in large displacements
=> Approximations in 3D structures

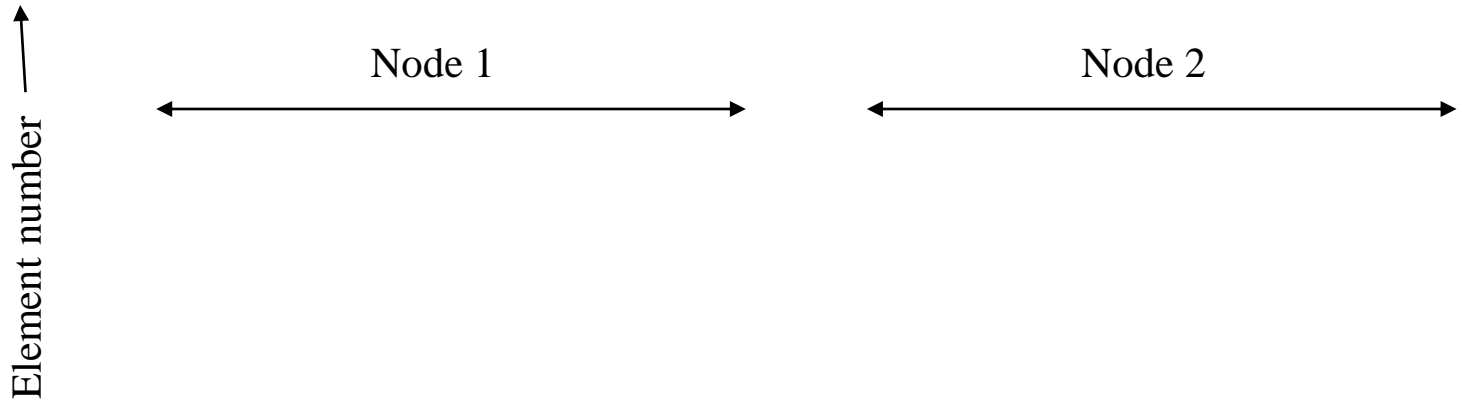
New solution = Relaxation of the force(s) at the end of the beam elements.

- One or several internal forces (M, N, V...) are forced to be equal to 0 at the end of the elements.
- It is also possible to introduce a semi-rigid connection for each DoF.

```

RELAX_ELEM ! Start of the section on relaxations
  BEAMS    ! Only beam elements can be relaxed
    ELEM    1      -1 -1 -1  -1  0  0  -1      -1 -1 -1  -1 -1 -1 -1
    ELEM   10      -1 -1 -1  -1 -1 -1 -1      -1 -1 -1  -1  0  0  -1
  END_BEAMS ! End of the beams
END_RELAX  ! End of the section

```



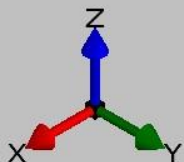
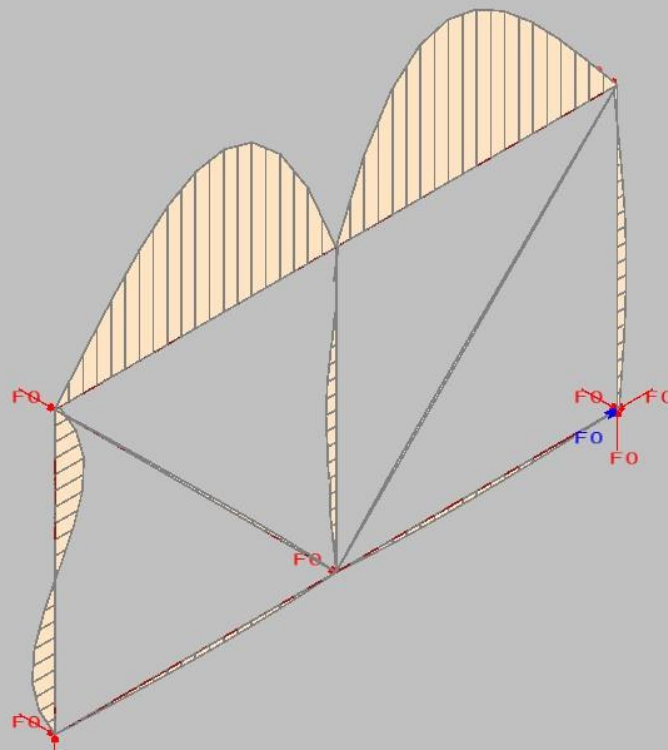
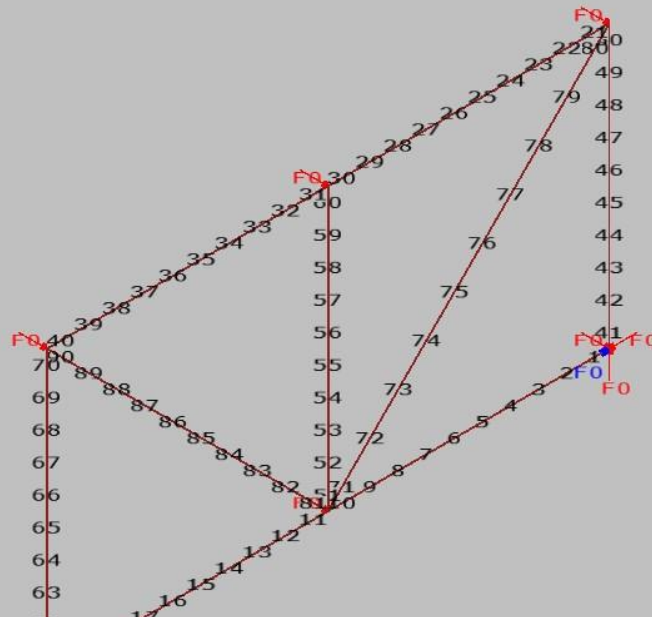
The structural member made of elements 1, 2,... 9, 10 has no bending moment with respect to local axes y and z at its ends:

Negative value means: No relaxation

Zero value means: Complete relaxation

Positive value means: Stiffness of the semi-rigid connection (in N/m or in Nm/rad)

Z

Minimum : 0
Maximum : 0.04767
Displacement Step : 0.00595875
Plot : Color
Components : Combined
Save Apply

Stresses
☒ Automatic ☐ User
Numb. of Colors : 8
Minimum : 0
Maximum : 0
Stress Step : 0
Plot : Color
Save Apply

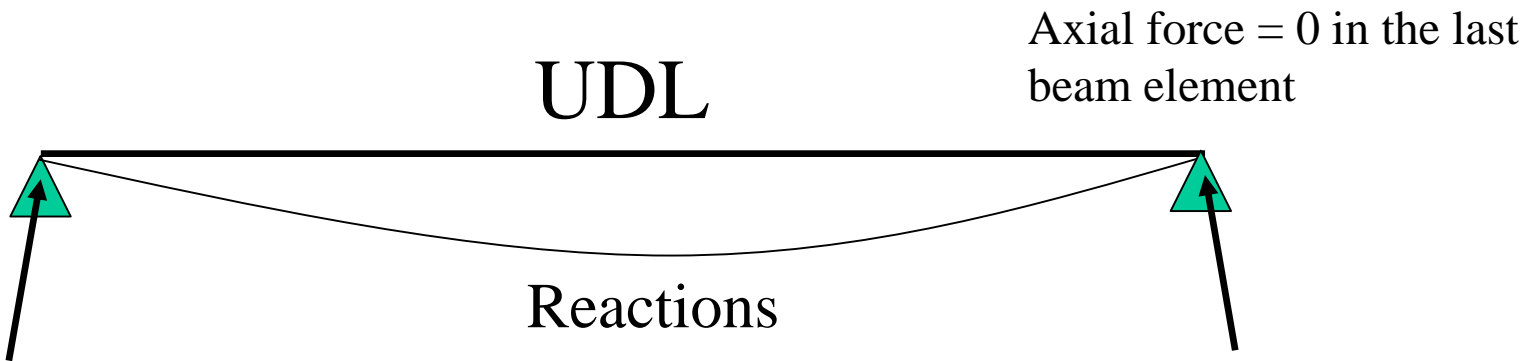
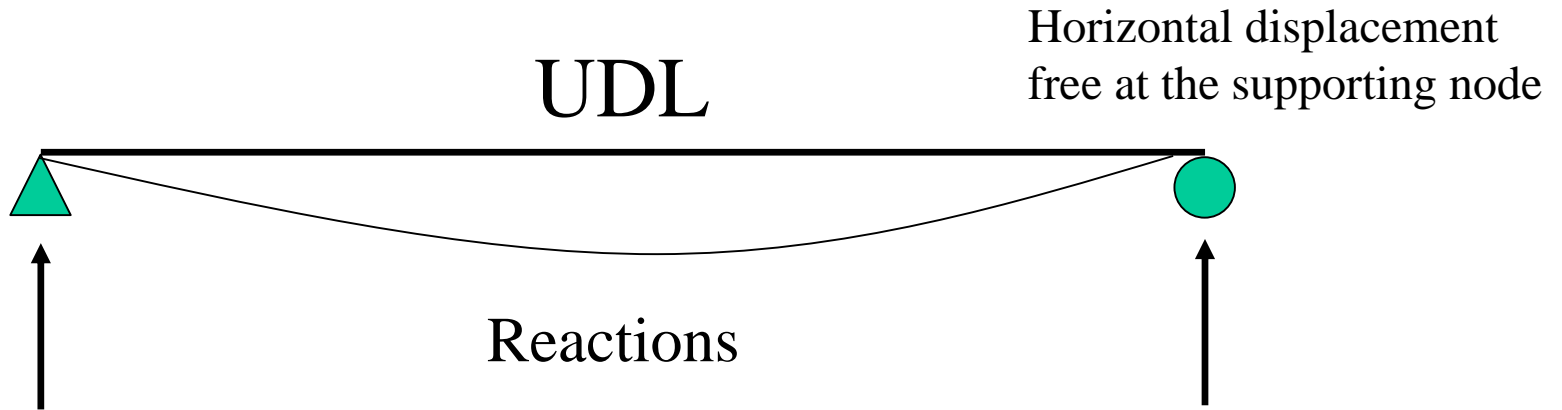
Scale factors
1 N (Ponctual loads) = 0.0001 m
1 N/m (Linear Loads) = 0.0001 m
1 N/m² (Surface Loads) = 0.0001 m
1 N (Reactions) = 0.0001 m
1 N (Force Diagrams) = 0.0001 m
1 Nm (Bend. Mom. Diag.) = 0.0001 m

Displacements
☒ Automatic ☐ User
Numb. of Colors : 8
Minimum : 0
Maximum : 0.04228
Displacement Step : 0.005285
Plot : Color
Components : Combined
Save Apply

Stresses
☒ Automatic ☐ User
Numb. of Colors : 8
Minimum : 0
Maximum : 0
Stress Step : 0
Plot : Color
Save Apply

Scale factors
1 N (Ponctual loads) = 0.0001 m
1 N/m (Linear Loads) = 0.0001 m
1 N/m² (Surface Loads) = 0.0001 m
1 N (Reactions) = 0.0001 m
1 N (Force Diagrams) = 0.0001 m
1 Nm (Bend. Mom. Diag.) = 0.0001 m
1 N (Spring Forces) = 0.0001 m
1 N/m² (Spring Press.) = 0.0001 m
1 kN/m (Memb. Forces) = 0.0001 m
1 kNm/m (Bend. Forces) = 0.002 m

! The relaxations are in the **local** System of Coordinates of the element



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The local equilibrium equation is :

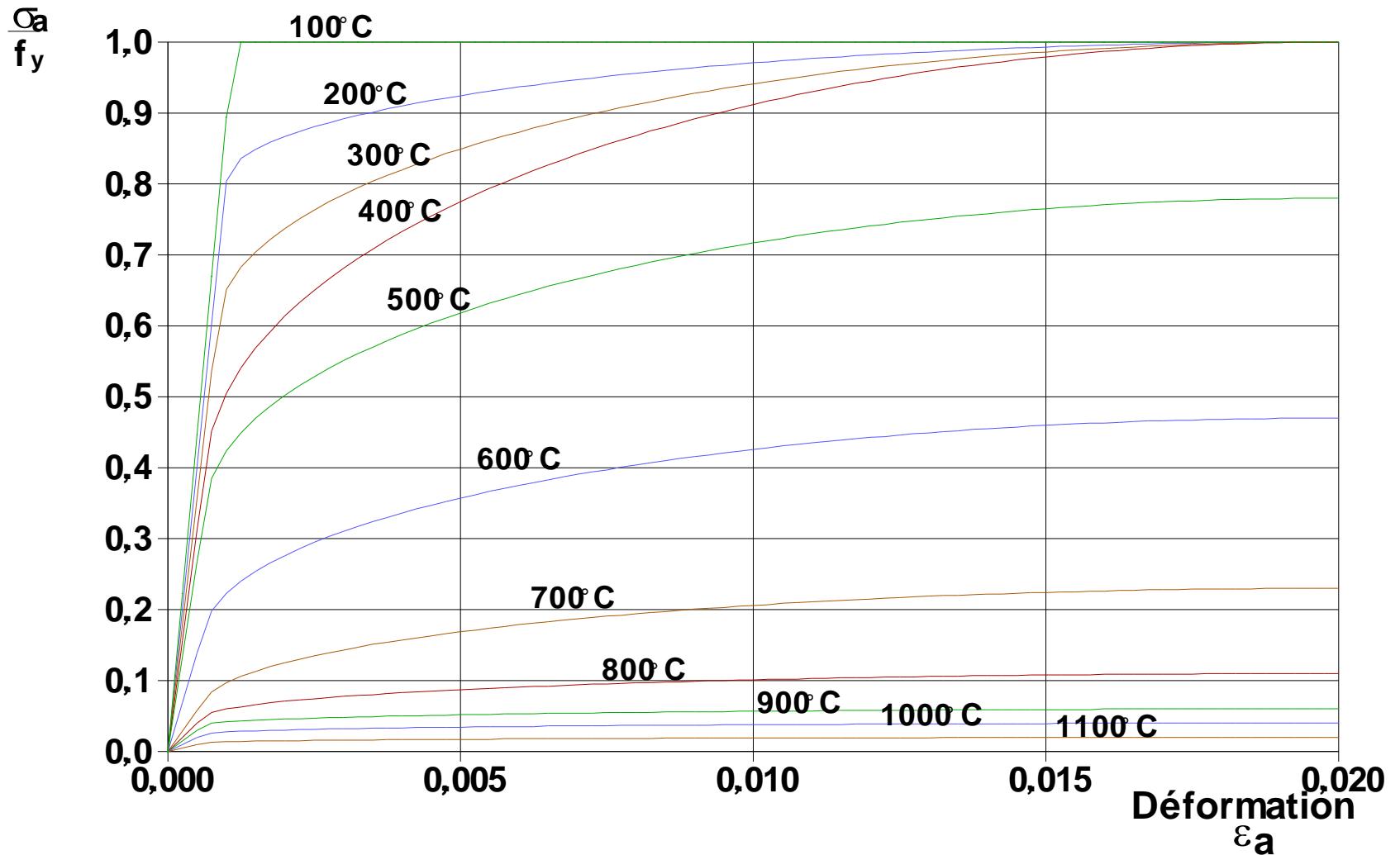
$$\frac{\partial \sigma_x}{\partial y} + \frac{\partial \sigma_y}{\partial x} \dots\dots\dots$$

The element equilibrium equation is :

$$[K]\{u\} = \{P\}$$

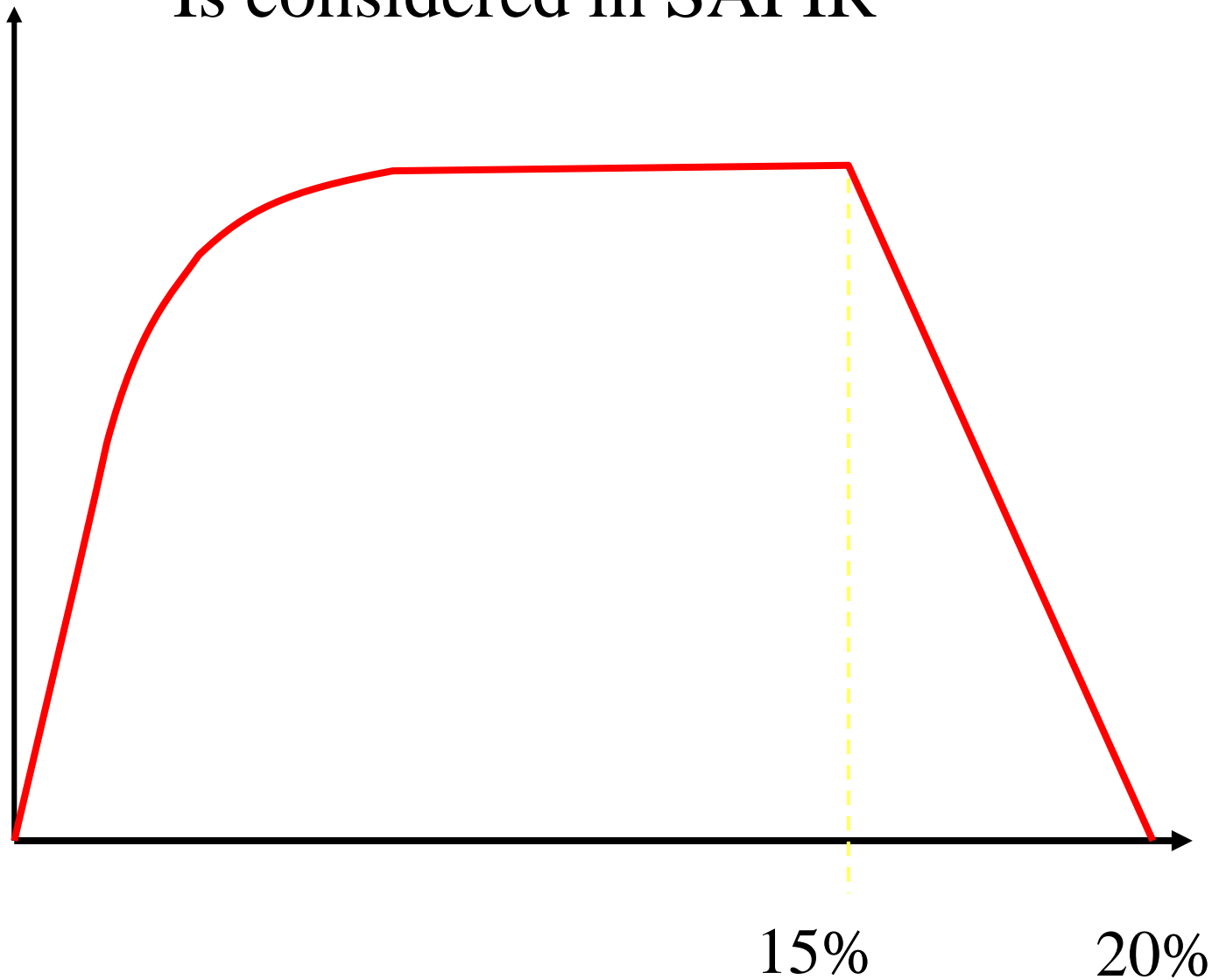
$$\begin{bmatrix} k_{1,1} & k_{1,2} & k_{1,3} & & & & k_{1,7} \\ & k_{2,2} & & & & & \\ & & k_{3,3} & & & & \\ & & & k_{4,4} & & & \\ & & & & k_{5,5} & & \\ & & & & & k_{6,6} & k_{6,7} \\ Sym & & & & & k_{7,7} \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ \\ \\ u_6 \\ u_7 \end{Bmatrix} = \begin{Bmatrix} p_1 \\ p_2 \\ \\ \\ p_6 \\ p_7 \end{Bmatrix}_{24}$$

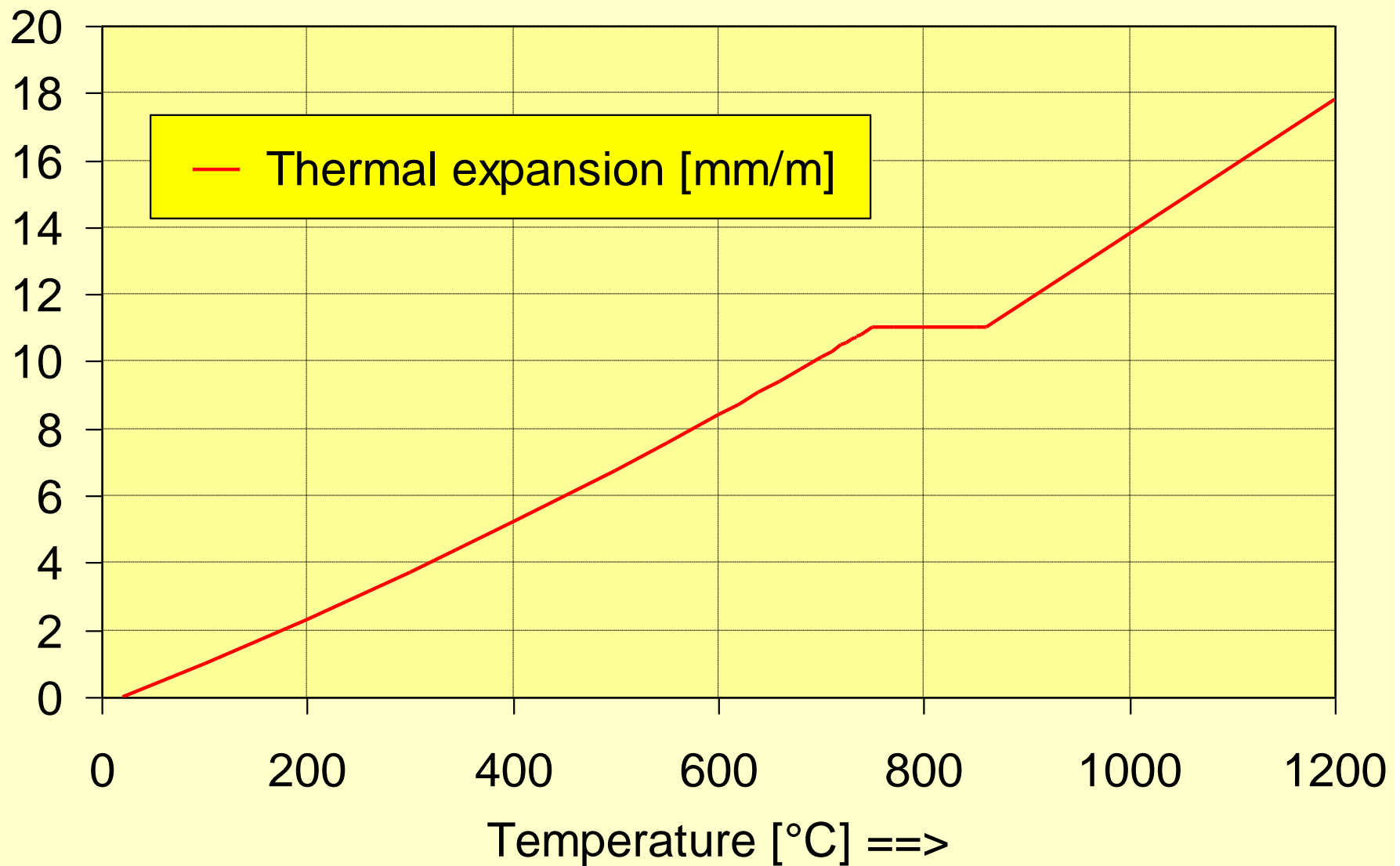
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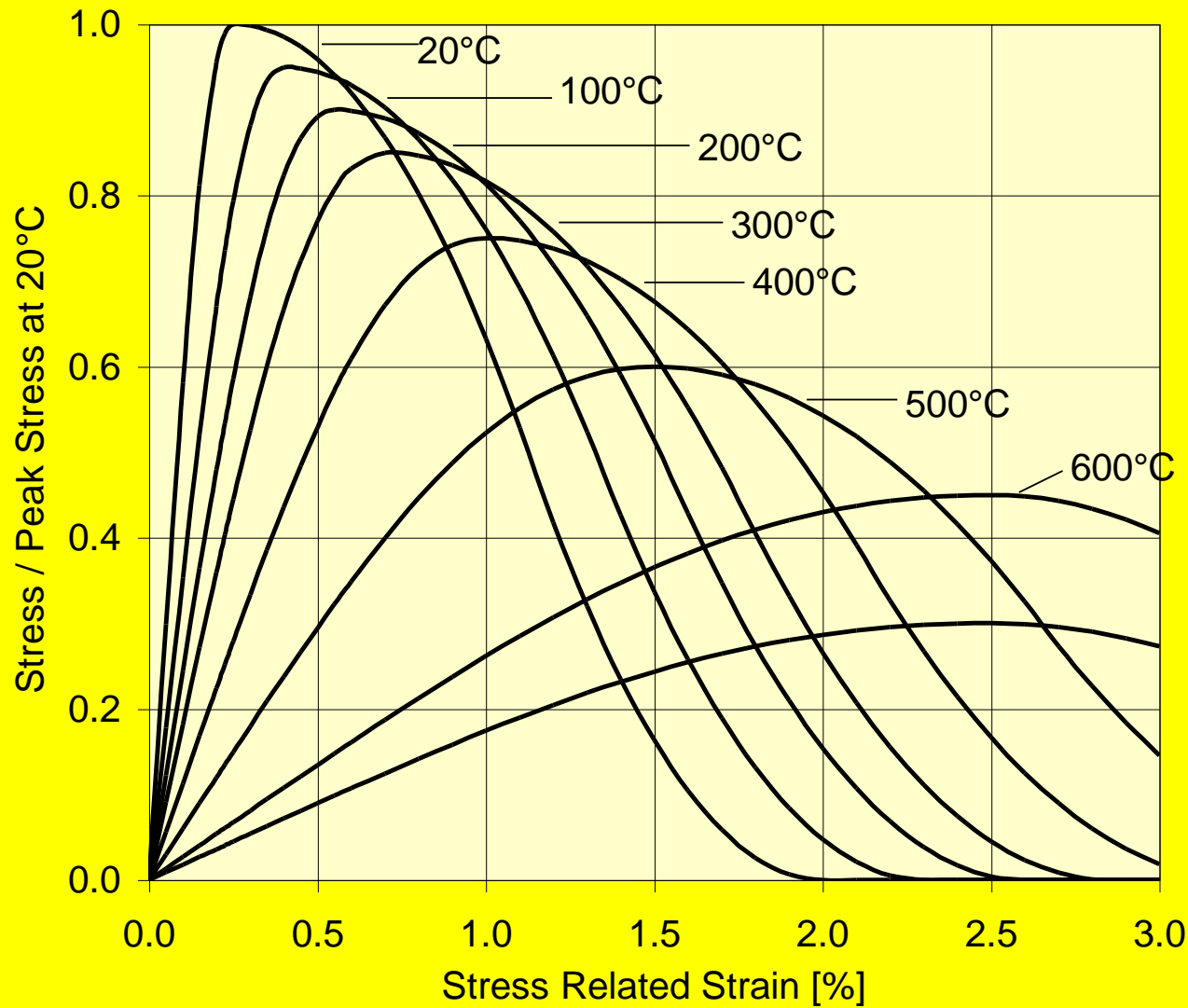
Stress-strain relationship in steel

Descending branch.
Is considered in SAFIR

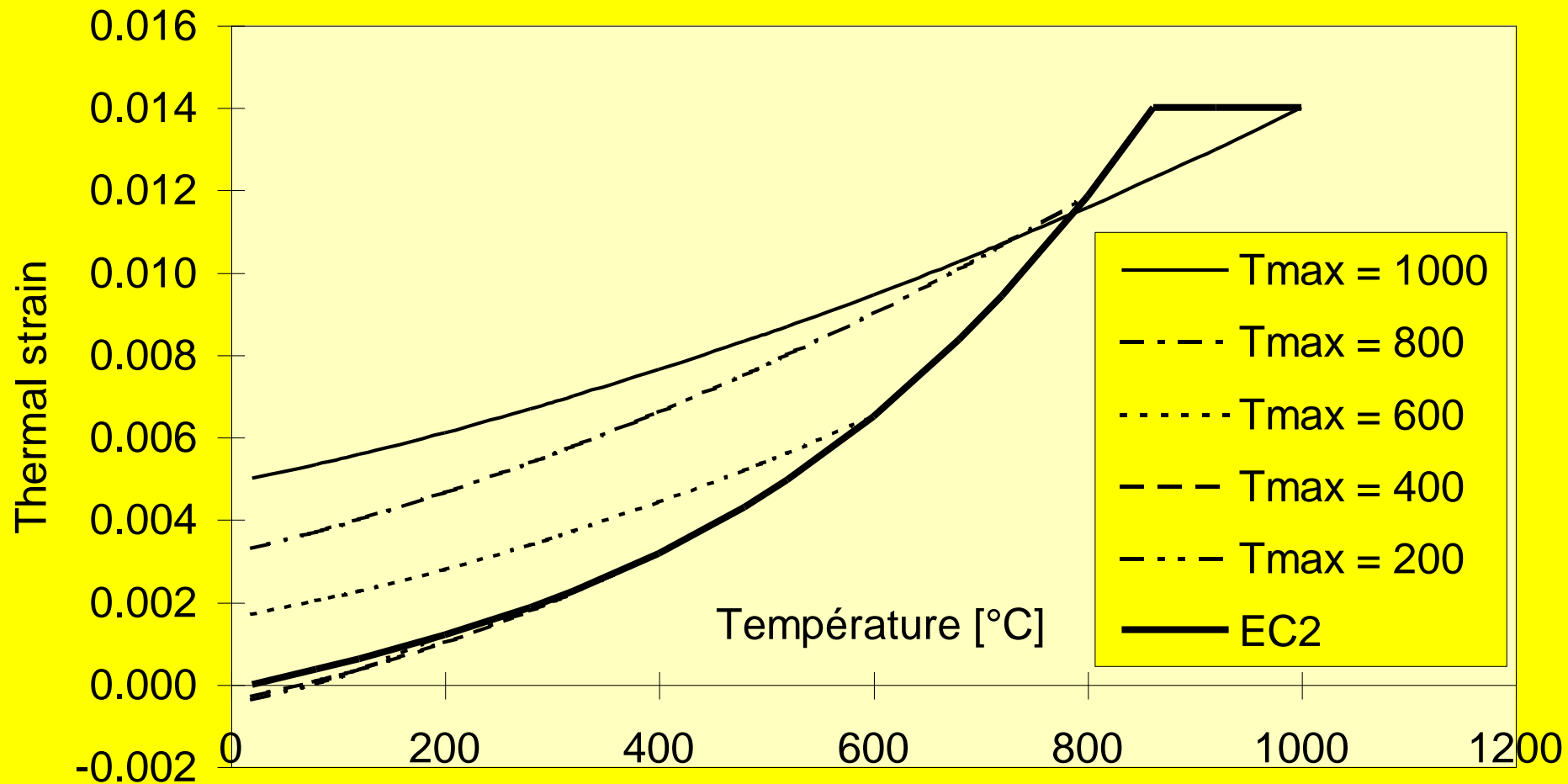




Thermal expansion in steel



Stress-Strain relationship in concrete



Thermal expansion of concrete
Non reversible during cooling

TRANSLATE ilocal iglobal

Section 1

Material 1 (steel)
Material 2 (concrete)

Section 2

Material 1 (concrete)
Material 2 (timber)

TRANSLATE 1 1
TRANSLATE 2 3

TRANSLATE 1 3
TRANSLATE 2 2

Structure

Material 1 (steel)
Material 2 (timber)
Material 3 (concrete)

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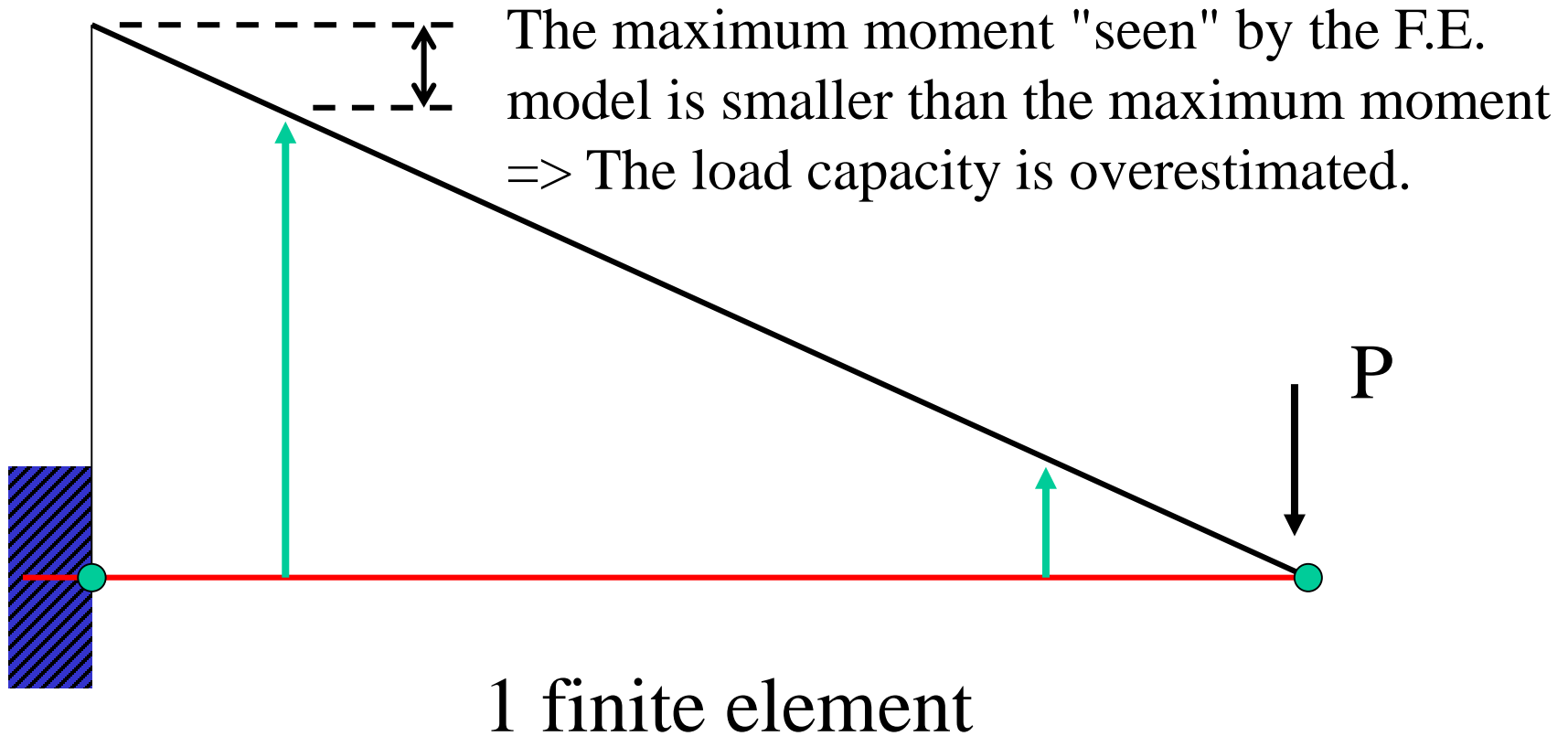
Results at the Gaussian integration points for a 3D beam:

- $N, M_y, M_z, M_t, V_y, V_z$
- EA, ES, EI (PRNEIBEAM)
- + at each fiber: $\sigma, E_t, \varepsilon_m$ (optional)

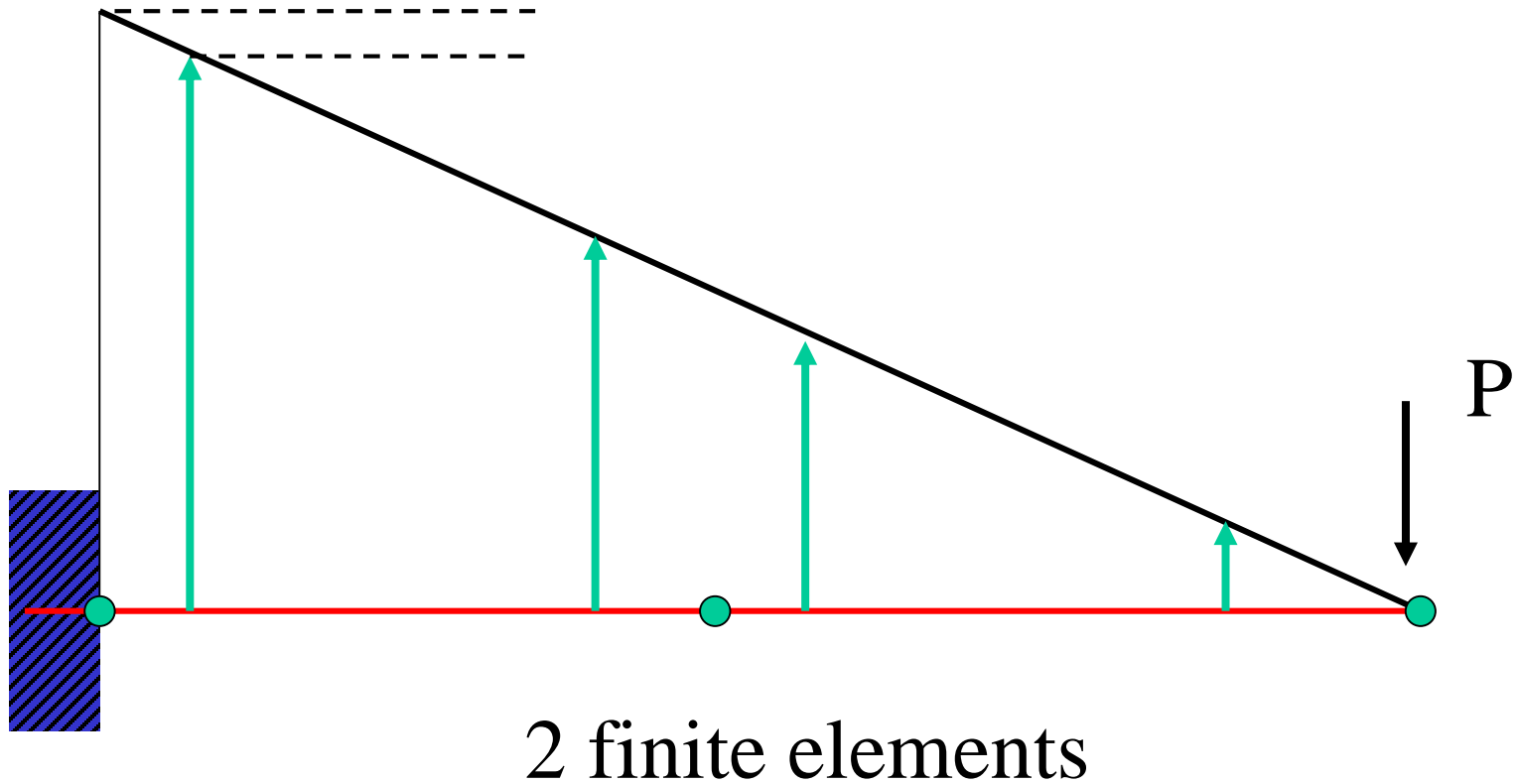


No point of integration at the ends of the element: consequence

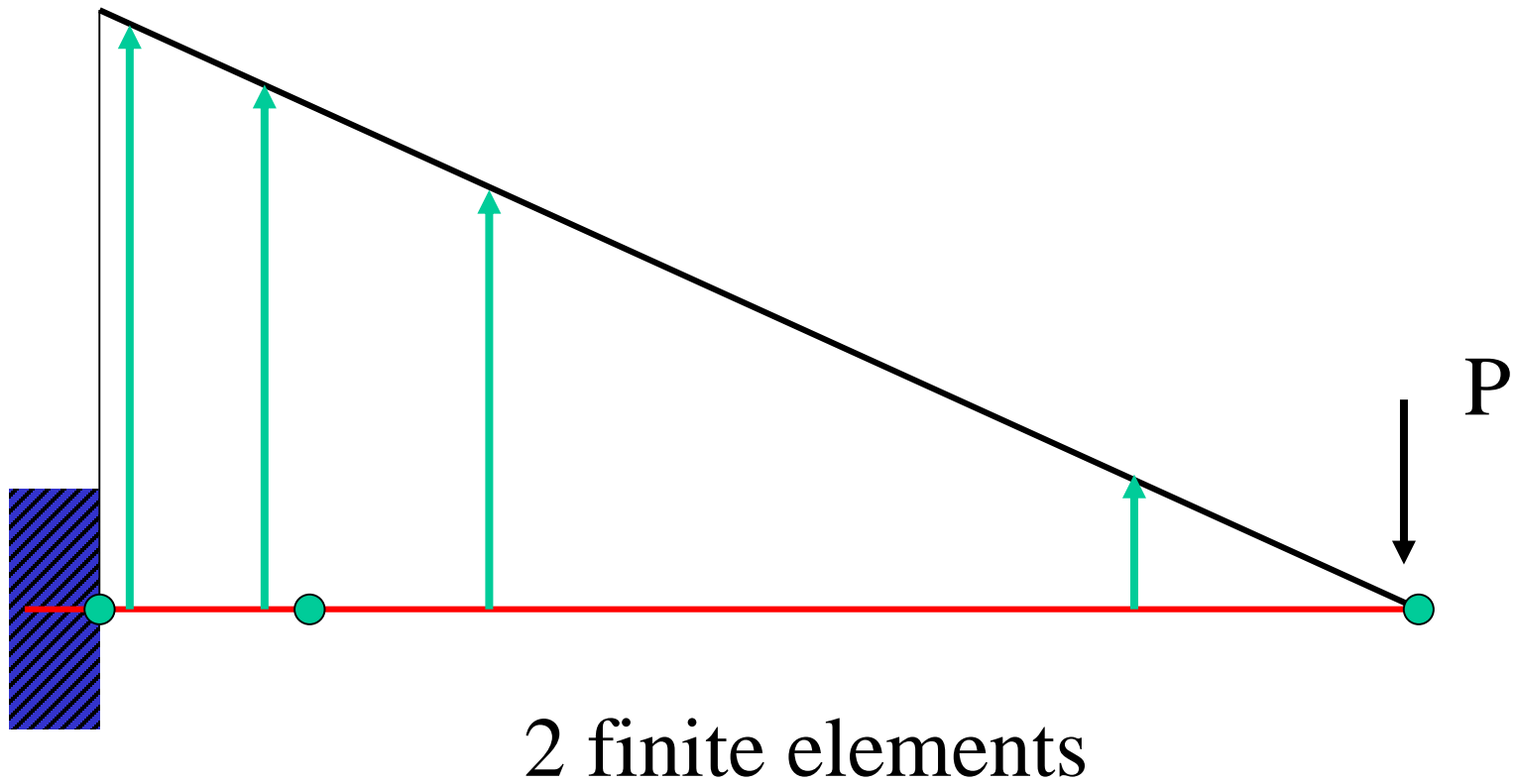
M (exact solution)



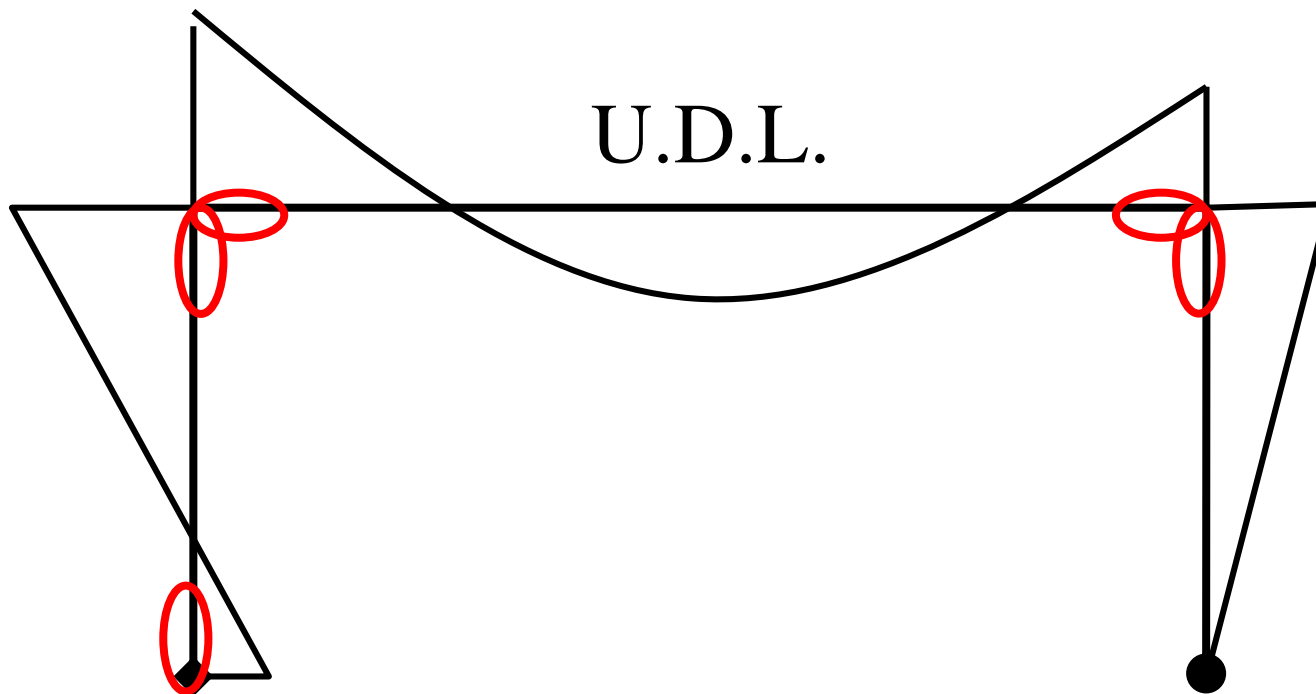
M (exact solution)



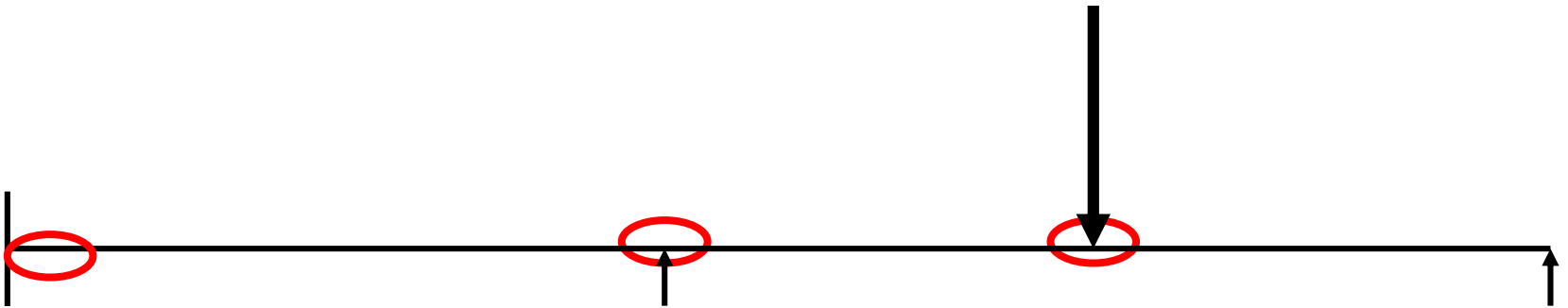
M (exact solution)



Conclusions: Beam F.E. not too long in the zones of peaks (= maximum or minimum) in the bending moment diagram



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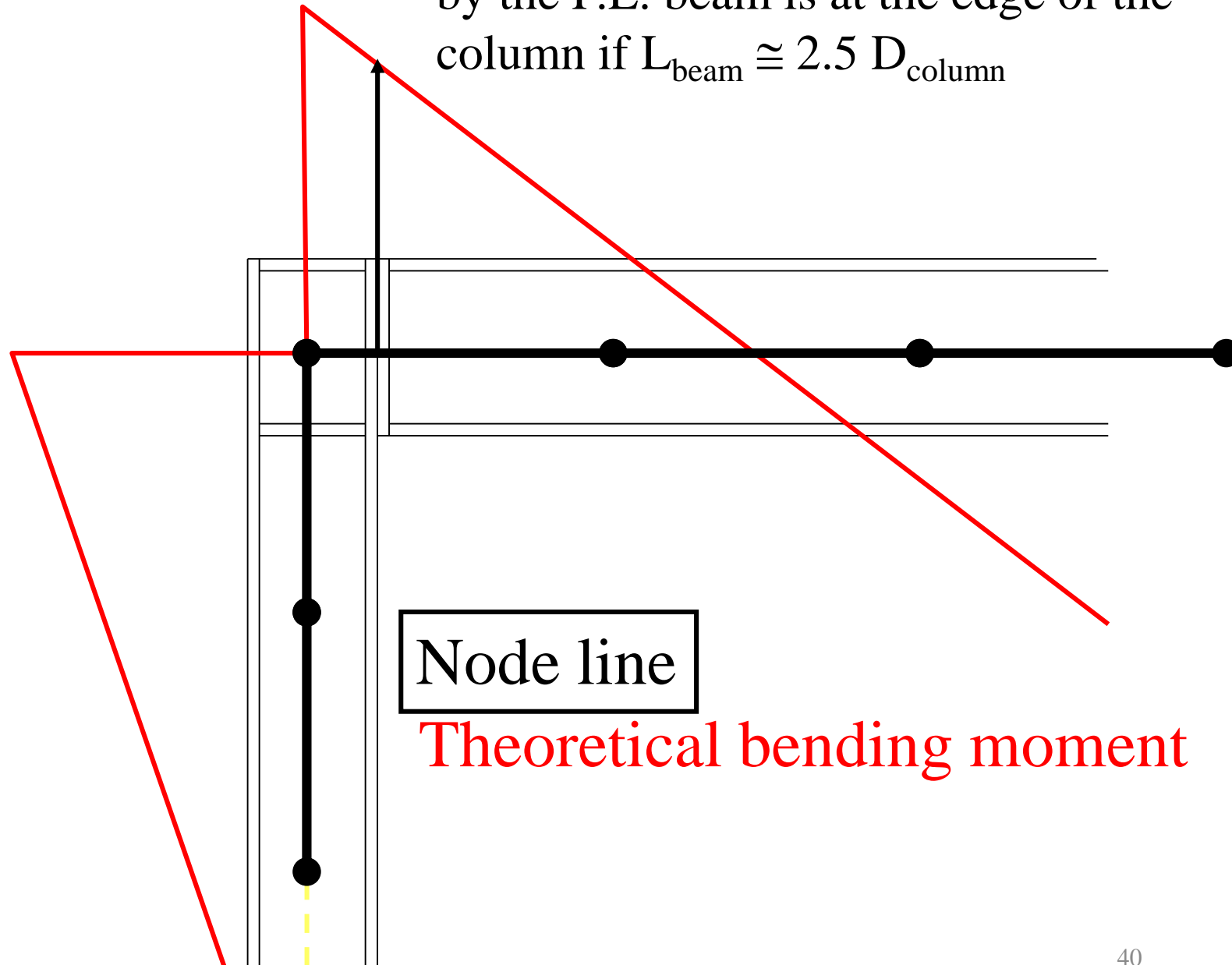


Conclusions: Beam F.E. not too long in the zones of peaks in the bending moment diagram

How long is too long ?

$$L_{\text{beam}} \geq D_{\text{beam}}$$

Position of the biggest moment seen
by the F.E. beam is at the edge of the
column if $L_{\text{beam}} \cong 2.5 D_{\text{column}}$



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$$\text{Nodal forces} = \int_V \sigma f(x, y, z) dV$$

$$\text{Stiffness} = \int_V E f(x, y, z) dV$$

$$\begin{aligned}
 \text{Nodal forces} &= \int_V \sigma f(x, y, z) dV \\
 &= \int_0^L \int_S \sigma f(x, y, z) dS dL
 \end{aligned}$$

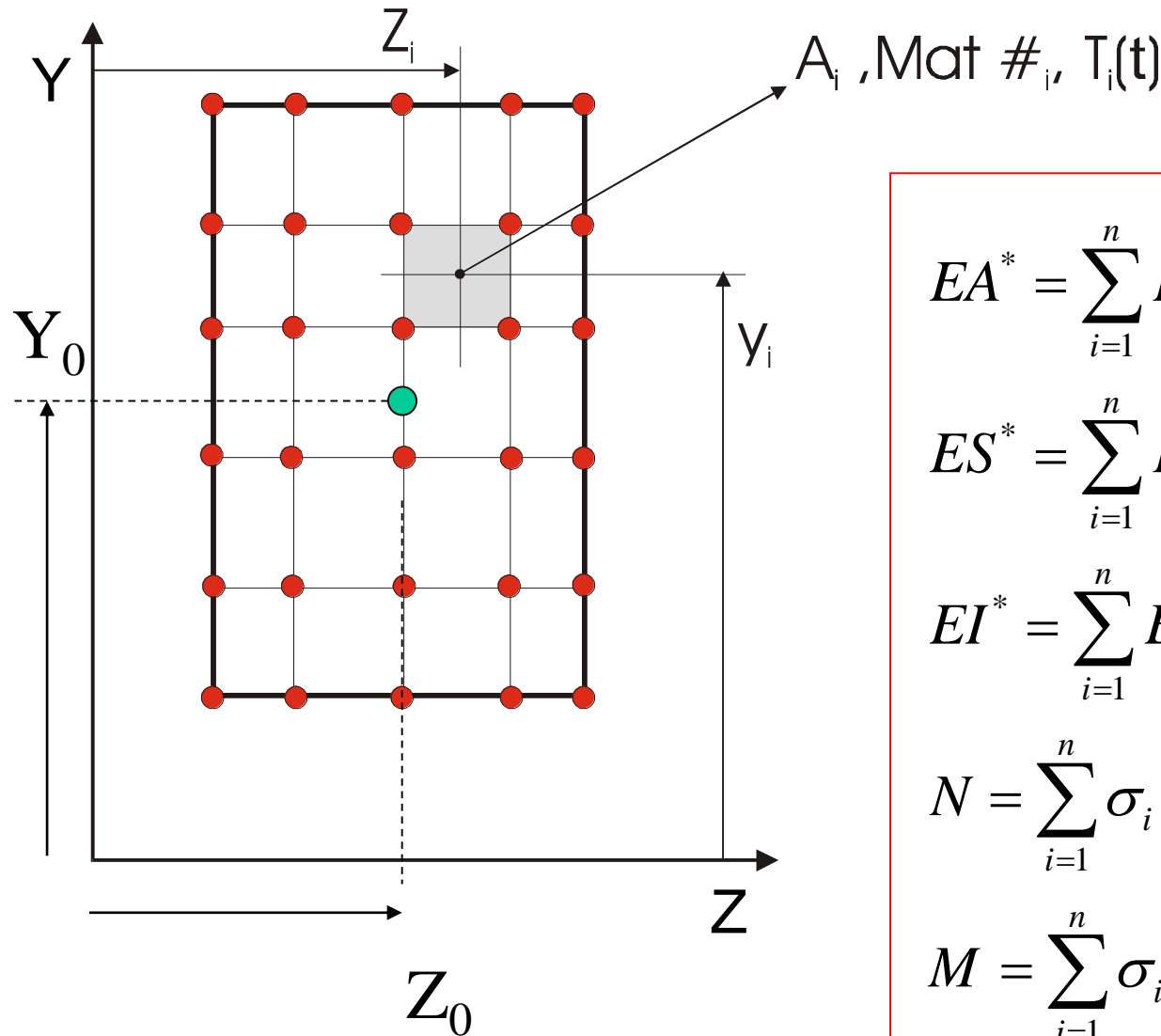
$$\begin{aligned}
 \text{Stiffness} &= \int_V E f(x, y, z) dV \\
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$$\begin{aligned}
 \text{Nodal forces} &= \int_V \sigma f(x, y, z) dV \\
 &= \int_0^L \int_S \sigma f(x, y, z) dS dL \\
 &= \sum_{i=1}^{NG} \omega_i \int_S \sigma f(x, y, z) dS
 \end{aligned}$$

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 \text{Stiffness} &= \int_V E f(x, y, z) dV \\
 &= \int_0^L \int_S E f(x, y, z) dS dL \\
 &= \sum_{i=1}^{NG} \omega_i \int_S E f(x, y, z) dS
 \end{aligned}$$

Integrations on the surface are made NG times, using the discretisation of the thermal analysis

Integration on the section of the beam element



$$EA^* = \sum_{i=1}^n E_i(T_i) \times A_i$$

$$ES^* = \sum_{i=1}^n E_i(T_i) \times (y_i - y_0) A_i$$

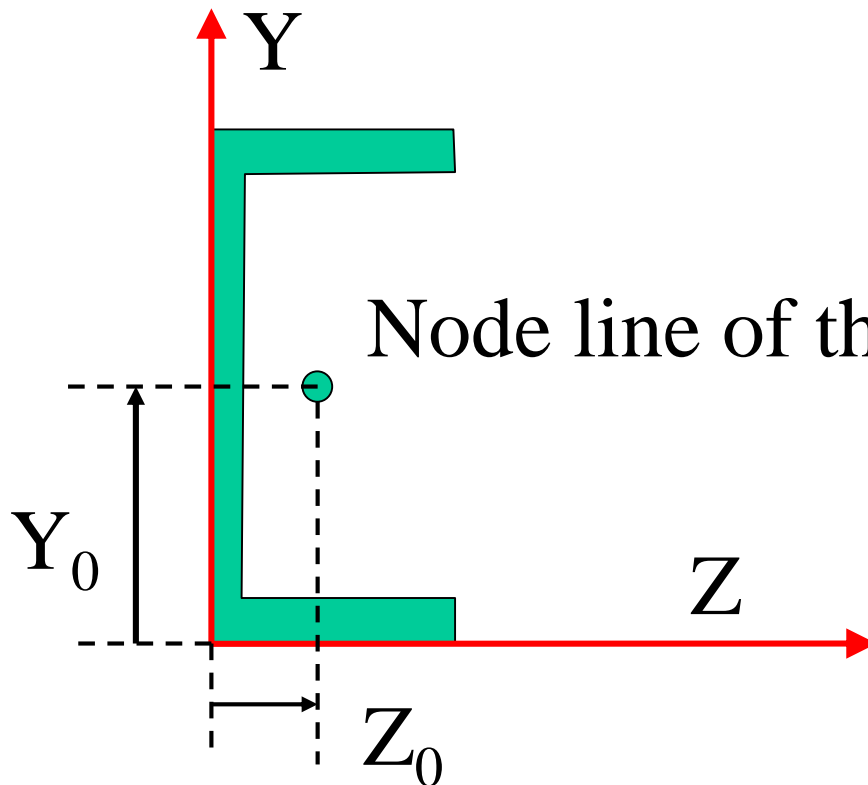
$$EI^* = \sum_{i=1}^n E_i(T_i) \times (y_i - y_0)^2 A_i$$

$$N = \sum_{i=1}^n \sigma_i(T_i) \times A_i$$

$$M = \sum_{i=1}^n \sigma_i(T_i) \times (y_i - y_0) A_i$$

Structure of the input file for thermal analyses

NODELINE	Y_0	Z_0
YC_ZC	Y_c	Z_c

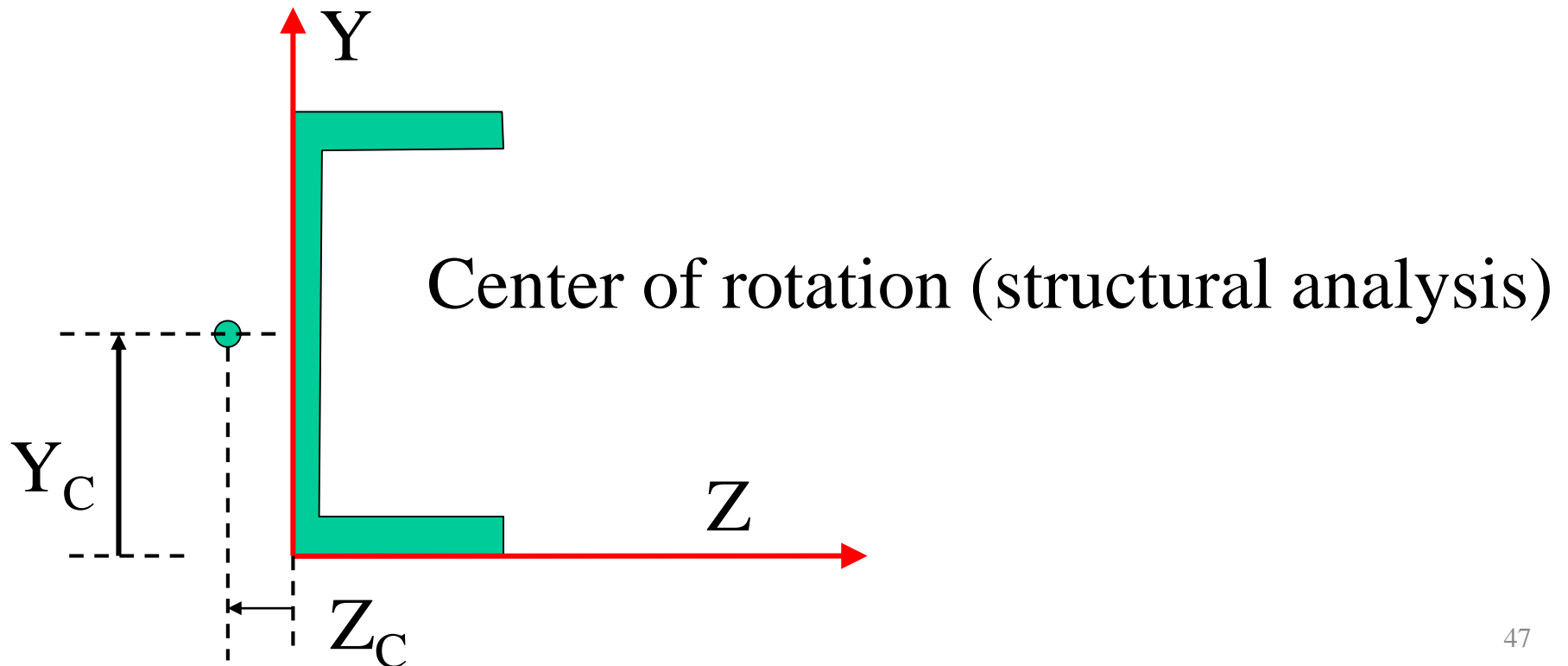


Node line of the structural analysis

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

Structure of the input file for thermal analyses

NODELINE	Y_0	Z_0
YC_ZC	Y_c	Z_c

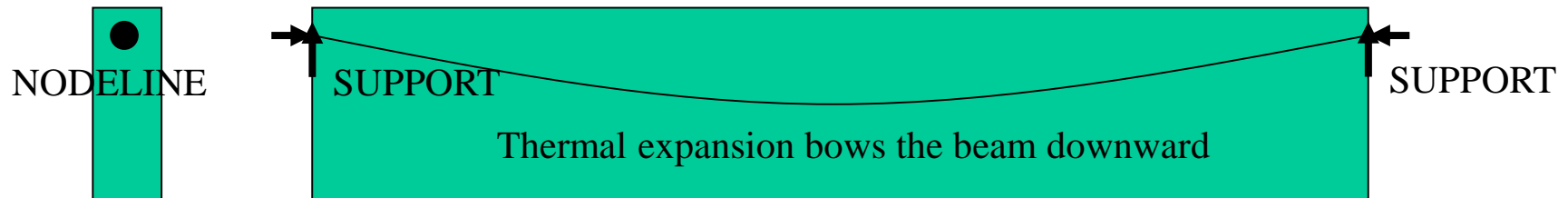
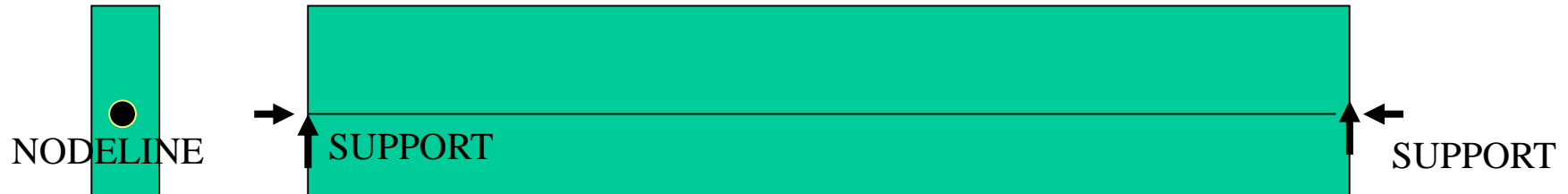
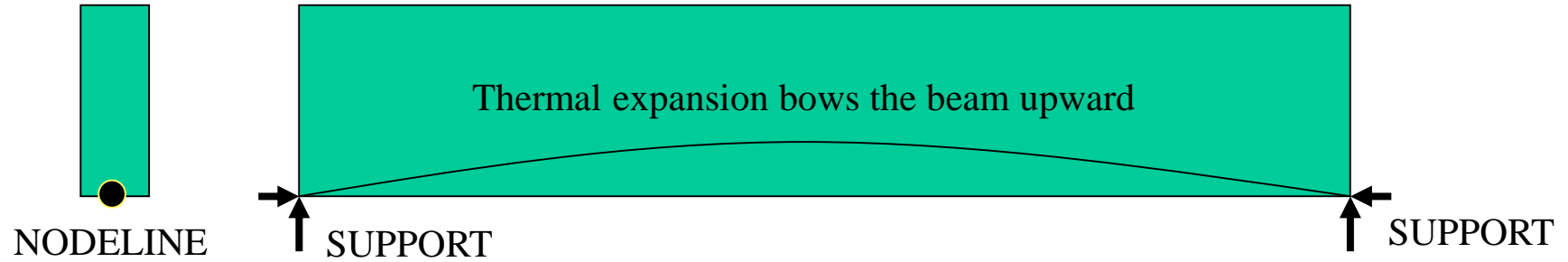


The beam elements are connected in the mechanical analysis by their end nodes, which are located on the nodeline in the section.

Concentrated forces and restrained Degrees of Freedom are applied to the nodes, hence at the node line.

The bending moments are also calculated and given with respect to this node line.

NODELINE Y0 Z0



NODELINE

Y0

Z0

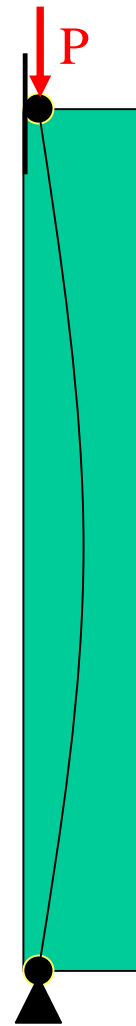
NODELINE
in the center



No bowing
(until buckling)

SUPPORT

NODELINE
on the edge

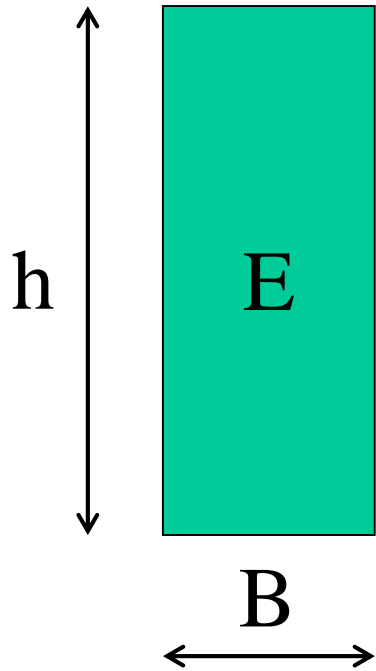


First order
bowing

SUPPORT

First order moments = 0 in both cases

Integration on the section of the beam element



$$EA^* = \sum_{i=1}^n E_i (T_i) \times A_i = EBh$$

$$EI^* = \sum_{i=1}^n E_i (T_i) \times (y_i - y_0)^2 A_i \neq EBh^3/12$$

NFIBERBEAM 450

FIBERS

The .TEM file

NODELINE .200E-01 .000E+00

YC ZC .000E+00 .000E+00

.333500E-02	.333333E-02	.889333E-04	1	.000000E+00
-.333500E-02	.333333E-02	.889333E-04	1	.000000E+00
.333500E-02	.100000E-01	.889333E-04	1	.000000E+00
-.333500E-02	.100000E-01	.889333E-04	1	.000000E+00
.333500E-02	.166667E-01	.889333E-04	1	.000000E+00
-.333500E-02	.166667E-01	.889333E-04	1	.000000E+00
.333500E-02	.233333E-01	.889333E-04	1	.000000E+00
-.333500E-02	.233333E-01	.889333E-04	1	.000000E+00

y_i z_i A_i Mat_i $\sigma_{r,i}$

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The 3D beam finite element needs the stiffness in torsion of the section.

SAFIR can calculate this stiffness.

PRINCIPLE

Use the same discretization as for the thermal analysis.

No fire curves.

Introduce appropriate material properties and fixations.

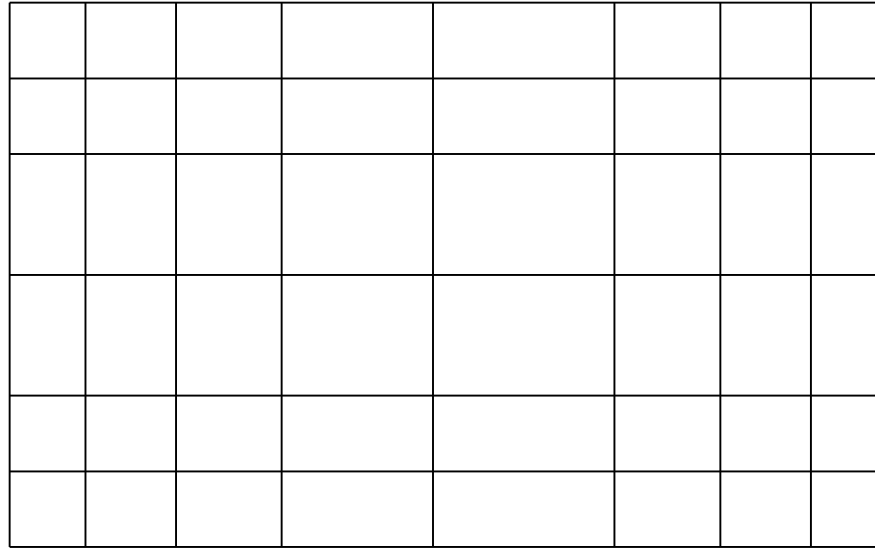
Introduce the result of the torsional analysis in the .TEM file.

Note: the calculated stiffness GJ is elastic, at room temperature. It is kept constant during the simulation.

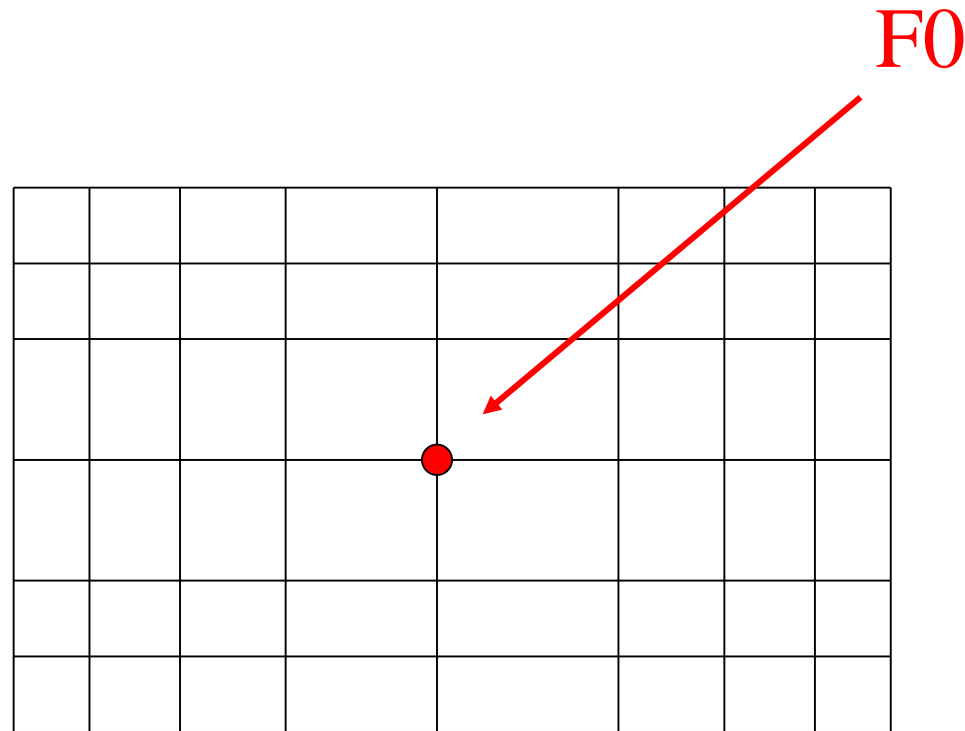
⇒ possibility to reduce GJ arbitrarily.

⇒ The beam FE is not appropriate if torsion is the main load path.

Basic principle:SAFIR calculates the value of the warping function ω at the nodes



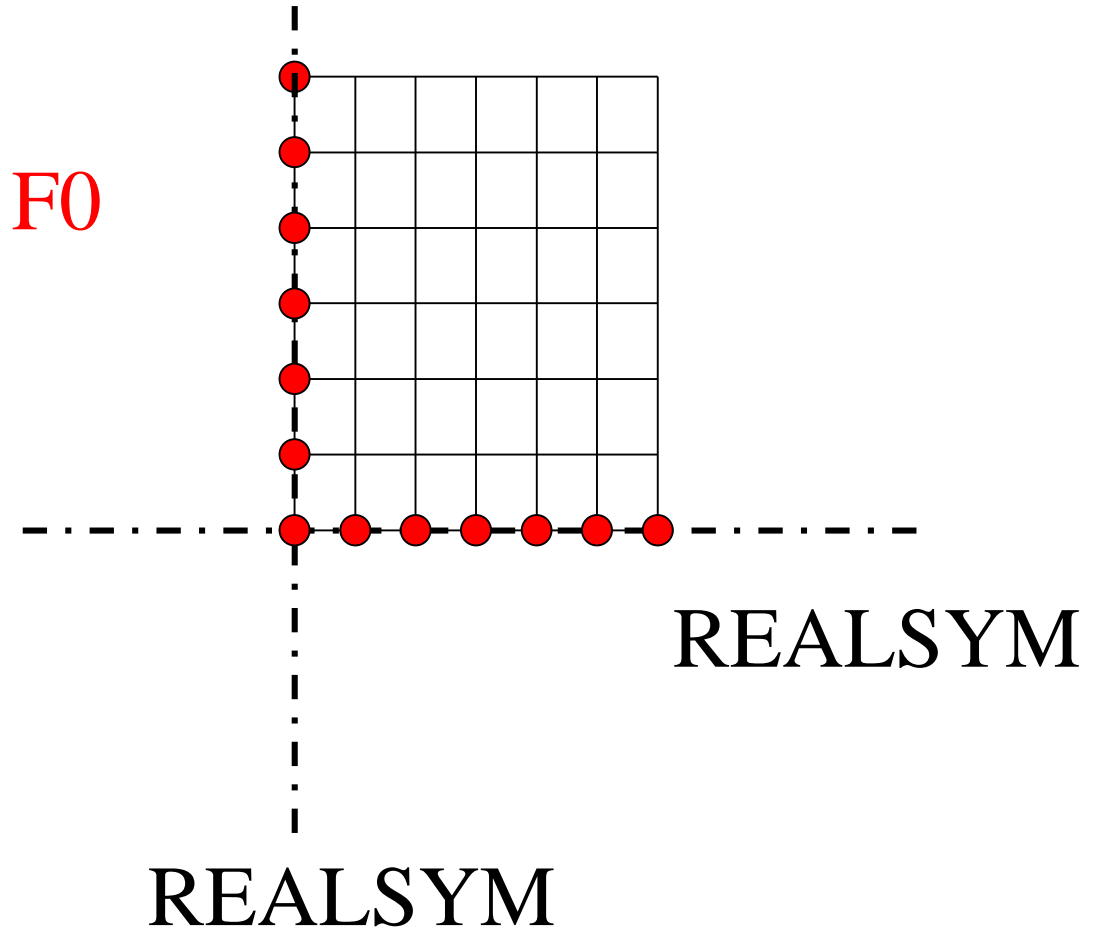
The derivatives of the warping function $d\omega/dy$ and $d\omega/dz$ are used to compute the stiffness in torsion GJ .
 \Rightarrow The solution can vary by a constant and GJ remains the same.



But, in order to have to correct behaviour, it is **NECESSARY** to fix the solution to 0 on the center of rotation.

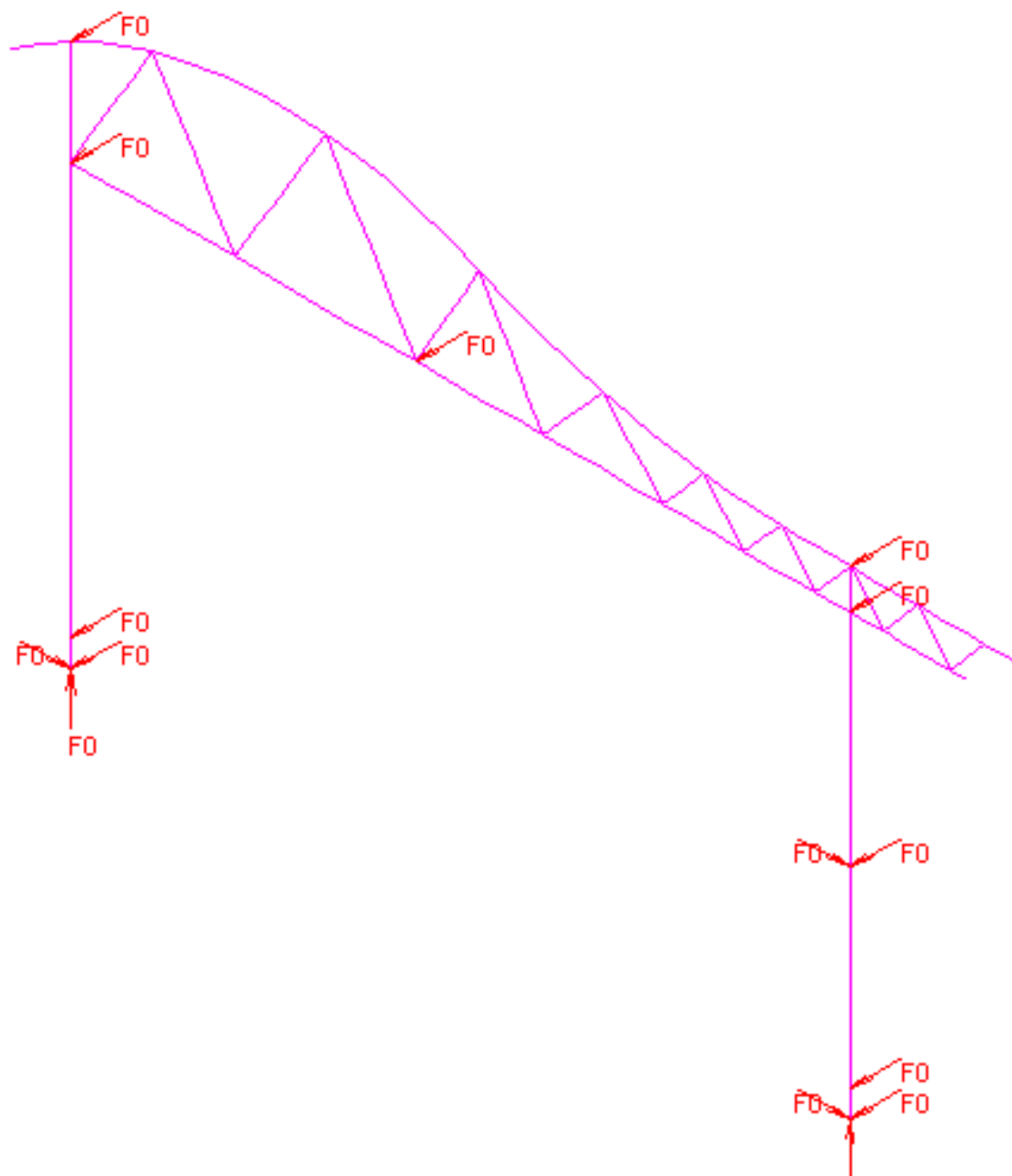
Note: a check has been added and SAFIR will not run if there is no single node fixed (check the .OUT file of the torsion analysis if you performed the torsion analysis at the same time as the thermal analysis in GiD)

If you use symmetries, the warping function must be set to 0 on the axes of symmetry.



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IMPOSED DOF PLOT



Diamond 2001

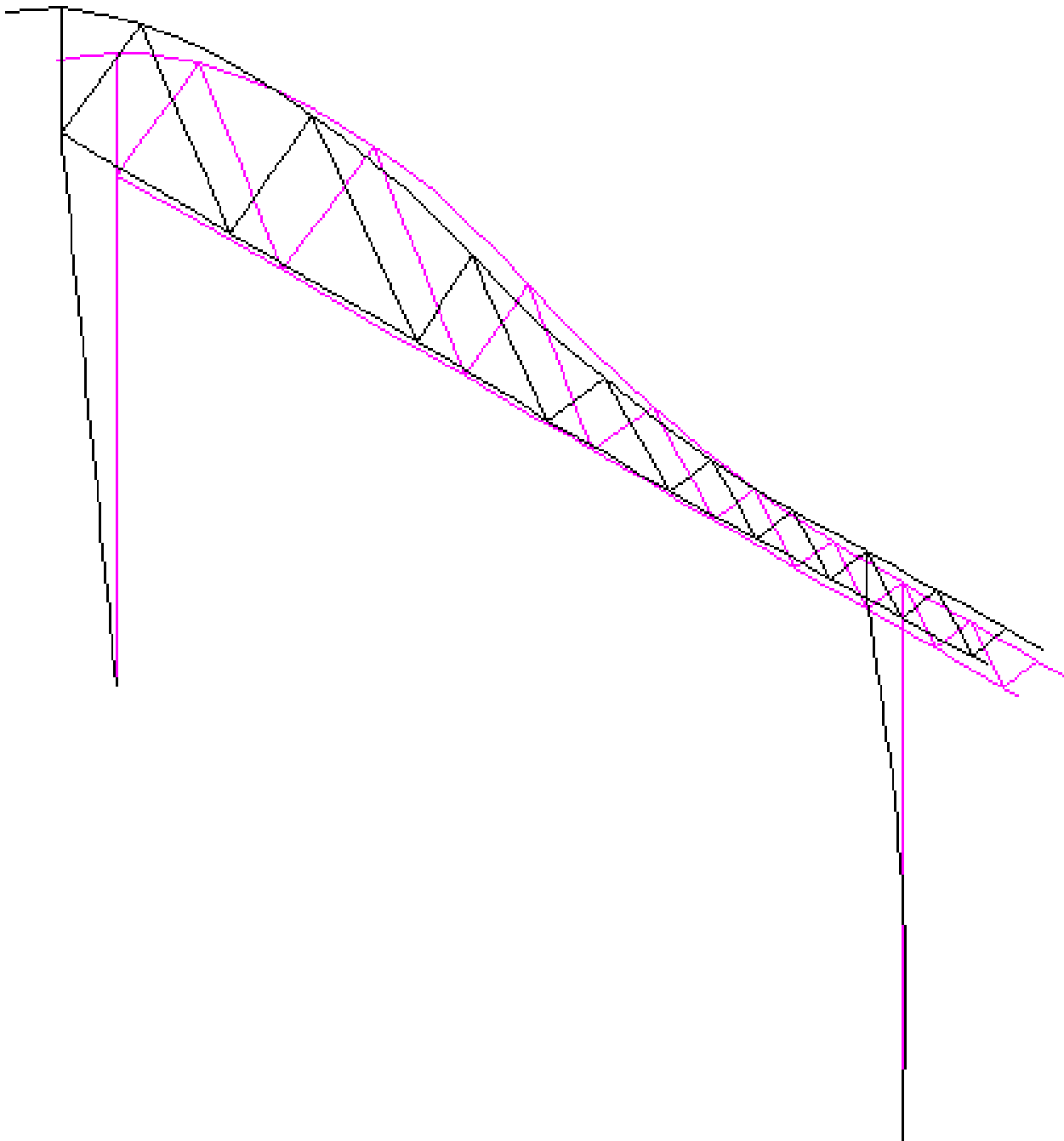
FILE: portique4.OUT

NODES: 356

ELEMENTS: 185

TIME: 752

DISPLACEMENT PLOT



Diamond 2001

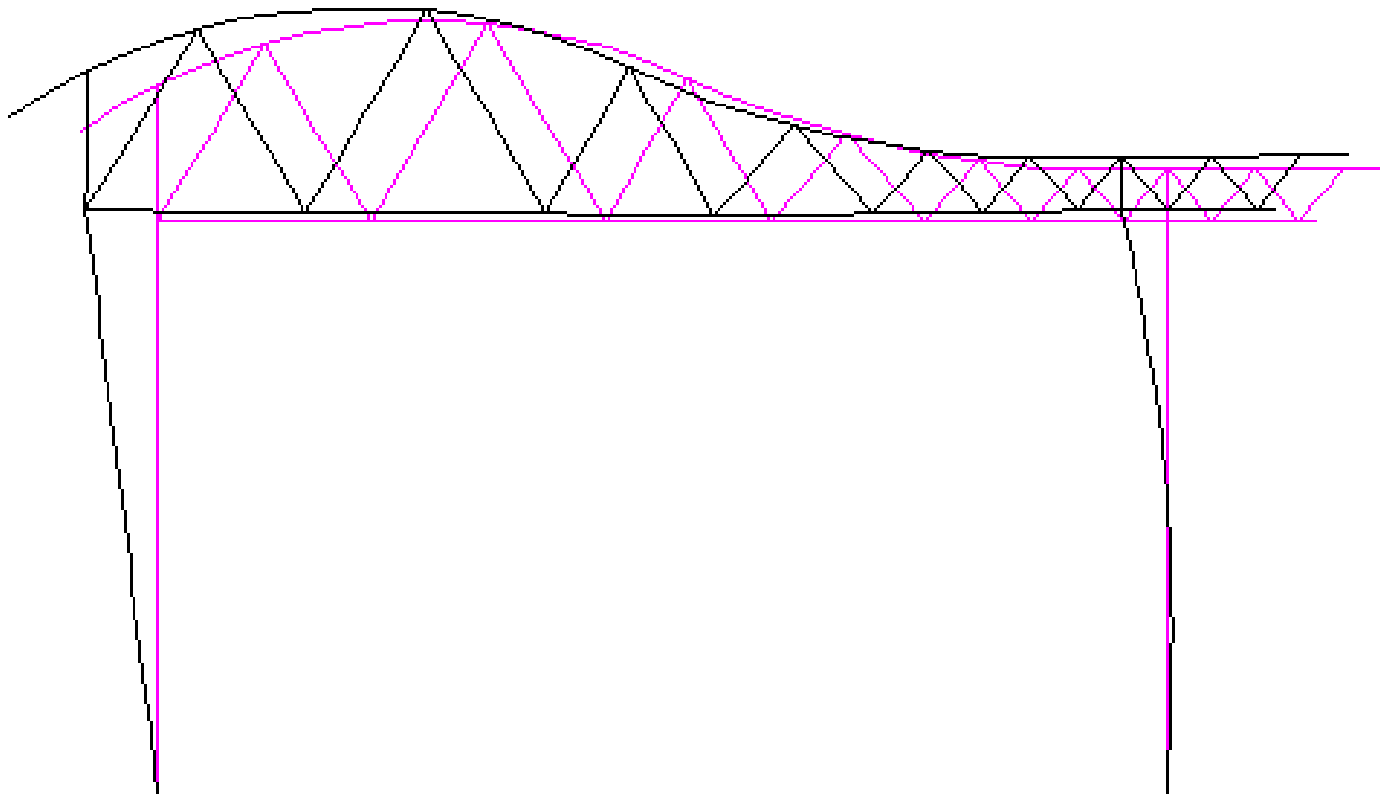
FILE: portique4.OUT

NODES: 356

ELEMENTS: 185

TIME: 752

DISPLACEMENT PLOT





Diamond 2001

FILE: portique4.OUT

NODES: 356

ELEMENTS: 185

TIME: 752

DISPLACEMENT PLOT

Diamond 2004 for SAFIR

FILE: bat

NODES: 1077

BEAMS: 520

TRUSSES: 0

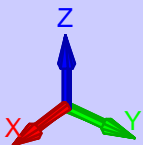
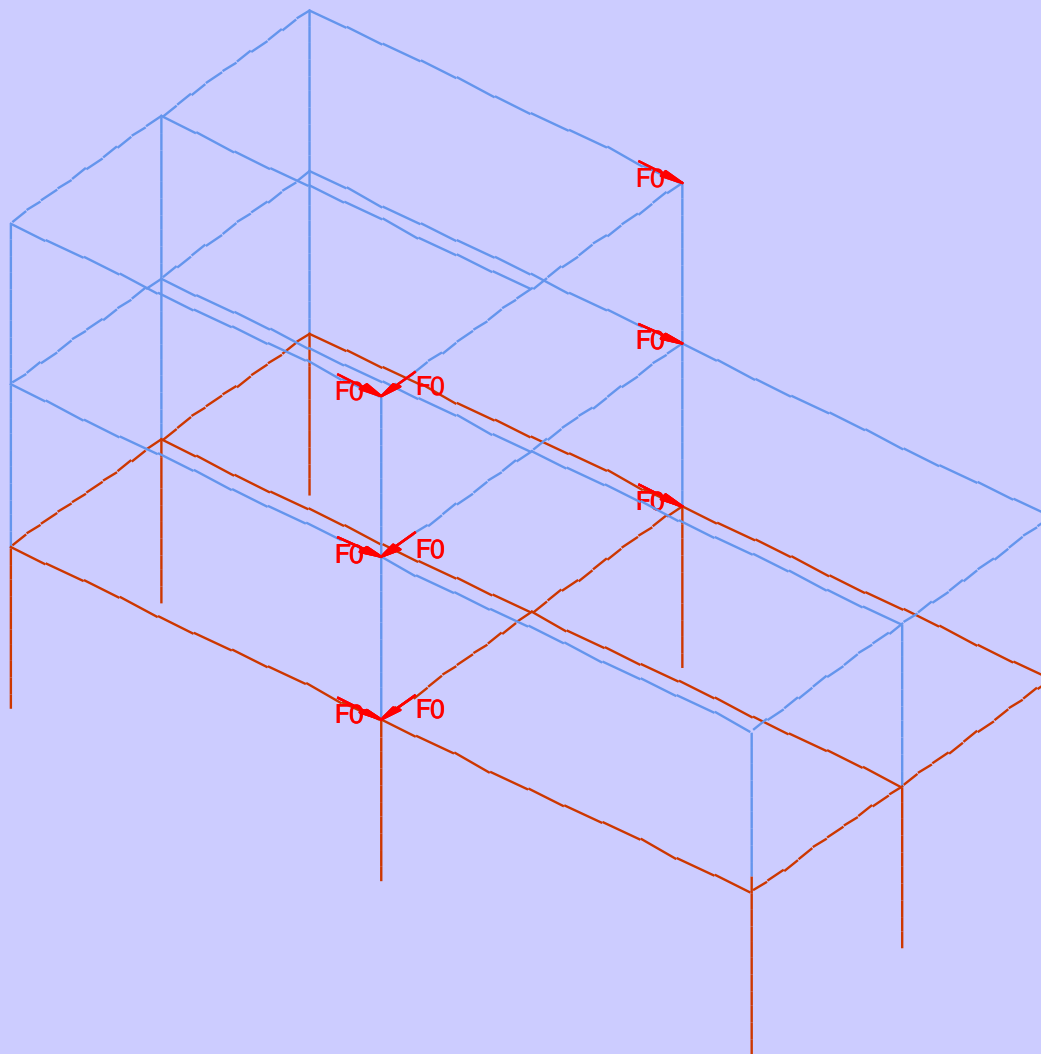
SHELLS: 0

SOILS: 0

BEAMS PLOT

IMPOSED DOF PLOT

 hea260fort.tem
 hea260fortC.tem



Diamond 2004 for SAFIR

FILE: bat

NODES: 1077

BEAMS: 520

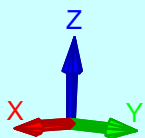
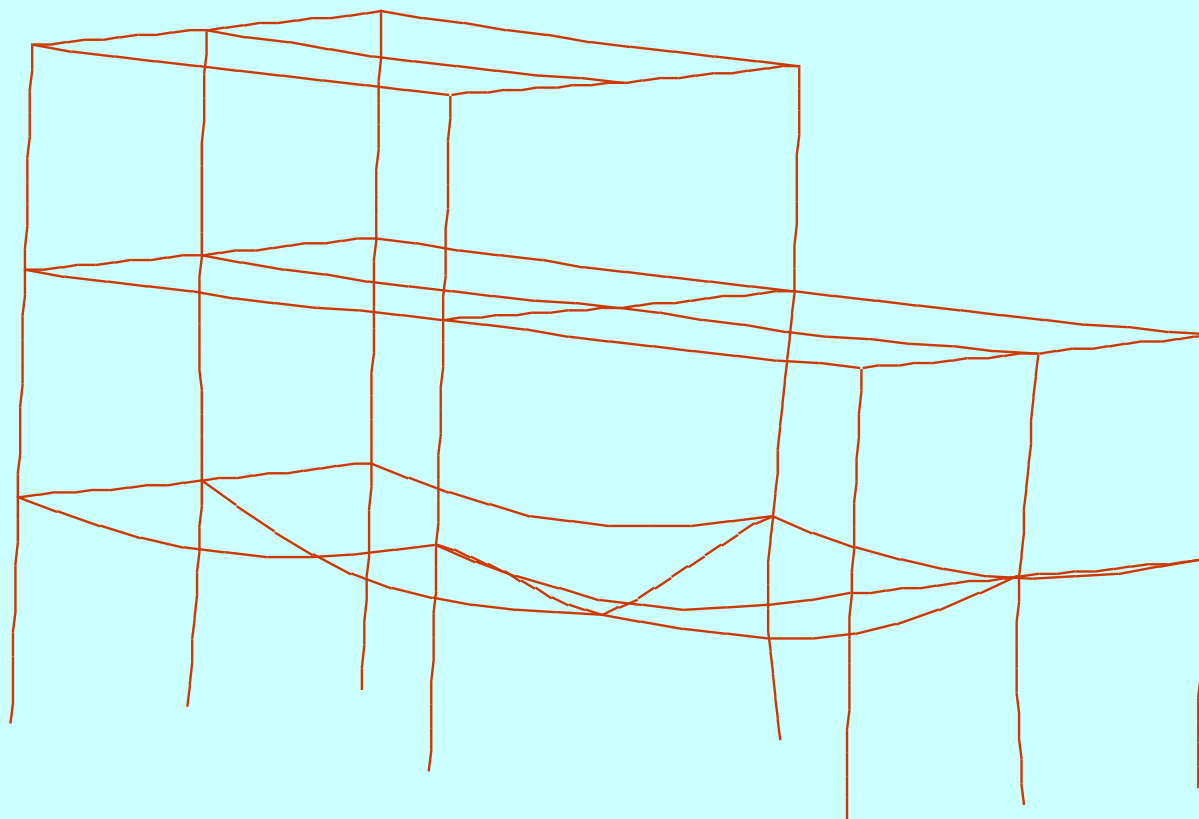
TRUSSES: 0

SHELLS: 0

SOILS: 0

DISPLACEMENT PLOT (x 1)

TIME: 3129.25 sec



5.0 E+00 m

Diamond 2004 for SAFIR

FILE: bat

NODES: 1077

BEAMS: 520

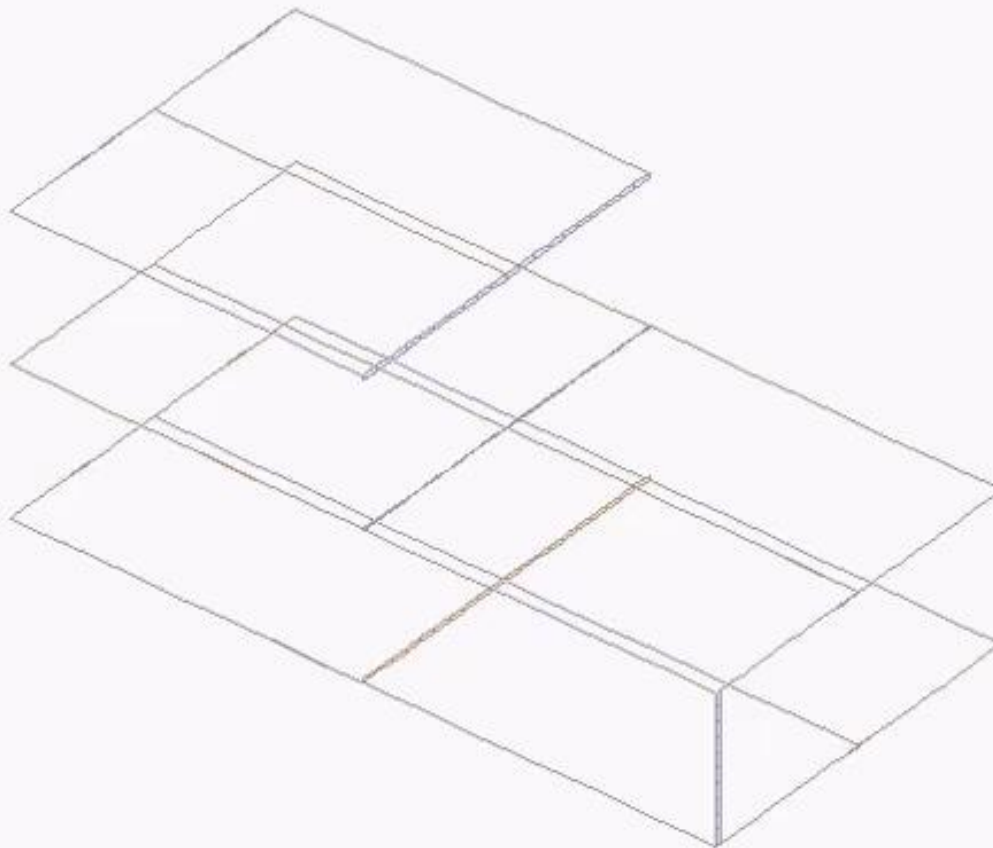
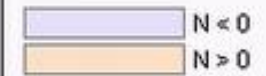
TRUSSES: 0

SHELLS: 0

SOILS: 0

AXIAL FORCE PLOT

TIME: 4 sec



5.0 E+05 N

Diamond 2004 for SAFIR

FILE: bat

NODES: 1077

BEAMS: 520

TRUSSES: 0

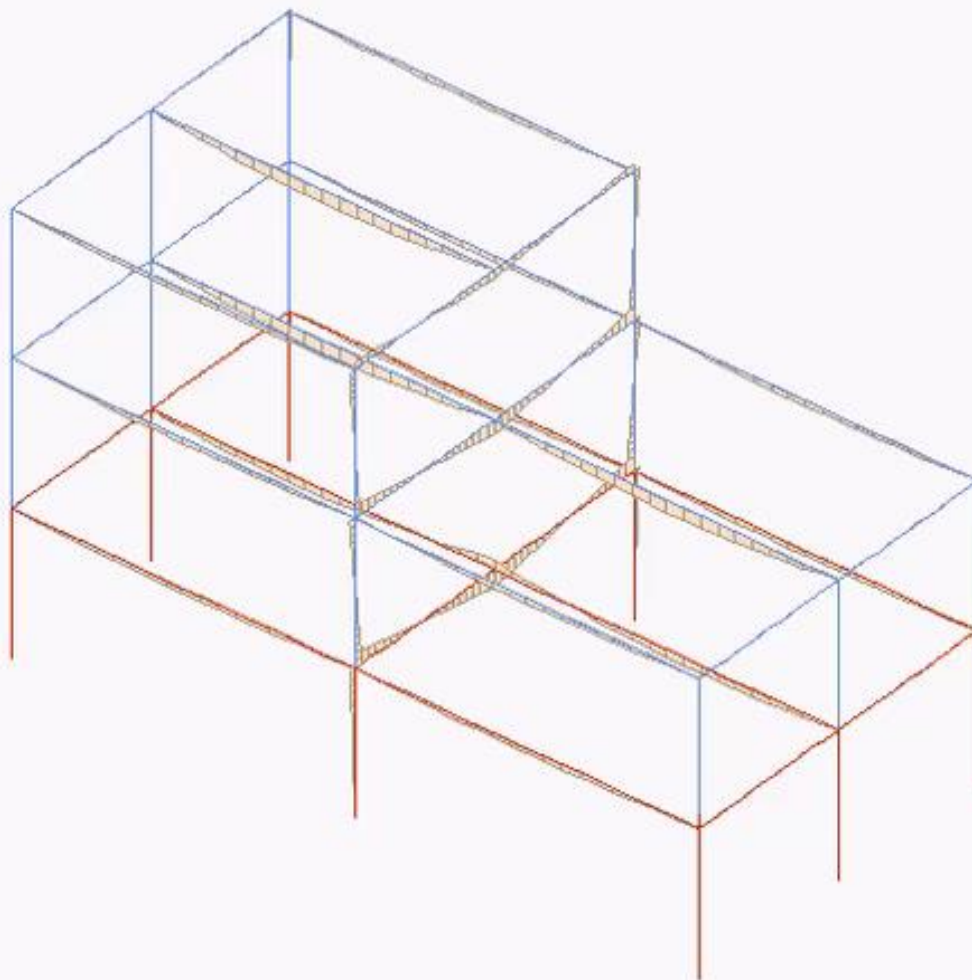
SHELLS: 0

SOILS: 0

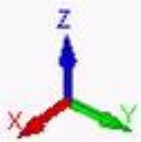
BEAMS PLOT

My BENDING MOMENT PLOT

TIME: 4 sec



5.0 E+05 Nm

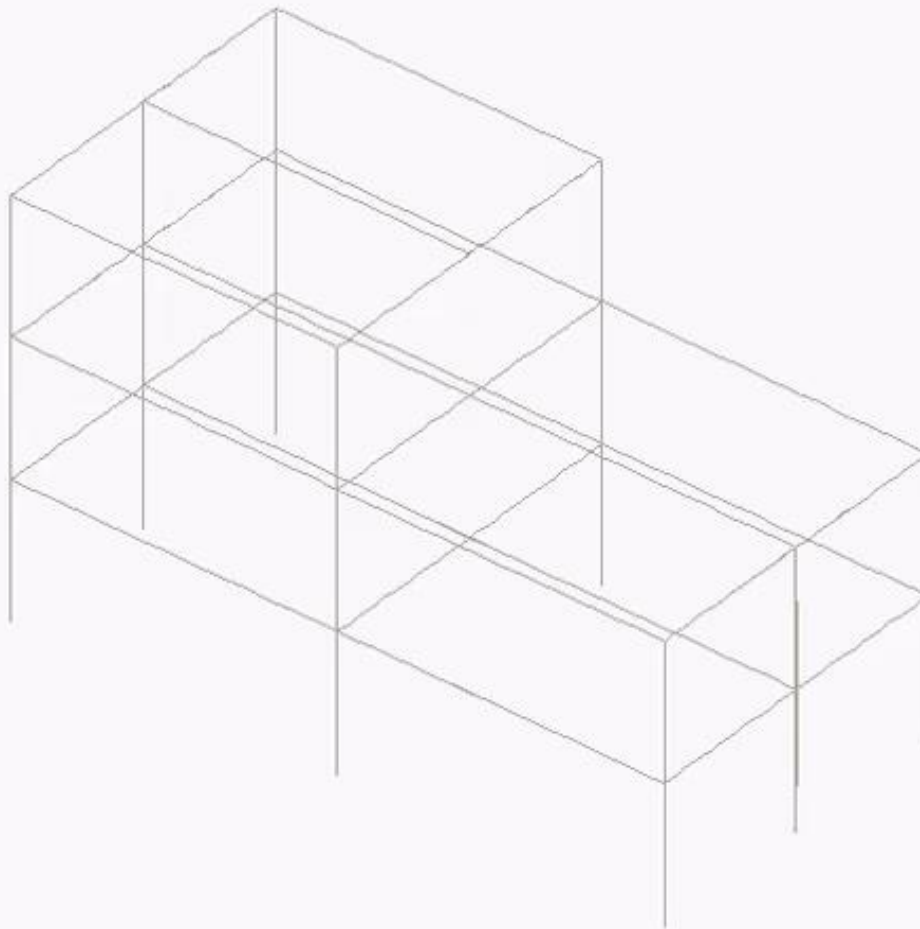


Diamond 2004 for SAFIR

FILE: bat
NODES: 1077
BEAMS: 520
TRUSSES: 0
SHELLS: 0
SOILS: 0

Mz BENDING MOMENT PLOT

TIME: 4 sec



— 5.0 E+04 Nm

FILE: Modelo_Def_3

NODES: 2624

BEAMS: 940

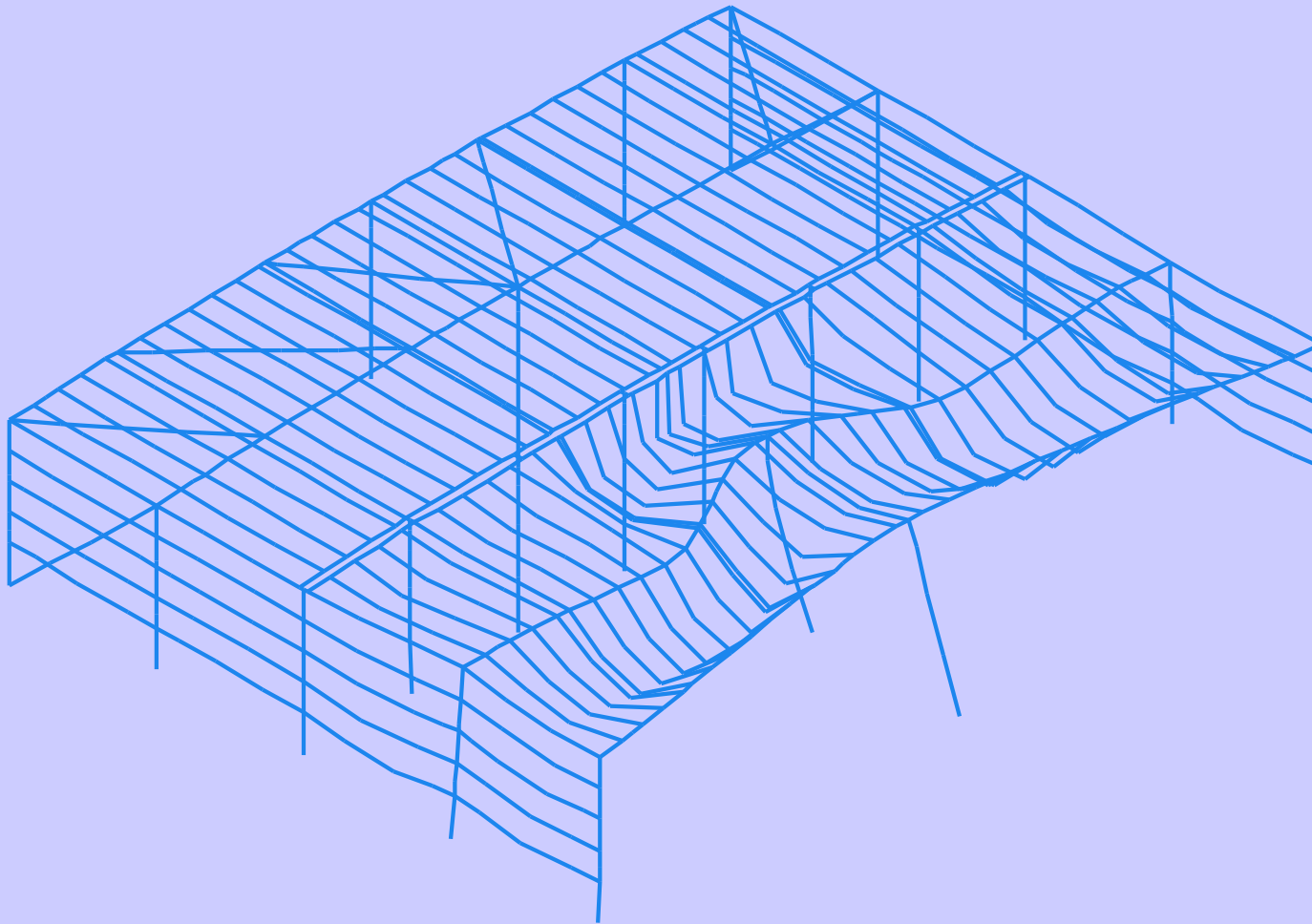
TRUSSES: 0

SHELLS: 0

SOILS: 0

DISPLACEMENT PLOT (x

TIME: 739.0464 sec



————— 1.0 E+01 m

Project FLUMILOG (CTICM)

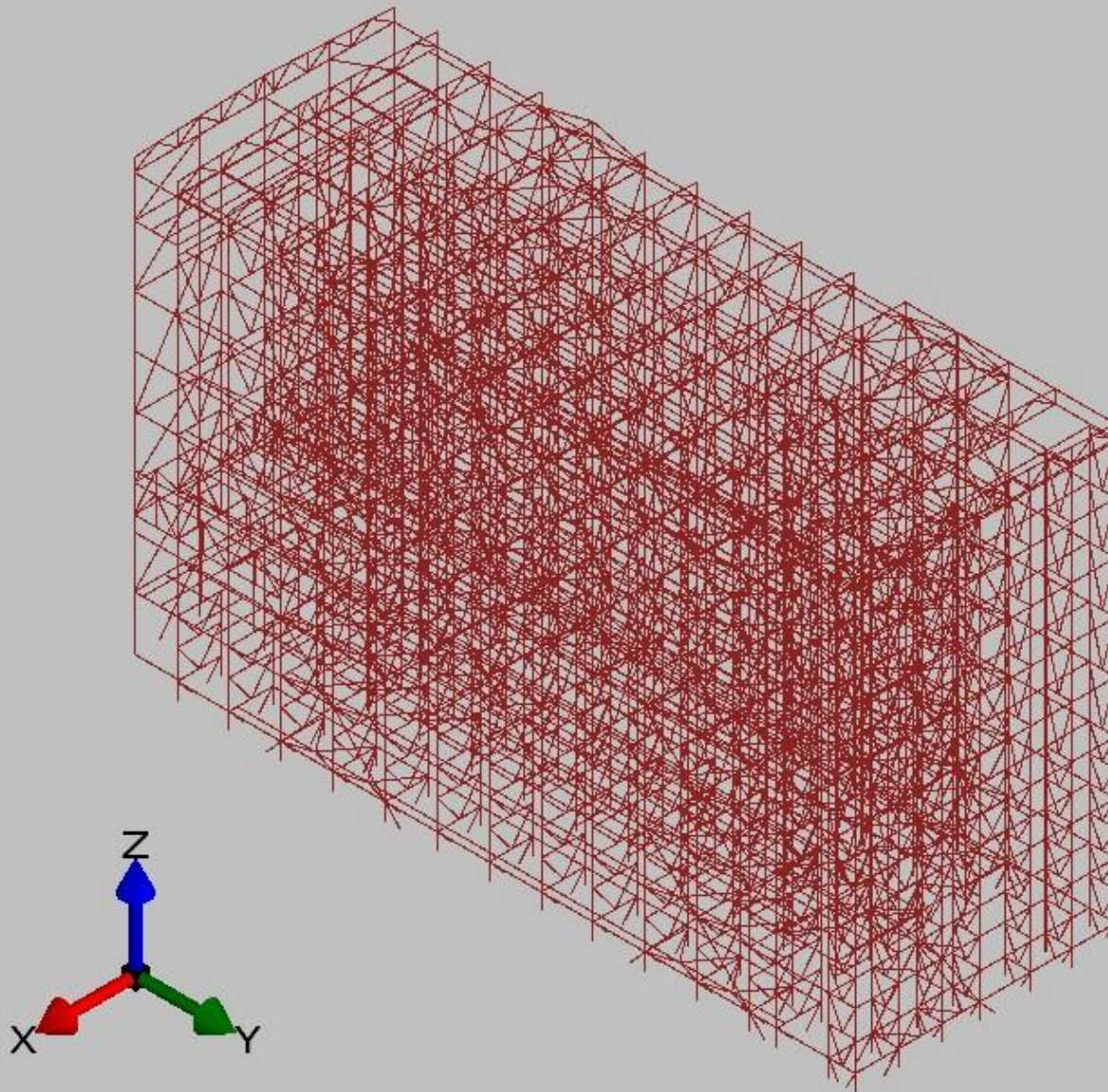








Steel rack structure (courtesy Angel Guerrero Castells, IGNIA, Spain)



Diamond 2016 for SAFIR

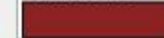
FILE : ItwmecX3

NODES : 28774

BEAMS : 14959

BEAMS PLOT

BEAMS :



Beam Element

Thank you

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

Jean Marc Franssen & Thomas Gernay

