



Finite element modelling of cold formed steel members under fire situation

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- ❑ Introduction
 - ✓ Fire safety in buildings
 - ✓ Cold formed steel profiles
- ❑ Basis for the numerical modelling of structures in fire
 - ✓ Fire action
 - ✓ Thermal analysis
 - ✓ Structural behaviour
- ❑ Numerical model development for cold formed profiles
 - ✓ Buckling modes
 - ✓ Initial imperfections
 - ✓ Material constitutive law
 - ✓ Numerical modelling of experimental fire test on cold formed z purlin
- ❑ Numerical analysis of unrestrained members
- ❑ Numerical modelling of beams restrained by sheeting
- ❑ Application example of fire safety engineering

Introduction

Fire in the athletics hall of the University of Physical Education in Budapest (15/10/2015)



Photos: FKI Facebook



Council Directive 89/106/EEC of 21 December 1988, replaced by Regulation (EU) No 305/2011 of 9 March 2011 of the European Parliament and of the Council, laying down harmonised conditions for the marketing of construction products.

Essential requirements

1. Mechanical resistance and stability
2. Safety in case of fire
3. Hygiene, health and the environment
4. Safety in use
5. Protection against noise
6. Energy economy and heat retention

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Essential requirements

1. Mechanical resistance and stability

2. Safety in case of fire

The construction works must be designed and built in such a way that in the event of an outbreak of fire:

- the load-bearing capacity of the construction can be assumed for a specific period of time,
- the generation and spread of fire and smoke within the works are limited,
- the spread of the fire to neighbouring construction works is limited,
- occupants can leave the construction works or be rescued by other means
- the safety of rescue teams is taken into consideration.

3. Hygiene, health and the environment

4. Safety in use

5. Protection against noise

6. Energy economy and heat retention

Safety in case of fire:

Reaction to fire: is the response of a product in contributing by its own decomposition to a fire to which it is exposed, under specified conditions.

Fire resistance: is the capacity of a building or construction element to resist the impact of fire as long as possible. The length of time this can be maintained is the fire resistance duration.

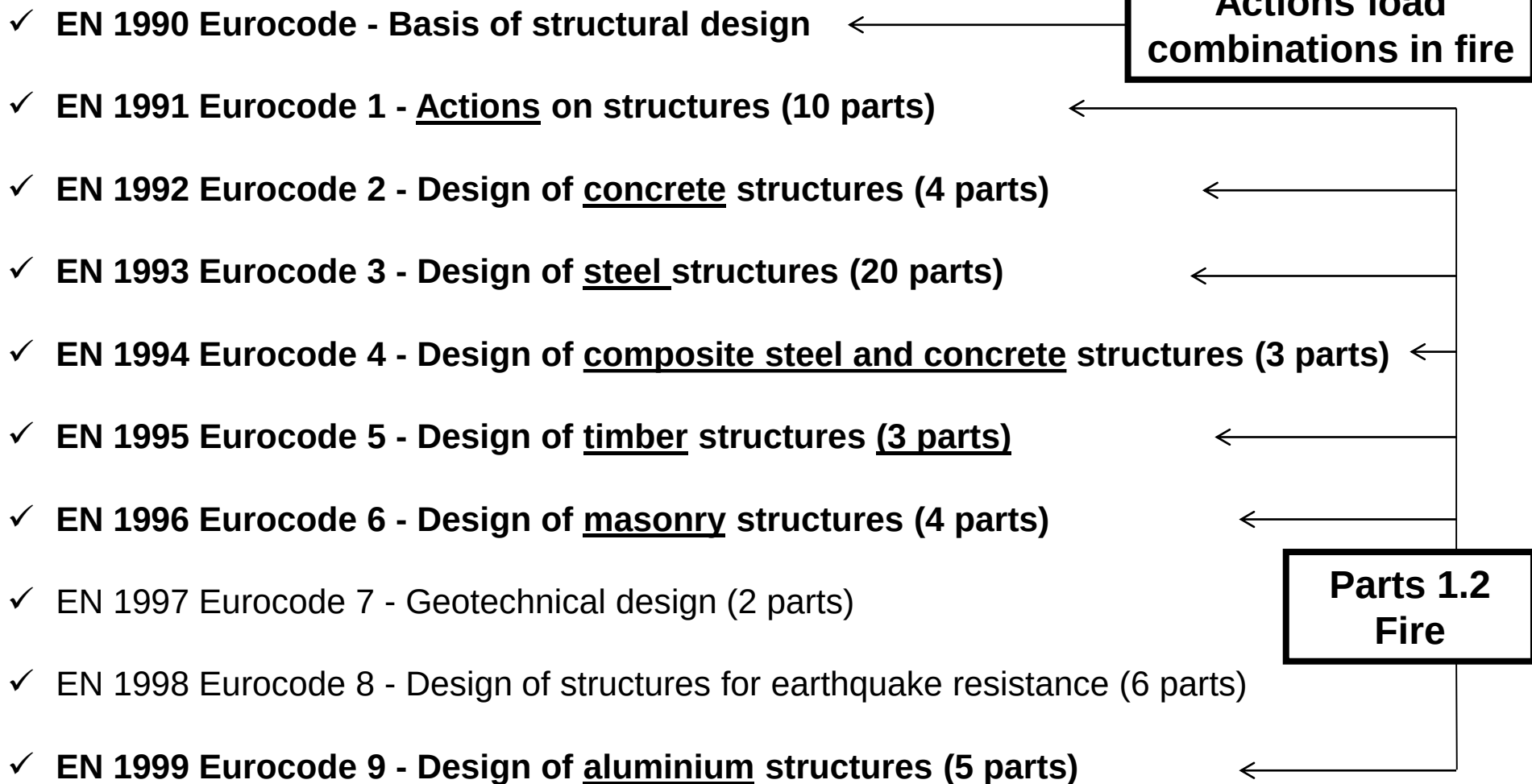
R - Load carrying capacity

E - Integrity

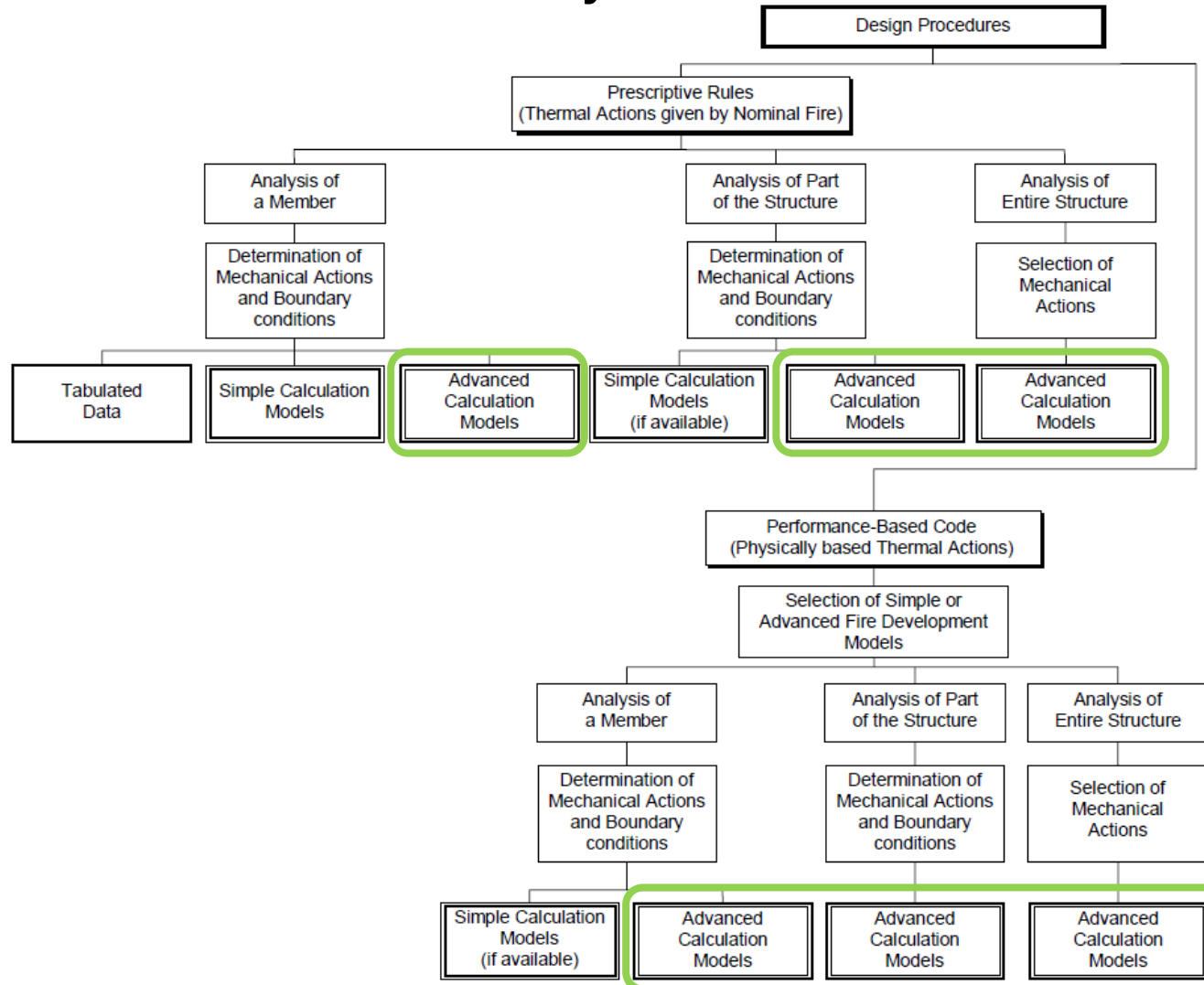
I - Insulation

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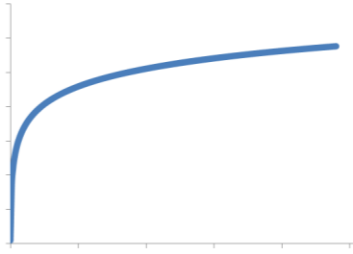
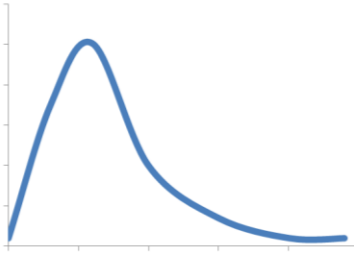
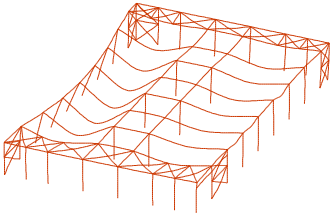
Structural Eurocodes – Analytical and numerical verification



Structural Eurocodes – Analytical and numerical verification

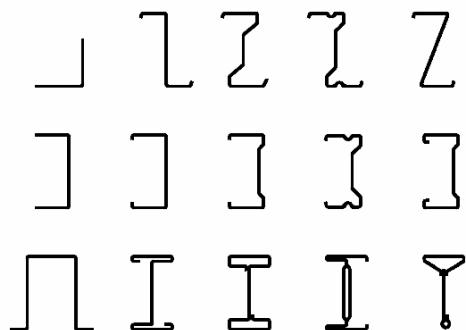


Structural Fire Safety Engineering vs. Classification

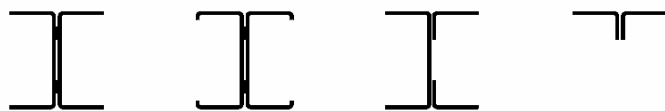
	Prescriptive: Standard fire	Performance based: Natural fire
Member 		
	Classification (R##)	Fire safety engineering
Part of the structure 	Fire safety engineering	Fire safety engineering

- Steel cold formed profiles can be applied in many of the existing building typologies
- Cold formed profiles are usually used because of their lightness and ability to overcome large spans, and are quite common as support elements of roofs or facades.
- The cold formed profiles are characterized for having the possibility of occurring collapse modes such as:
 - local buckling;
 - distortional buckling;
 - and global buckling (lateral buckling in the case of beams).

Cross-sections



a) Single open sections

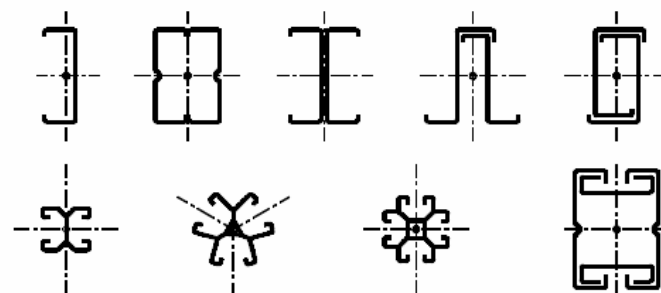


b) Open built-up sections

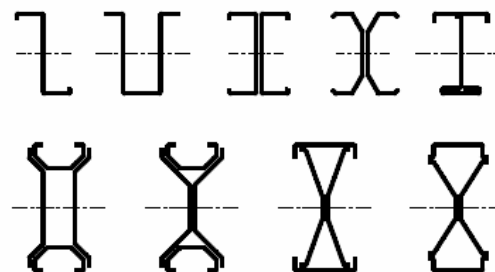


c) Closed built-up sections

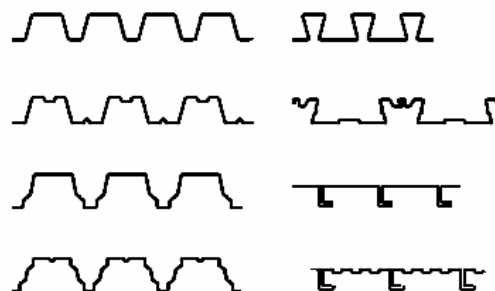
- Recommended thickness
 - $0.45 \text{ mm} < t_{cor} < 15 \text{ mm}$
- $T_{cor} = t_{nom} - 0.04 \text{ mm}$



a) Compression members and tension members

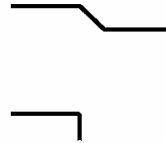


b) Beams and other members subject to bending

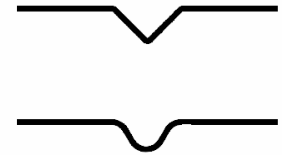


c) Profiled sheets and liner trays

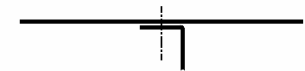
Cross-sections



a) Folds and bends



b) Folded groove and curved groove



c) Bolted angle stiffener

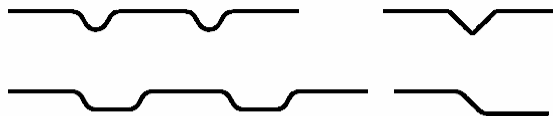
End stiffeners



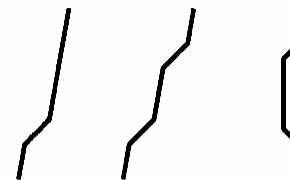
a) Single edge fold stiffeners

b) Double edge fold stiffeners

Intermediate stiffeners



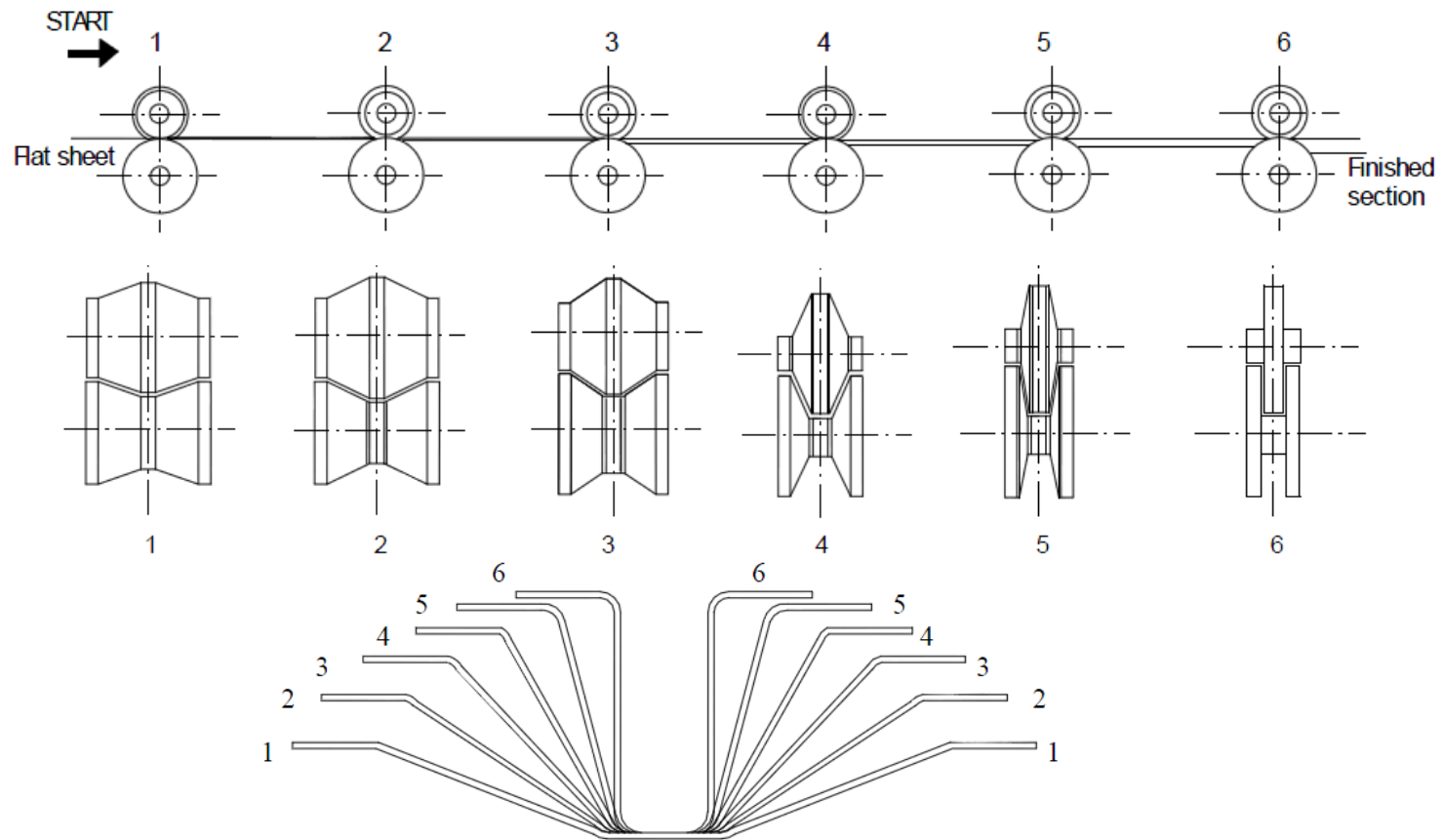
a) Intermediate flange stiffeners



b) Intermediate web stiffeners

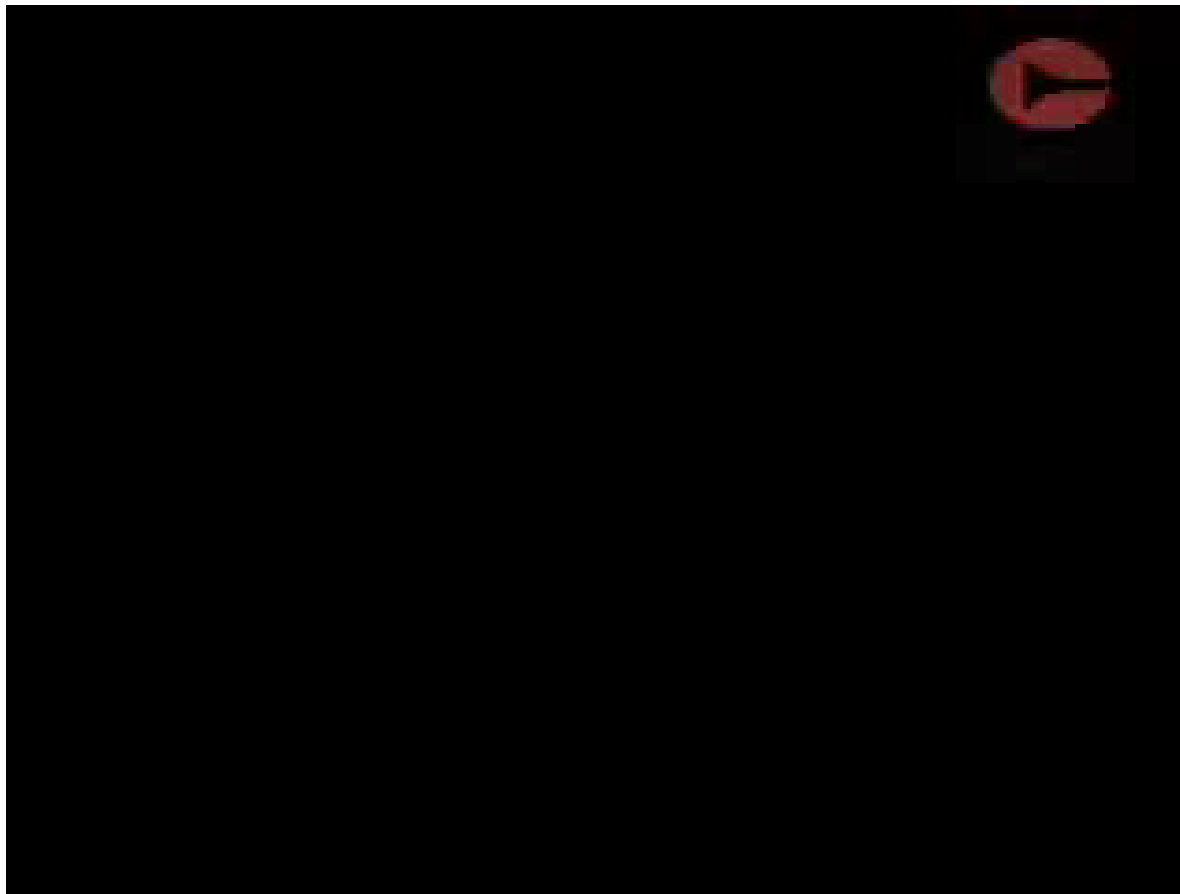
Fabrication processes

- with roles



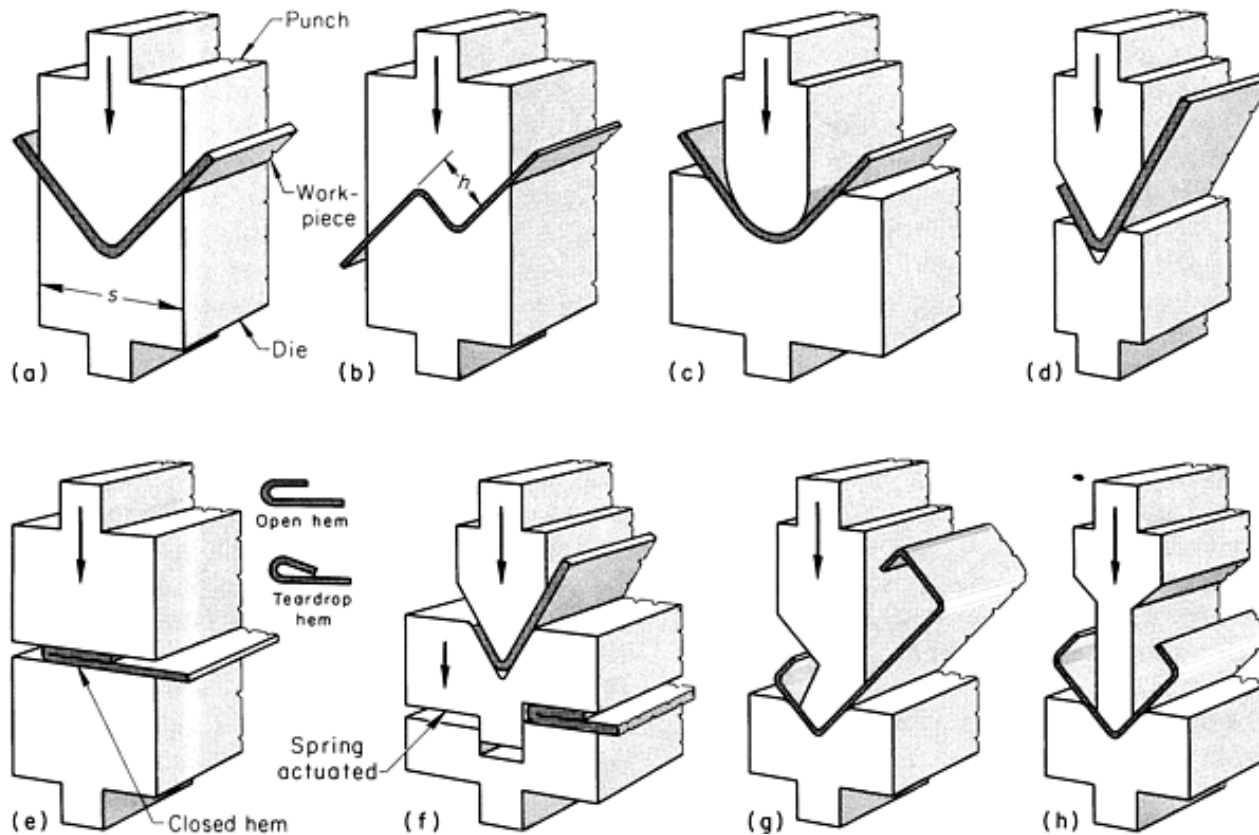
Fabrication processes

- With roles



Fabrication processes

- Press braked



Fabrication processes

- Press braked



Decathlon in Aveiro, Portugal (constalica, SA)



Decathlon in Aveiro, Portugal (constalica, SA)



Decathlon in Aveiro, Portugal (constalica, SA)





Fotografia Gentilmente cedida pela Ecoworks





PERFISA



Fotografia Gentilmente cedida pela SES Consulting

**House in Aveiro
(Rui Bastos, 2013)**



**House in Aveiro
(Rui Bastos, 2013)**





- The **thin walls** of cold formed profiles, together with the high thermal **steel conductivity**, provide a great **loss of strength and stiffness** on these structural elements when subjected to **fire**.
- To consider this mechanical resistance and stiffness loss, it is necessary to apply:
 - the reduction factor of Young's modulus at high temperature;

$$E_{a,\theta} = k_{E,\theta} E_a$$
 - and the reduction factor of the conventional limit of proportionality at 0.2%.

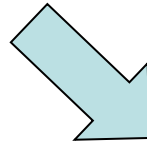
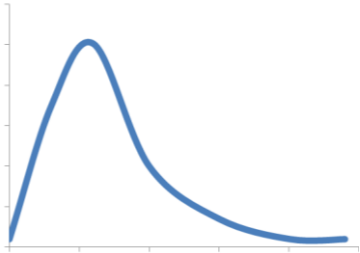
$$f_{0,2,p,\theta} = k_{0,2,p,\theta} f_y$$



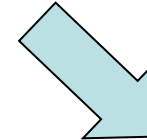
Basis for the numerical modelling of structures in fire

Basis for the numerical modelling of structures in fire

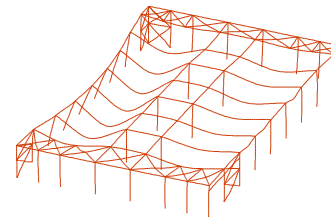
Fire action (temperature-time curve)



Thermal analysis of the sections



**Behaviour of the structure until
collapse in function of the time**



Modelling of the thermal action (EN 1991-1-2)

- ✓ **Nominal fires**
 - ✓ **ISO 834**
 - ✓ **External fire**
 - ✓ **Hydrocarbon fire**

- ✓ **Simplified fire models**
 - ✓ **Localised fires**
 - ✓ **Parametric fires**

- ✓ **Advanced fire models**
 - ✓ **Zones models**
 - ✓ **Computer fluid dynamics (CFD)**

Natural fire concept

- ✓ Standard curve **ISO 834**

$$T = 345 \log_{10}(8t + 1) + 20$$

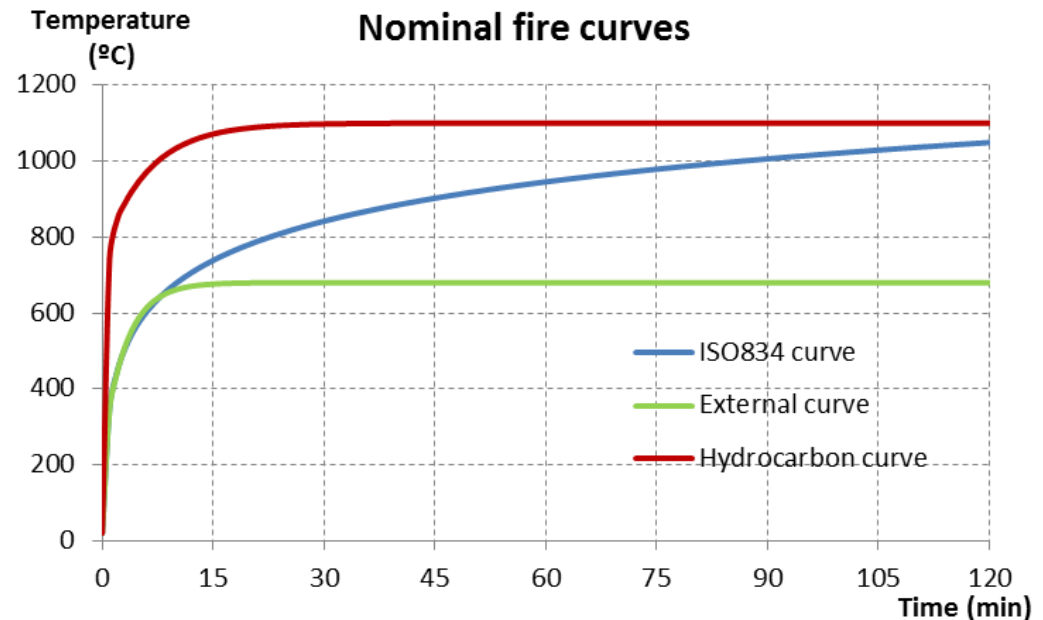
- ✓ External fire curve (external members treated with simplified model)

$$T = 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) + 20$$

- ✓ Hydrocarbon curve

$$T = 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t}) + 20$$

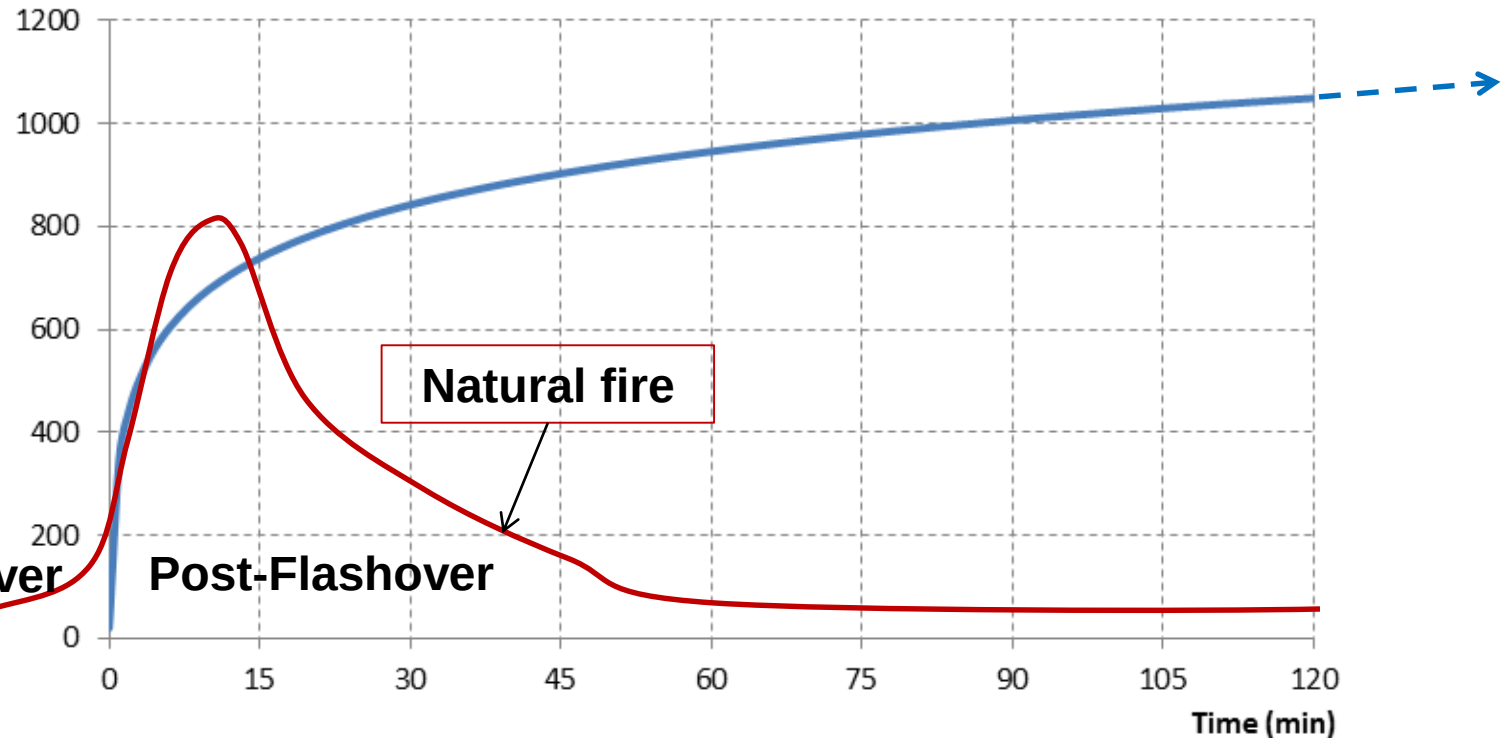
No data needed





Temperature (°C)

ISO834 curve



- ✓ Does not depend on fire load and ventilation conditions
- ✓ Never decreases
- ✓ Does not consider the Pre-Flashover phase
- ✓ Same temperature in whole compartment

- ✓ **Simplified fire models**
 - ✓ **Localised fires**
 - ✓ **Parametric fires**
- ✓ **Advanced fire models**
 - ✓ **Zone models**
 - ✓ **CFD**

In function of:

- ✓ Rate of heat release
- ✓ Fire surface

Fire

- ✓ Boundary properties
- ✓ Opening area
- ✓ Ceiling height
- ✓ Exact geometry (advanced fire models)

Compartment

Fire Load Density (see EN 1991-1-2 national annexes for each country)

$$q_{f,d} = \delta_{q1} \cdot \delta_{q2} \cdot \prod \delta_{ni} \cdot m \cdot q_{f,k}$$

Combustion factor, 0.8 for
cellulosic materials

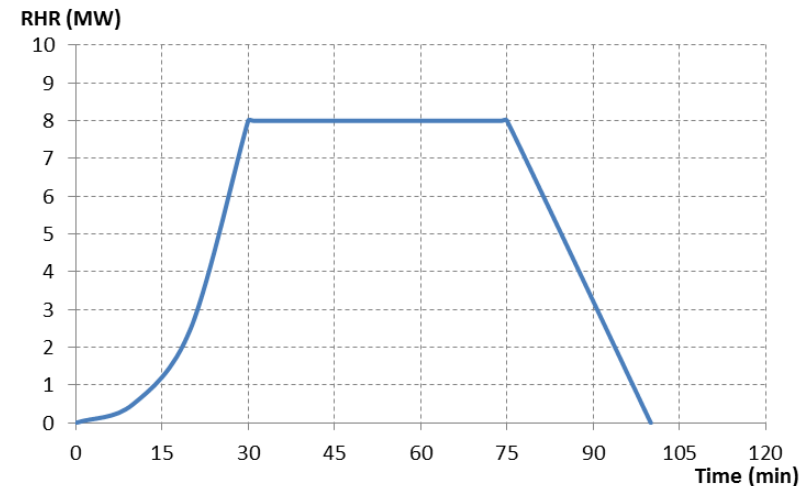
In function of the
compartment floor area

In function of the
occupancies

In function of the active fire
fighting measures

Rate of heat release

- ✓ Growing phase - $Q = 10^6 \left(\frac{t}{t_\alpha} \right)^2$ [W]
- ✓ Steady state - RHR_f
- ✓ Decay phase - starts when 70 % of the total fire load has been consumed



Characteristic of the Fire for Different Buildings

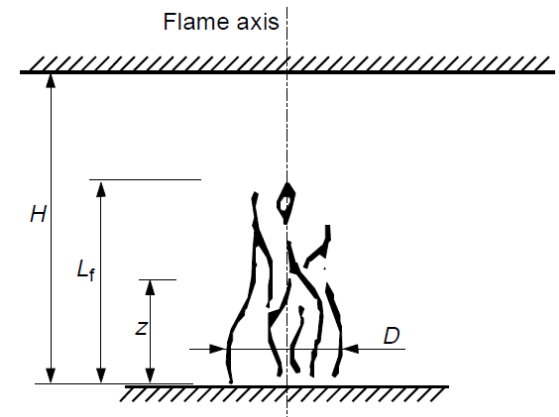
Occupancy	Fire Growth rate	RHR_f [kW/m ²]	Fire Load $q_{f,k}$ (80% fractile) [MJ/m ²]
Dwelling	Medium	250	948
Hospital (room)	Medium	250	280
Hotel (room)	Medium	250	377
Library	Fast	500	1824
Office	Medium	250	511
School	Medium	250	347
Shopping centre	Fast	250	730
Theatre (cinema)	Fast	500	365
Transport (public space)	Slow	250	122

Localised fires (when Flashover is unlikely to occur)

- ✓ **Heskestad** (Flame is not impacting the ceiling of a compartment)

Temperature only in function of the height

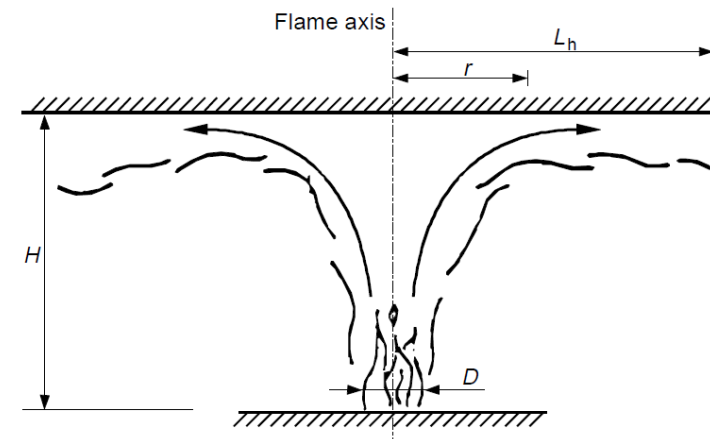
Example: columns in compartments with high ceiling



- ✓ **Hasemi** (Flame is impacting the ceiling)

Temperature in function of the distance to the flame

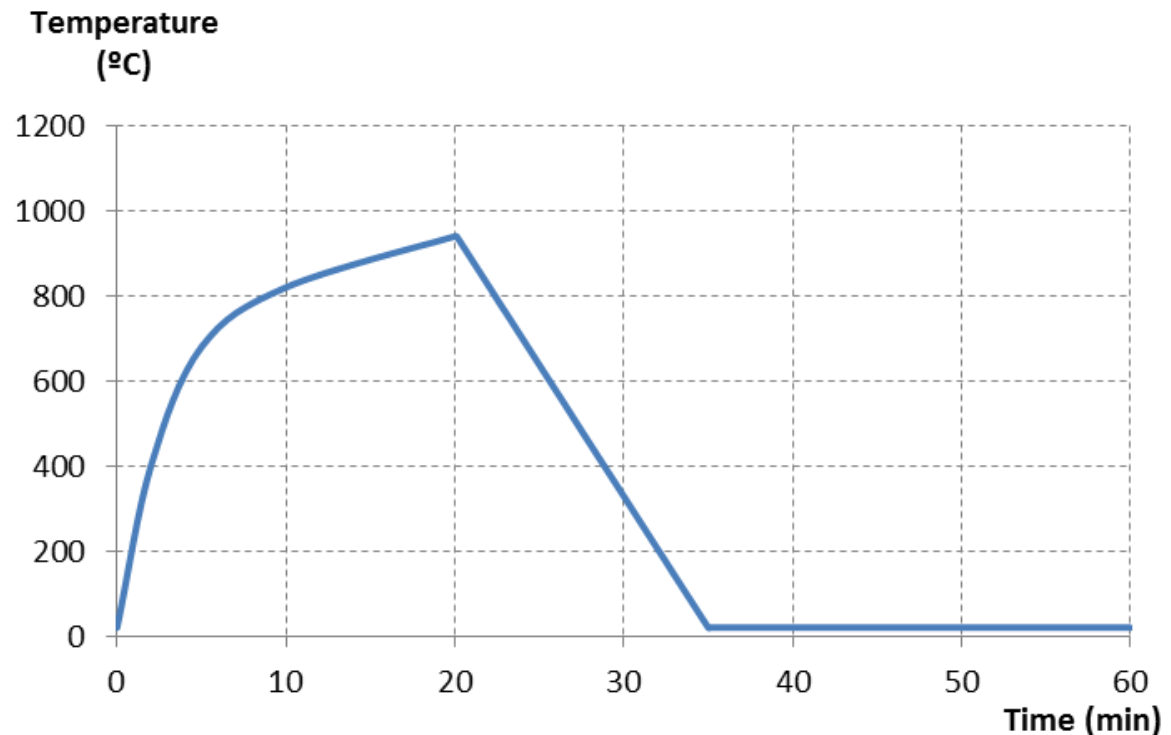
Example: car parks



Parametric fires (Fully engulfed fire)

In function of:

- ✓ Parameter to account for the thermal properties of the enclosure
- ✓ Parameter to account for the openings in the vertical walls
- ✓ Fire load density

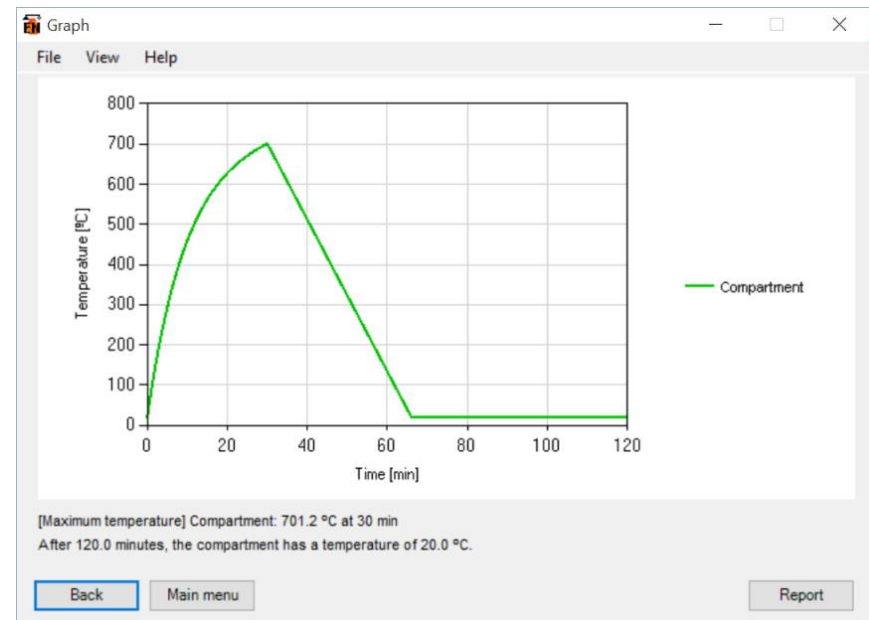




Temperature-time curves:

- ☐ Standard fire curve, ISO 834
- ☐ Hydrocarbon fire curve
- ☒ Parametric fire curve
- ☐ User defined fire curve
- ☐ Localised fire

Back Next



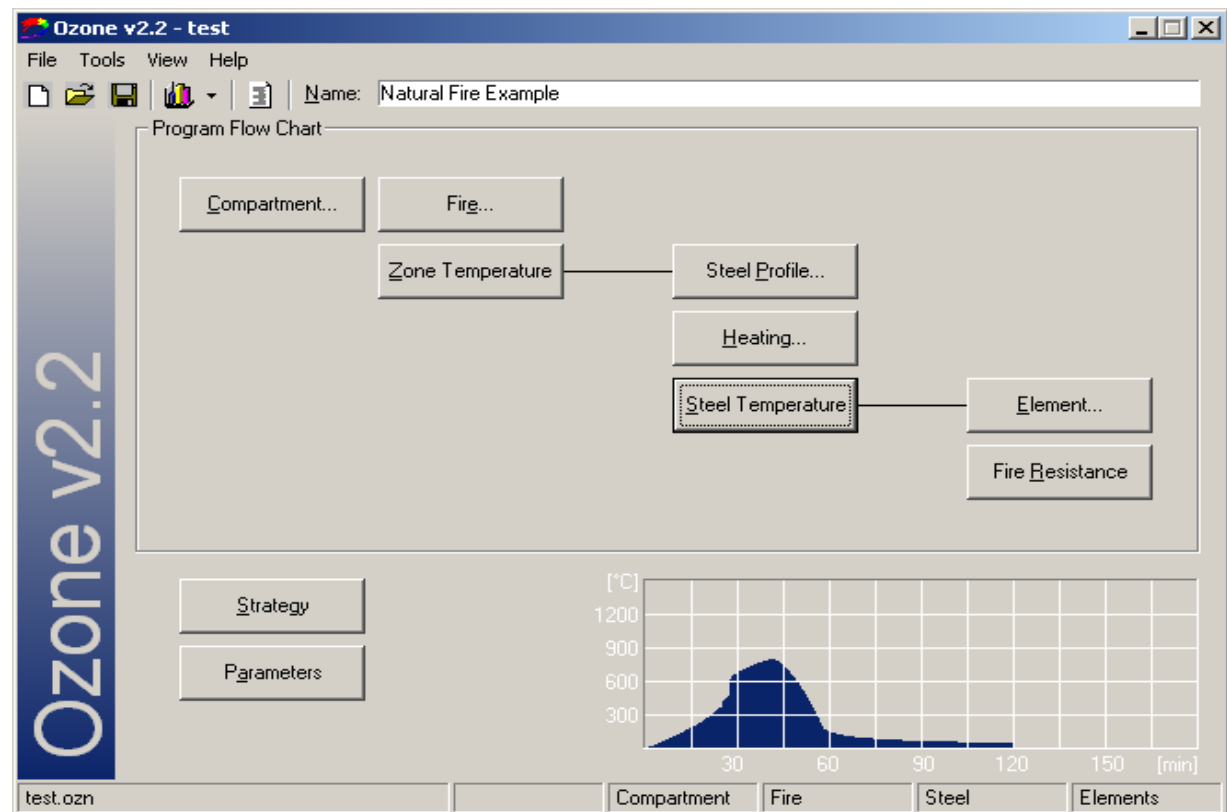
Offered together with the book:
J.-M. Franssen, P. Vila Real, Fire Design of steel Structures, ECCS, Ernst & Sohn, 2nd edition, 2015

Two zones models

When a localised fire transforms to a fully engulfed fire, it will be formed a upper hot layer and a lower cool layer. It is based on the resolution of equations of Mass balance and Energy balance.

Softwares:

- ✓ OZone
- ✓ CFAST
- ✓ MRFC



Computer fluid dynamics - CFD

It has physical and theoretical background, with no empirical limits of applicability and it can handle complex geometries.

Softwares:

- ✓ Specific: FDS, SOFIE
- ✓ General: Fluent, CFX, PHOENIX

Input and output are complex and should be handled carefully.

Obtained data to be used in the thermal analysis

✓ Compartment fires

Time (min)	Gas temperature (°C)
1	20
2	128
3	355
...	...

✓ Localised fires

Temperature in function of time and position

Modelling of the thermal analysis in cross-sections by finite element method

Resulting from an imposition of a temperature-time evolution or a heat flux at the boundary of cross-sections

- ✓ **Boundary conditions**
- ✓ **Heat conduction in the material**
- ✓ **Linking thermal to mechanical analysis**

Software chosen for this lecture - SAFIR (developed at University of Liege specially for the analysis of structures in case of fire)

Other softwares: Abaqus, Ansys, Vulcan, Diana, etc

Heat transfer from the gas to the surface of the material

Combination between convection and radiation

- ✓ Coefficient of heat transfer by convection on the exposed surface

Heating conditions	α_c [W/m ² K]
ISO834	25
Hydrocarbon curve	50
Natural fire	35

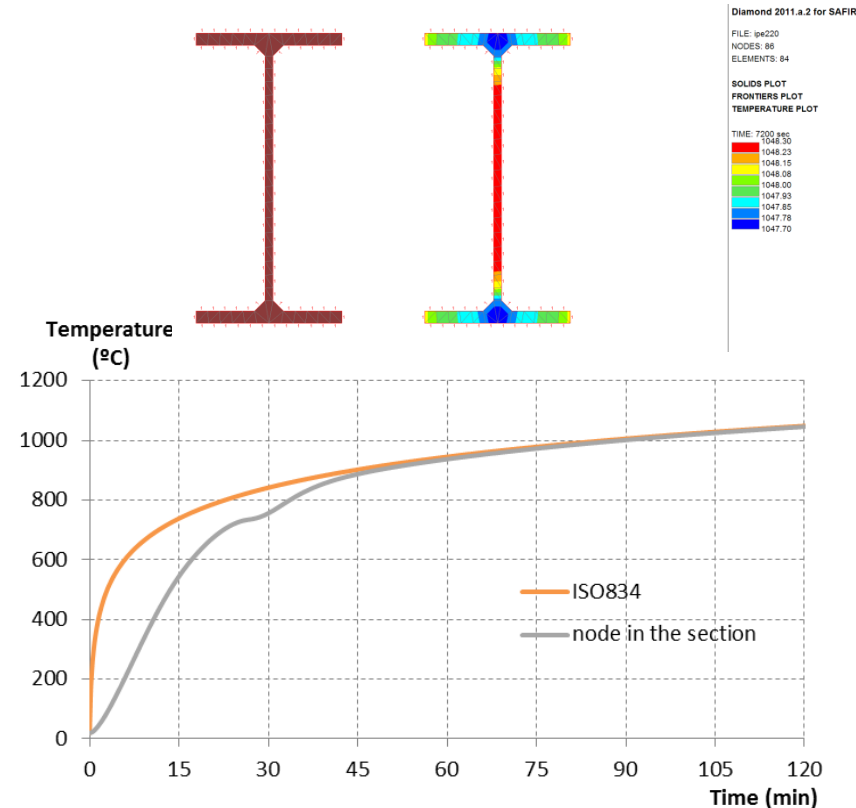
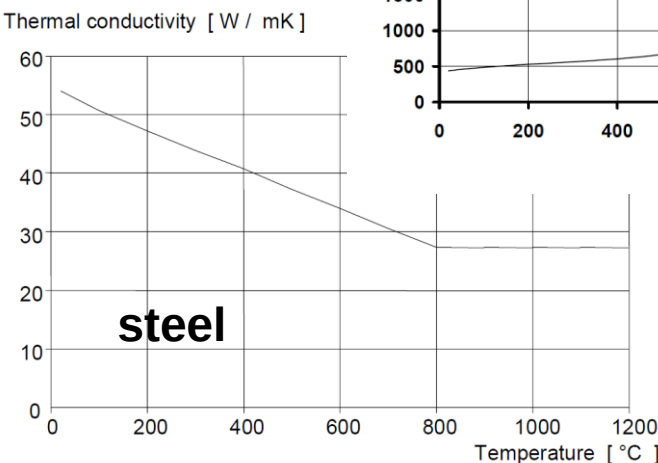
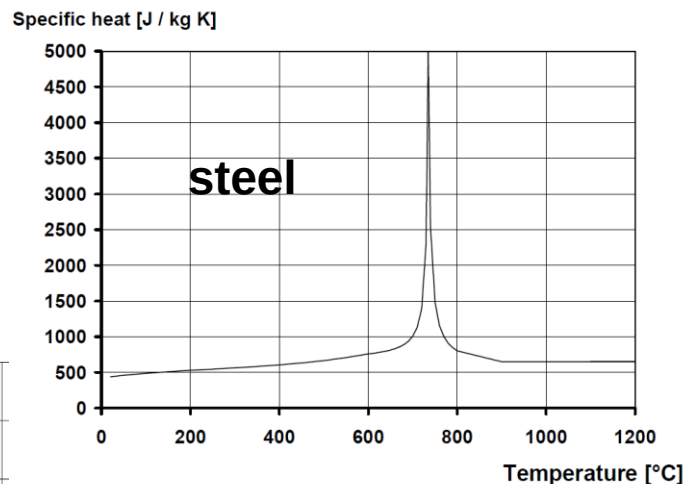
- ✓ Coefficient of heat transfer by convection on the unexposed surface if radiation implicitly considered in the convection $\alpha_c = 9$ W/m²K, if not $\alpha_c = 4$ W/m²K
- ✓ Surface emissivity $\varepsilon_m = 0.7$;
- ✓ Fire emissivity $\varepsilon_f = 1.0$

Heat transfer within the material (Fourier equation)

Thermal properties (specific heat and thermal conductivity) in function of the temperature. For example:

$$\frac{\partial}{\partial x} \left(\lambda_a \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_a \frac{\partial \theta}{\partial y} \right) + \dot{Q} = \rho_a c_a \frac{\partial \theta}{\partial t}$$

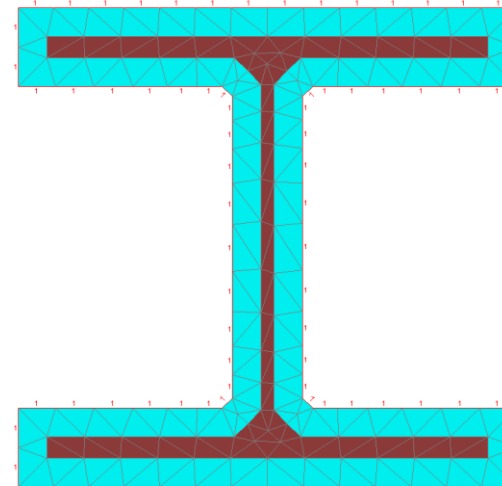
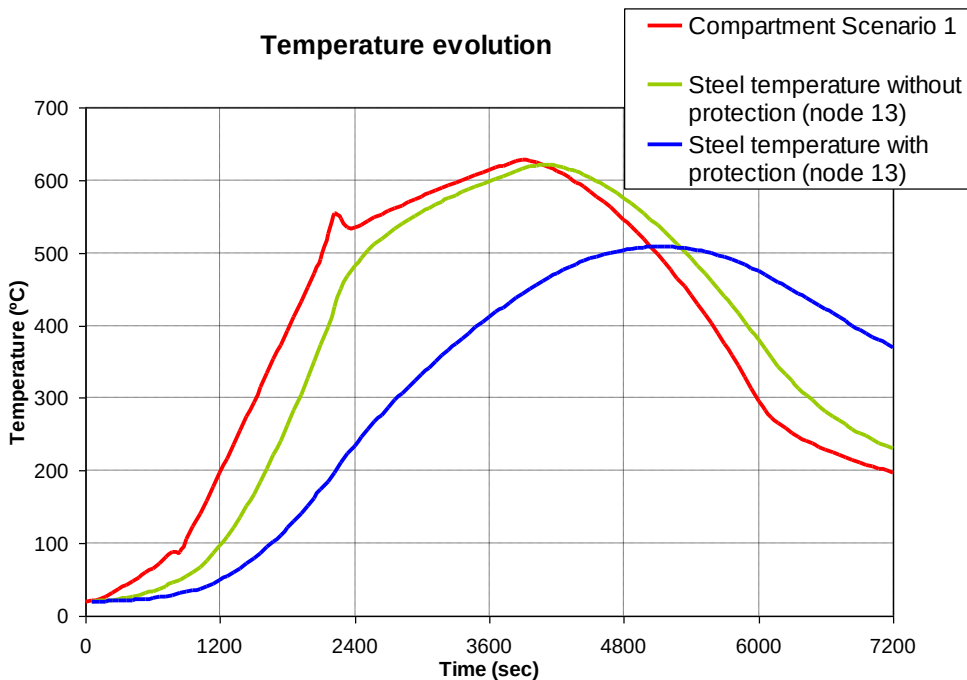
✓ steel (EN1993-1-2)



For the protection the following data should also be given:

- ✓ Thickness
- ✓ Specific mass of the dry material
- ✓ Water content

Temperature evolution



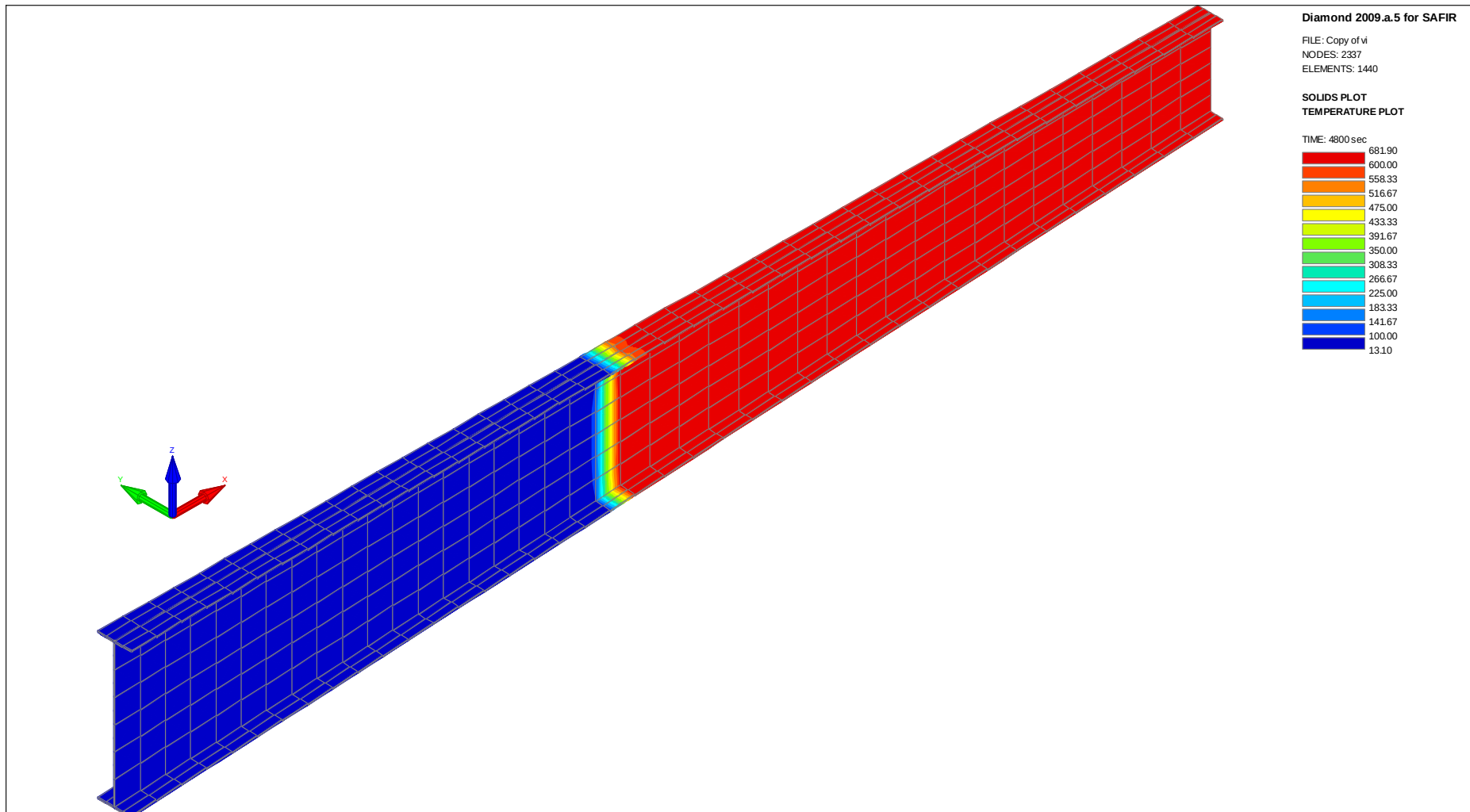
Diamond 2011.a.2 for SAFIR

FILE: he260a
NODES: 166
ELEMENTS: 248

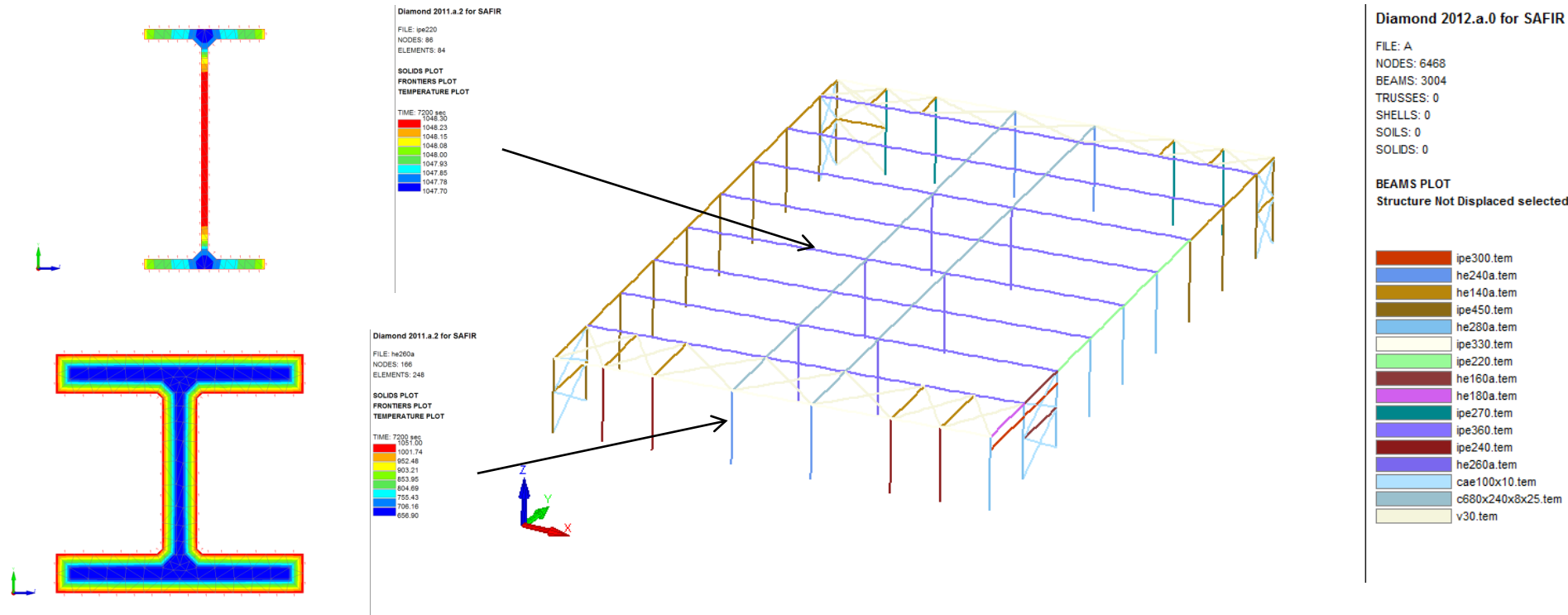
SOLIDS PLOT
FRONTIERS PLOT

STEELEC3
INSULATION
hot.fc

3D analysis (longitudinal axis of the beam)

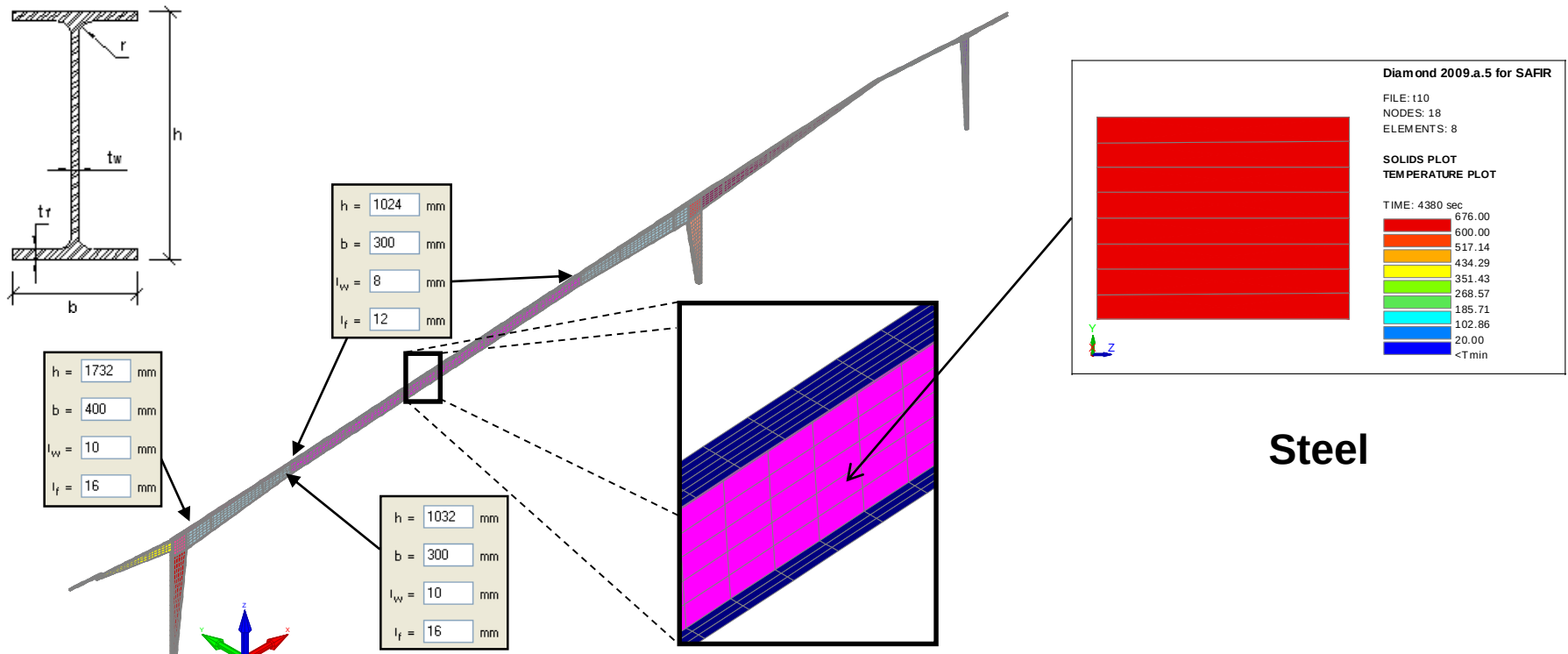


For beam finite elements in the mechanical model the thermal analysis is made with 2D finite elements



The beam element is constituted by fibres that correspond to the prolongation of the elements throughout the longitudinal axis. In any longitudinal integration point, all the variables (temperature, stresses and strains) are constant in each fibre.

For shell finite elements in the mechanical model the thermal analysis is made with 1D finite elements



In shell elements, the temperature distribution can be non-uniform across the thickness of the shell having no heat transfer in the plane of the shell.

- ✓ **Mechanical actions**
- ✓ **Materials properties at high temperatures**
 - ✓ **Constitutive laws**
 - ✓ **Thermal elongation**
- ✓ **Application of the finite element method**
- ✓ **Results discussion**
 - ✓ **Displacements and internal efforts**
 - ✓ **Fire resistance time**

Software chosen for this lecture - SAFIR

Other softwares: Abaqus, Ansys, Vulcan, Diana, etc

Actions: dead load, imposed load, snow, wind

Combination: **accidental situation**

$$G + \psi_{(1 \text{ or } 2),1} \cdot Q_1 + \sum_{i>1} \psi_{2,i} \cdot Q_i$$

$\psi_{1,1}$ or $\psi_{2,1}$ according to national annexes

In Portugal the choice was on the $\psi_{1,1}$ otherwise wind loads would never be considered

EN1990

Action	Ψ_1	Ψ_2
Imposed loads in buildings, category (see EN 1991-1-1)		
Category A : domestic, residential areas	0.5	0.3
Category B : office areas	0.5	0.3
Category C : congregation areas	0.7	0.6
Category D : shopping areas	0.7	0.6
Category E : storage areas	0.9	0.8
Category F : traffic area, vehicle weight $\leq 30\text{kN}$	0.7	0.6
Category G : traffic area, $30\text{kN} < \text{vehicle weight} \leq 160\text{kN}$	0.5	0.3
Category H : roofs	0	0
Snow loads on buildings (see EN 1991-1-3)*		
Finland, Iceland, Norway, Sweden	0.5	0.2
Remainder of CEN Member States, for sites located at altitude $H > 1000\text{ m a.s.l.}$	0.5	0.2
Remainder of CEN Member States, for sites located at altitude $H \leq 1000\text{ m a.s.l.}$	0.2	0
Wind loads on buildings (see EN 1991-1-4)	0.2	0
Temperature (non-fire) in buildings (see EN 1991-1-5)	0.5	0
NOTE: The values may be set by the National annex. * For countries not mentioned below, see relevant local conditions.		

The constitutive laws are affected by the elevated temperatures

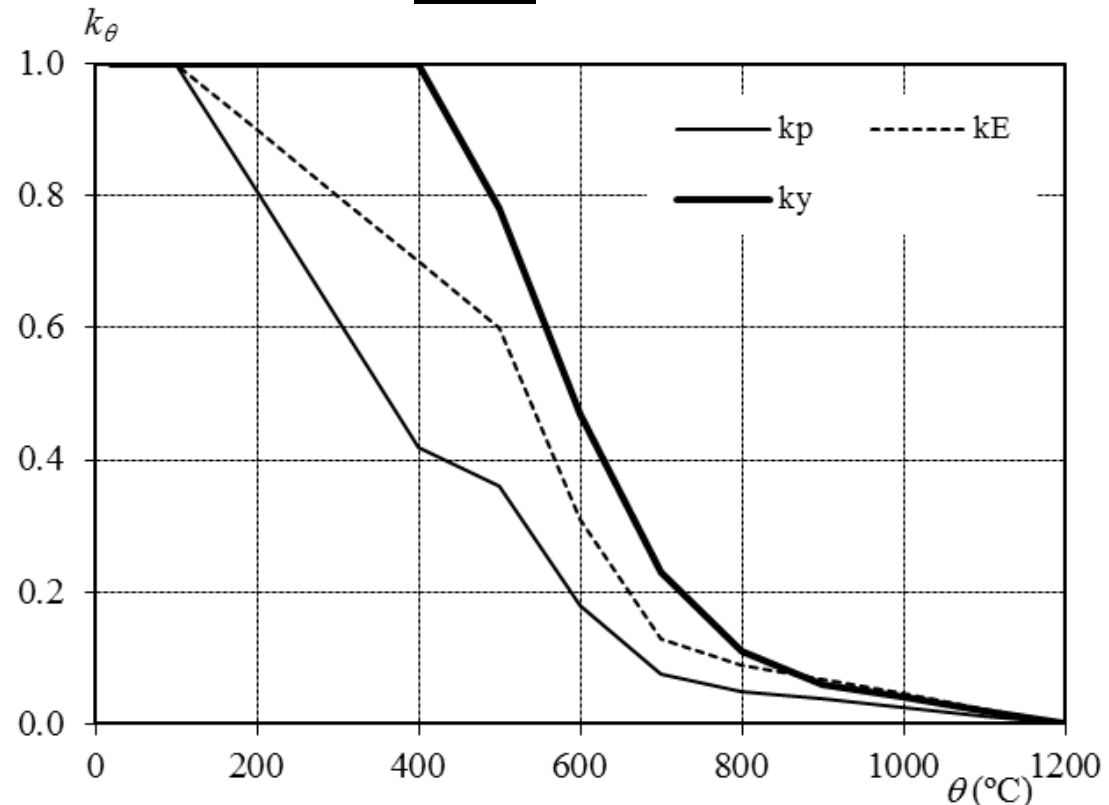
- ✓ Strength and stiffness reduction of **steel** in function of the temperature:

EN1993-1-2

$$k_{y,\theta} = f_{y,\theta}/f_y;$$

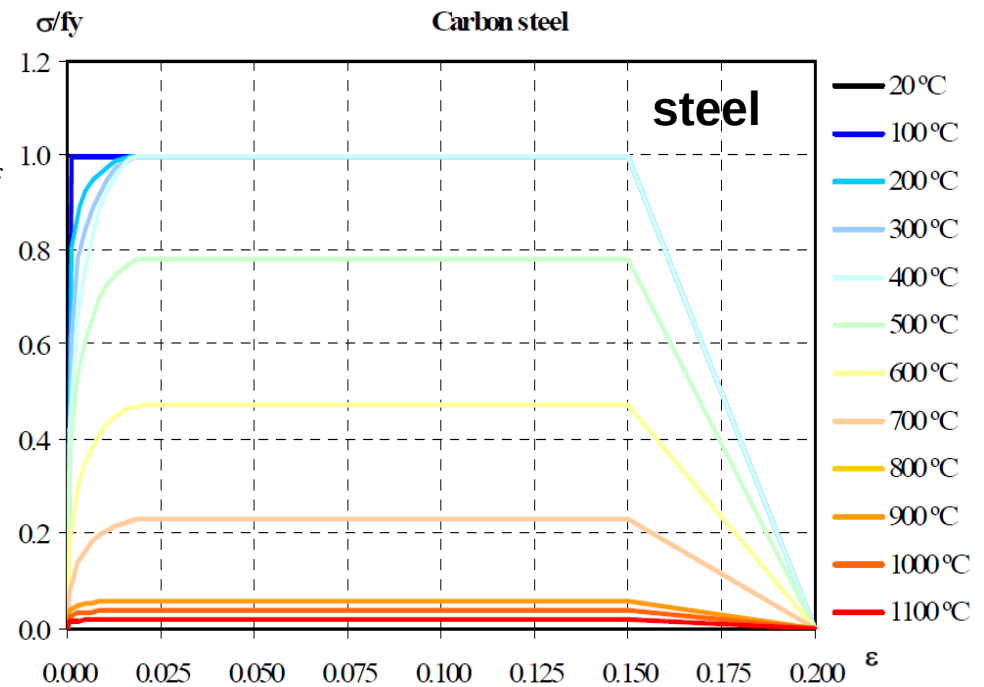
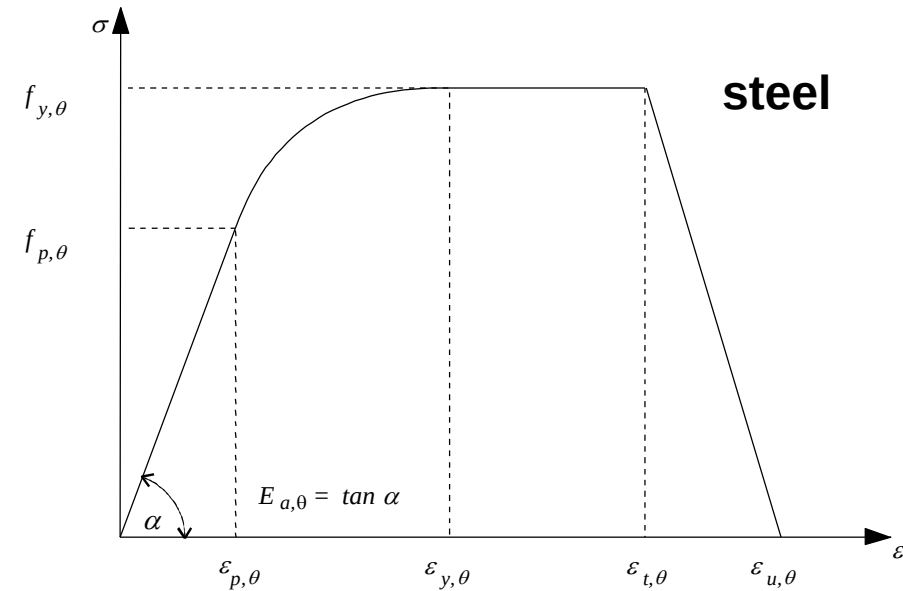
$$k_{p,\theta} = f_{p,\theta}/f_y;$$

$$k_{E,\theta} = E_{a,\theta}/E_a.$$

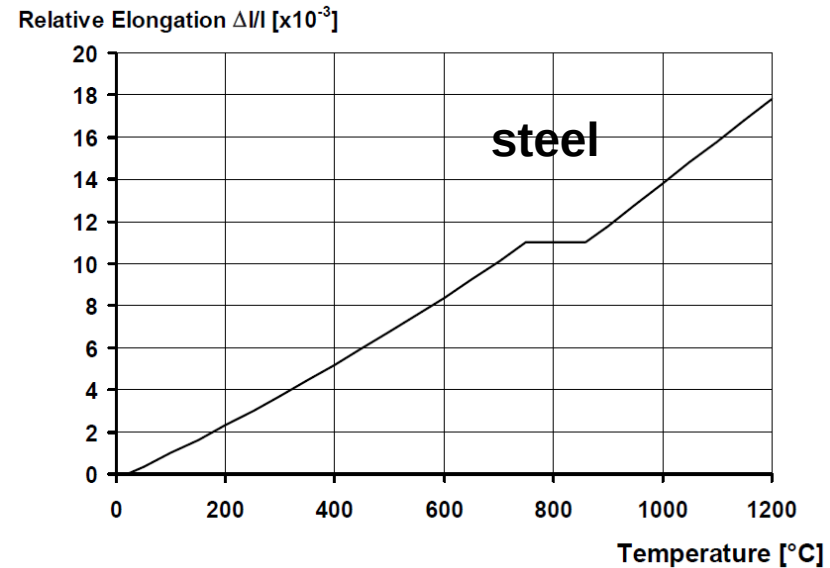


Note: The French national annex proposes different reduction factors for cold formed profiles

EN1993-1-2

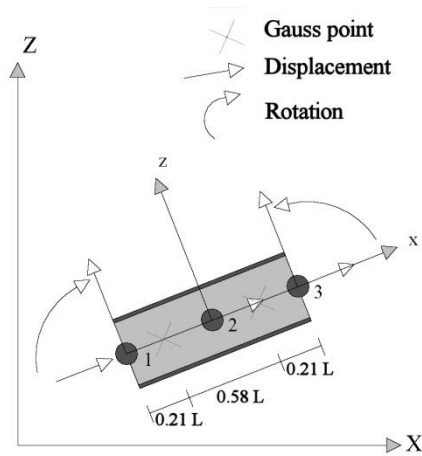


Thermal elongation (influence the efforts values)

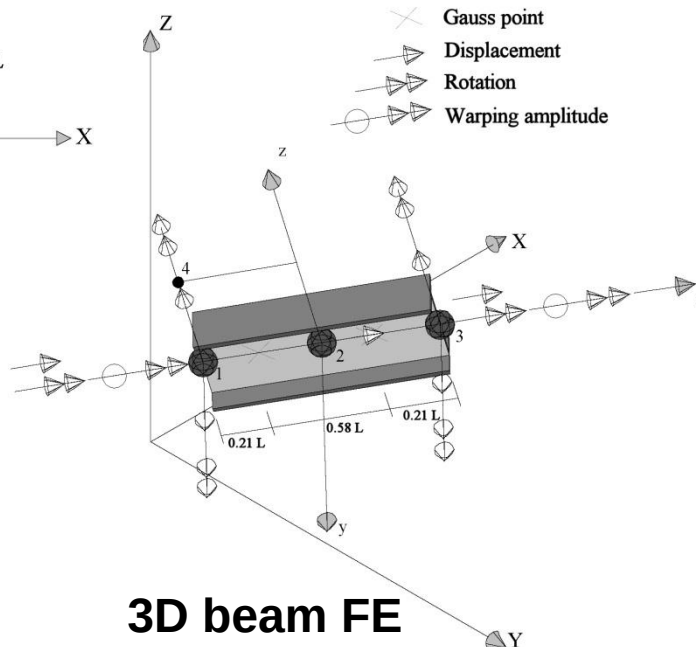


EN1993-1-2

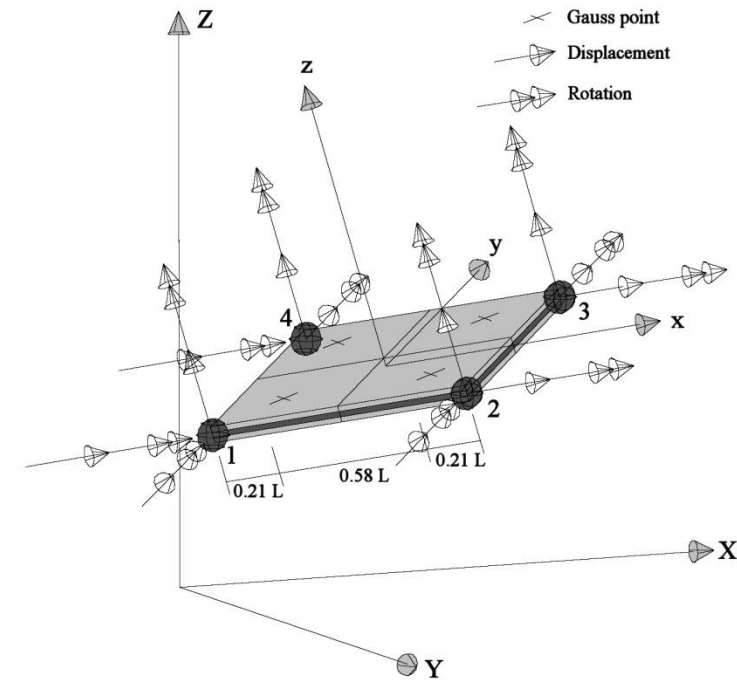
Possible finite elements types



2D beam FE

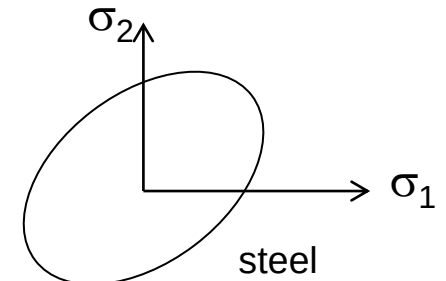


3D beam FE



shell FE

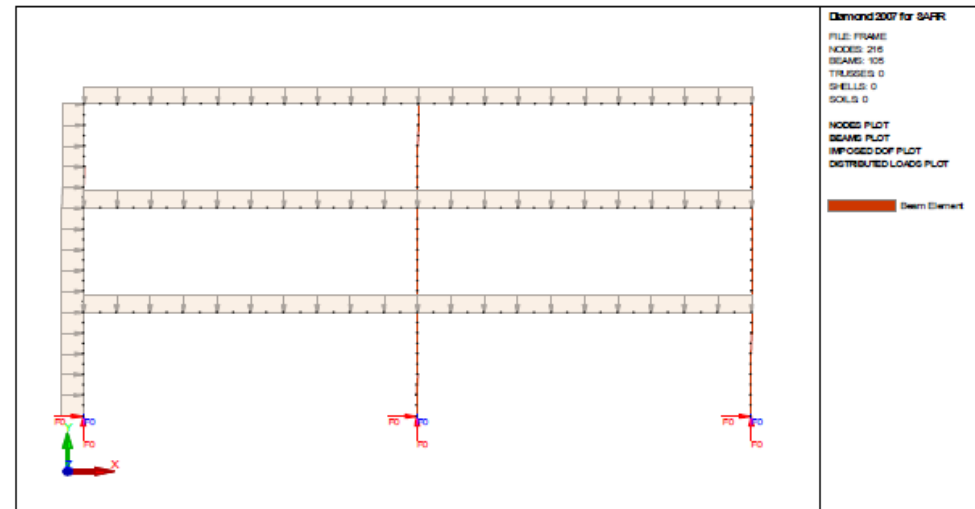
Plane stress state



For the structural analysis (normally geometrically and materially non-linear), the temperature's time history and the section geometry (created during the previous thermal analysis) are needed.

In addition:

- ✓ Mesh
 - ✓ Restraints
 - ✓ Loads
- ✓ Geometric Imperfections
 - ✓ Residual stresses
 - ✓ etc...



Calculation procedure must take into account temperature dependence of both stiffness and strength of the structure.

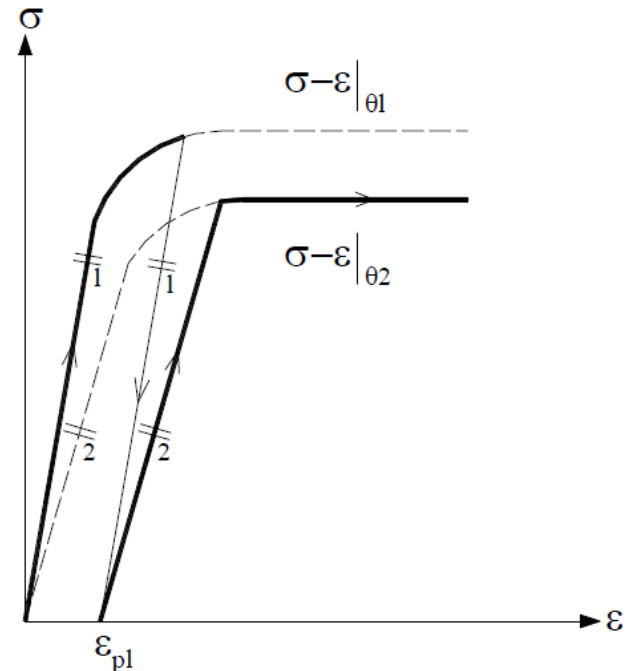
The calculation strategy is based on an incremental procedure (step by step) until failure of the structure, defined commonly as the instant when the stiffness matrix becomes not positive definite, thus becoming impossible to establish the equilibrium of the structure.

Total strain $\varepsilon_t = \varepsilon_{th} + (\varepsilon_\sigma + \varepsilon_c) + \varepsilon_{res}$

thermal elongation ε_{th} stress ε_σ residual stress ε_{res} creep effect at elevated temperatures ε_c

kinematical material model

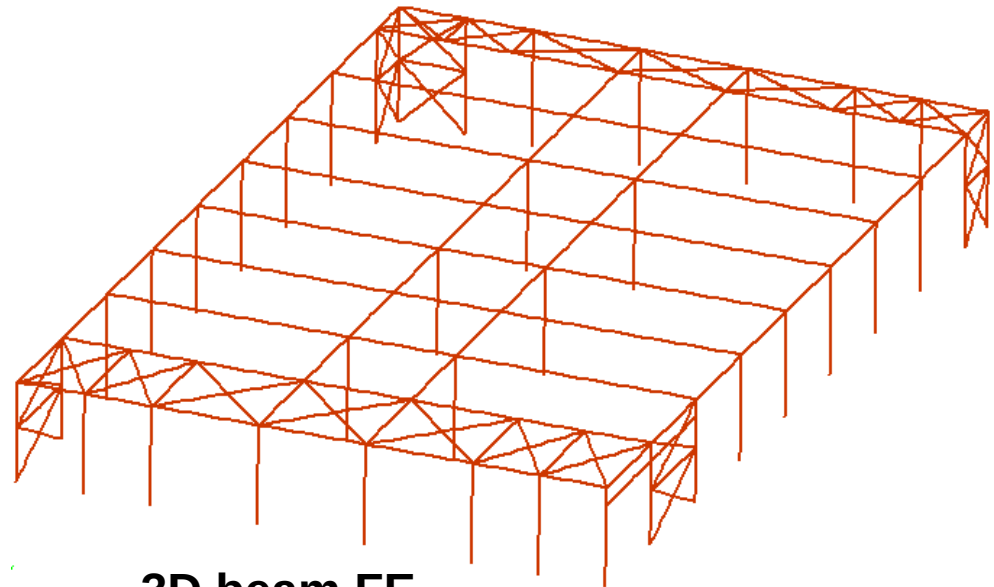
Steel kinematical material model to account the temperature evolution



Structures with beam finite elements

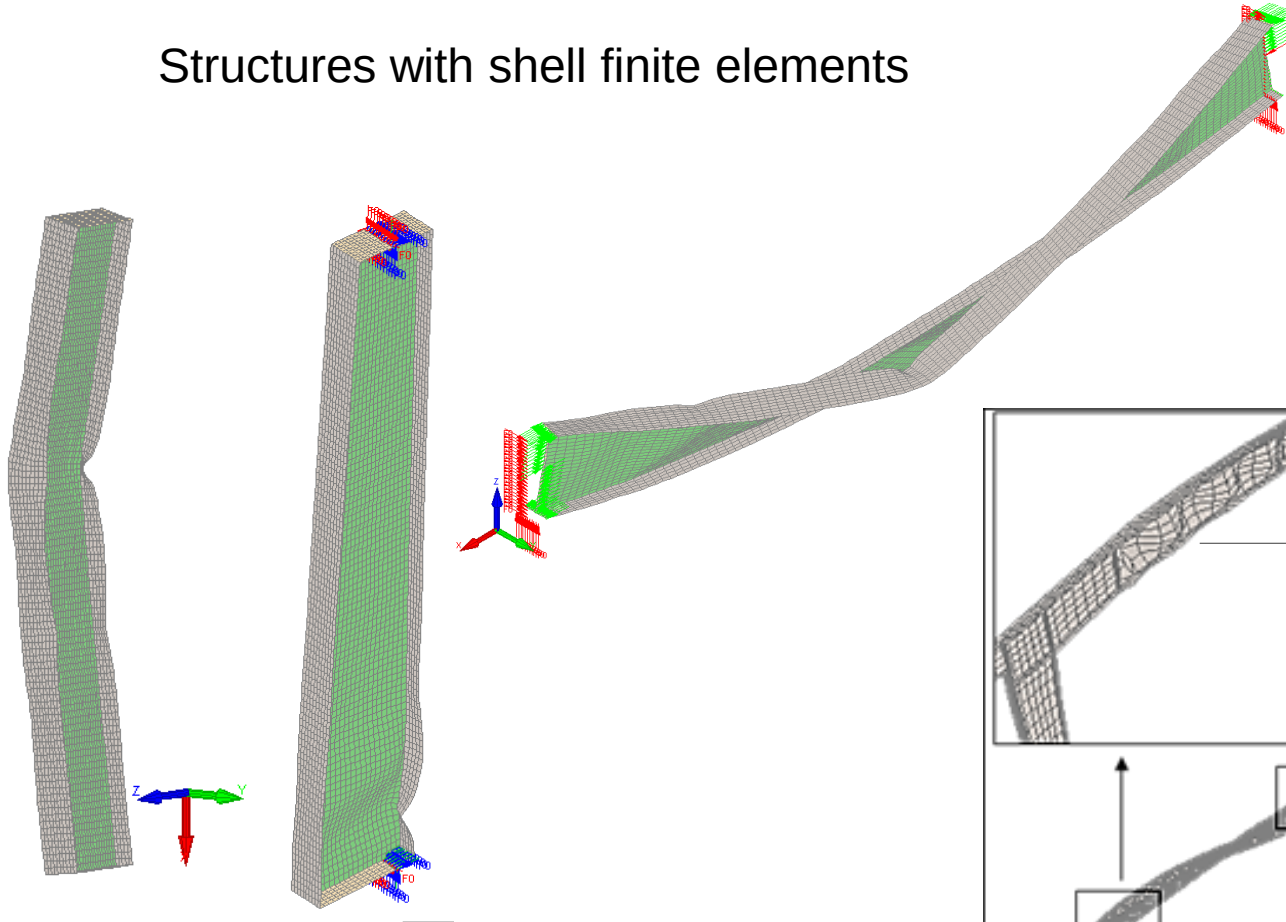


2D beam FE

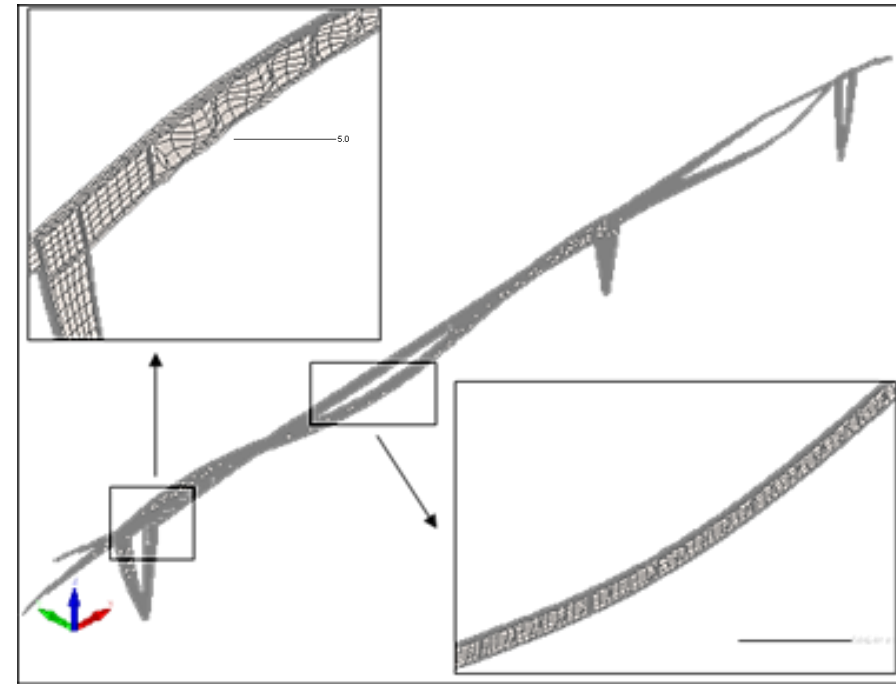


3D beam FE

Structures with shell finite elements

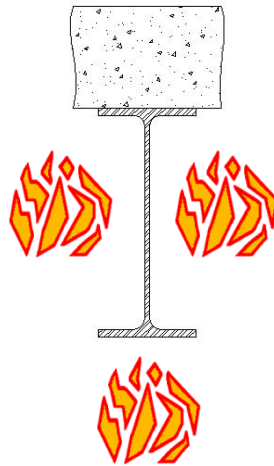
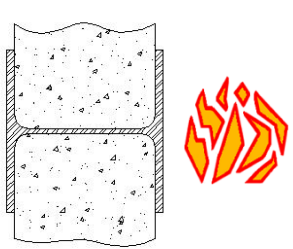


Class 4 steel sections (local buckling)



Outcome of a structural analysis for fire resistance

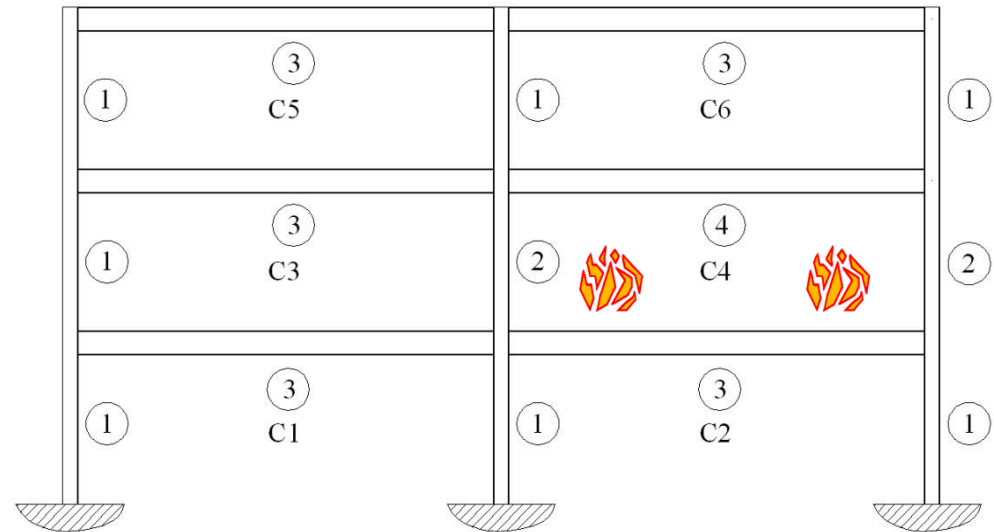
Example: office building portal frame



Cross-sections

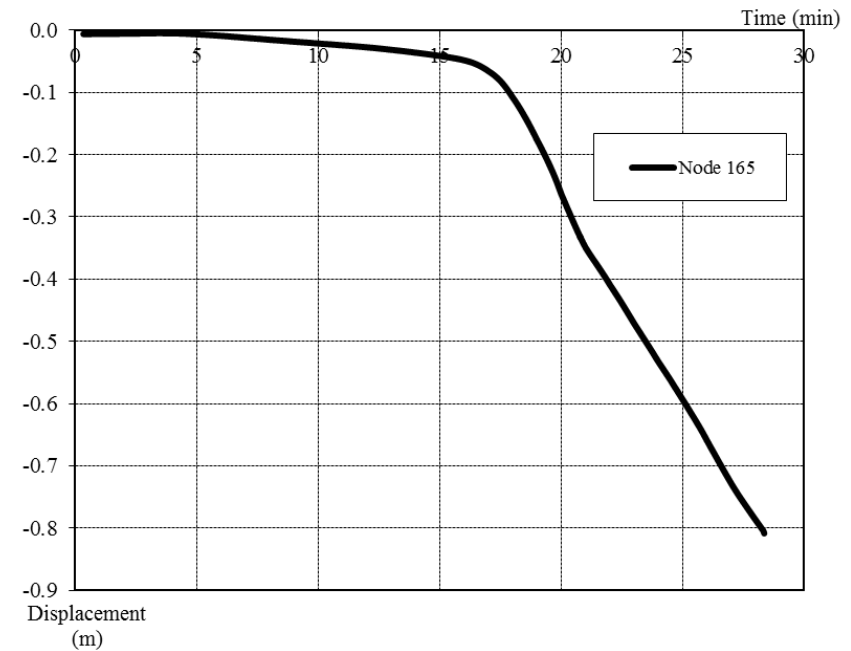
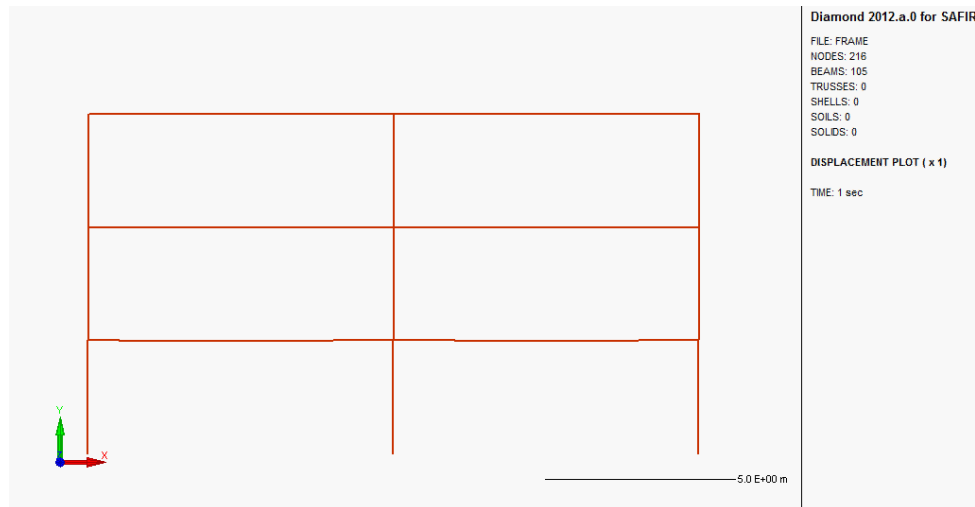
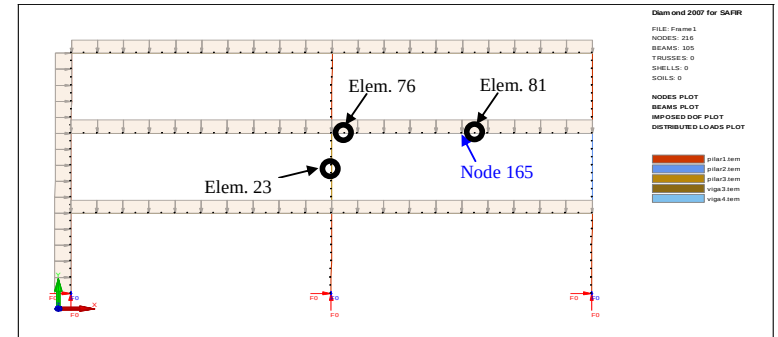
Beams - IPE 450

Columns - HEA 300

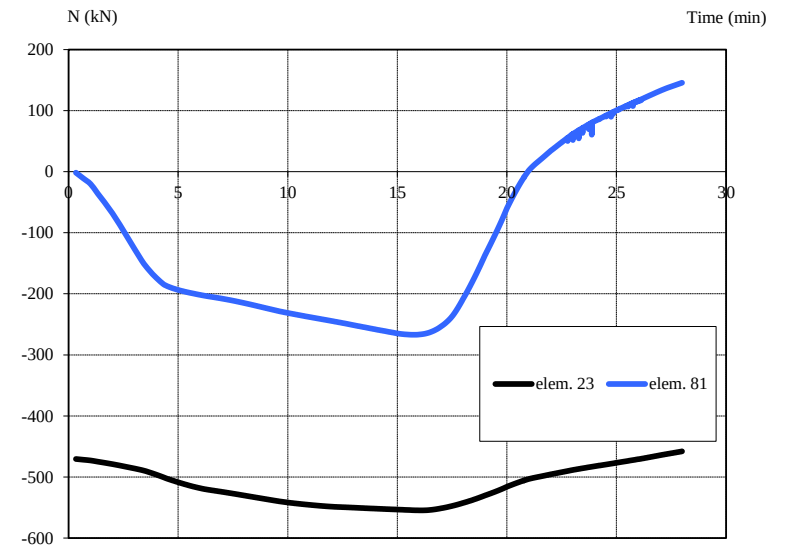
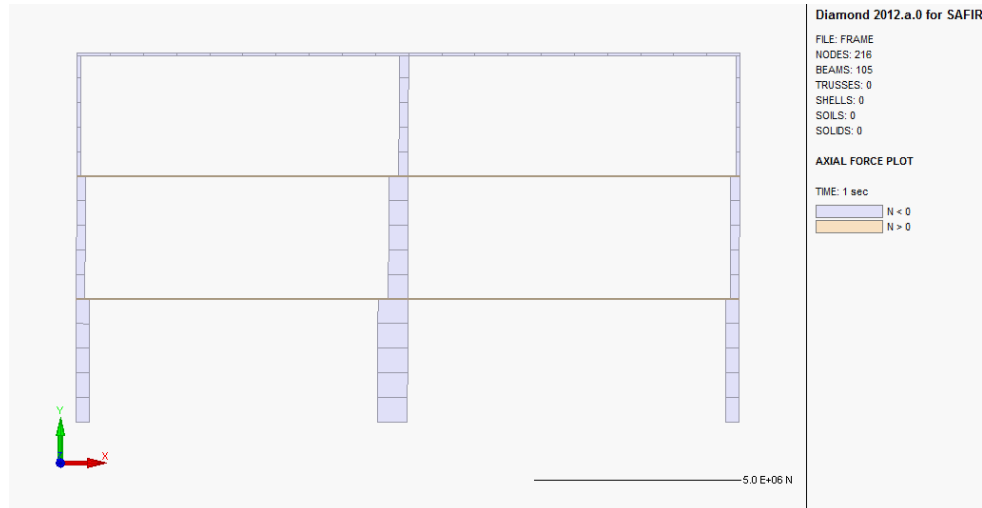
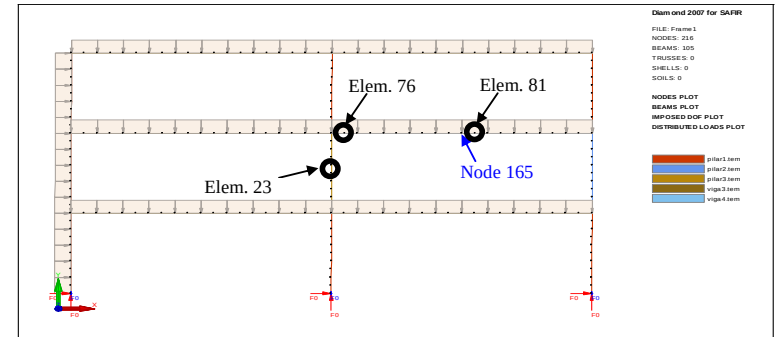


Required fire resistance - R30

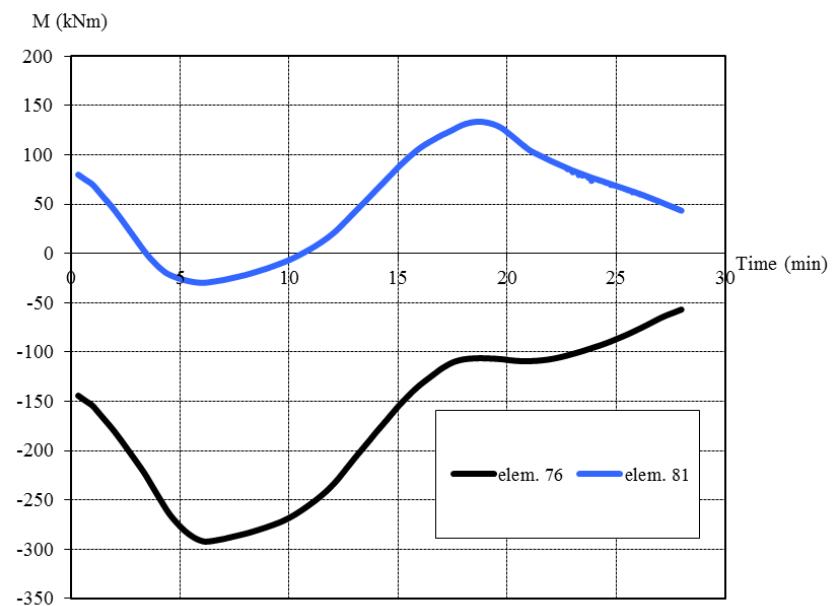
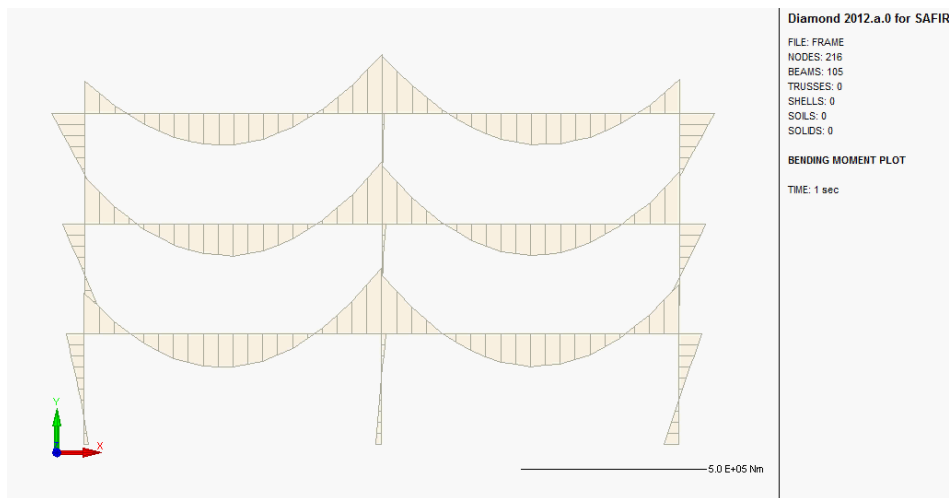
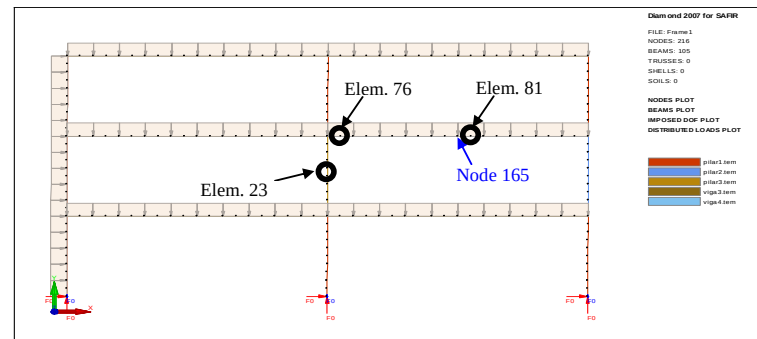
Displacements



Axial efforts



Bending moments



Fire resistance time

The fire resistance will be given by the instant of collapse of the structure and is compared to the fire resistance requirement.

If lower, passive or active fire protection measures should be introduced.

The fire resistance of the example is below the standard fire resistance defined as R30, being necessary to use fire protection to fulfil these required fire resistance.

Collapse time	
Portal frame	28.4 min



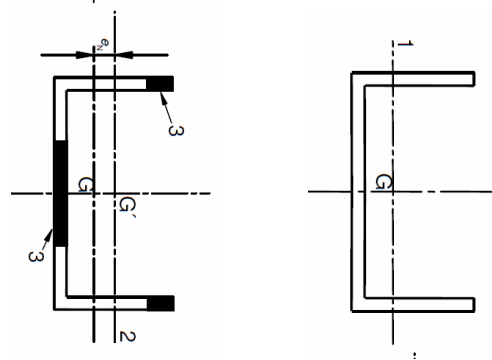
Numerical model development for cold formed profiles

- ✓ Buckling modes
- ✓ Initial imperfections
- ✓ Material constitutive law
- ✓ Numerical modelling of experimental fire test on cold formed z purlin
Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

Local buckling

EN1993-1-5&(4.3 e 4.4)

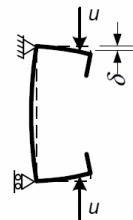
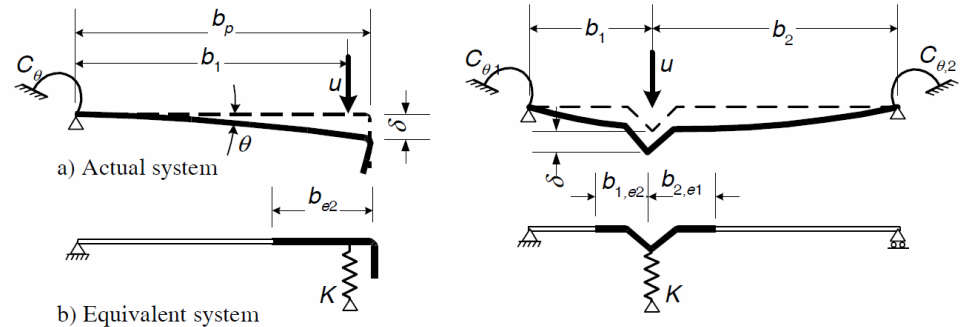
Effective widths



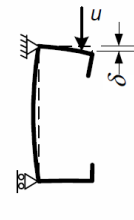
Distortional buckling

EN1993-1-3&(5.5)

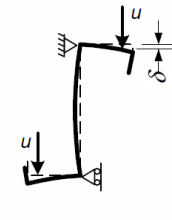
Reduced thicknesses



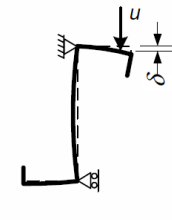
Compression



Bending

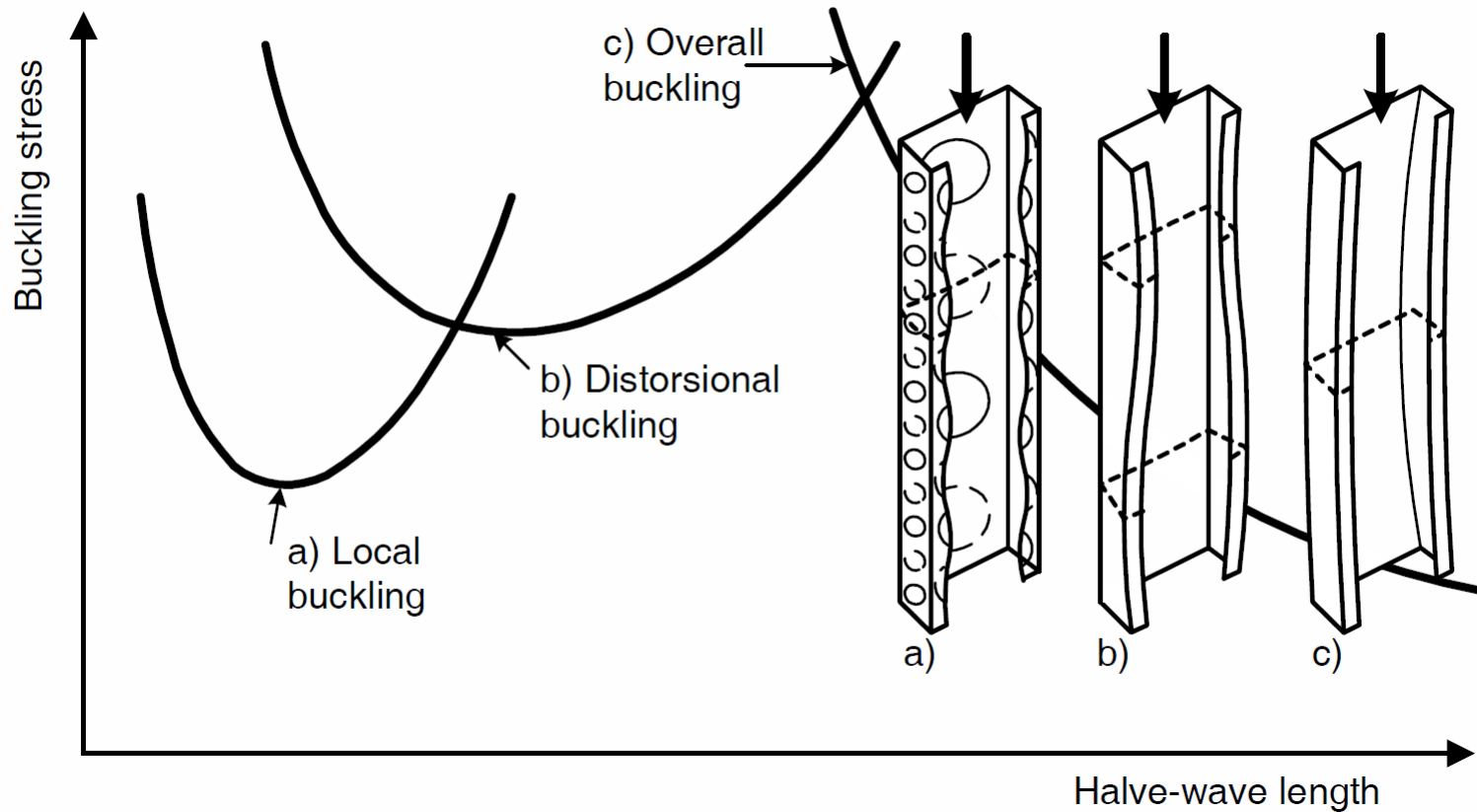


Compression



Bending

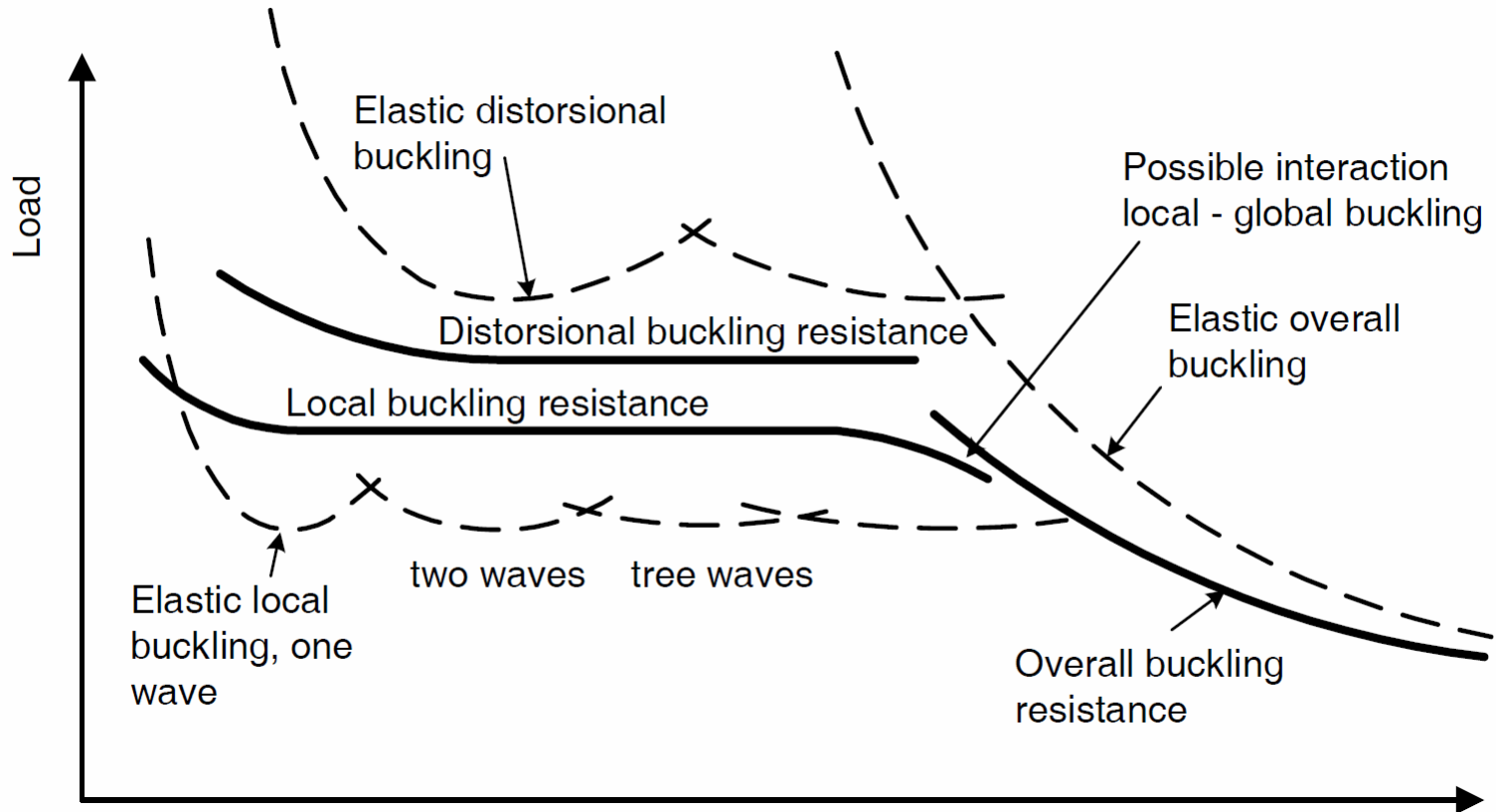
Axial compression



Note: needed even for simplified calculation methods

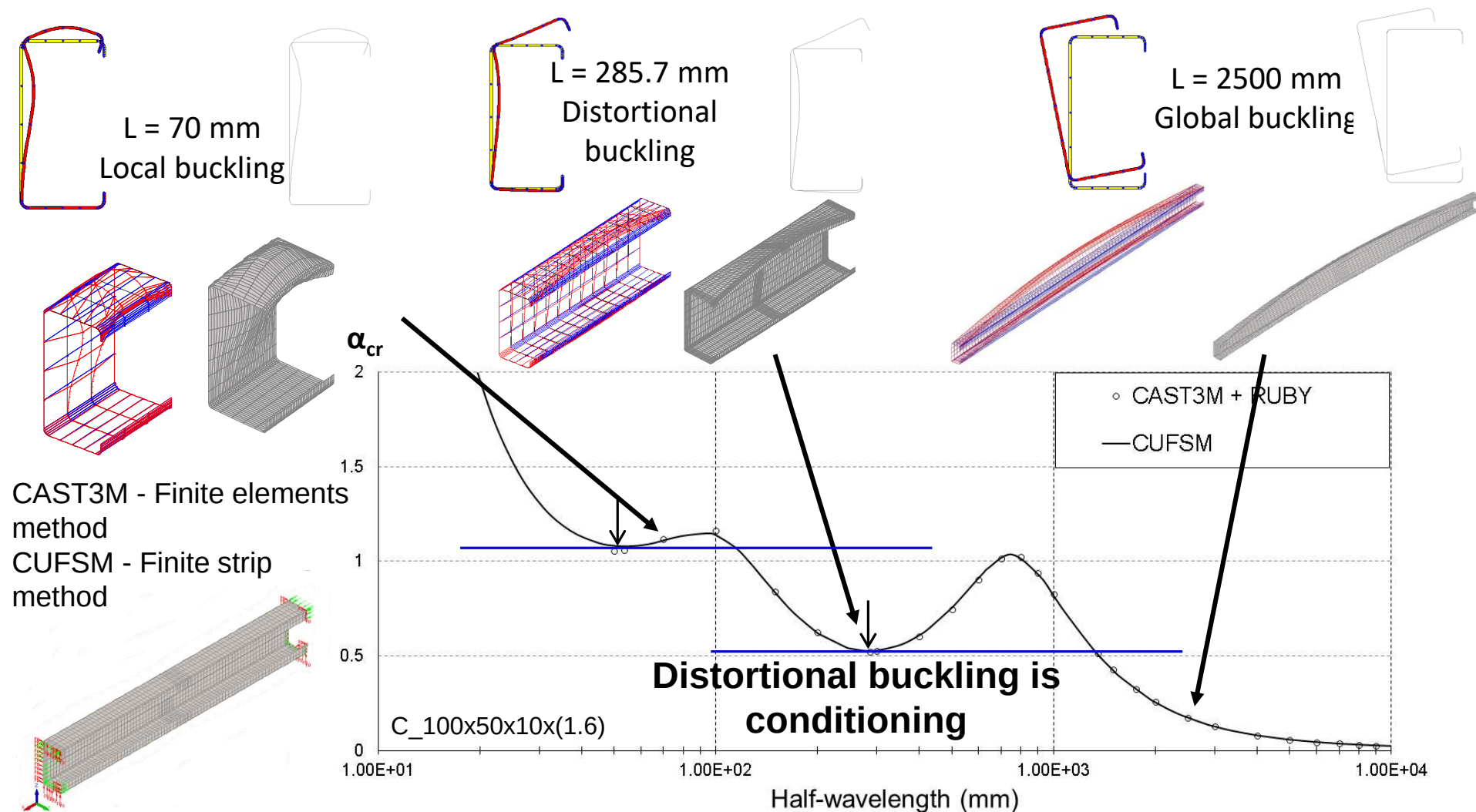


Buckling modes



Note: needed even for simplified calculation methods

Bending: Instability modes based on half-wavelength

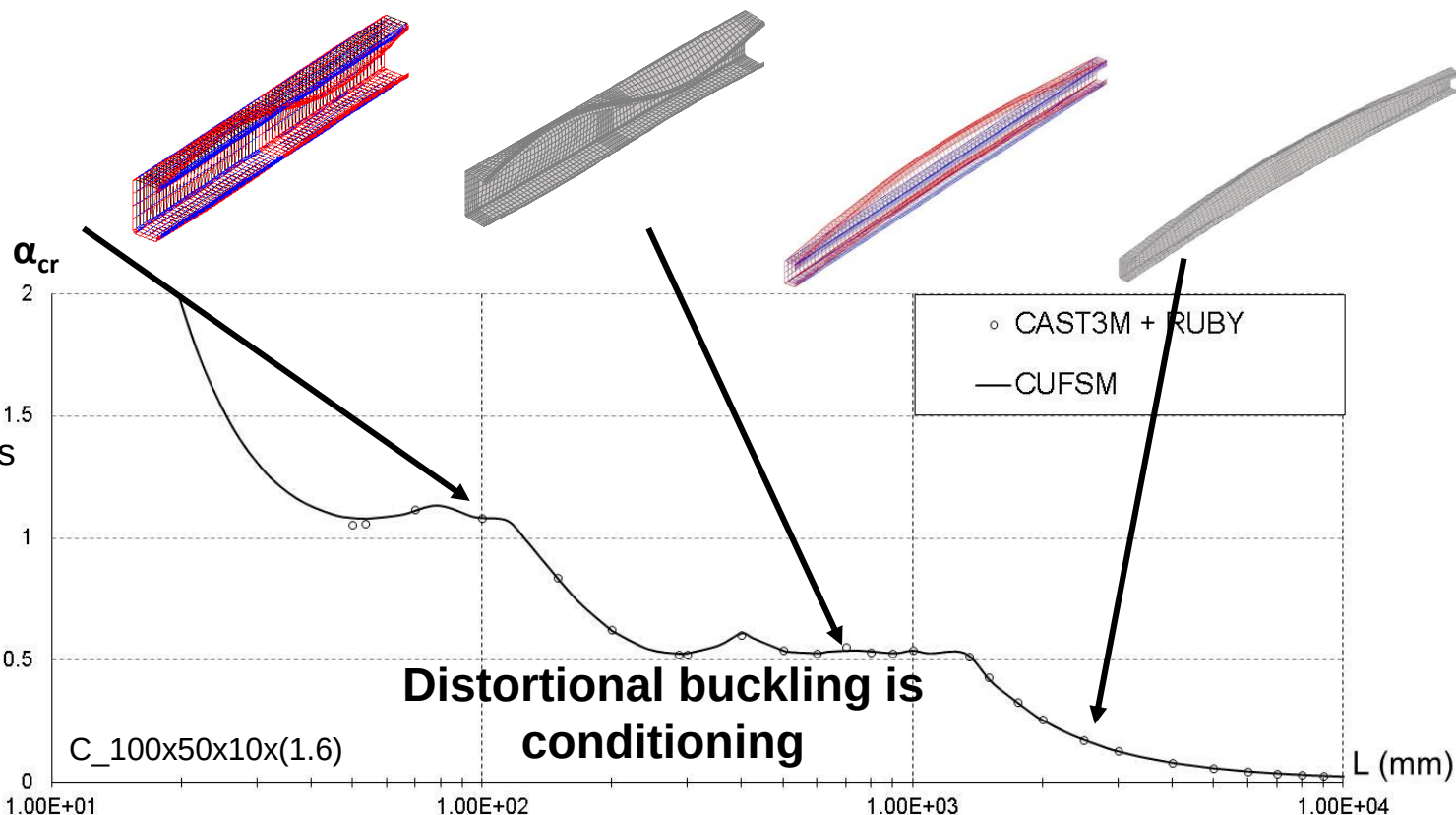


Bending: First instability modes based on element length

$L = 100 \text{ mm}$
 Local buckling

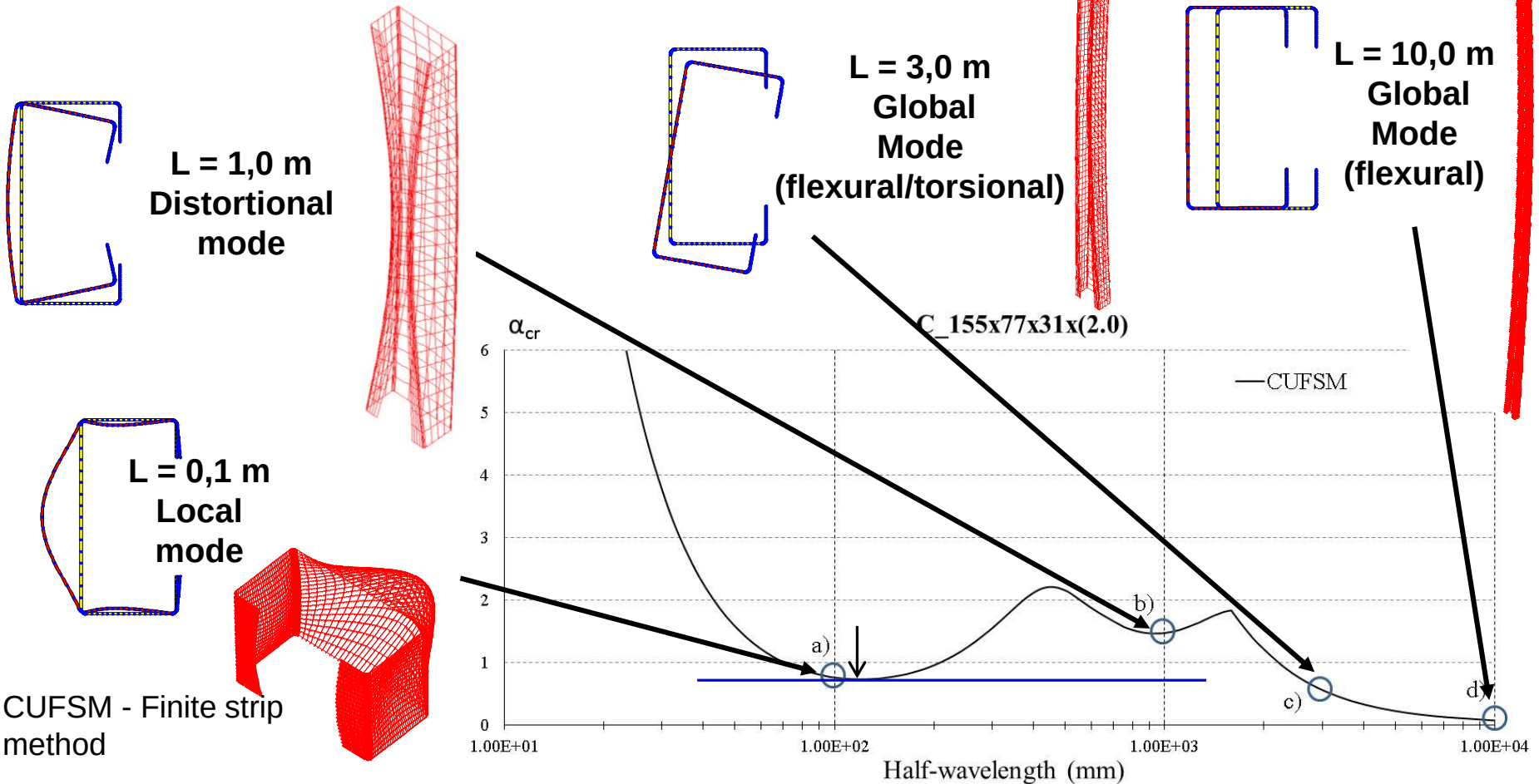
$L = 700 \text{ mm}$
 Distortional buckling

$L = 2500 \text{ mm}$
 Global buckling

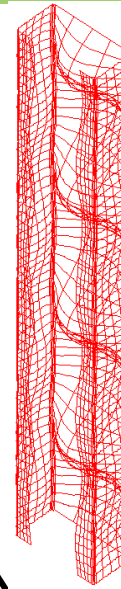


CAST3M - Finite elements
 method
 CUFSM - Finite strip
 method

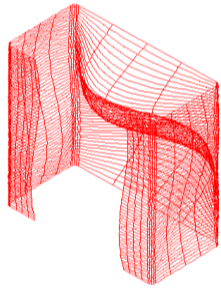
Axial compression: Instability modes based on half-wavelength



Axial compression: First instability modes based on element length

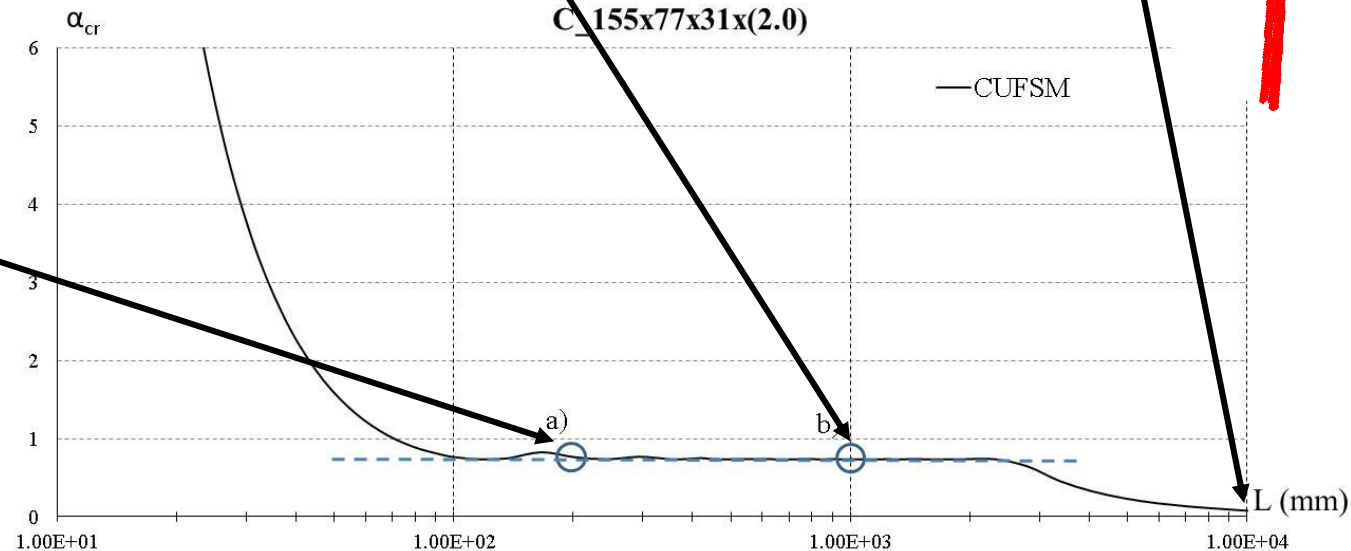


**L = 1,0 m
Local
mode**



**L = 0,2 m
Local
mode**

**L = 10,0 m
Global
mode**

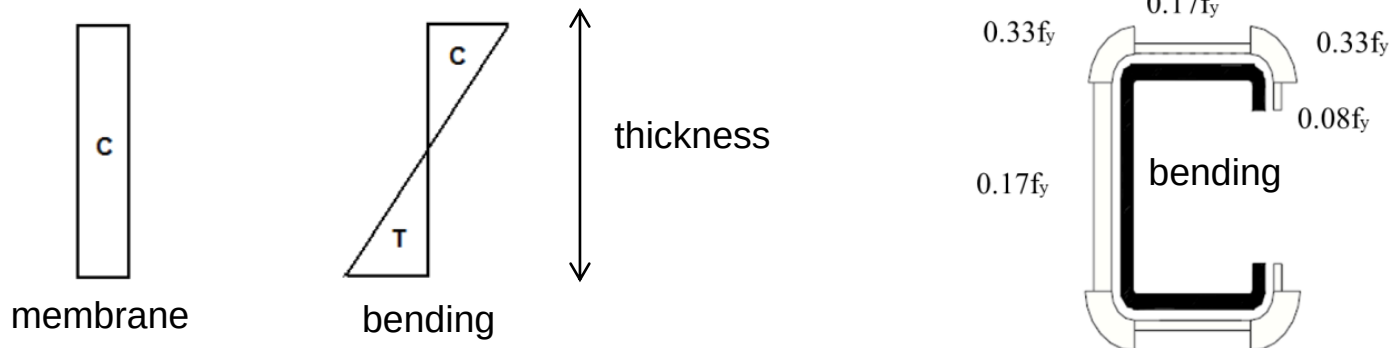


CUFSM - Finite strip
method

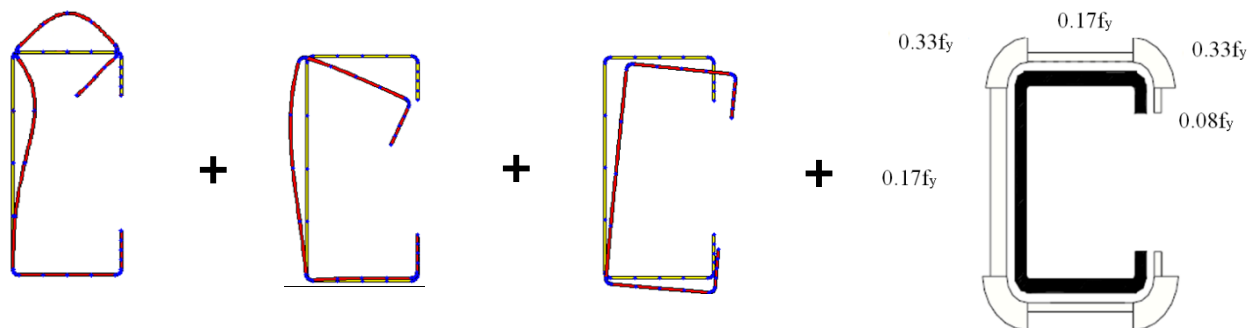
(EN 1993-1-5)

Principal Imp. + 70% Acomp. Imp. 1 + 70% Acomp Imp. 2 + ...

- Geometric imperfections corresponded to:
 - The local buckling mode with maximum amplitude of **$0.8b/100$**
 - The distortional buckling mode with maximum amplitude of **$0.8b/100$**
 - The global buckling mode with maximum amplitude of **$0.8L/750$**
- Material imperfections regarding residual stresses



➤ Imperfection combinations (beams)



Principal Imp. + 70% Acomp. Imp. 1 + 70% Acomp Imp. 2 + ...

Bending
diagram

$\Psi=1$

$\Psi=0$

$\Psi=-1$

$\Psi=1$

$\Psi=0$

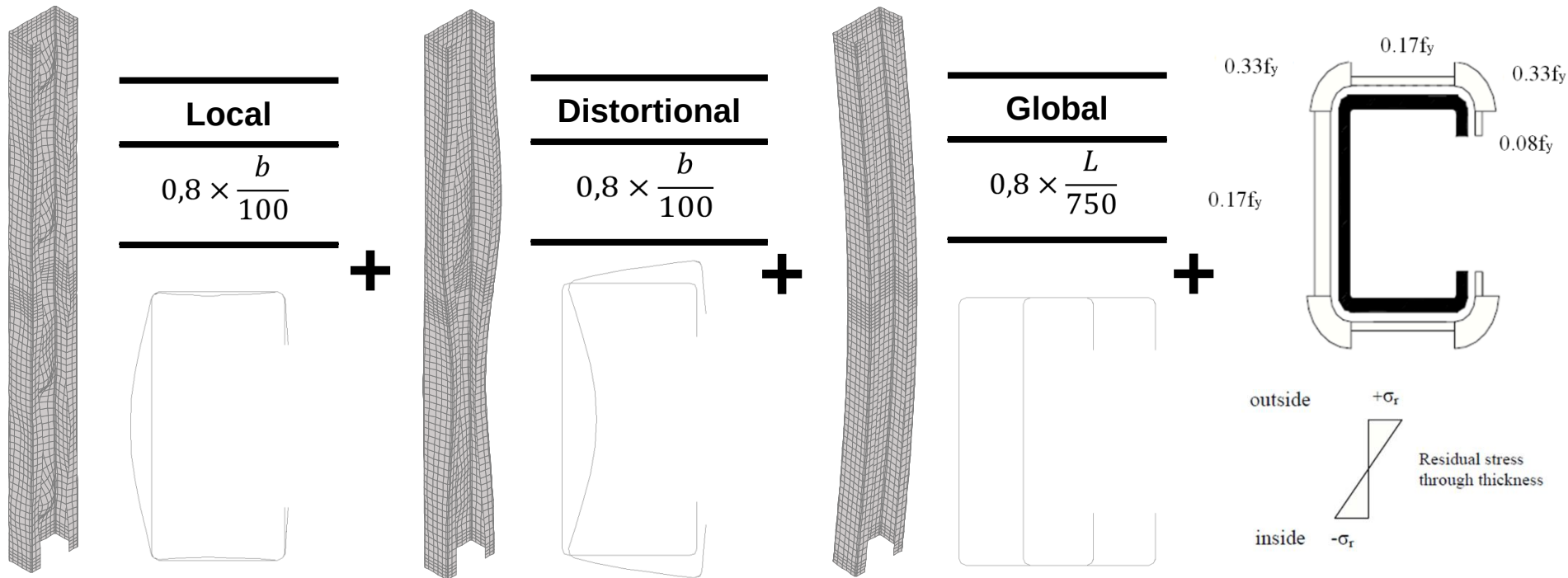
$\Psi=-1$

(x50)

(x50)

(x50)

➤ Imperfection combinations (columns)



Principal Imp. + 70% Acomp. Imp. 1 + 70% Acomp Imp. 2 + ...

EN1993-1-3&(3)

- Yield strength
 - $f_{yb} = f_y = R_{eh}$ or $R_{p0.2}$
- Ultimate strength
 - $f_u = R_m$
- Yield strength due to fabrication processes (corners enhanced strength)
 - $f_{ya} = f_{yb} + (f_u - f_{yb})k_n t^2 / A_g$
 - Lower or equal to $(f_u + f_{yb})/2$
 - Only applied when $A_{eff} = A_g$, etc...

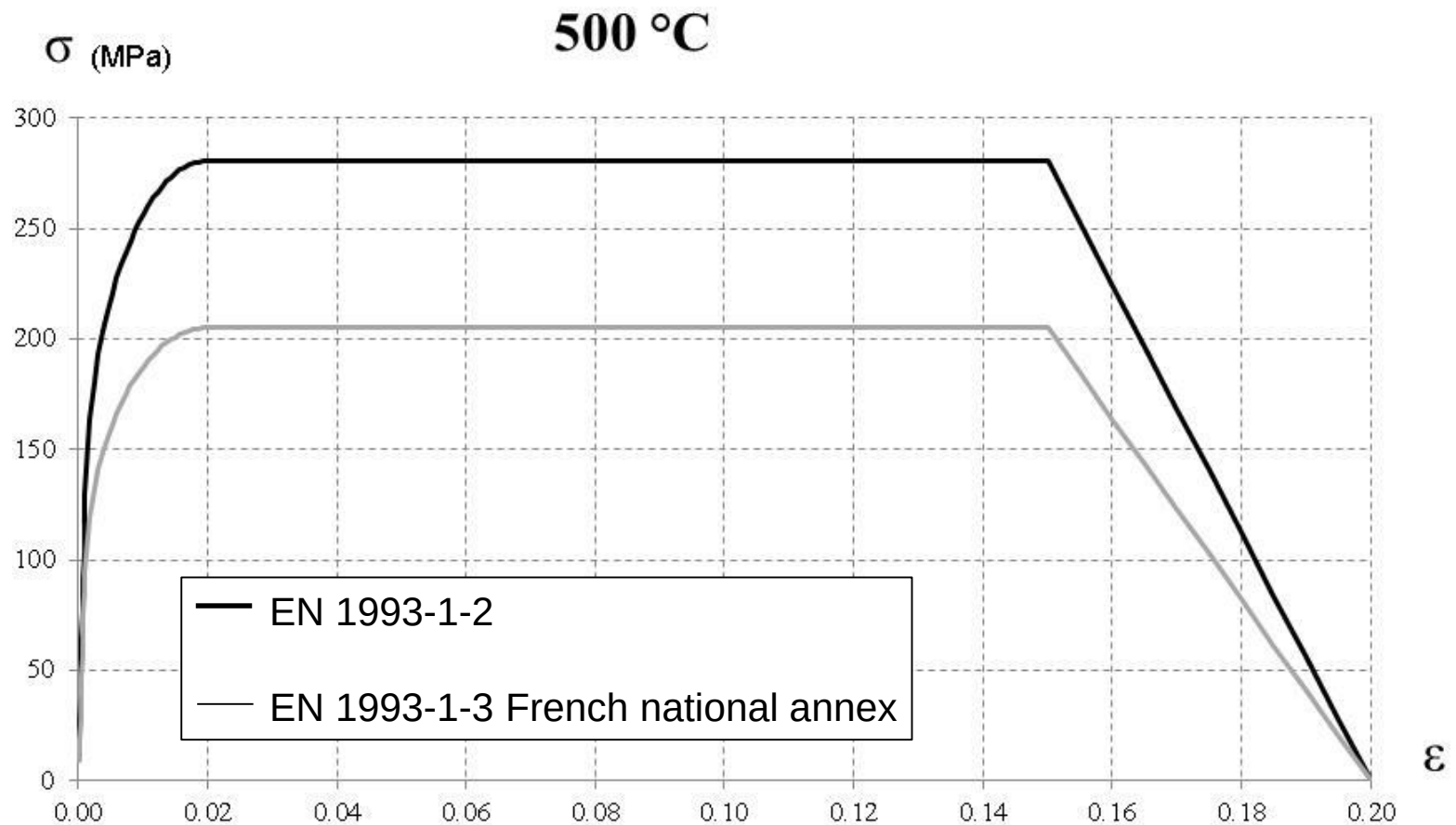
Reduction factors to temperature θ

EC3 (EN 1993-1-2) + Annex E

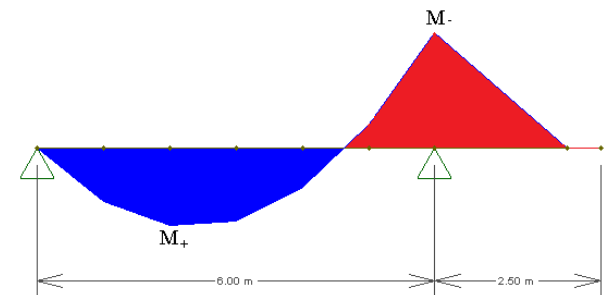
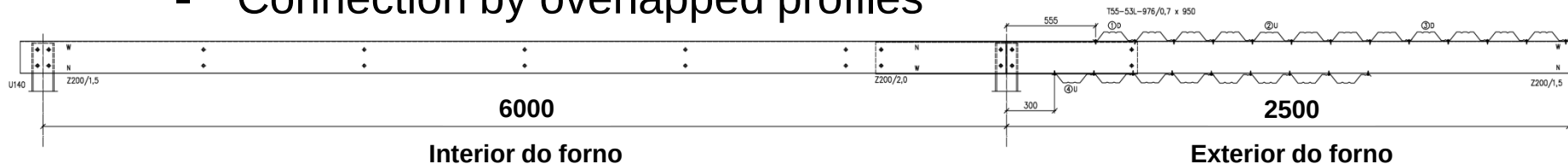
Steel temperature θ_a	Reduction factors referred to the values of f_y or E_a at 20 °C			
	$k_{E,\theta} = \frac{E_{a,\theta}}{E_a}$	$k_{y,\theta} = \frac{f_{y,\theta}}{f_y}$	$k_{p,\theta} = \frac{f_{p,\theta}}{f_y}$	$k_{0.2,p,\theta} = \frac{f_{0.2,p,\theta}}{f_y}$
20 °C	1,000	1,000	1,000	1,000
100 °C	1,000	1,000	1,000	1,000
200 °C	0,900	1,000	0,807	0,890
300 °C	0,800	1,000	0,613	0,780
350 °C	0,750	1,000	0,517	0,715
400 °C	0,700	1,000	0,420	0,650
500 °C	0,600	0,780	0,360	0,530
600 °C	0,310	0,470	0,180	0,300
700 °C	0,130	0,230	0,075	0,130
800 °C	0,090	0,110	0,050	0,070
900 °C	0,068	0,060	0,038	0,050
1000 °C	0,045	0,040	0,025	0,030
1100 °C	0,023	0,020	0,013	0,020
1200 °C	0,000	0,000	0,000	0,000

EC3 (EN 1993-1-2) + Annex NF

Steel temperature θ_a	Reduction factors referred to the values of f_y or E_a at 20 °C			
	$k_{E,\theta} = \frac{E_{a,\theta}}{E_a}$	$k_{y,\theta} = \frac{f_{y,\theta}}{f_y}$	$k_{p,\theta} = \frac{f_{p,\theta}}{f_y}$	$k_{0.2,p,\theta} = \frac{f_{0.2,p,\theta}}{f_y}$
20 °C	1,000	1,000	1,000	1,000
100 °C	1,000	1,000	1,000	1,000
200 °C	0,900	1,000	0,807	0,896
300 °C	0,800	1,000	0,613	0,793
350 °C	0,740	0,945	0,494	0,705
400 °C	0,680	0,890	0,374	0,616
500 °C	0,450	0,570	0,263	0,407
600 °C	0,250	0,340	0,130	0,229
700 °C	0,110	0,180	0,059	0,117
800 °C	0,080	0,070	0,032	0,049
900 °C	0,060	0,053	0,024	0,037
1000 °C	0,040	0,035	0,016	0,025
1100 °C	0,020	0,018	0,008	0,013
1200 °C	0,000	0,000	0,000	0,000

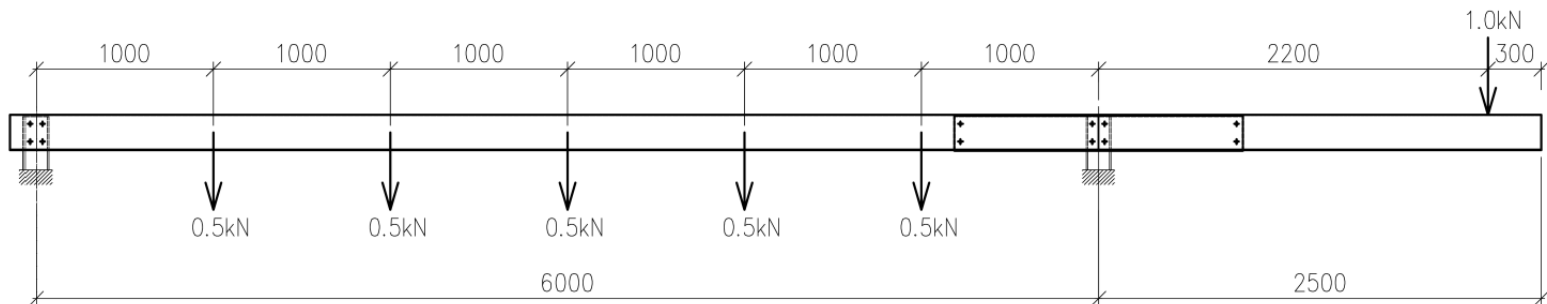


- Cold formed profile with Z section
- 2 spans:
 - laterally restrained cantilever at normal temperature
 - 6 m span inside the furnace
- Connection by overlapped profiles



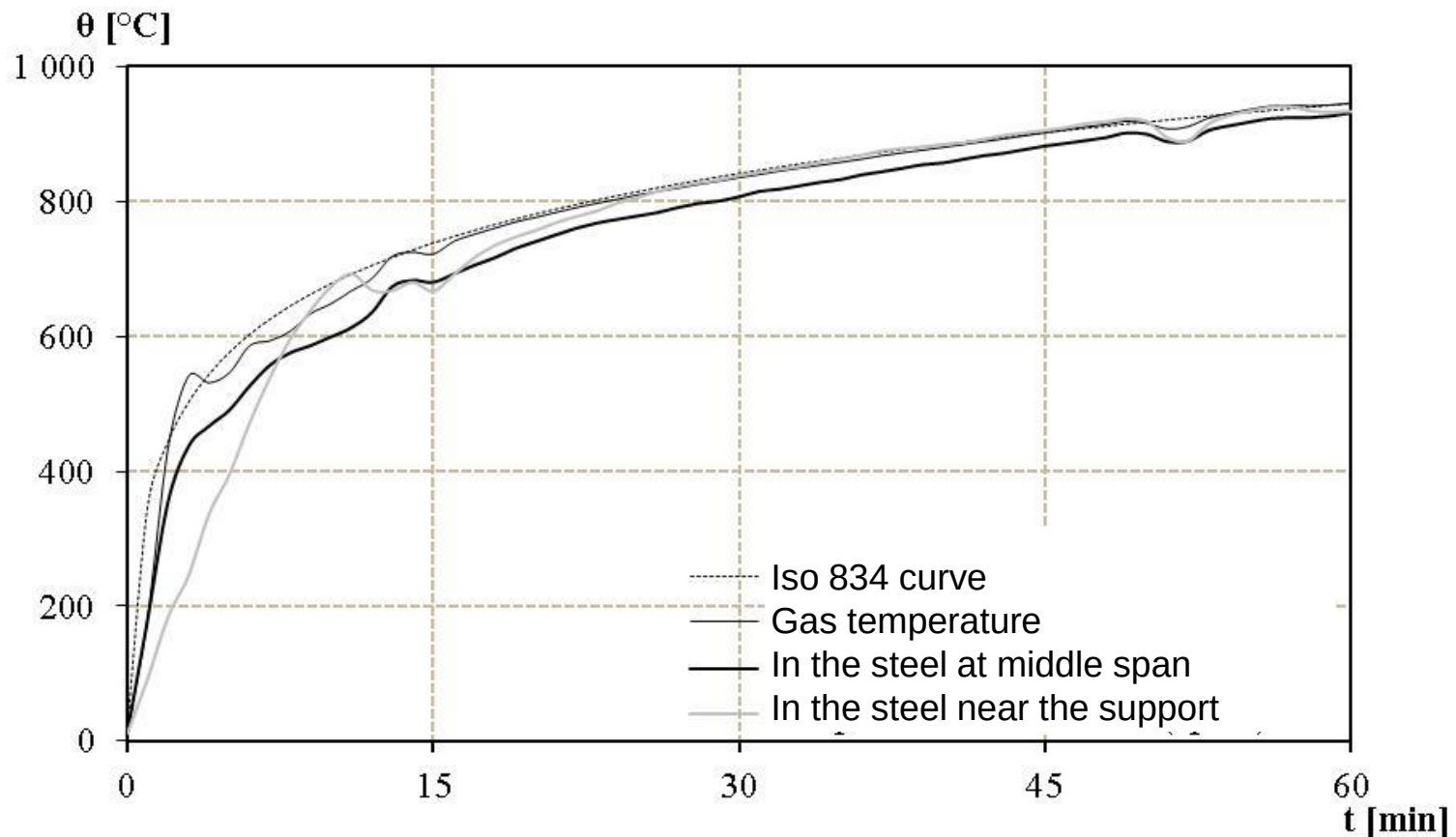
*Experimental test performed at PAVUS fire laboratory by Czech Technical University

- Load application



*Experimental test performed at PAVUS fire laboratory by Czech Technical University

- Temperature: Standard fire curve ISO ISO834

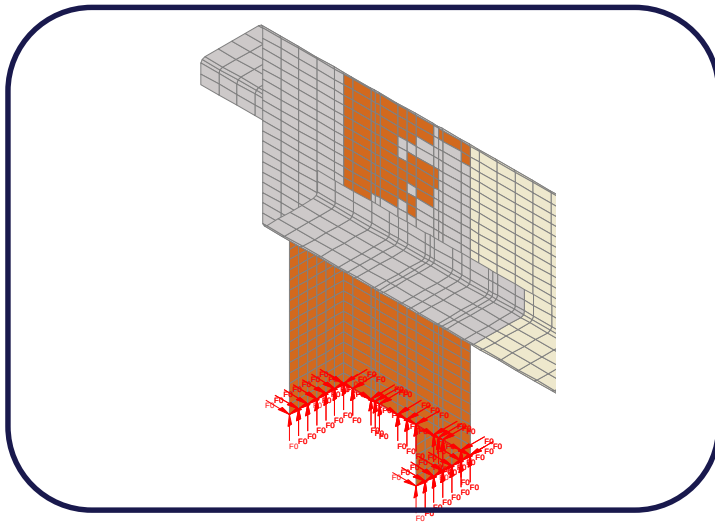


*Experimental test performed at PAVUS fire laboratory by Czech Technical University

Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

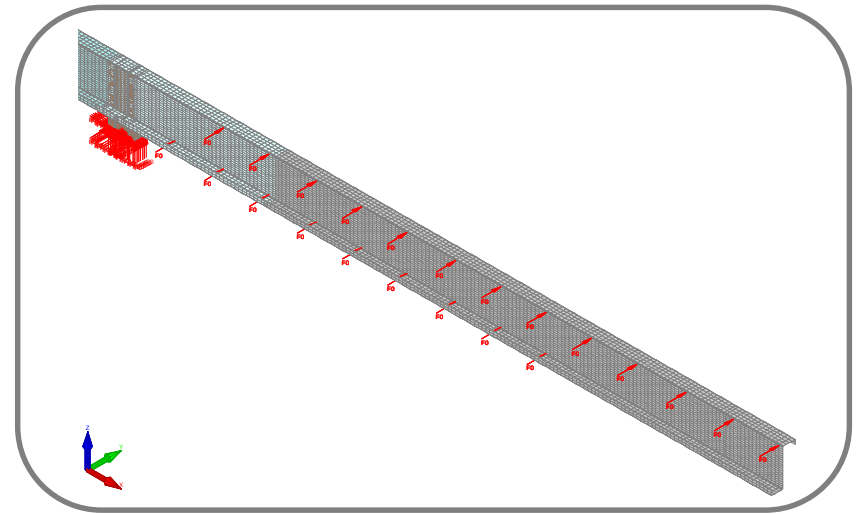
➤ Support conditions

- U profile

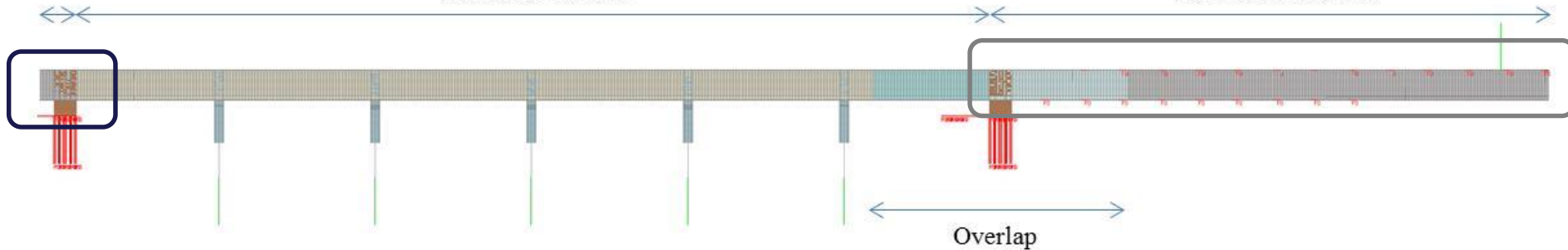


Inside the furnace

- Cantilever



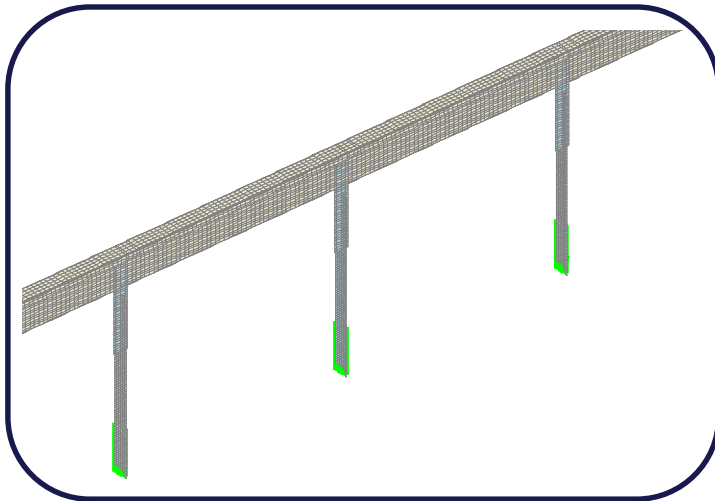
Outside the furnace



Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

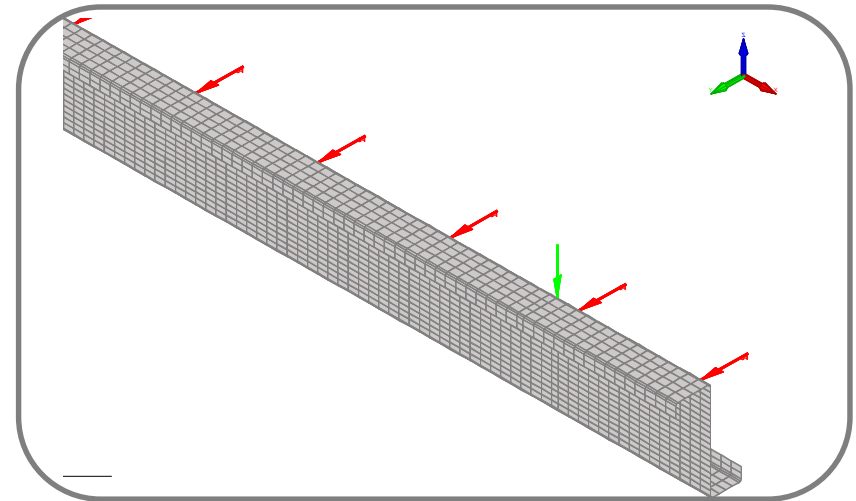
➤ Loads application

- Distributed loads

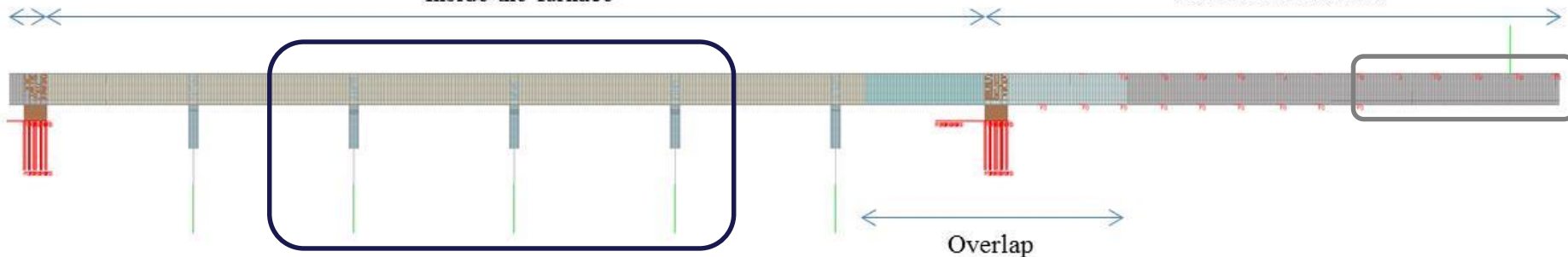


Inside the furnace

- Concentrated load

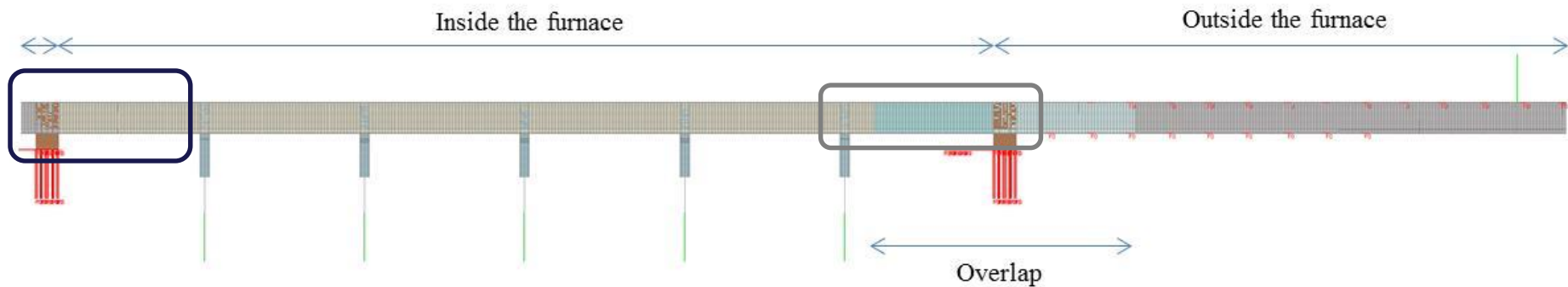
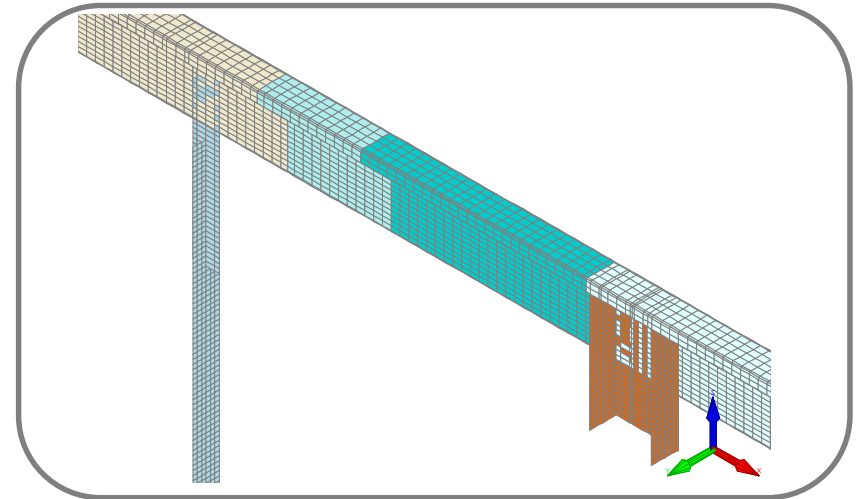
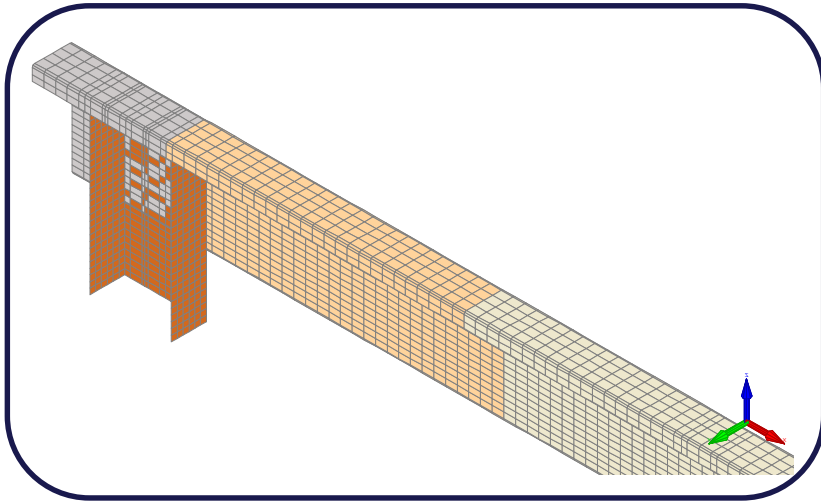


Outside the furnace



➤ Temperatura

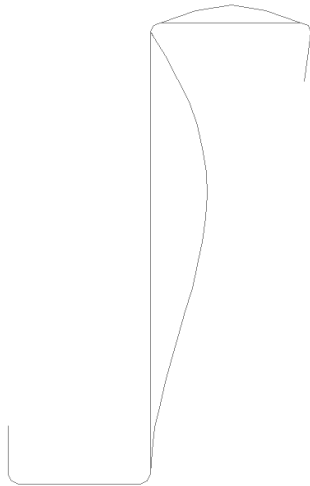
Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)



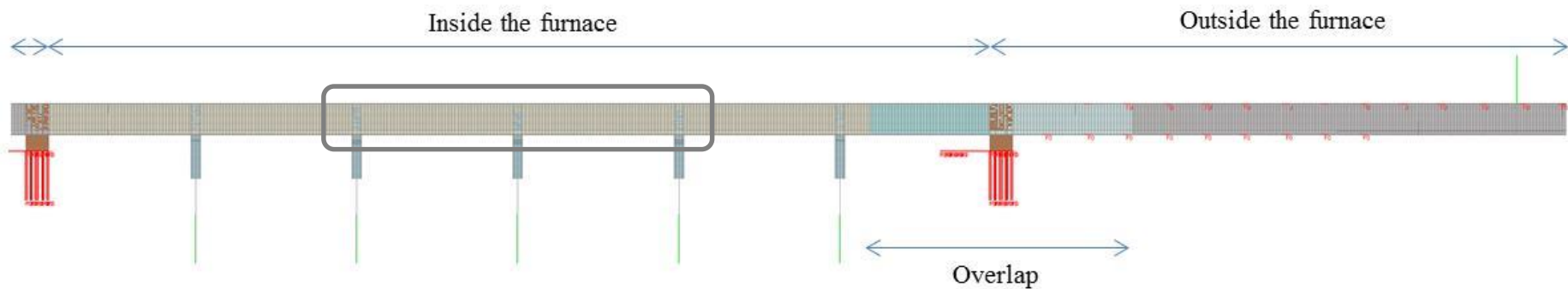
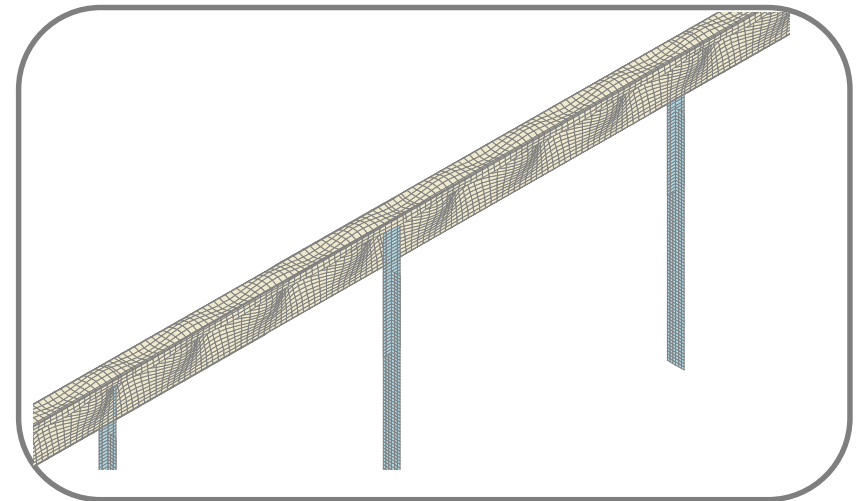
Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

➤ Initial geometric imperfections

- Local



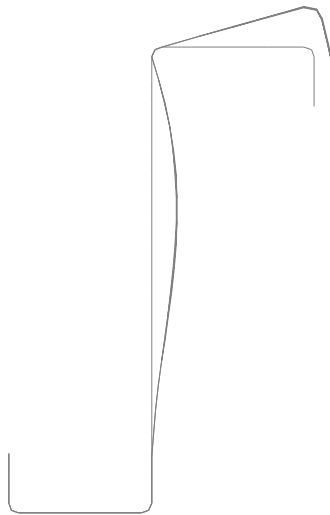
$$0,8 \times \frac{b}{100}$$



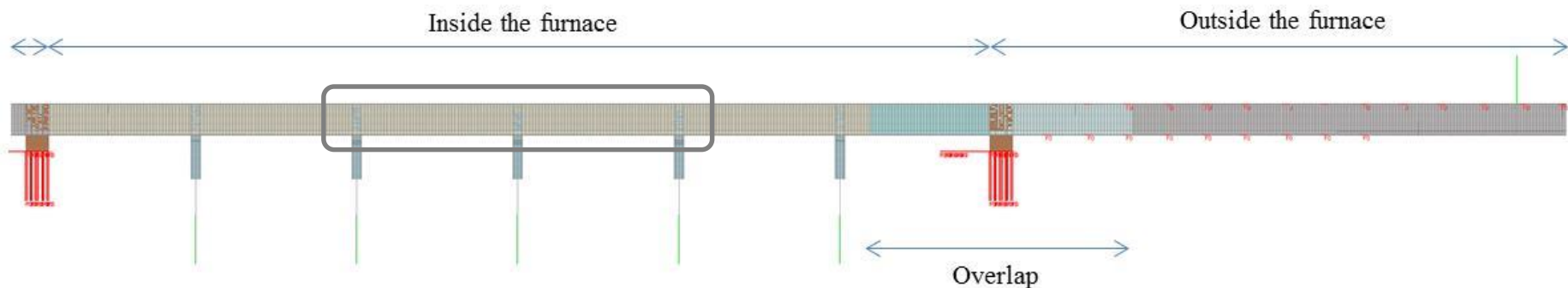
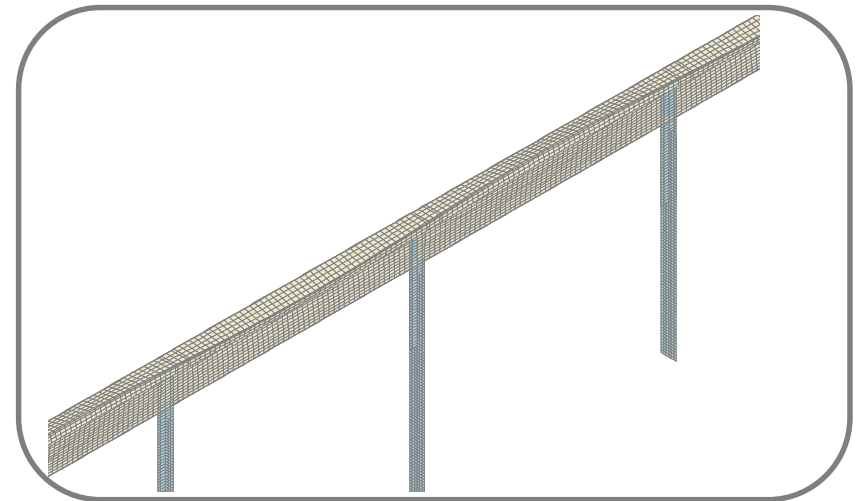
Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

➤ Initial geometric imperfections

- Distortional



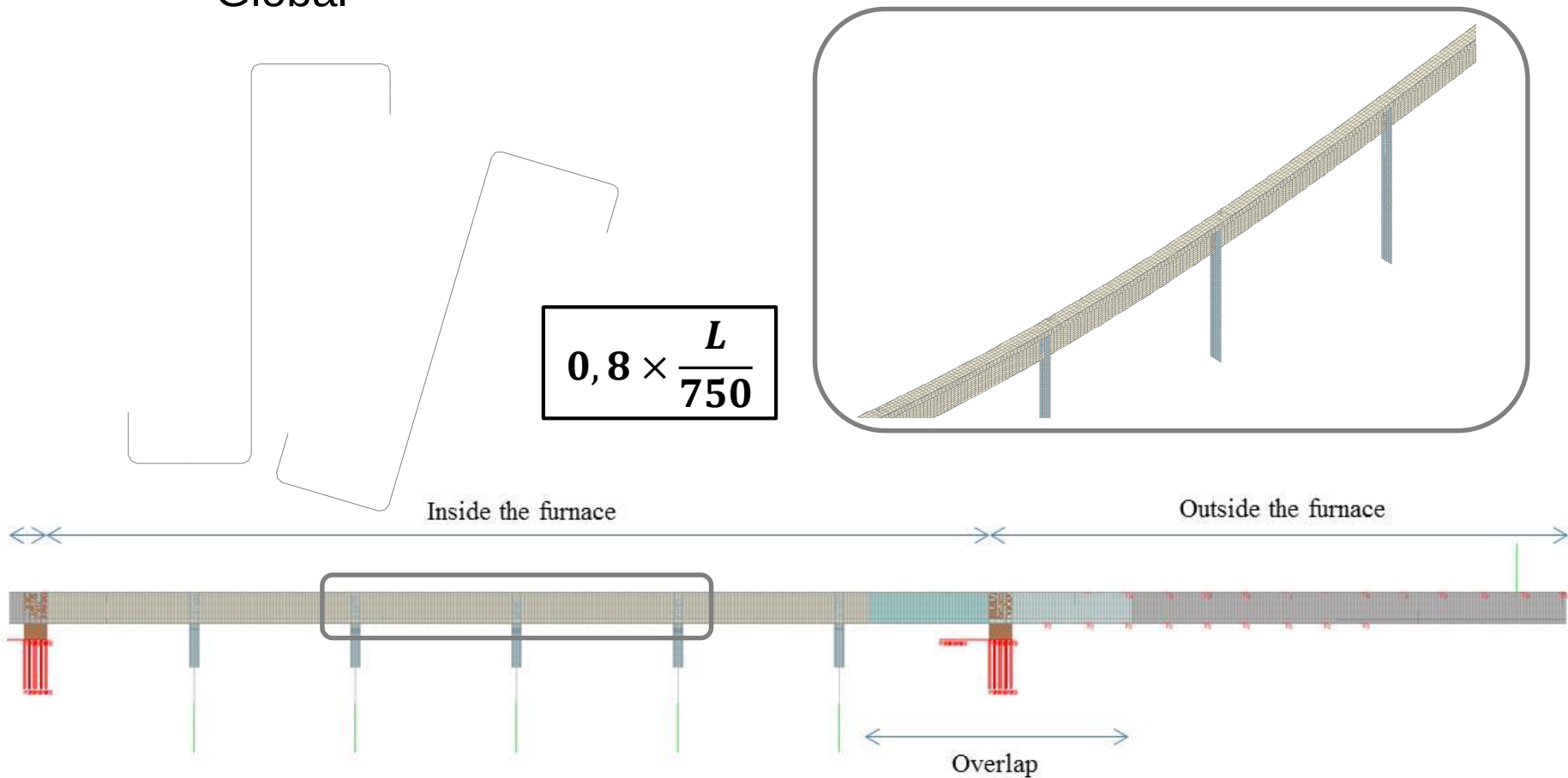
$$0,8 \times \frac{b}{100}$$



Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

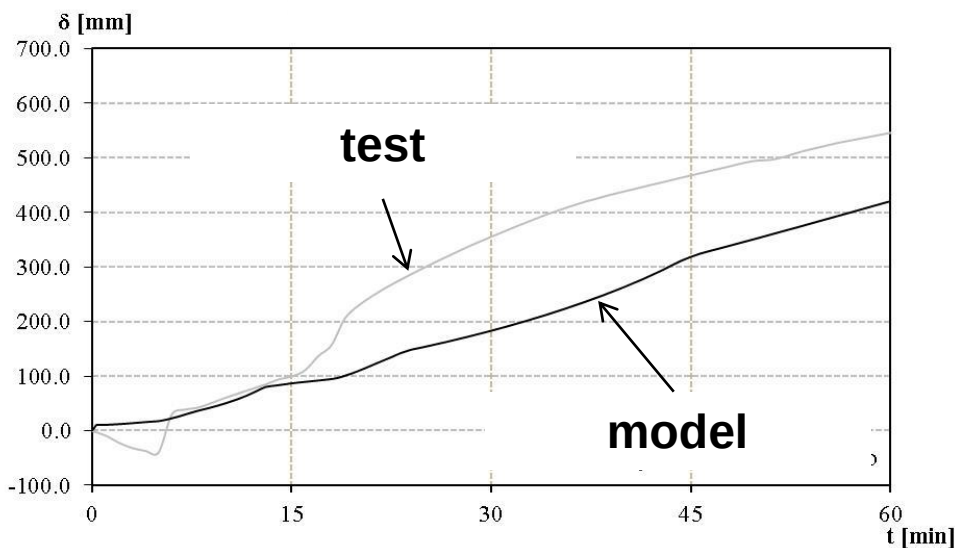
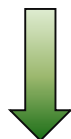
➤ Initial geometric imperfections

- Global

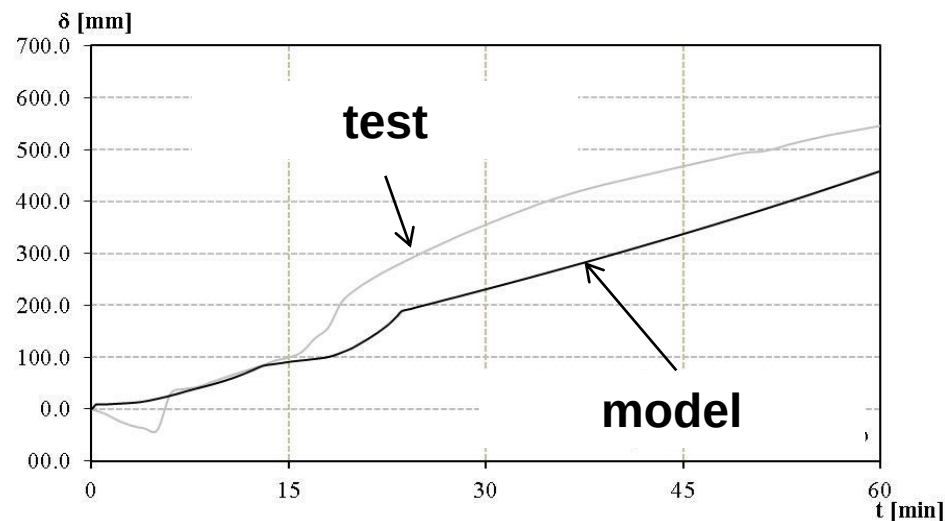


➤ Deflection at mid span

EC3 (EN 1993-1-2)
Annex E



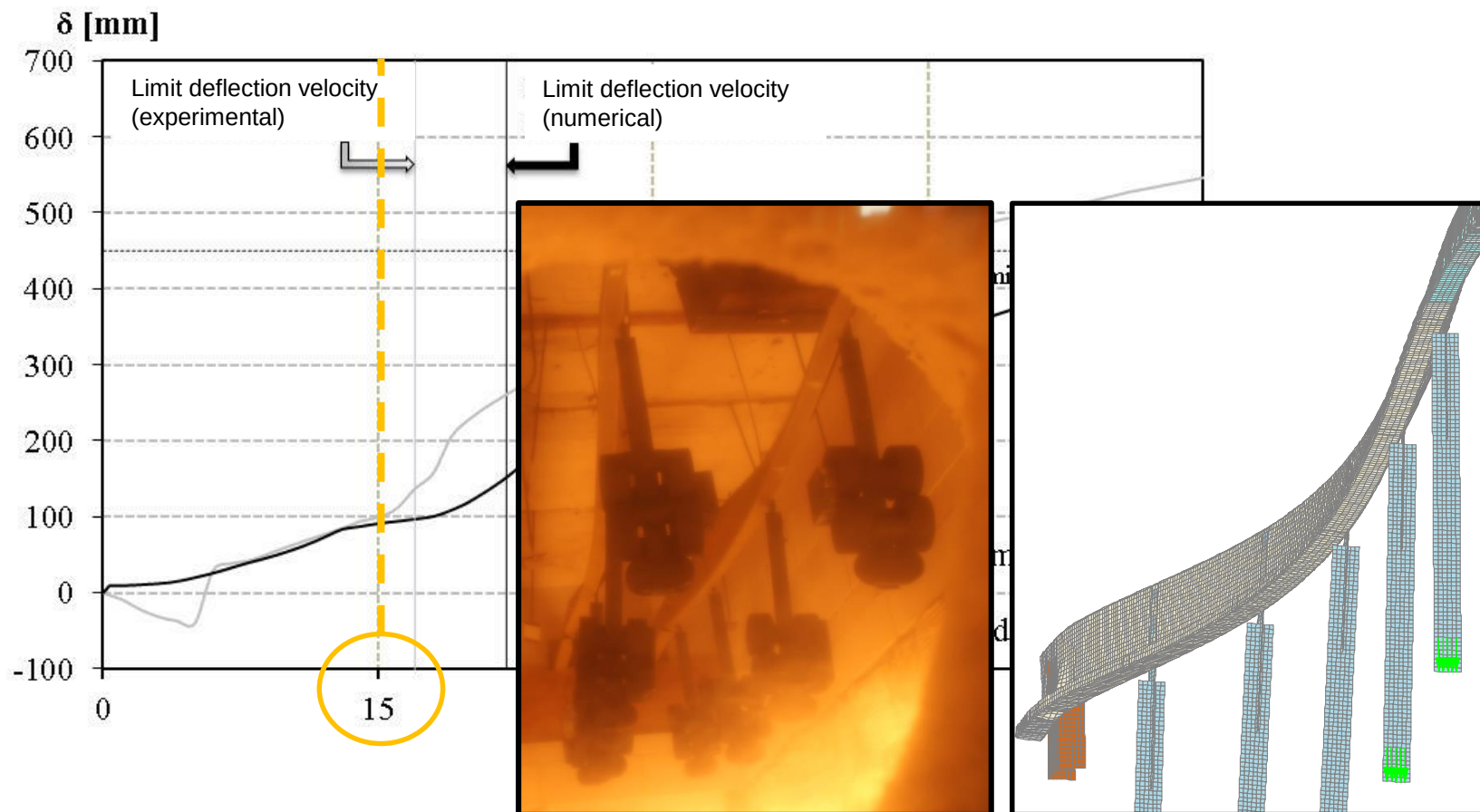
Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)



EC3 (EN 1993-1-2)
Annex NF

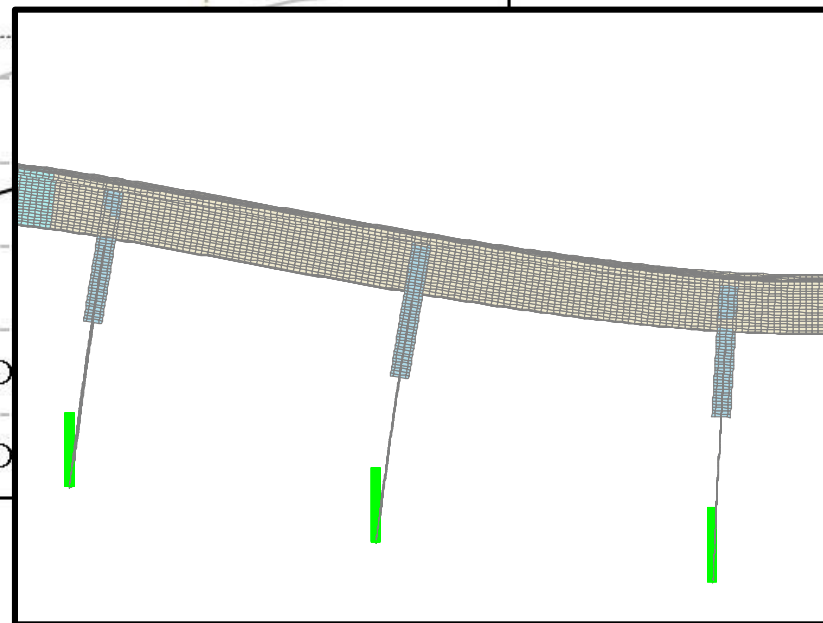
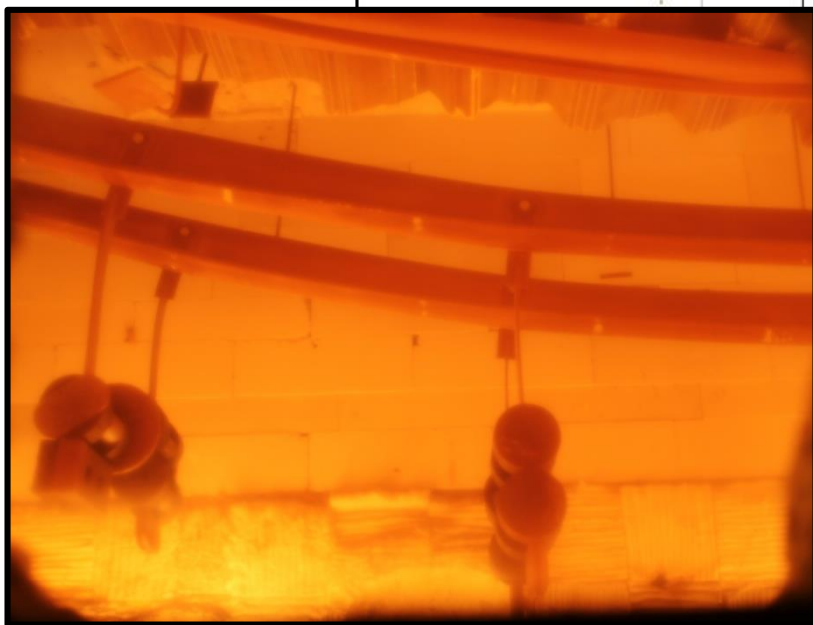
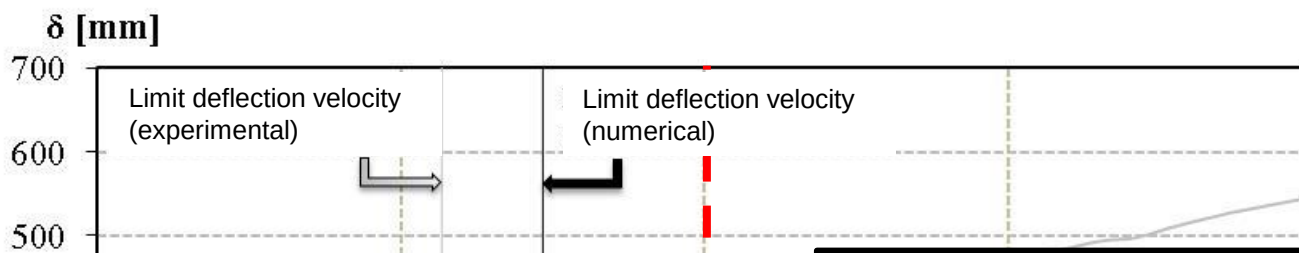
Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

➤ Results (Lateral buckling)



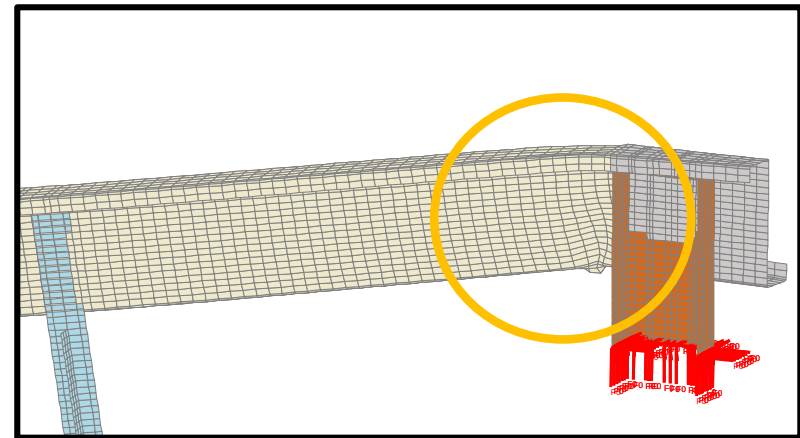
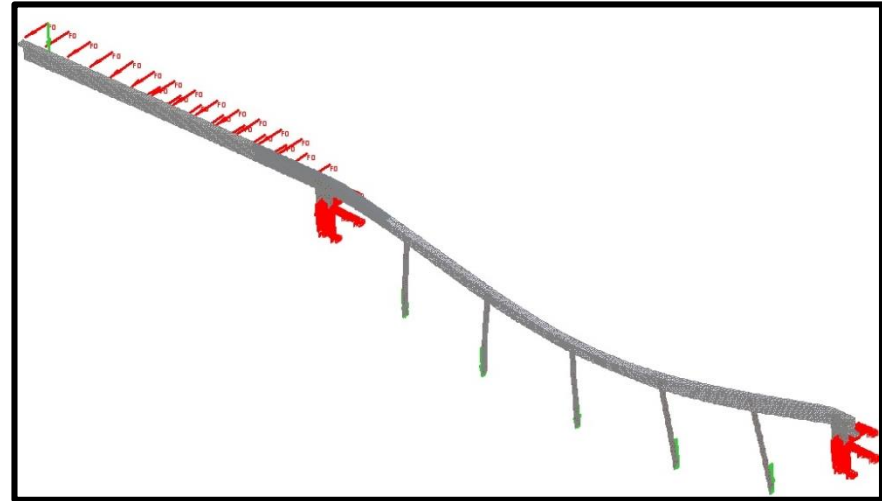
Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

➤ Results (catenary action)



Flávio Arrais; Nuno Lopes; Paulo Vila Real; Michal Jandera; Ivo Schwarz (2015)

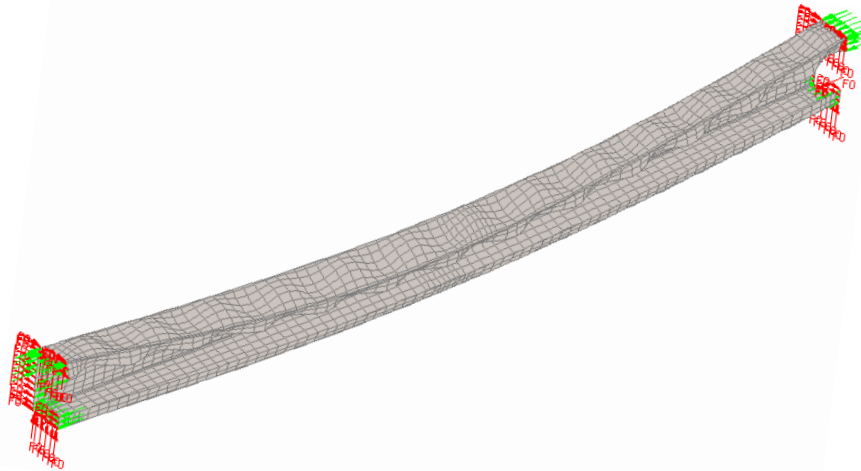
➤ Results (after the test)



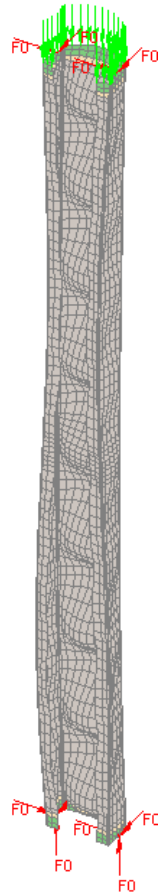
Numerical analysis of unrestrained members

Flávio Arrais; Nuno Lopes; Paulo Vila Real (2013-2017)

- **Geometrical imperfections and residual stresses** considered



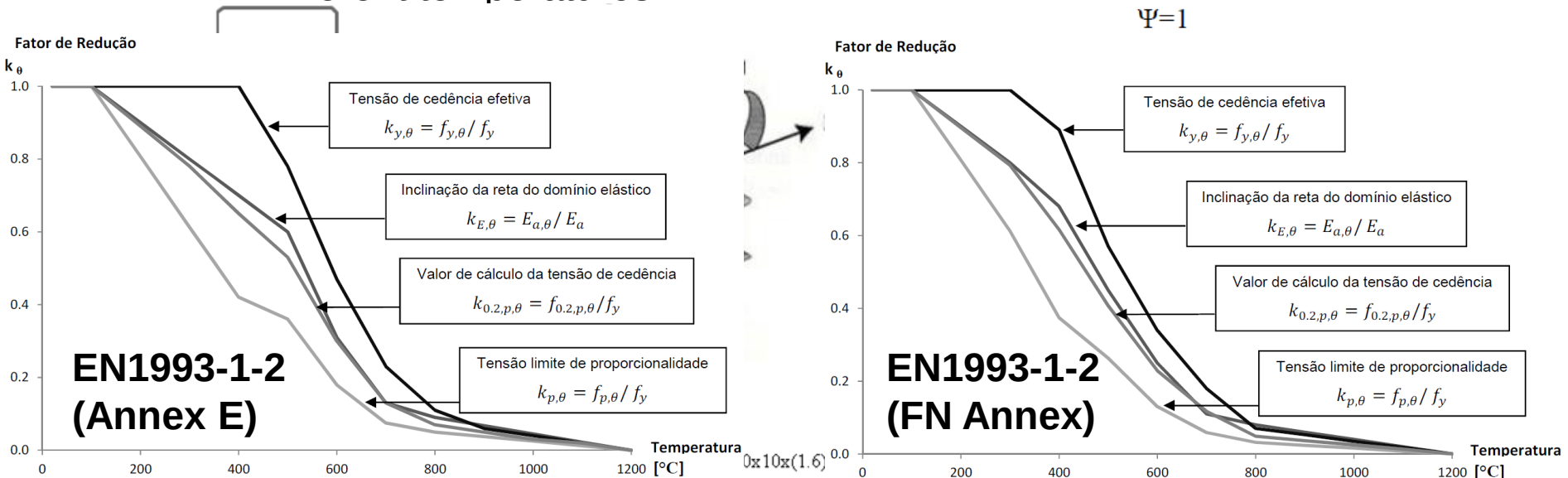
- In the numerical study, the following programs were used:
 - **CUFSM** (Johns Hopkins University, USA)
 - **CAST3M** (Commissariat à l'Énergie Atomique, France); **RUBY** interface (University of Aveiro, Portugal)
 - **SAFIR** (University of Liege, Belgium).



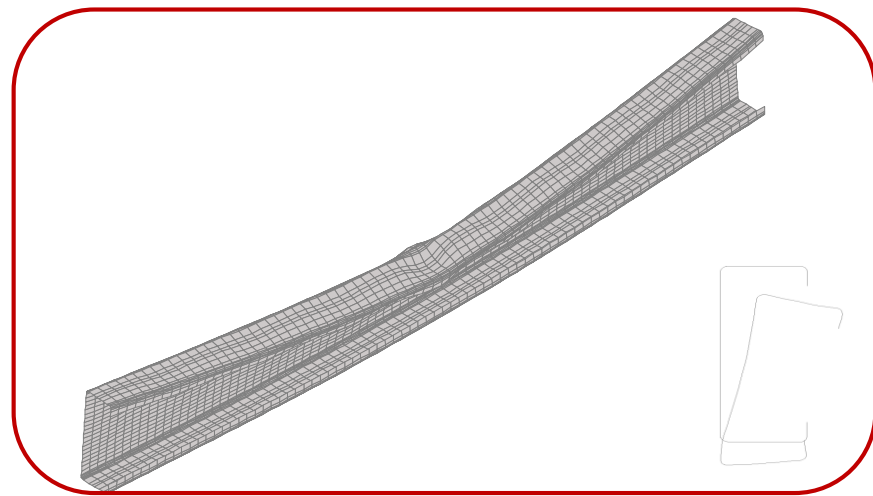
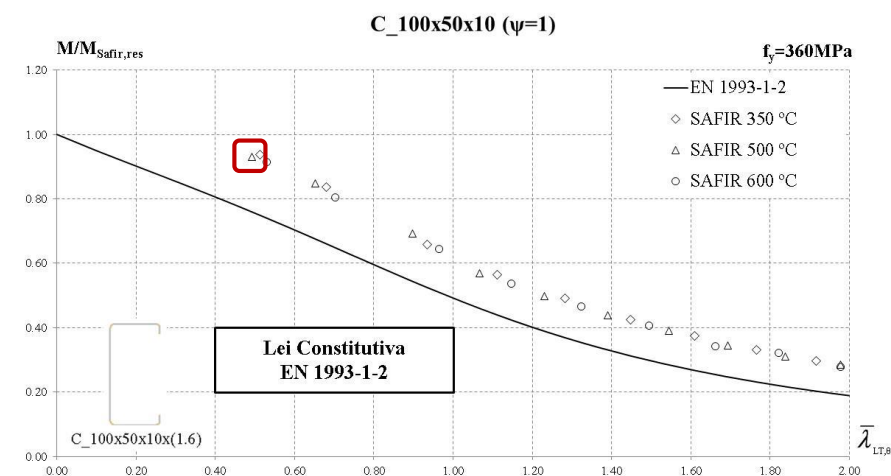
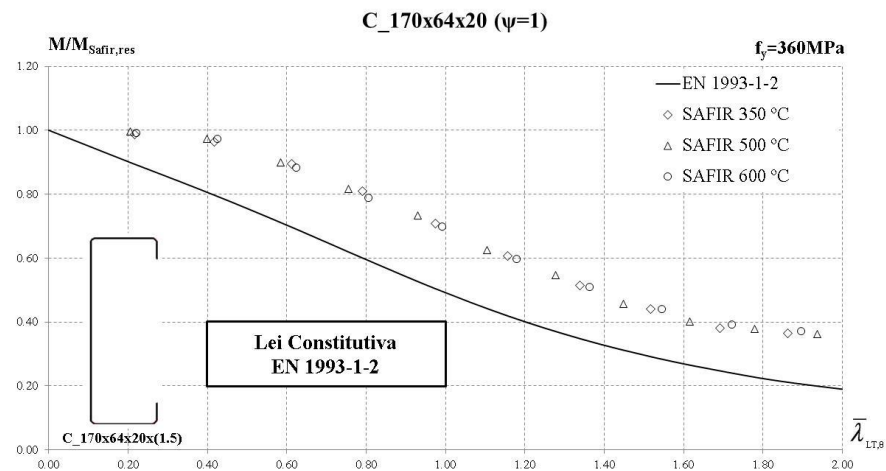
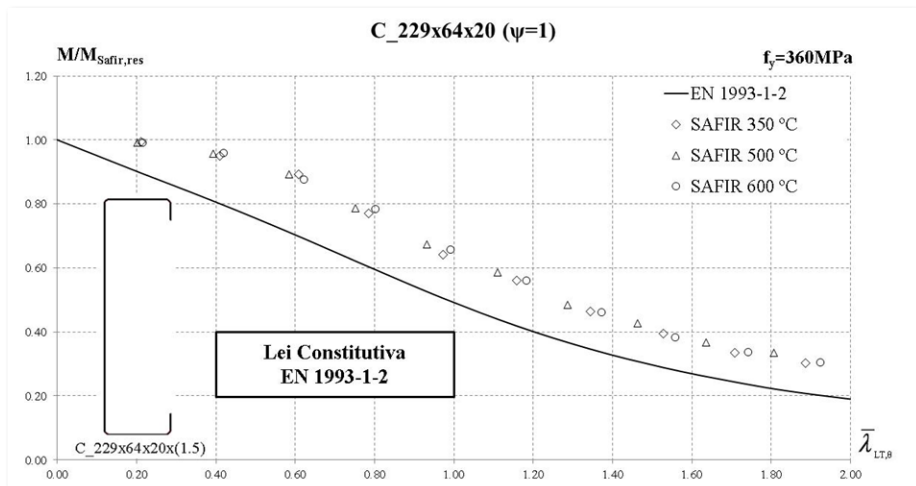
➤ **Parametric analysis** taken into account the following parameters:

- Different C cross-sections slendernesses
- Different steel grades
- Different loading types
- Different constitutive laws
- Different temperatures

Steel temperature θ_a
350 °C
500 °C
600 °C

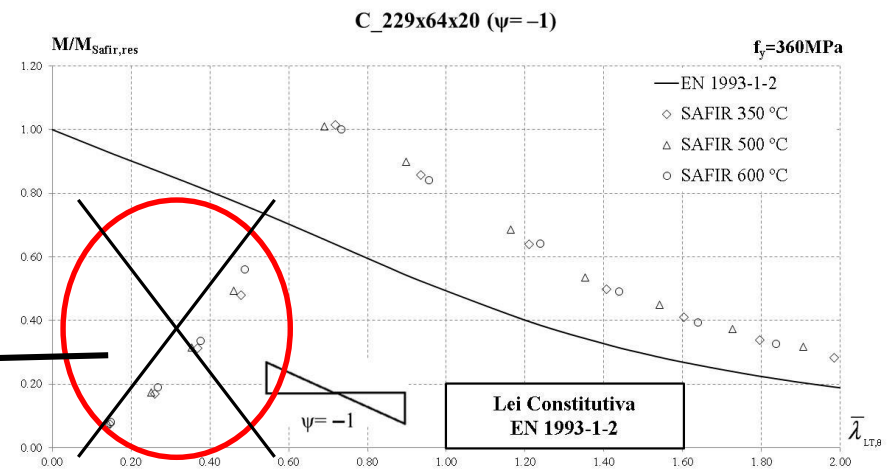
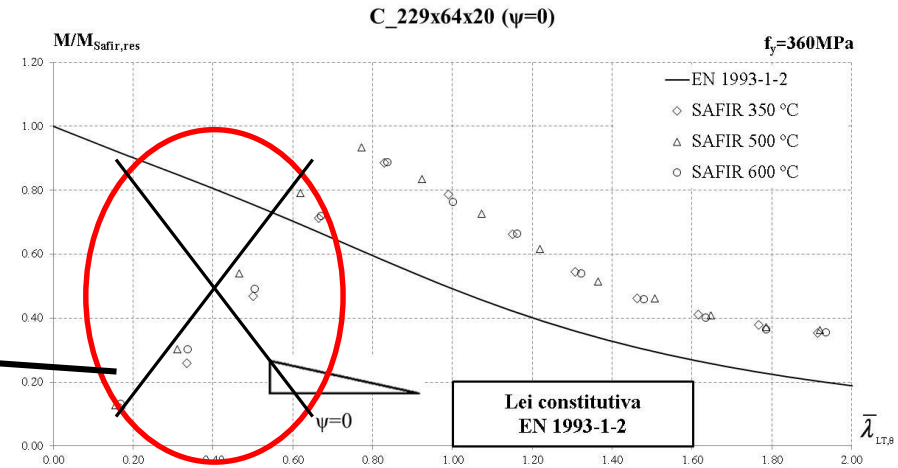
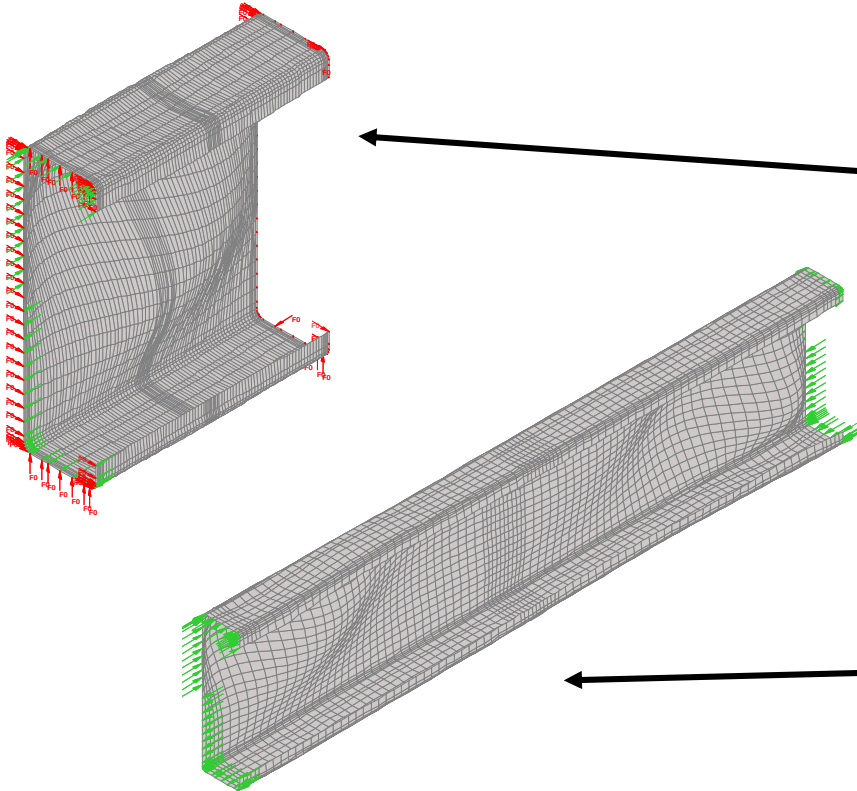


Cross-section influence:



Loading type influence:

Web collapse
(shear buckling)

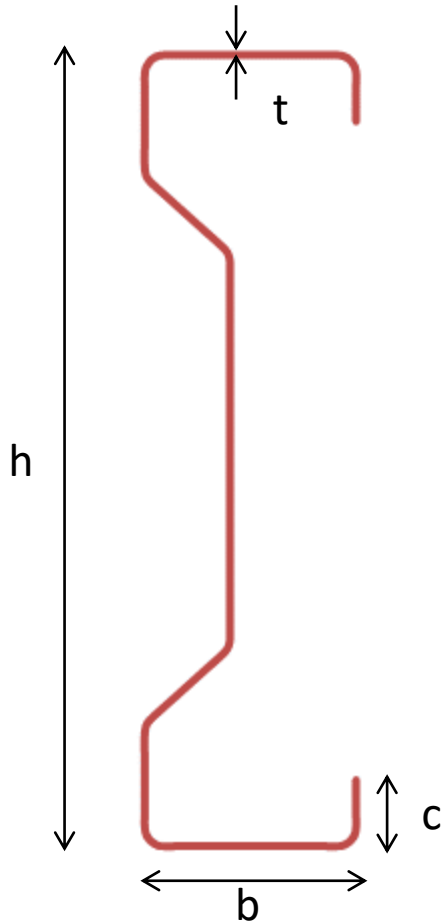


Case study

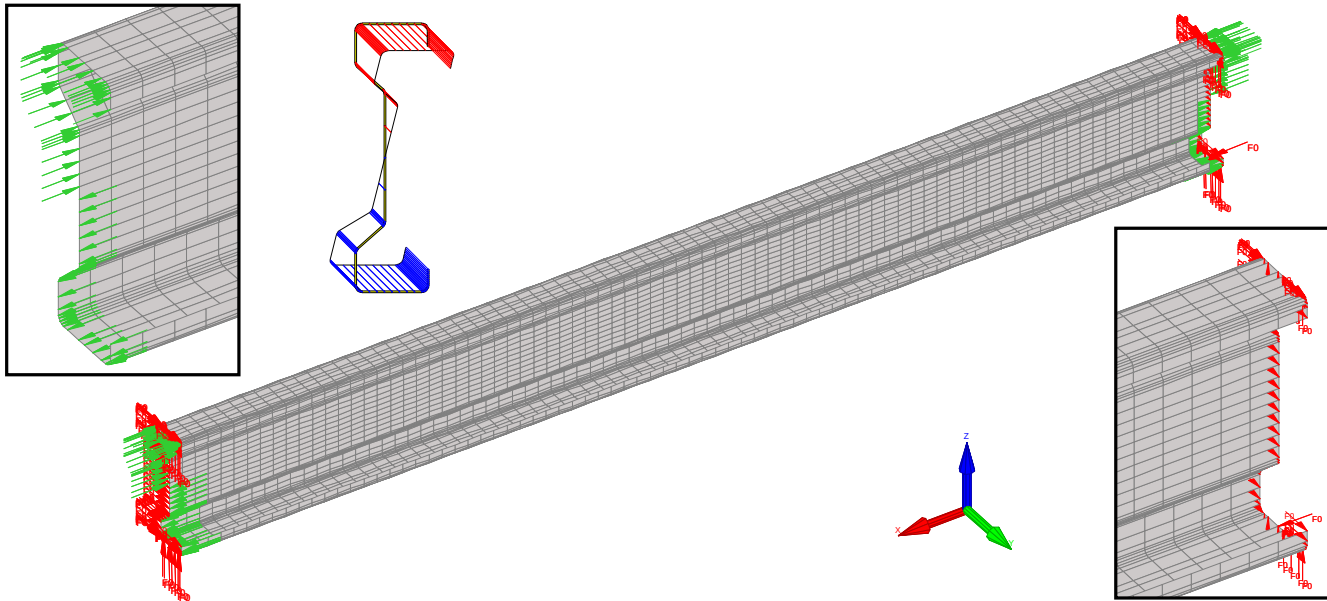
- Simply supported beams
- Cross-sections equivalent to Class 4 cross-sections
- Dimensions:

Designation	Web [mm]	Flange [mm]	Lip [mm]	Thickness [mm]
$\Sigma_{229 \times 64 \times 20 \times (1.5)}$	229	64	20	1.5
$\Sigma_{150 \times 43 \times 20 \times (2.0)}$	150	43	20	2.0

- Temperature considered uniform throughout the cross-section



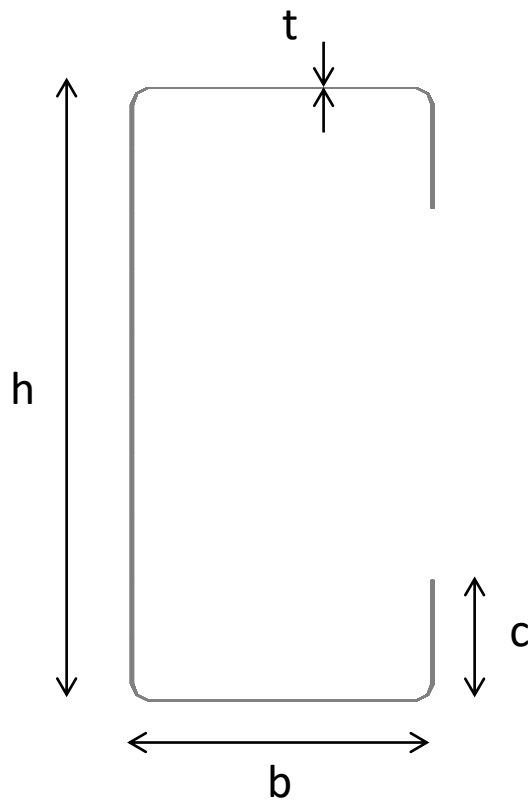
- Concentrated loads applied, in the parallel directions to the beam axis, according to the linear stresses distribution resulting from simple bending around the strong axis.



- Restrictions imposed in order to reproduce one end pinned support and one roller support at the ends of the beam.

Case study

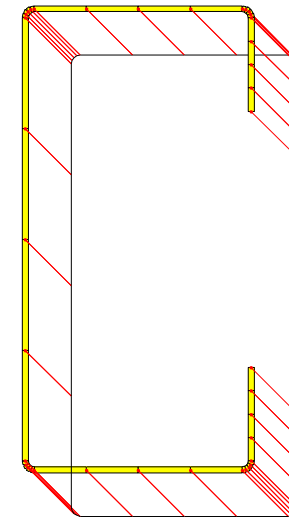
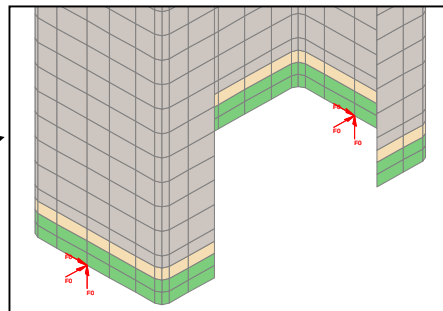
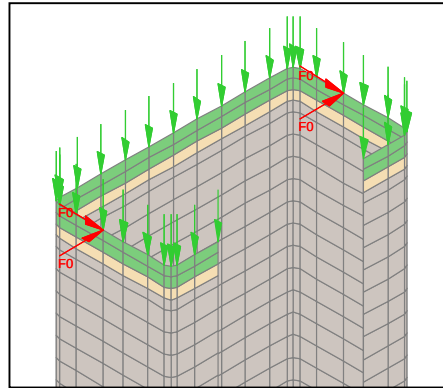
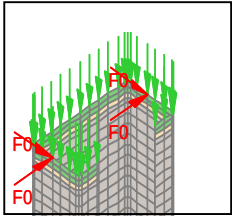
- Simply supported columns
- Cross-sections equivalent to Class 4 cross-sections
- Dimensions:



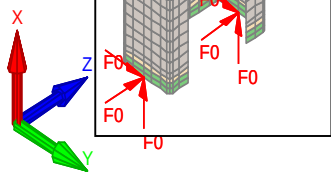
Designation	Web [mm]	Flange [mm]	Lip [mm]	Thickness [mm]
C_229x64x20x(1.5)	229	64	20	1.5
C_155x77x31x(2.0)	155	77	31	2.0

- Temperature considered uniform throughout the cross-section

- Concentrated loads applied, in the parallel directions to the column axis, according to the linear stresses distribution resulting from compression.

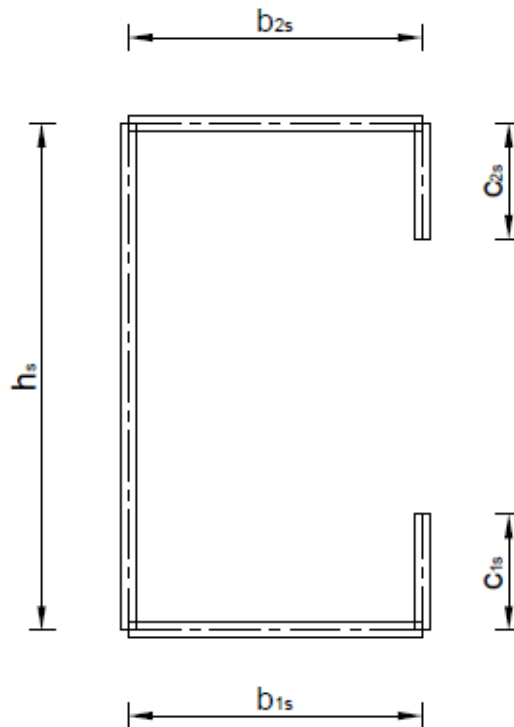


- Restrictions imposed in order to reproduce one end pinned support and one roller support at the ends of the column.

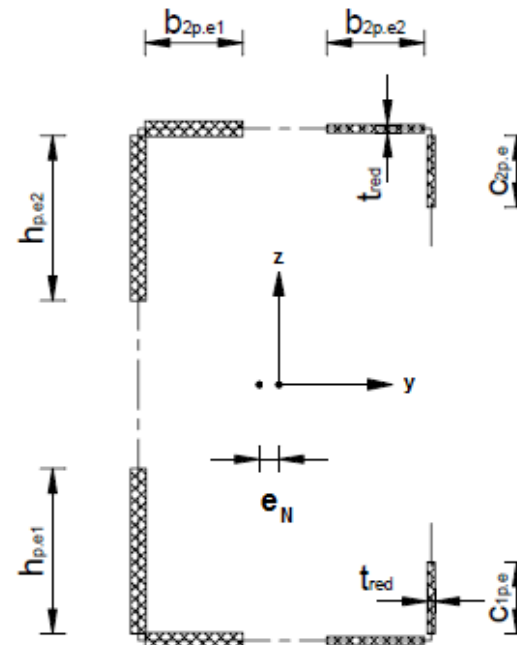


Shift of cross-section geometric centre:

Cross-section:



Effective cross-section:



$$\Delta M_{Ed} = N_{Ed} e_N$$

EC3 (EN 1993-1-2) + Annex E

$$\frac{N_{fi,Ed}}{N_{b,fi,t,Rd}} + k_y \frac{M_{y,fi,Ed} + \Delta M_{y,Ed}}{M_{fi,t,Rd,y}} + k_z \frac{M_{z,fi,Ed} + \Delta M_{z,Ed}}{M_{fi,t,Rd,z}} \leq 1.0$$

$$\frac{N_{fi,Ed}}{N_{b,fi,t,Rd,z}} + k_{LT} \frac{M_{y,fi,Ed} + \Delta M_{y,Ed}}{M_{b,fi,t,Rd}} + k_z \frac{M_{z,fi,Ed} + \Delta M_{z,Ed}}{M_{fi,t,Rd,z}} \leq 1.0$$

EC3 (EN 1993-1-2) + FN Annex

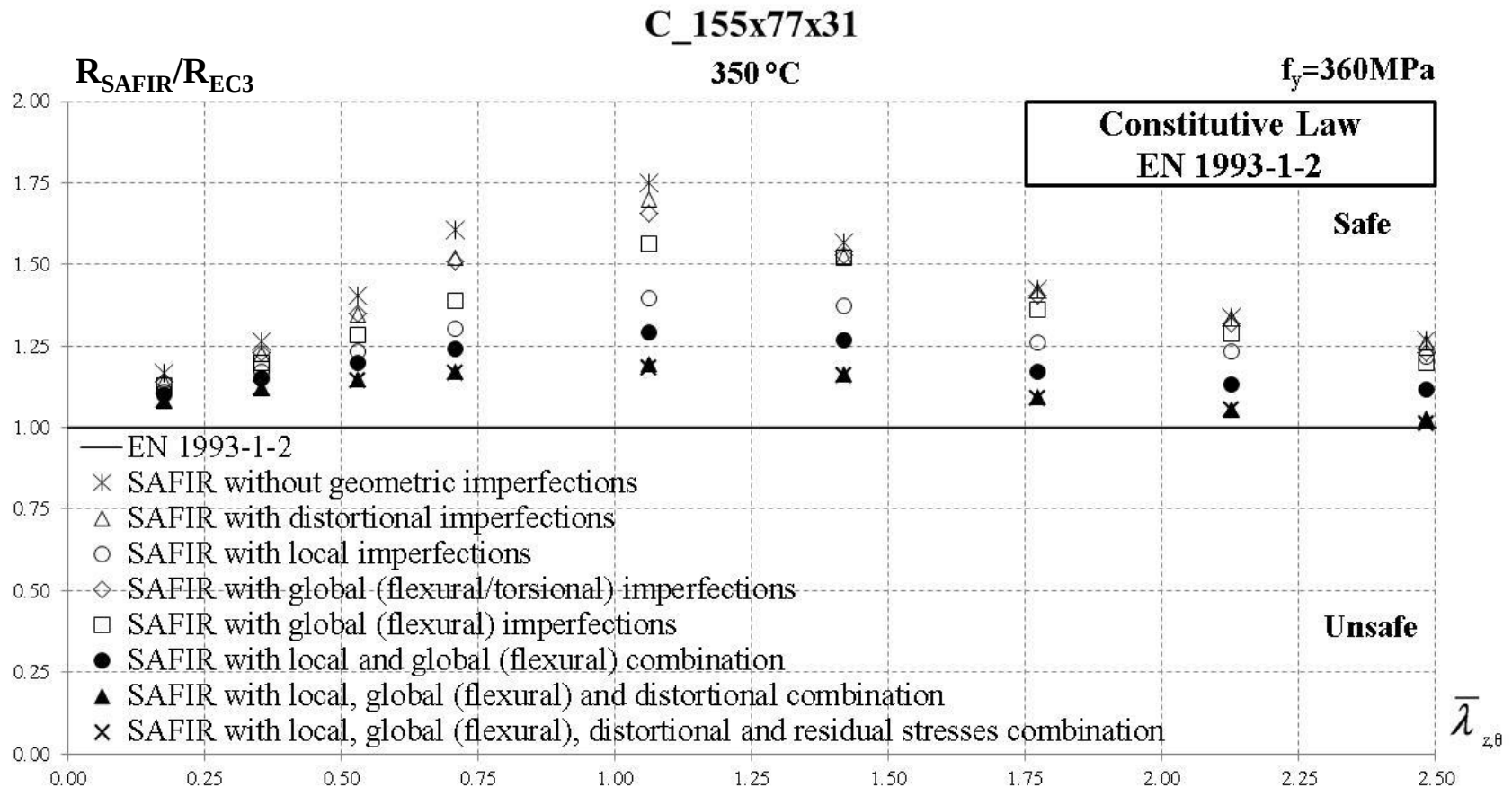
$$\frac{N_{fi,Ed}}{N_{b,fi,t,Rd,y}} + k_{yy} \frac{M_{y,fi,Ed} + \Delta M_{y,Ed}}{M_{b,fi,t,Rd}} + k_{yz} \frac{M_{z,fi,Ed} + \Delta M_{z,Ed}}{M_{fi,t,Rd,z}} \leq 1.0$$

$$k_{yy} = k_{yz} = 1$$

$$k_{zy} = k_{zz} = 1$$

$$\frac{N_{fi,Ed}}{N_{b,fi,t,Rd,z}} + k_{zy} \frac{M_{y,fi,Ed} + \Delta M_{y,Ed}}{M_{b,fi,t,Rd}} + k_{zz} \frac{M_{z,fi,Ed} + \Delta M_{z,Ed}}{M_{fi,t,Rd,z}} \leq 1.0$$

Influence of different imperfections

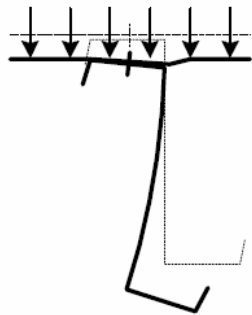


Numerical modelling of beams restrained by sheeting

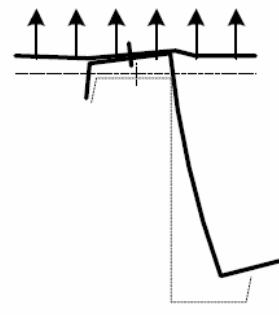
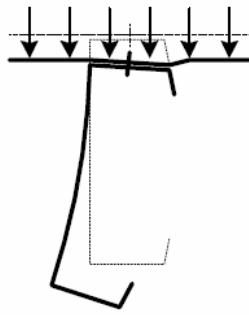
Pedro Chaves; Nuno Lopes; Paulo Vila Real (2014)

Numerical modelling of beams restrained by sheeting

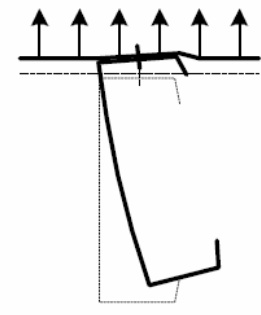
EN1993-1-3&(10.1)



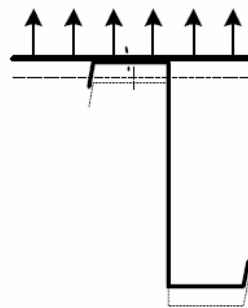
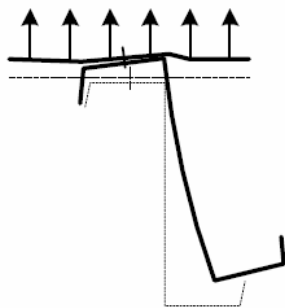
Gravity loading



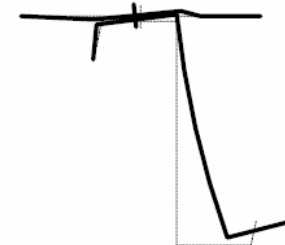
Uplift loading



a) Z and C section purlin with upper flange connected to sheeting



In-plane bending



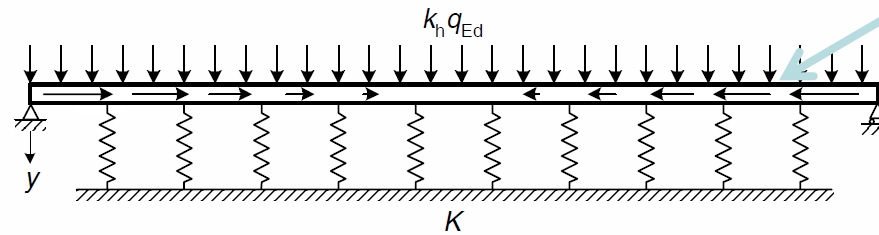
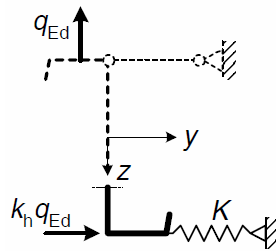
Torsion and lateral bending

b) Total deformation split into two parts

Numerical modelling of beams restrained by sheeting

EN1993-1-3&(10.1)

Simplified model



Lower flange

Modelling the sheeting



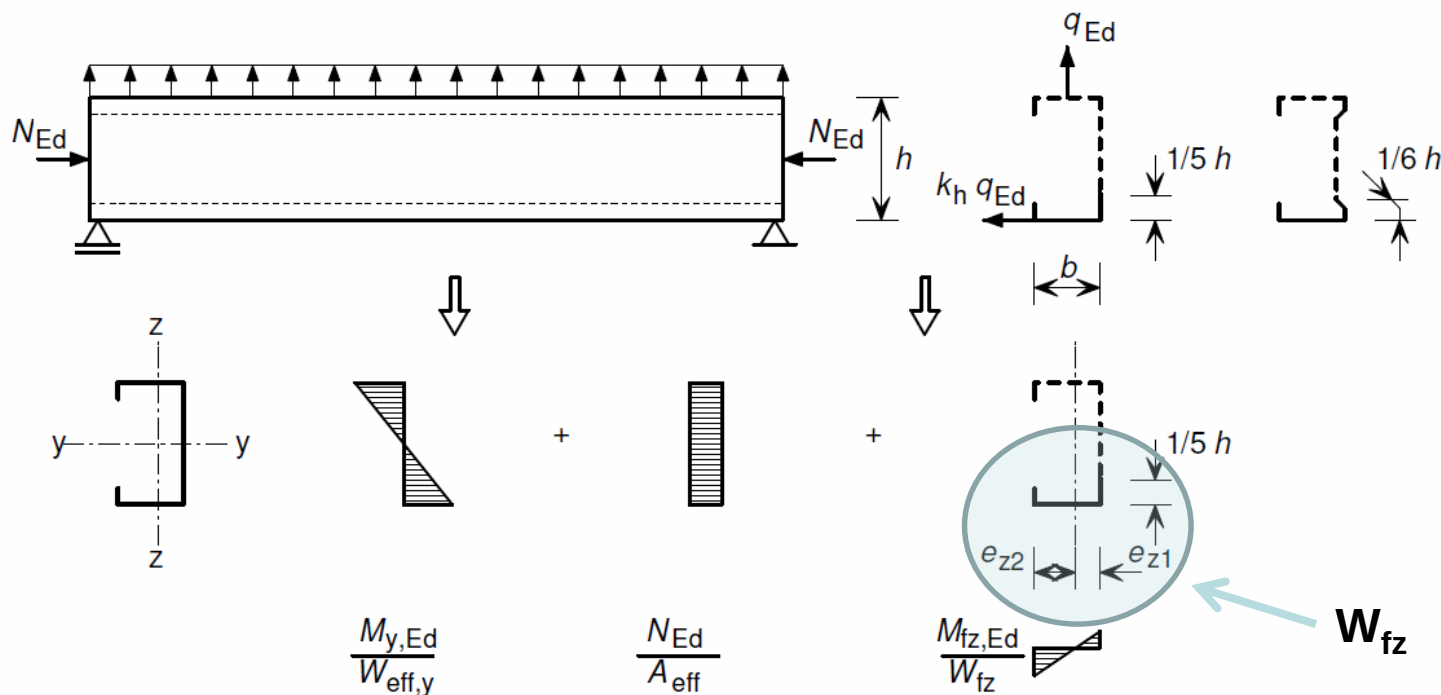
EN1993-1-3&(10.1.4.1)

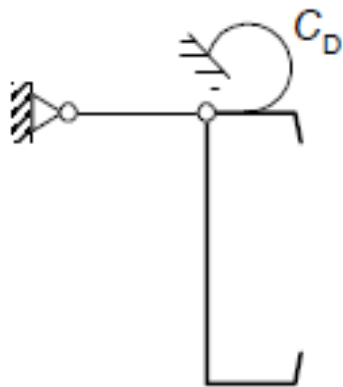
- restrained flange:

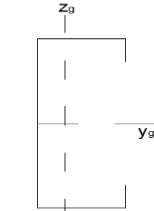
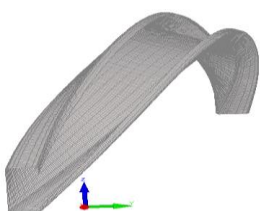
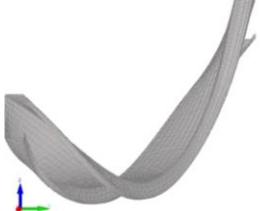
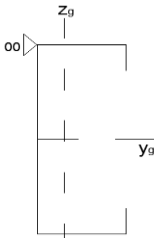
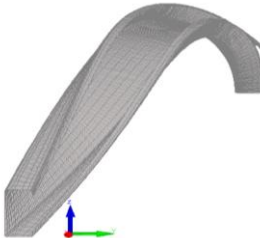
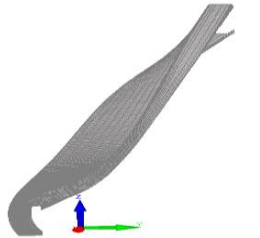
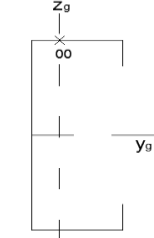
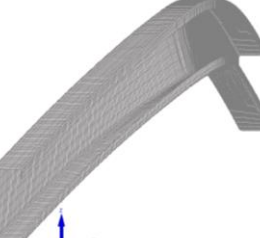
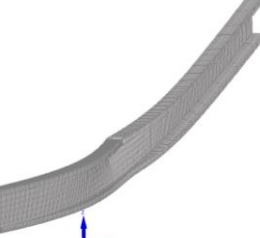
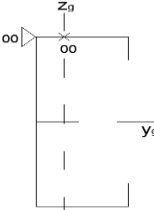
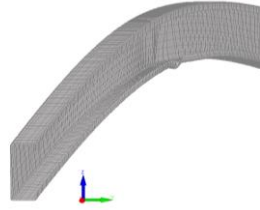
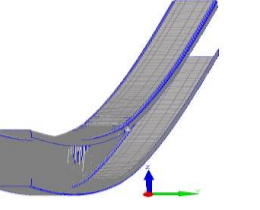
$$\sigma_{\max,Ed} = \frac{M_{y,Ed}}{W_{eff,y}} + \frac{N_{Ed}}{A_{eff}} \leq f_y / \gamma_M$$

- free flange:

$$\sigma_{\max,Ed} = \frac{M_{y,Ed}}{W_{eff,y}} + \frac{N_{Ed}}{A_{eff}} + \frac{M_{fz,Ed}}{W_{fz}} \leq f_y / \gamma_M$$



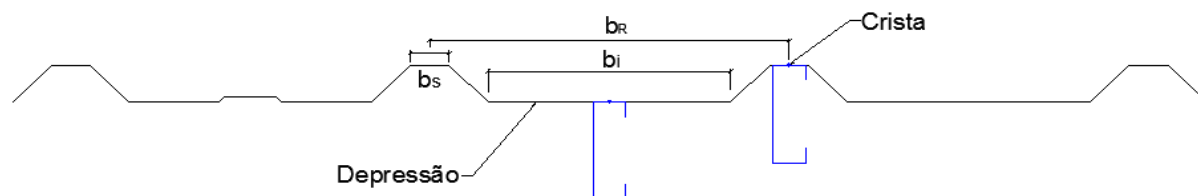


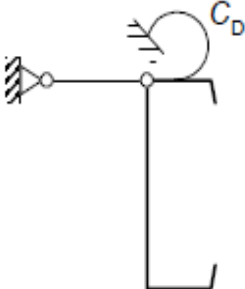
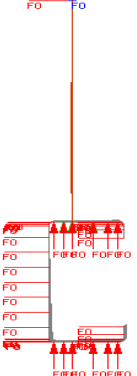
Considered models	Uplift loading	Gravity loading
1 		
2 		
3 		
4 		

$$\text{Rotational stiffness } C_D : C_{D,A} = C_{100} \cdot k_{ba} \cdot k_t \cdot k_{bR} \cdot k_A \cdot k_{bT}$$

Influences of:

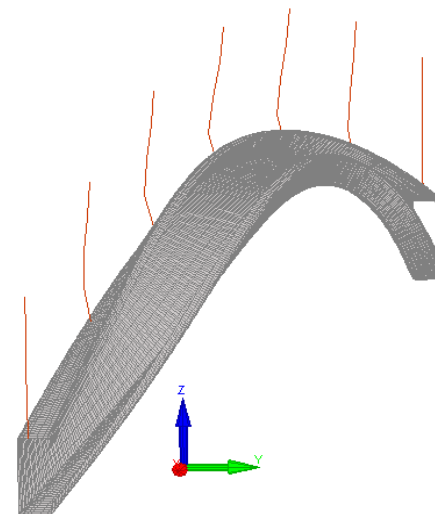
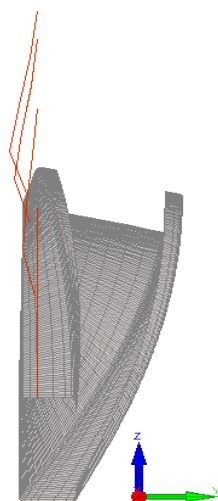
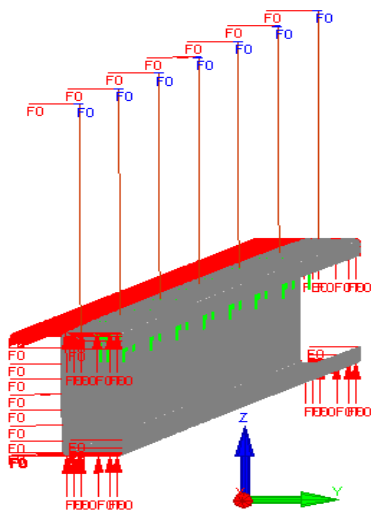
1. Profiled sheeting geometry shape;
2. Sheeting thickness;
3. Connectors spacing;
4. Fixation position;
5. Profile cross-section;
6. Profile and sheeting temperatures.



Model EC3	Adopted model	SAFIR Model
	 $C_D = \frac{4EI}{L}$	

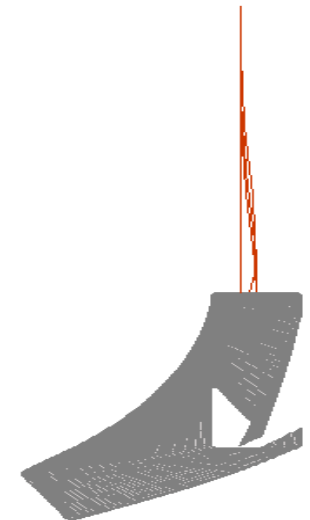
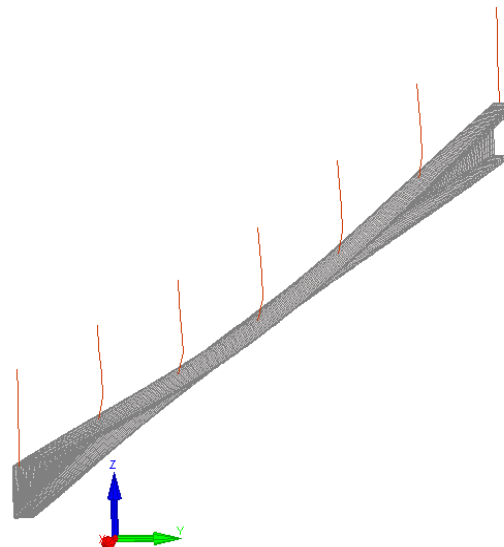
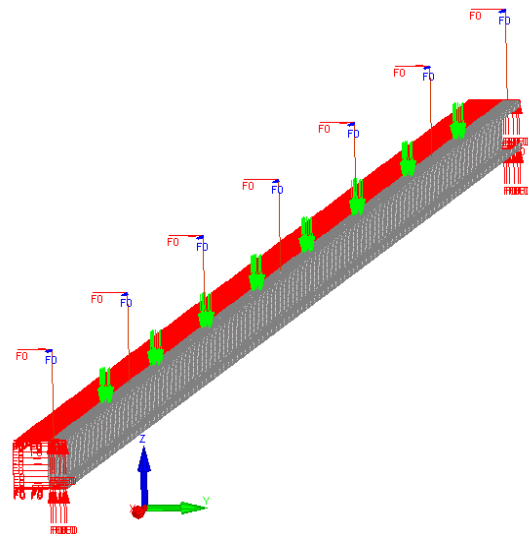
Uplift loading

° C	$P_{collapse}$ (kN/m)	$M_{collapse}$ (kN.m)	k_h	$q_{h,Ed}$ (kN)	$M_{0,fz,Ed}$ (kN.m)	$M_{fz,Ed}$ (kN.m)	$\sigma_{collapse}$ (Mpa)	$\sigma_{Reference}$ (Mpa)
20	0.30	1.36	0.56	0.17	0.76	0.0034	243.3	320
500	0.12	0.56	0.56	0.07	0.31	0.0001	126.2	115.2



Gravity loading

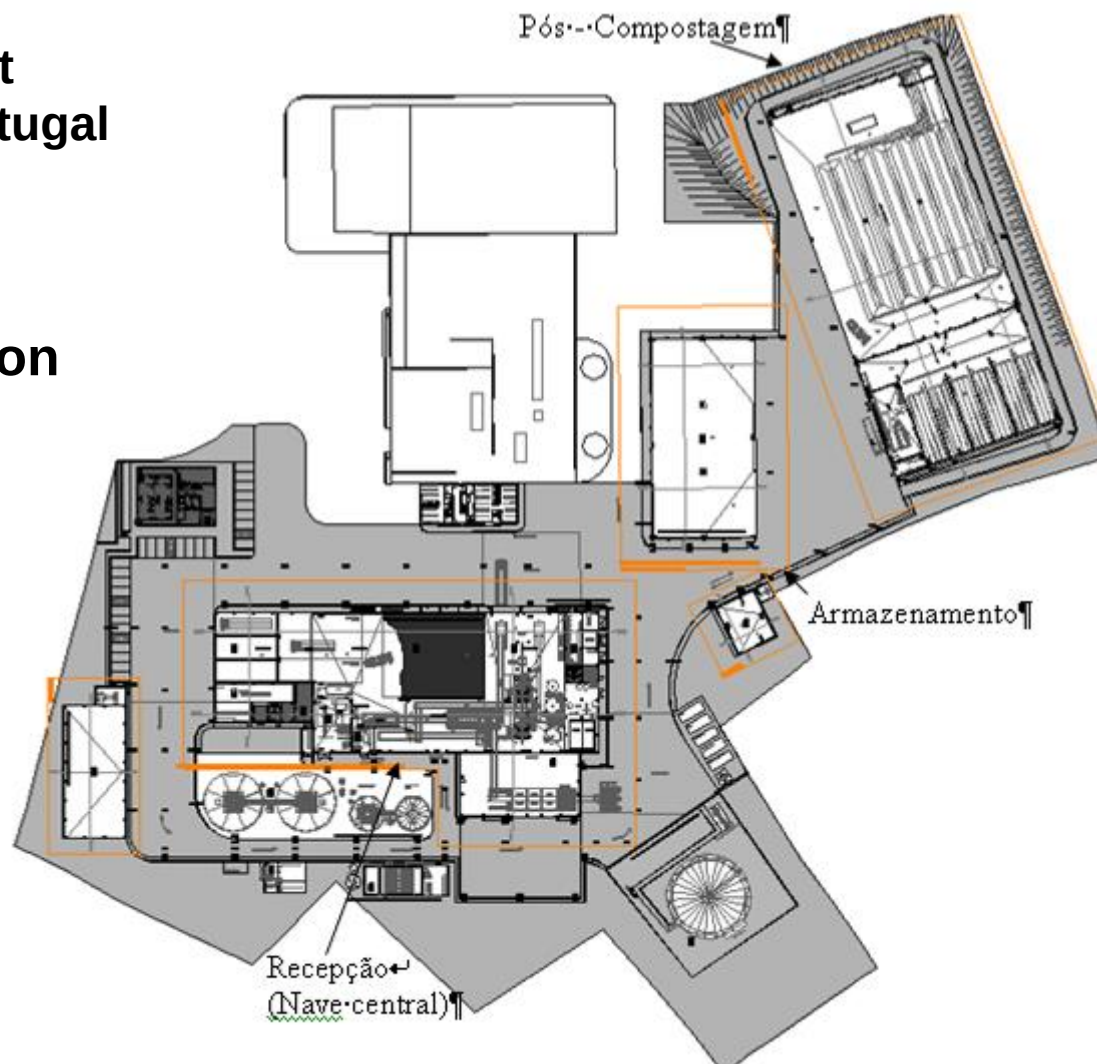
$^{\circ}\text{C}$	$P_{\text{collapse}} \text{ (kN/m)}$	$M_{\text{collapse}} \text{ (kN.m)}$	$\sigma_{\text{collapse}} \text{ (Mpa)}$	$\sigma_{\text{Reference}} \text{ (Mpa)}$
20	0.182	0.82	79.8	320
500	0.103	0.46	45.0	130.2



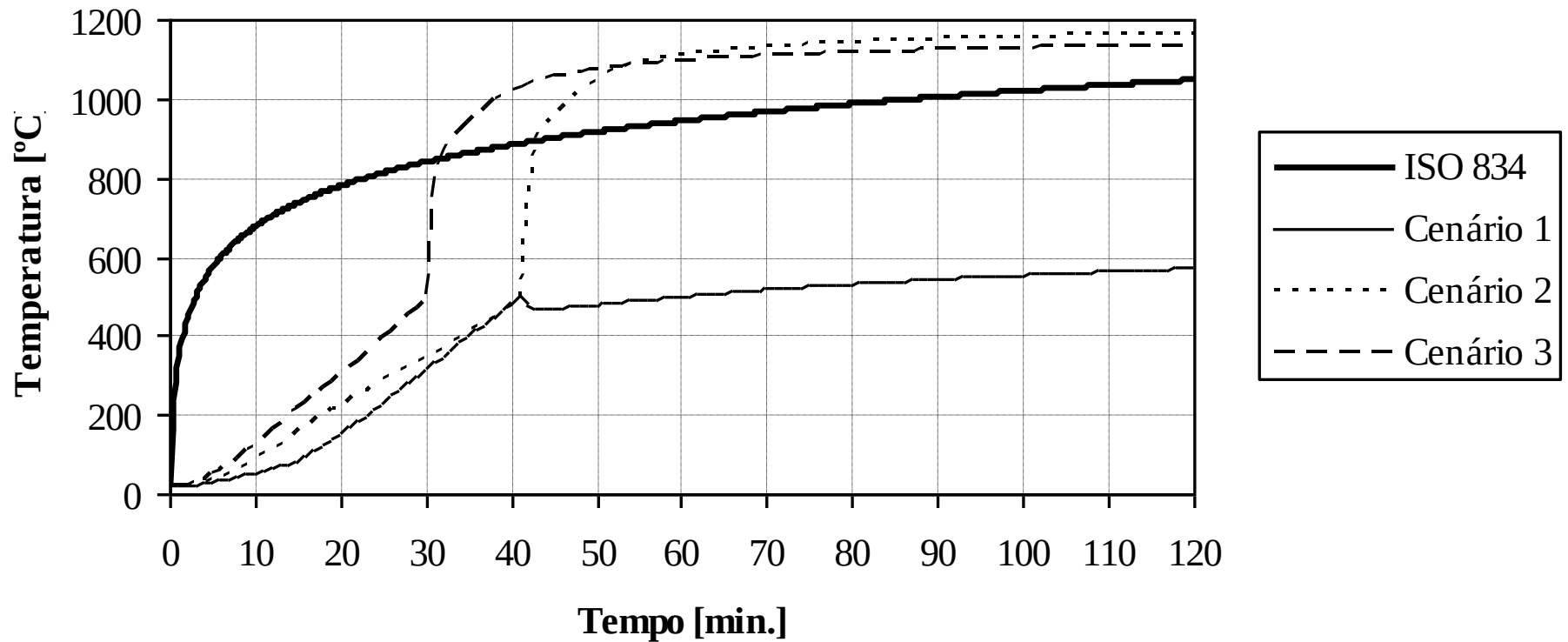
Application example of fire safety engineering

Waste treatment plant, Gaia, Portugal

Implantation



Fire scenarios



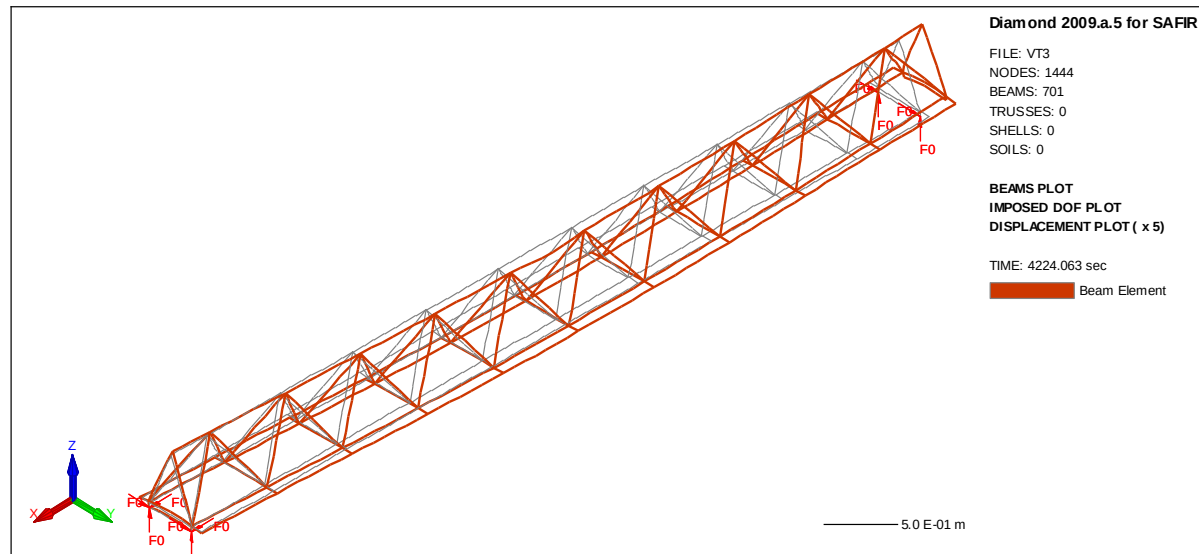
Structural analysis

Reception hall (central) subjected to scenario 1

Principal structural truss



SAFIR



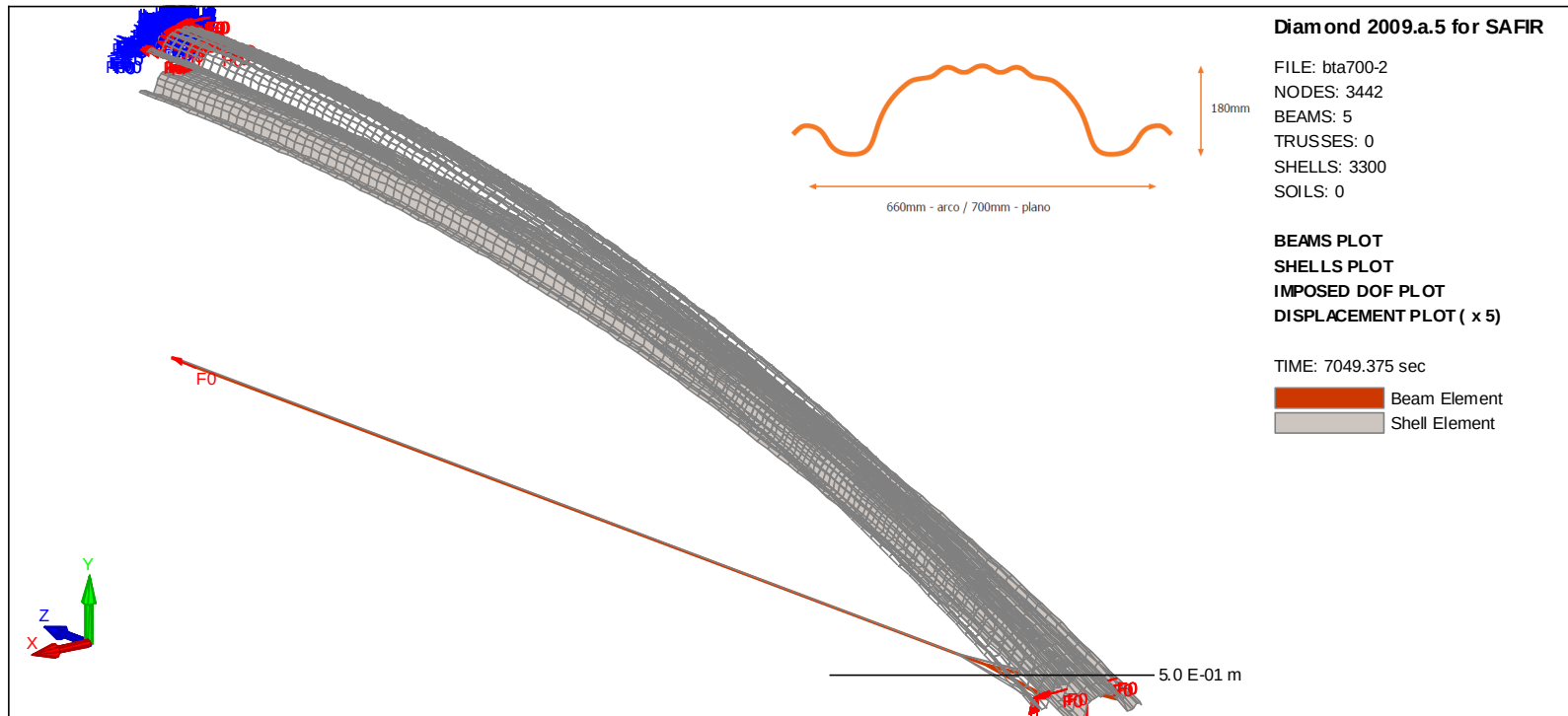
Structural analysis

Reception hall (central) subjected to scenario 1

**Cold formed strutural profiled sheets BNTA 700
with 1.12 mm thickness plus tensioned rod**



SAFIR



- ✓ CEN, Eurocodes:
EN1991-1-2, EN1992-1-2, EN1993-1-2, EN1993-1-3, EN1994-1-2, EN1995-1-2, EN1996-1-2, EN1999-1-2.
- ✓ European project DIFISEK+ “Dissemination of Structural Fire Safety Engineering Knowledge throughout Europe”, European Commission through the Research Fund for Coal and Steel, 2008.
- ✓ J.-M. Franssen, P. Vila Real, Fire Design of steel Structures, ECCS, Ernst & Sohn, 2nd edition, 2015.
- ✓ J.-M. Franssen, SAFIR. A Thermal/Structural Program Modelling Structures under Fire, Engineering Journal, A.I.S.C., Vol 42, N 3, 143-158, 2005.
- ✓ More on SiF movement web site (<http://structuresinfire.com/>)

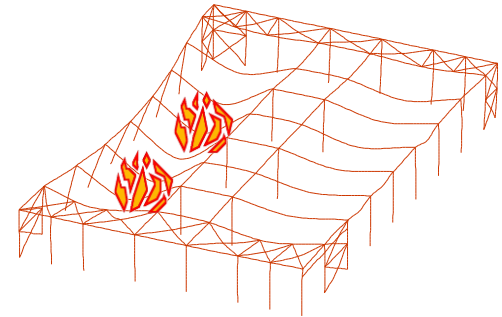
✓ Networks:

- ✓ Paulo Vila Real is member of the Steering committee of the SiF movement (<http://structuresinfire.com/>)
- ✓ Paulo Vila Real is the Chairman of the TC3 (fire) of ECCS (European Convention for constructional Steelwork)



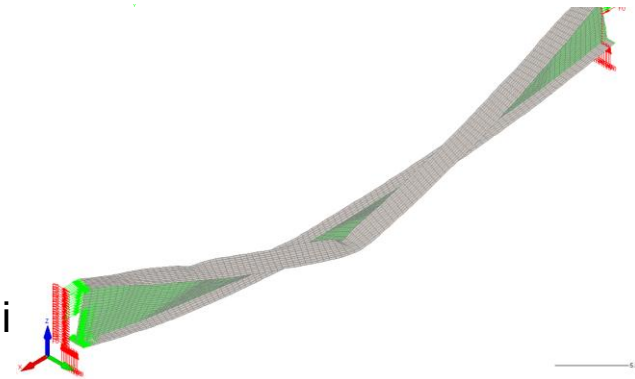
✓ Transfer of knowledge:

- ✓ Fire resistance laboratory
- ✓ Fire design engineering projects
- ✓ Development of the Software Elefir-EN



✓ European projects:

- ✓ FIDESC4; Difisek+; Macs+; COST TU0904; LocaFi





Finite element modelling of cold formed
steel members under fire situation

Thank you for your attention

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*nuno.lopes@ua.pt

University of Aveiro

