



Finite element modelling of steel structures in case of fire

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✓ Introduction

✓ Fire action

✓ Thermal analysis

✓ Structural behaviour

✓ Application examples

✓ Recommended bibliography

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

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

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.

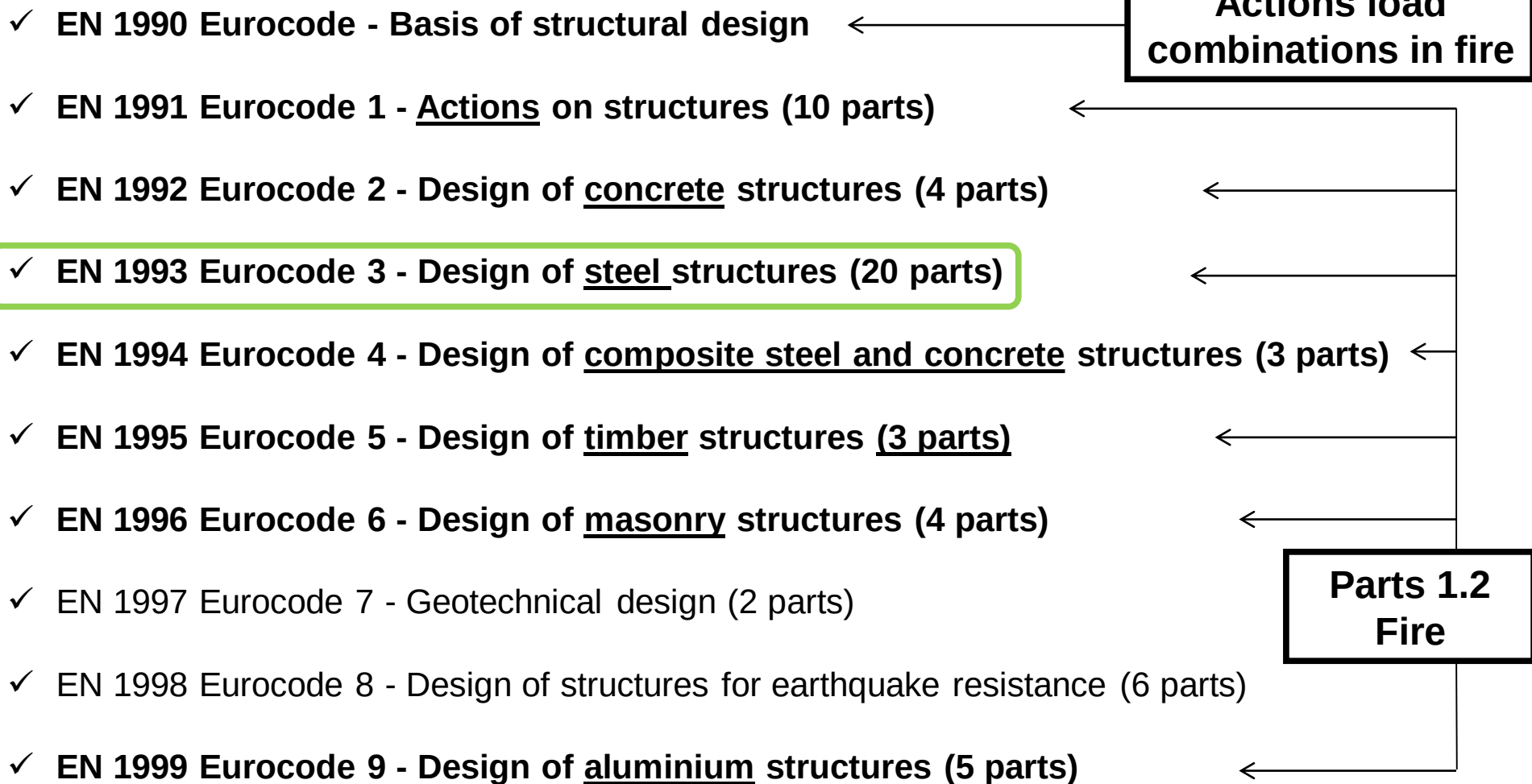
R - Load carrying capacity

E - Integrity

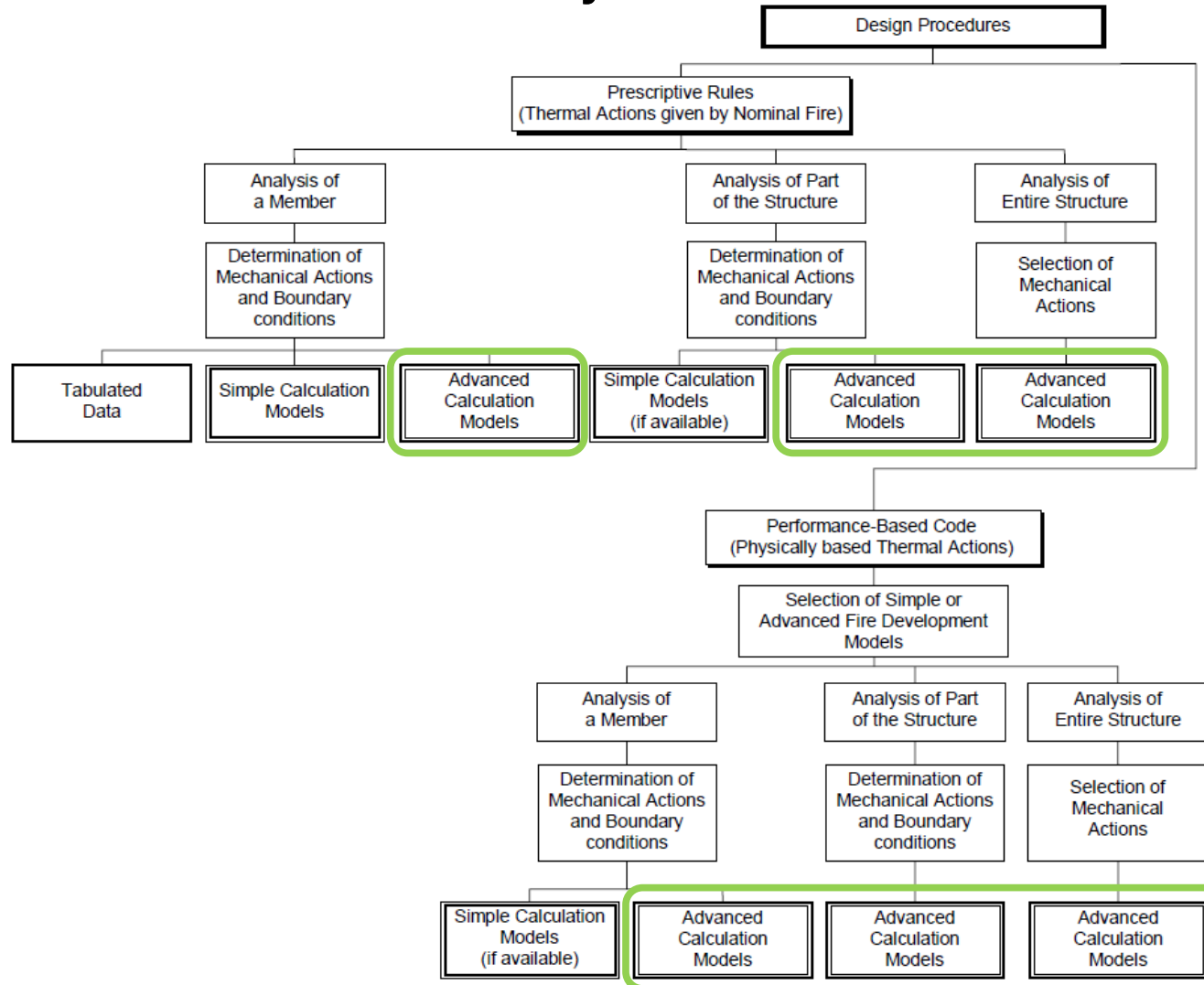
I - Insulation

...

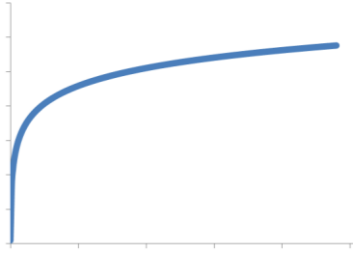
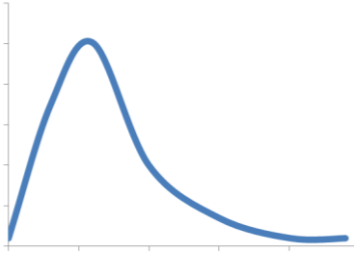
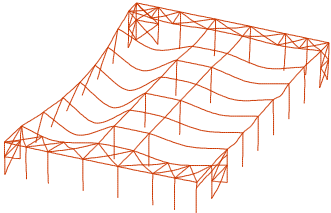
Structural Eurocodes – Analytical and numerical verification



Structural Eurocodes – Analytical and numerical verification

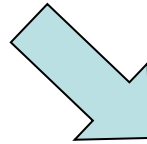
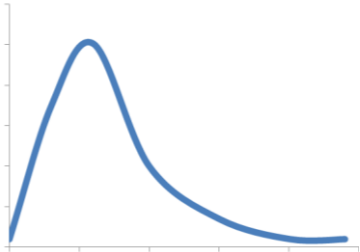


Structural Fire Safety Engineering vs. Classification

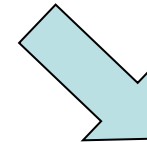
	Prescriptive: Standard fire	Performance based: Natural fire
Member 		
Part of the structure 	Classification (R##)	Fire safety engineering
	Fire safety engineering	Fire safety engineering

Procedure for the numerical modelling of structures under fire conditions

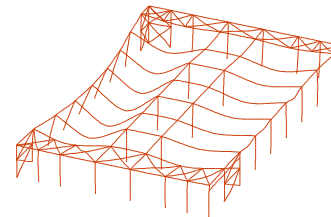
Fire action (temperature-time curve)



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**

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

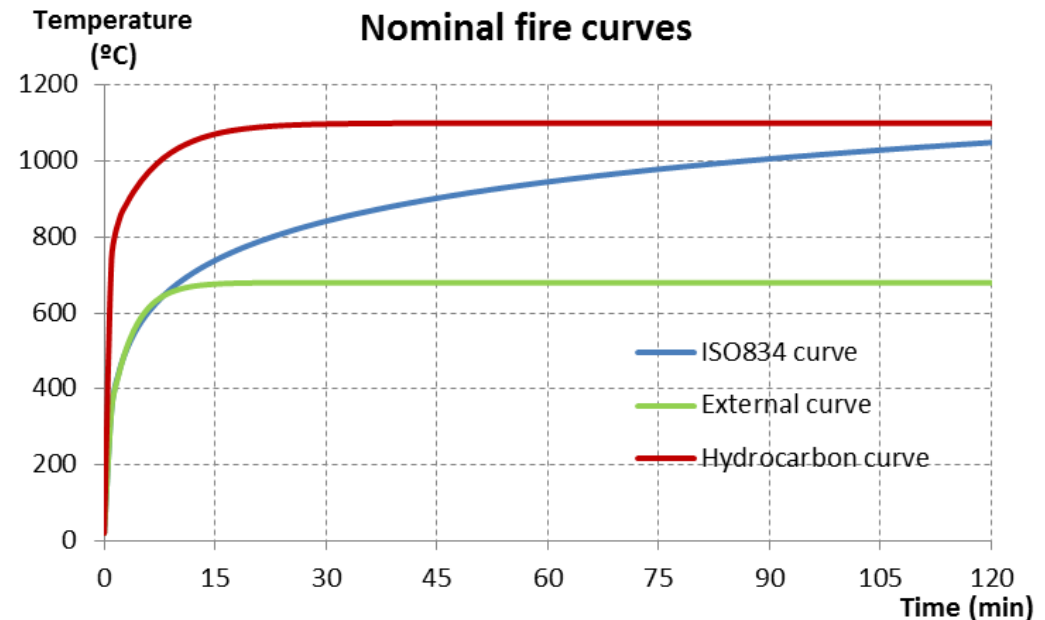
- ✓ External fire curve (external members treated with simplified model)

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

- ✓ Hydrocarbon curve

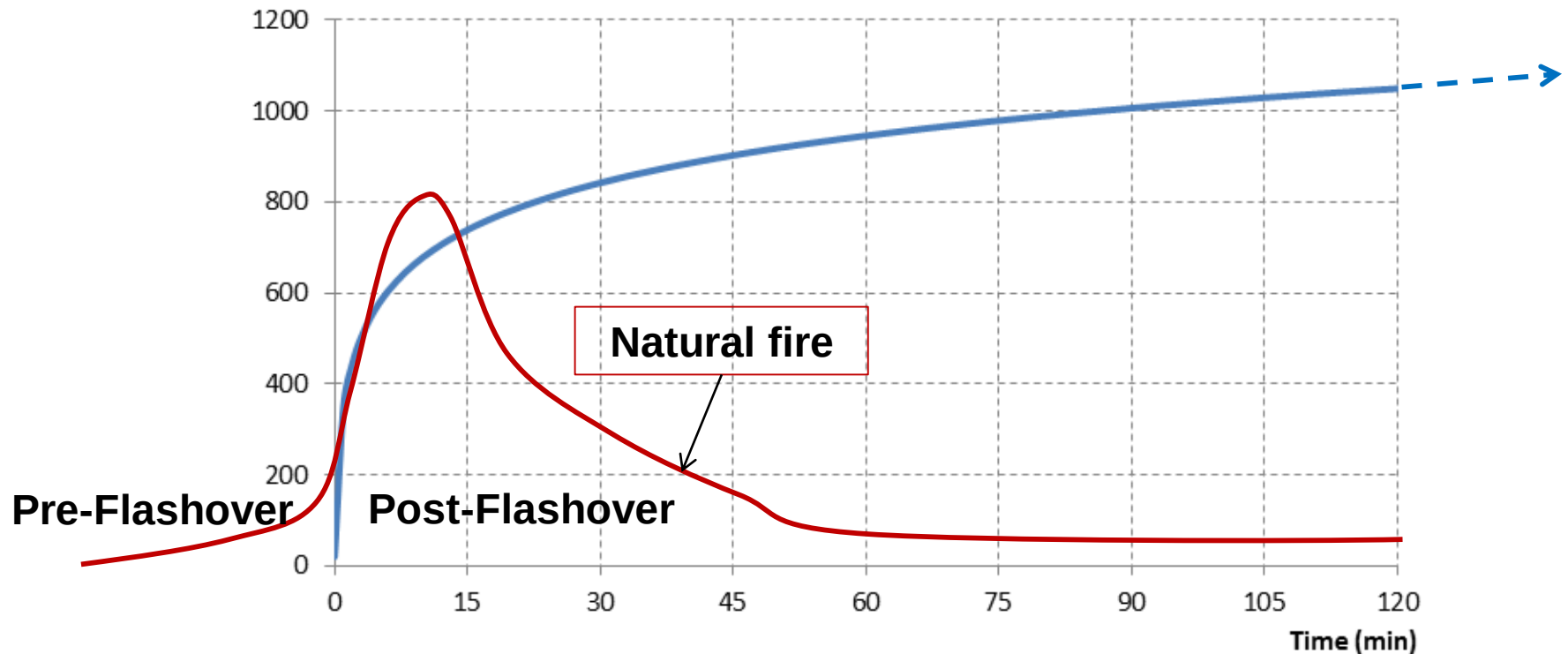
$$T = 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t}) + 20$$

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

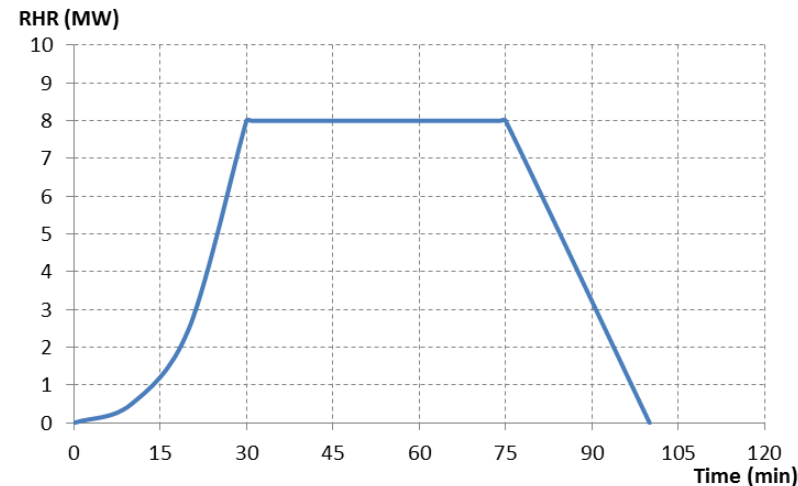
In function of the
compartment floor area

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

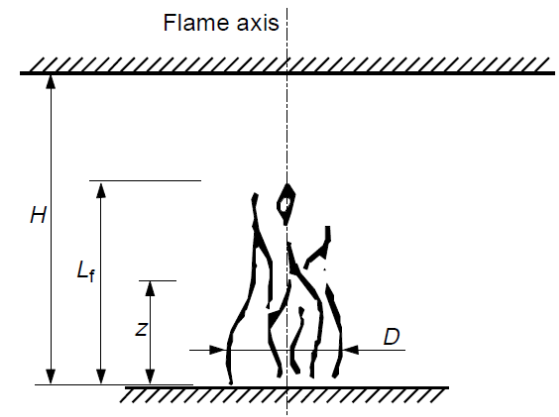
Occupancy	Fire Growth rate	RHR_f [kW/m ²]	Fire Load $q_{f,k}$ (80% fractile) [MJ/m ²]
Dwelling	Medium	250	948
Hospital (room)	Medium	250	280
Hotel (room)	Medium	250	377
Library	Fast	500	1824
Office	Medium	250	511
School	Medium	250	347
Shopping centre	Fast	250	730
Theatre (cinema)	Fast	500	365
Transport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

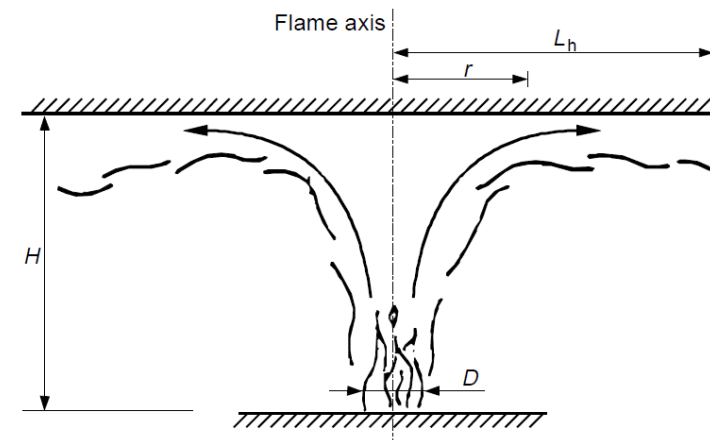
Example: columns in compartments with high ceiling



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

Temperature in function of the distance to the flame

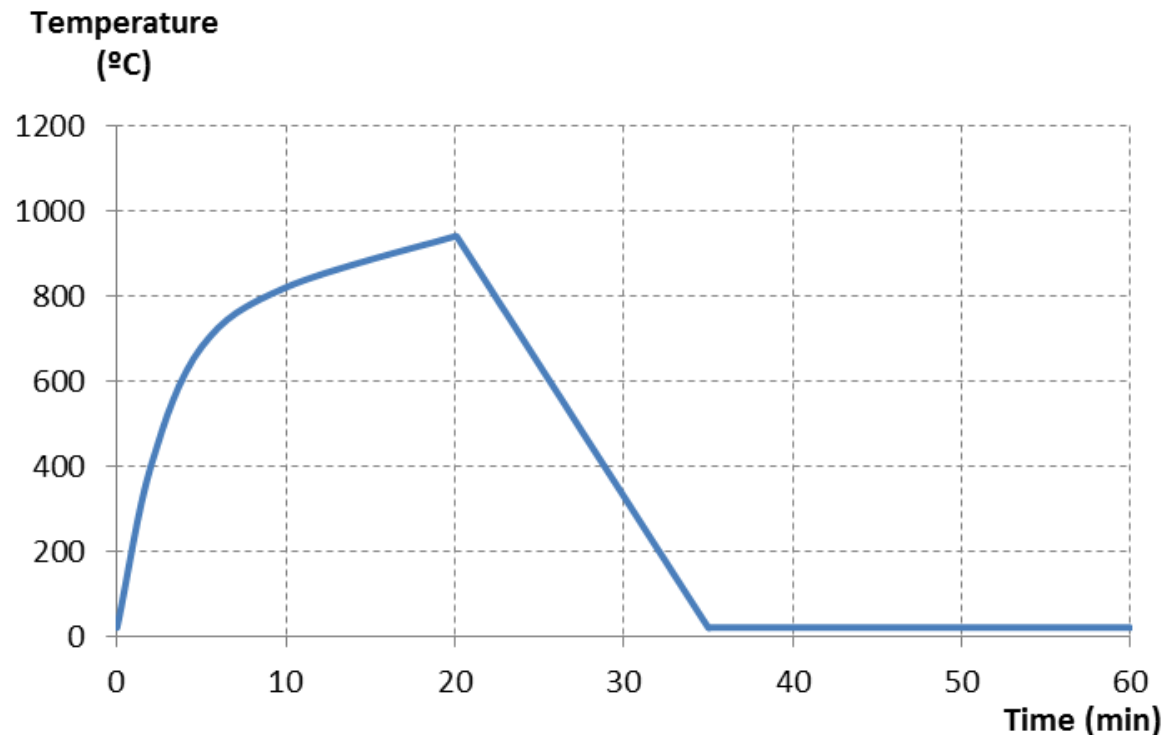
Example: car parks



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

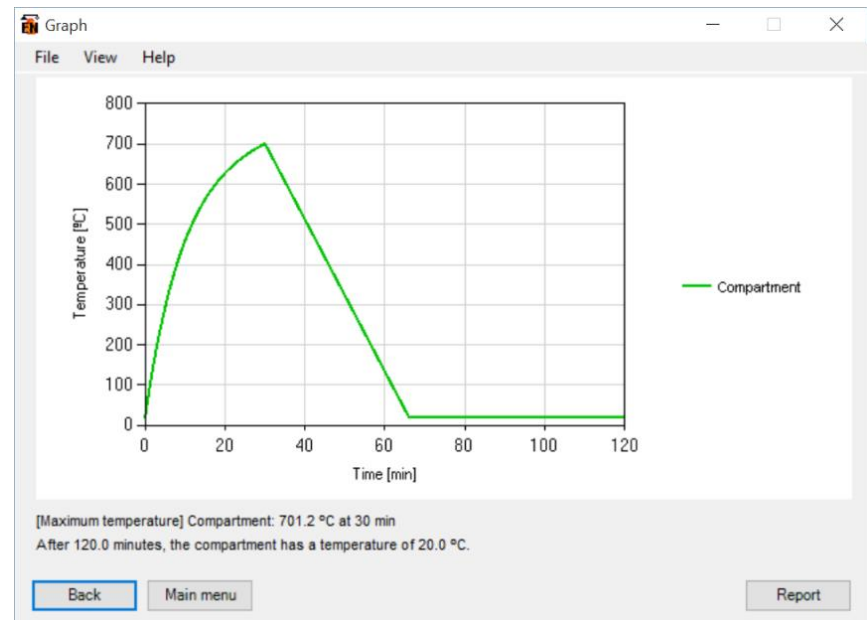




Temperature-time curves:

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

Back Next



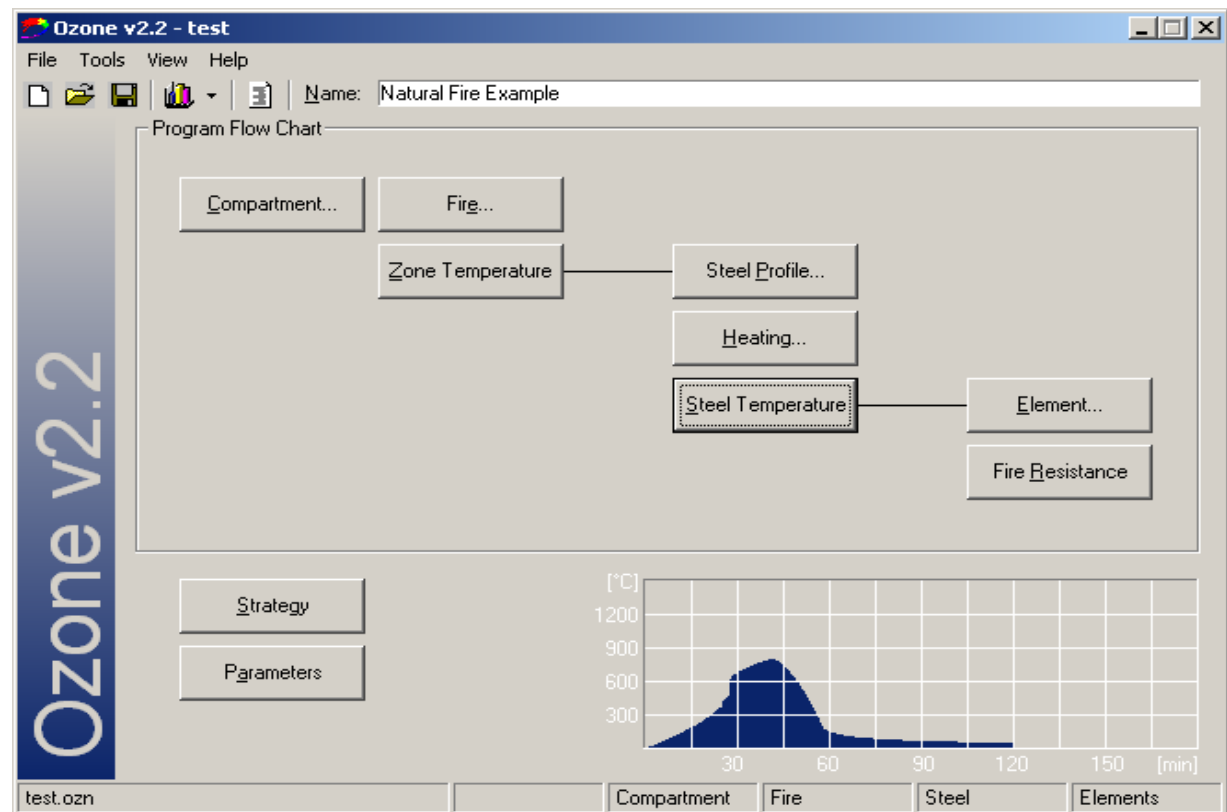
Offered together with the book:
J.-M. Franssen, P. Vila Real, Fire Design of steel Structures, ECCS, Ernst & Sohn, 2nd edition, 2015

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

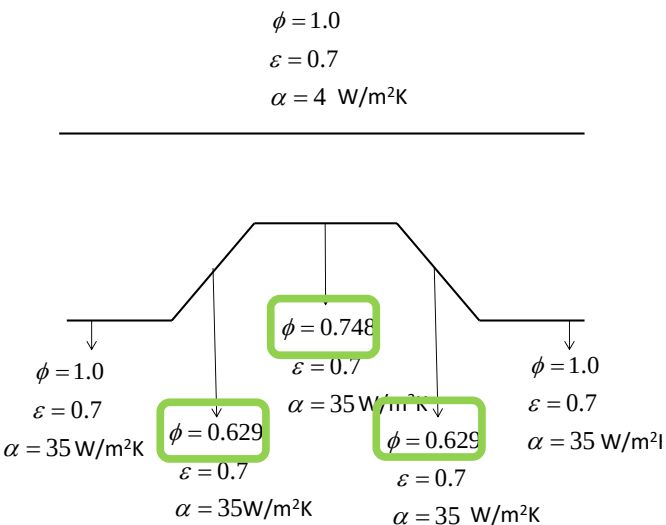
Combination between convection and radiation

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

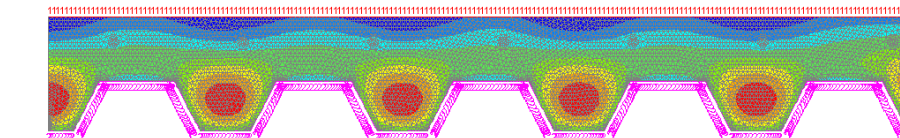
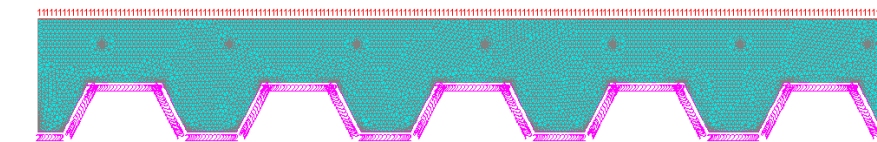
Heating conditions	α_c [W/m ² K]
ISO834	25
Hydrocarbon curve	50
Natural fire	35

- ✓ 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 $\varepsilon_f = 1.0$

Example of a composite slab (concrete plus steel deck and rebars)



ϕ - View factor to account for the concave part being shielded from the radiative heat



Diamond 2011.a.2 for SAFIR

FILE: lage - Copy
NODES: 5957
ELEMENTS: 11133

SOLIDS PLOT
FRONTIERS PLOT

	STEELEC3EN
	SILCONC_EN
	STEELEC3EN
	STEELEC3EN
	STEELEC2EN
1	F20
2	hot.fc

Diamond 2011.a.2 for SAFIR

FILE: lage - Copy
NODES: 5957
ELEMENTS: 11133

SOLIDS PLOT
FRONTIERS PLOT
TEMPERATURE PLOT

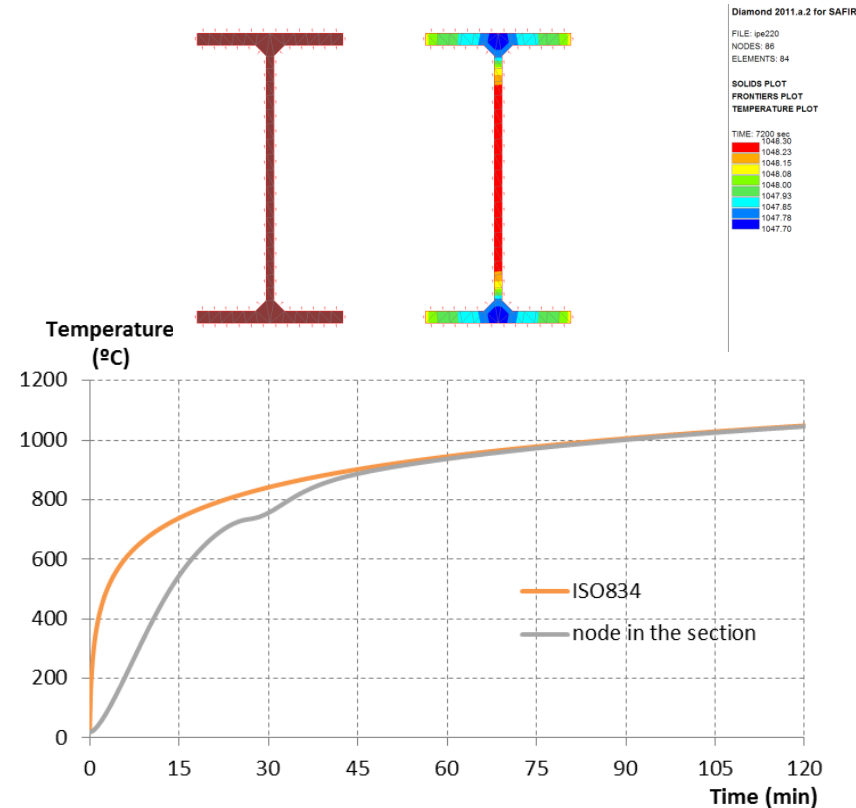
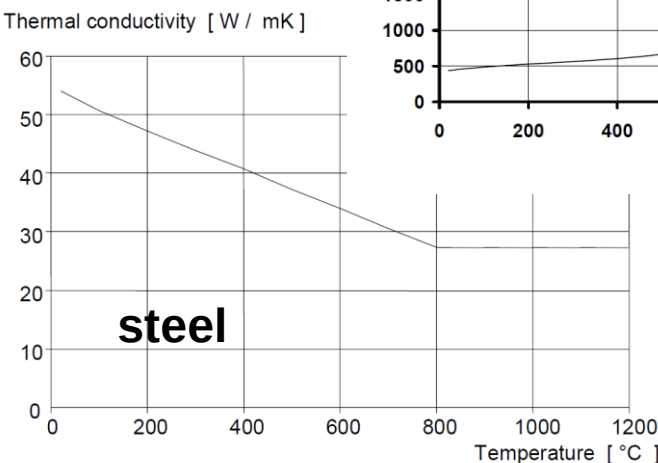
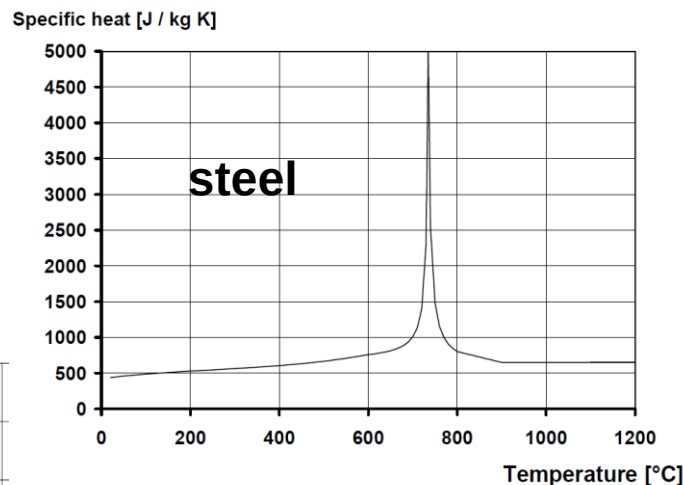
TIME: 5100 sec
296.70
274.23
251.75
229.28
206.80
184.33
161.85
139.38
116.90

Heat transfer within the material (Fourier equation)

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

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

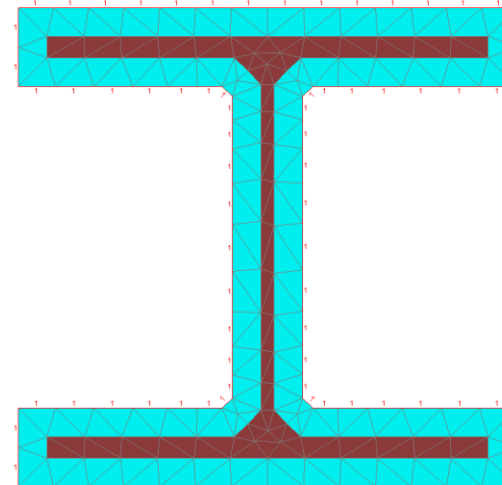
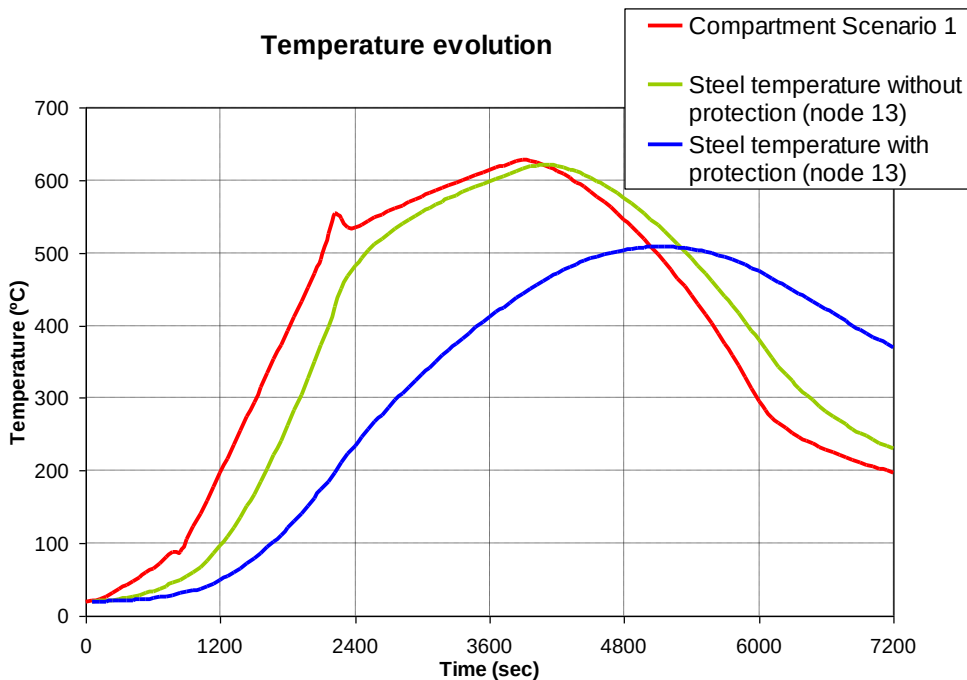
✓ steel (EN1993-1-2)



For the protection the following data should also be given:

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

Temperature evolution



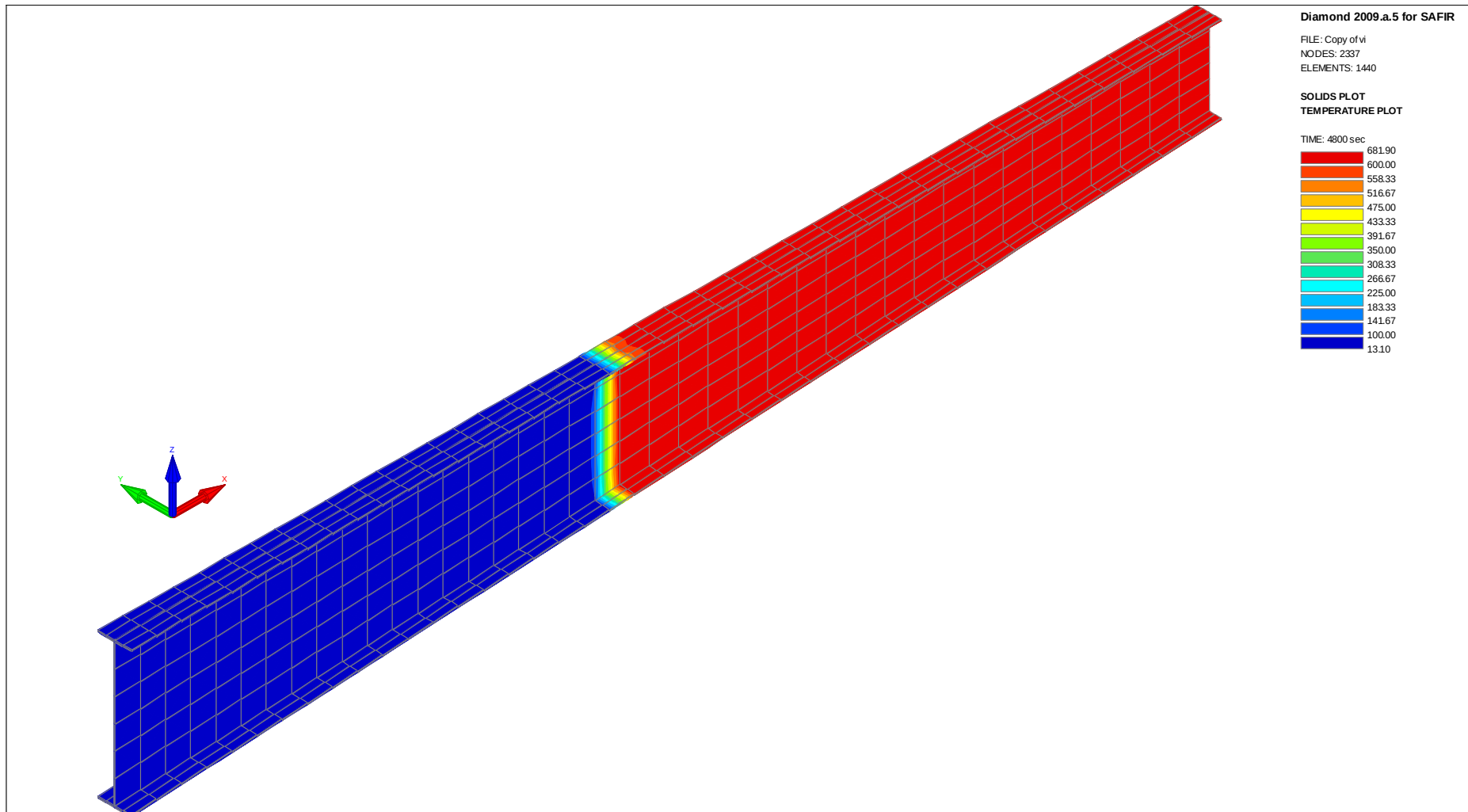
Diamond 2011.a.2 for SAFIR

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ELEMENTS: 248

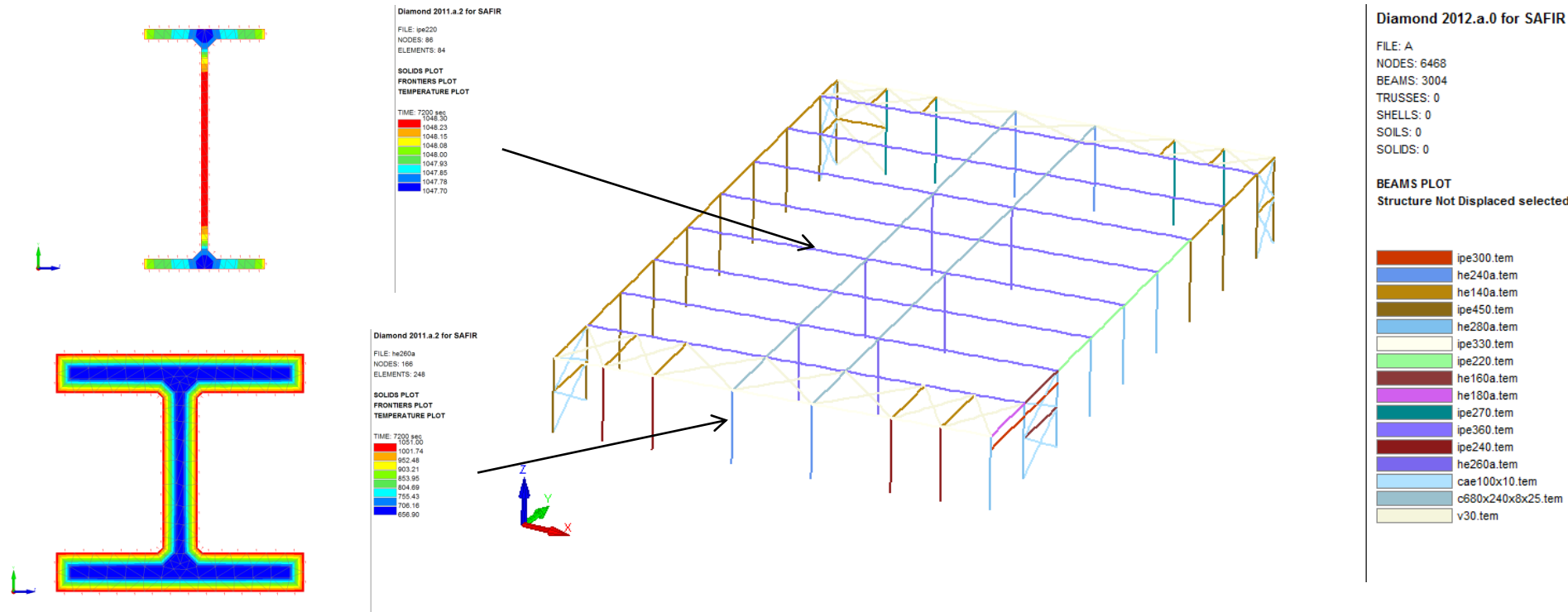
SOLIDS PLOT
FRONTIERS PLOT

STEELEC3
INSULATION
hot.fc

3D analysis (longitudinal axis of the beam)

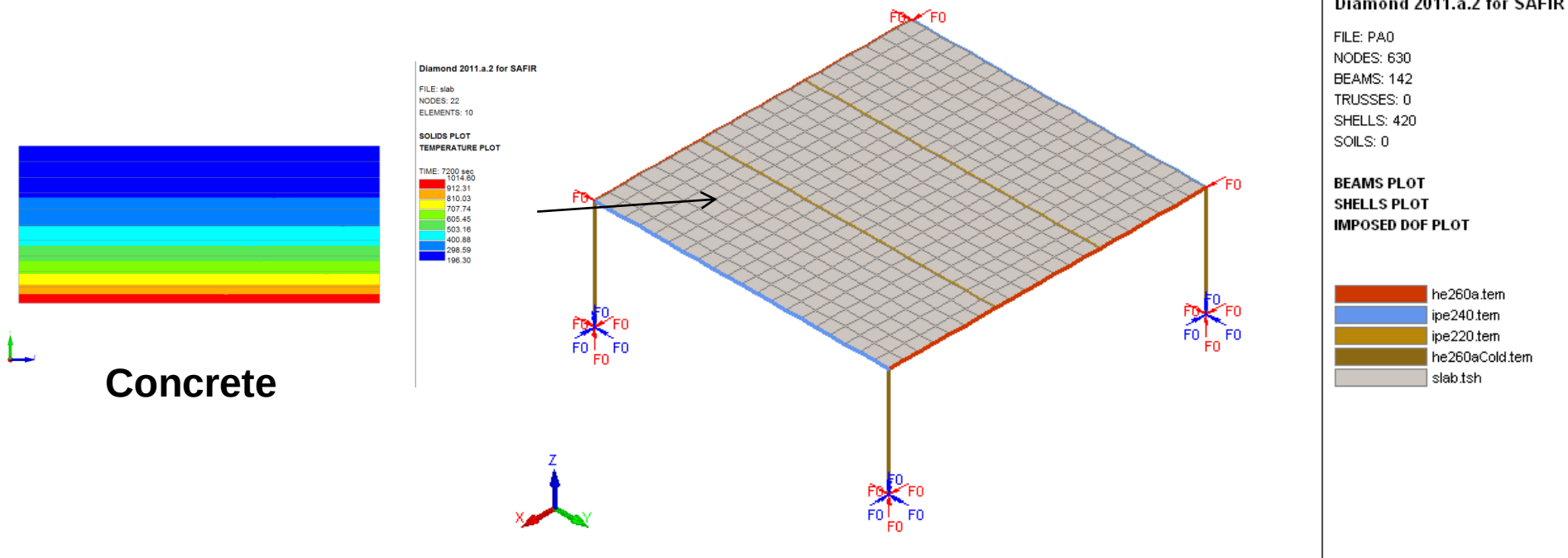


For beam finite elements in the mechanical model the thermal analysis is made with 2D finite elements



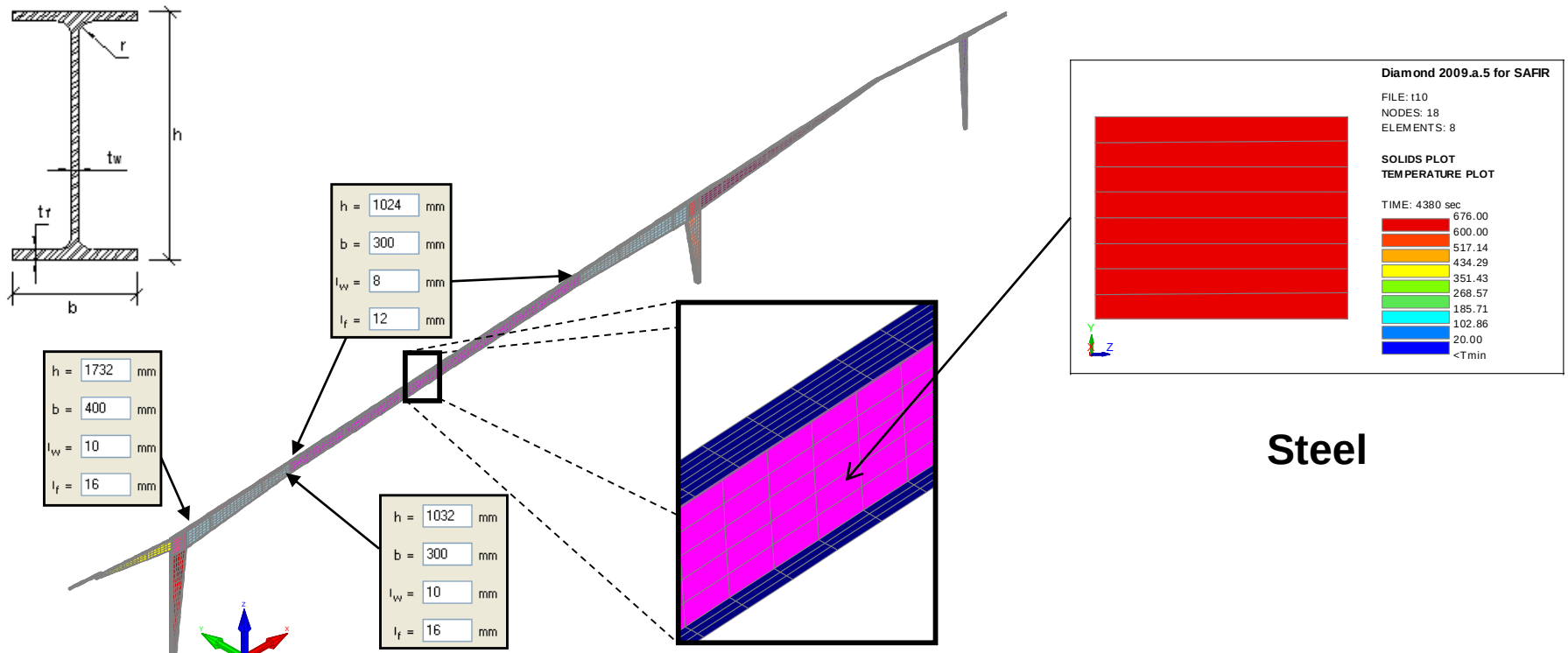
The beam element is constituted by fibres that correspond to the prolongation of the elements throughout the longitudinal axis. In any longitudinal integration point, all the variables (temperature, stresses and strains) are constant in each fibre.

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.

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**
 - ✓ **Specific considerations**
- ✓ **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

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

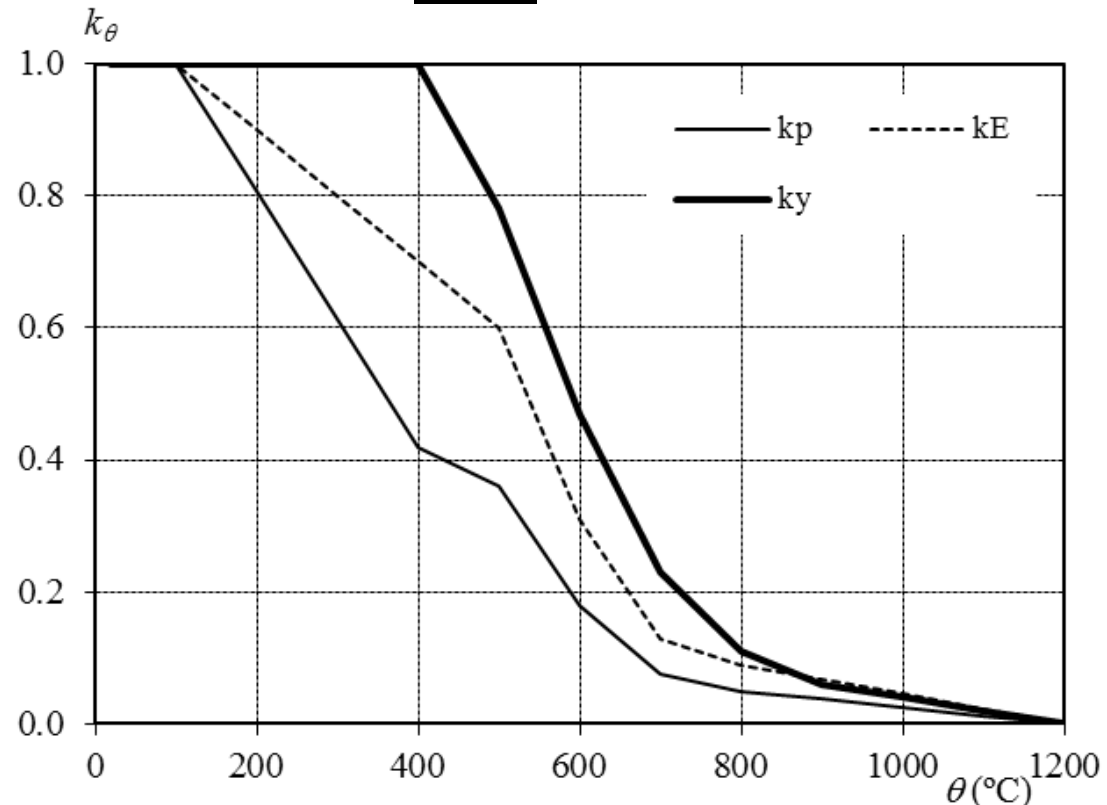
- ✓ Strength and stiffness reduction of **steel** in function of the temperature:

EN1993-1-2

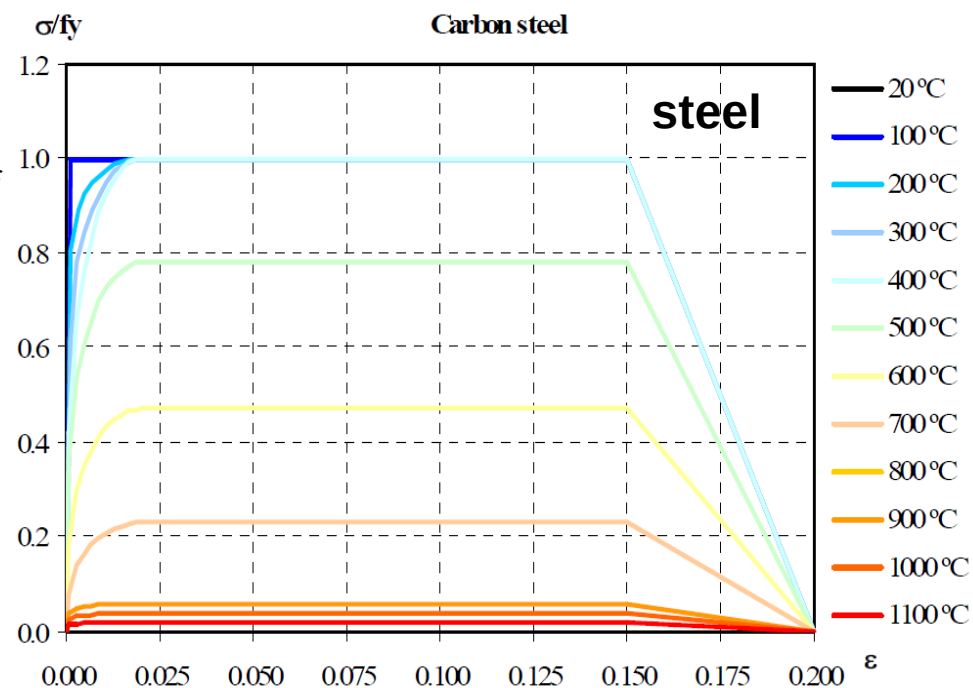
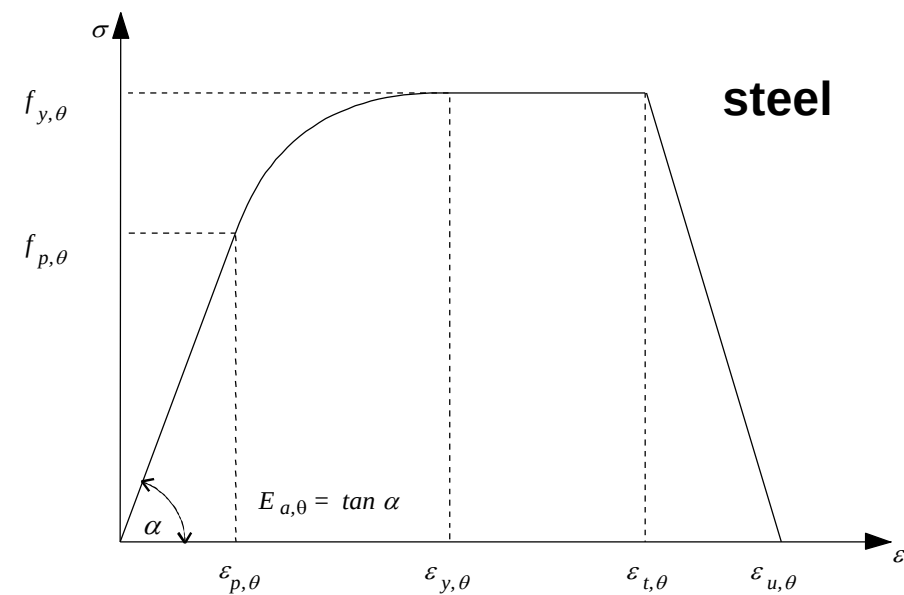
$$k_{y,\theta} = f_{y,\theta}/f_y;$$

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

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

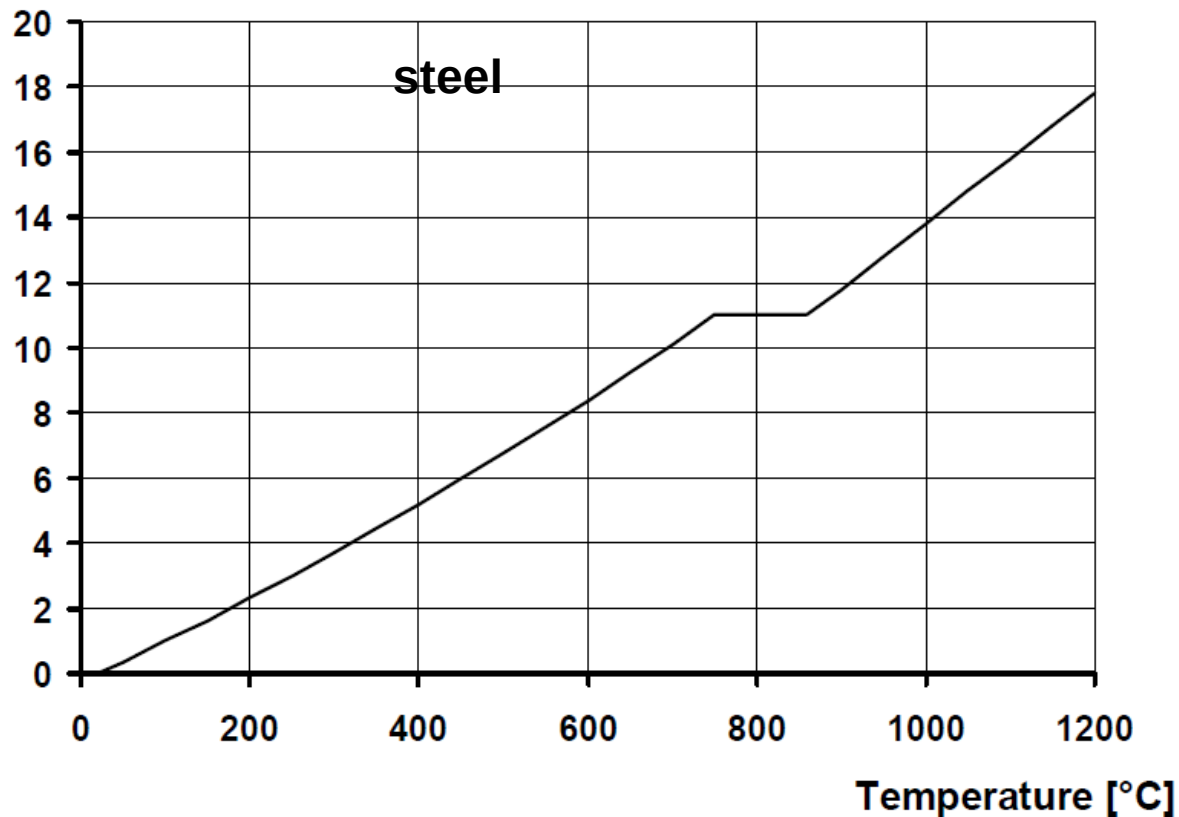


EN1993-1-2



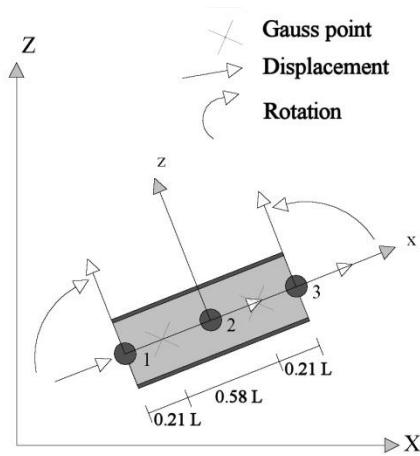
Thermal elongation (influence the efforts values)

Relative Elongation $\Delta l/l$ [$\times 10^{-3}$]

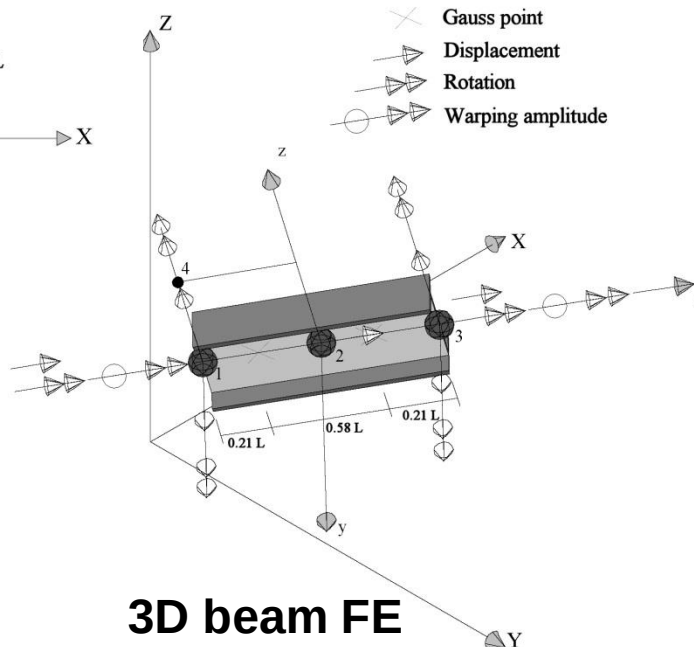


EN1993-1-2

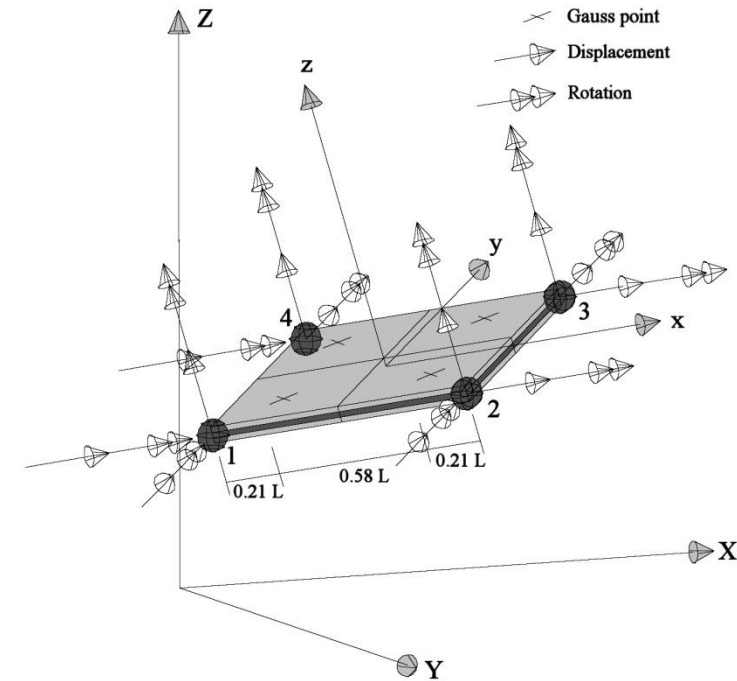
Possible finite elements types



2D beam FE

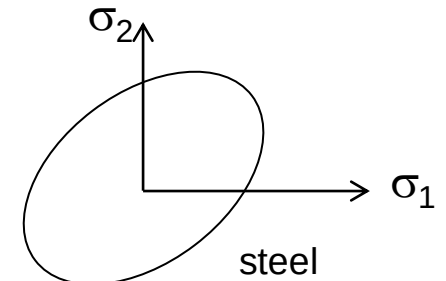


3D beam FE



shell FE

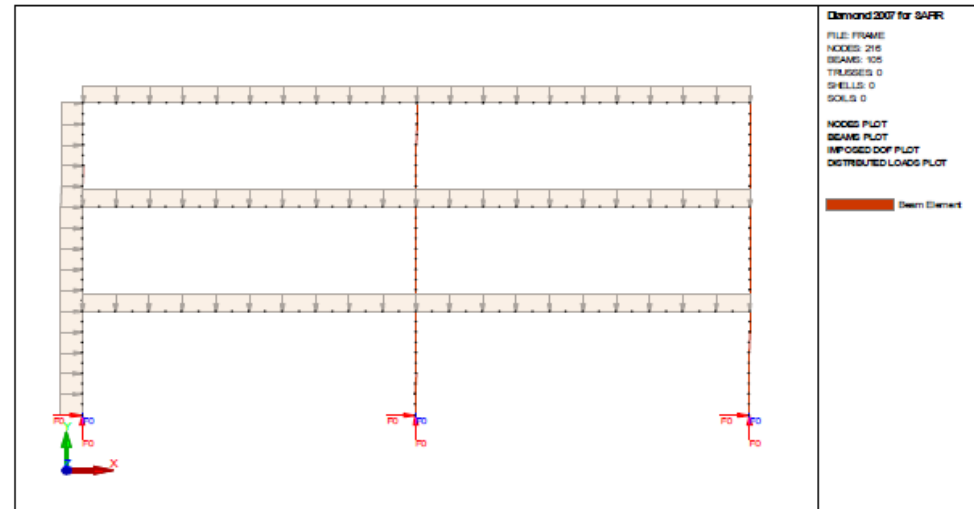
Plane stress state



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 account of temperature dependance of both stiffness and strength of the structure.

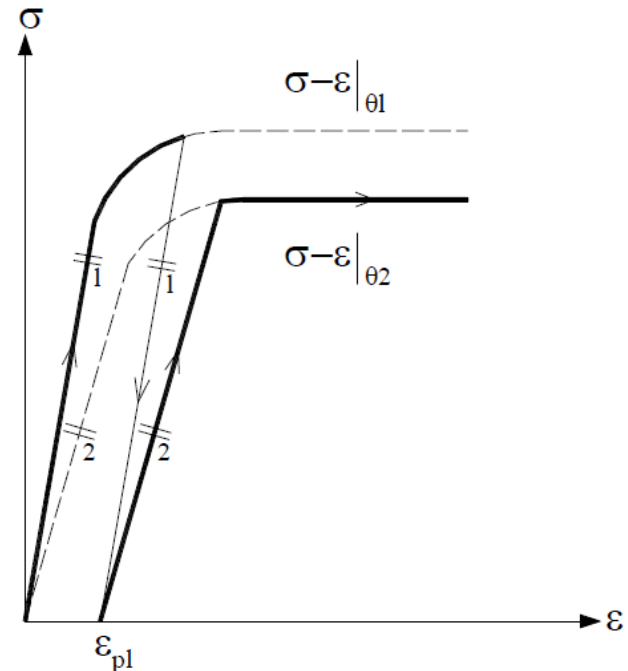
The calculation strategy is based on an incremental procedure (step by step) until failure of the structure, defined commonly as the instant when the stiffness matrix becomes not positive definite, thus becoming impossible to establish the equilibrium of the structure.

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

thermal elongation $\downarrow$ ε_{th}
 stress $\swarrow$ ε_σ
 creep effect at elevated temperatures $\uparrow$ ε_c
 residual stress $\swarrow$ ε_{res}

kinematical material model

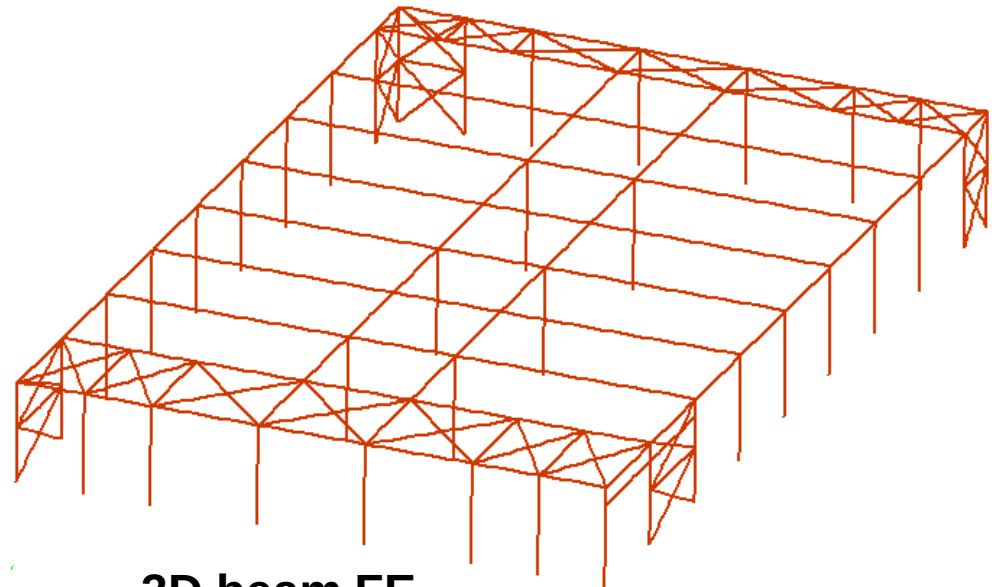
Steel kinematical material model to account the temperature evolution



Structures with beam finite elements

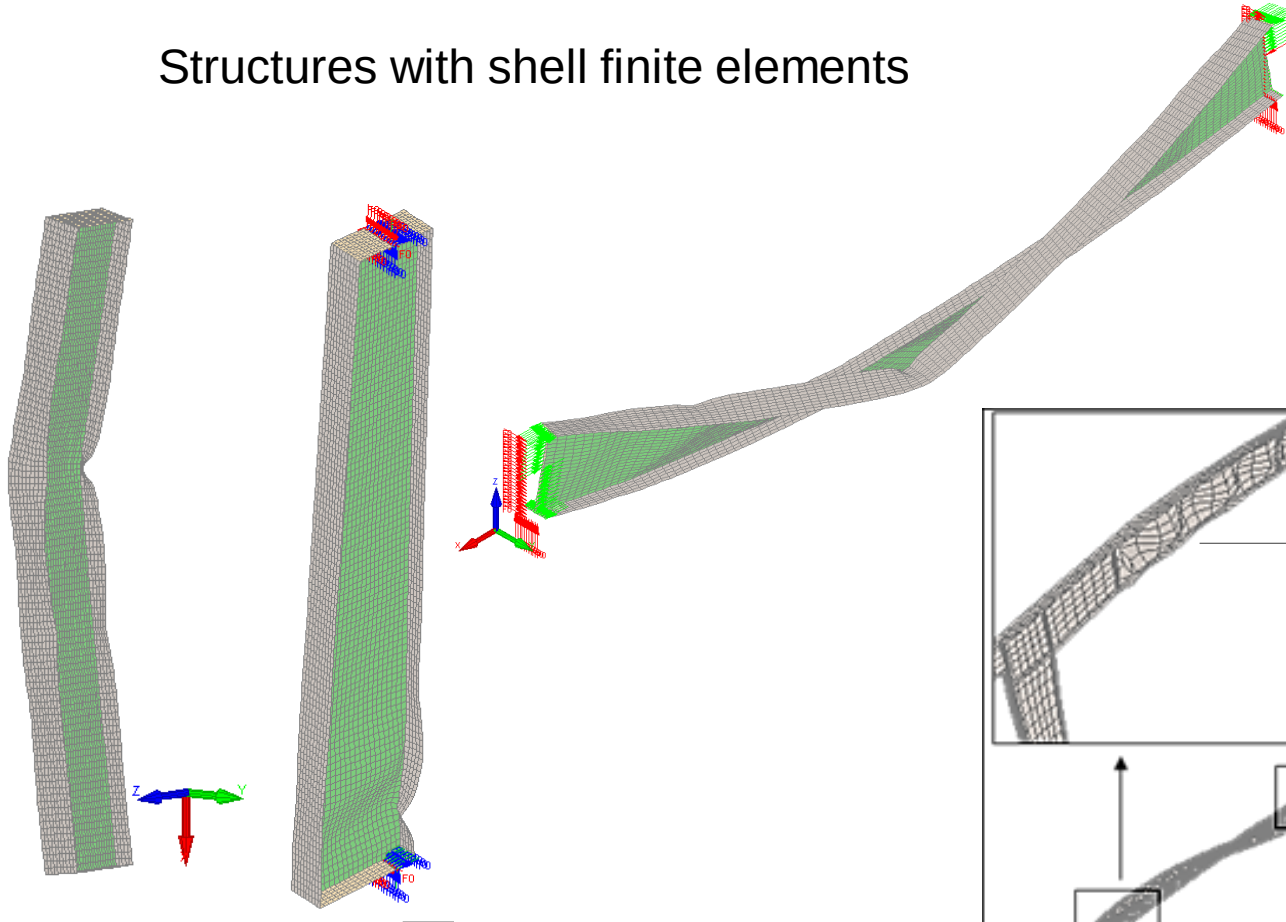


2D beam FE

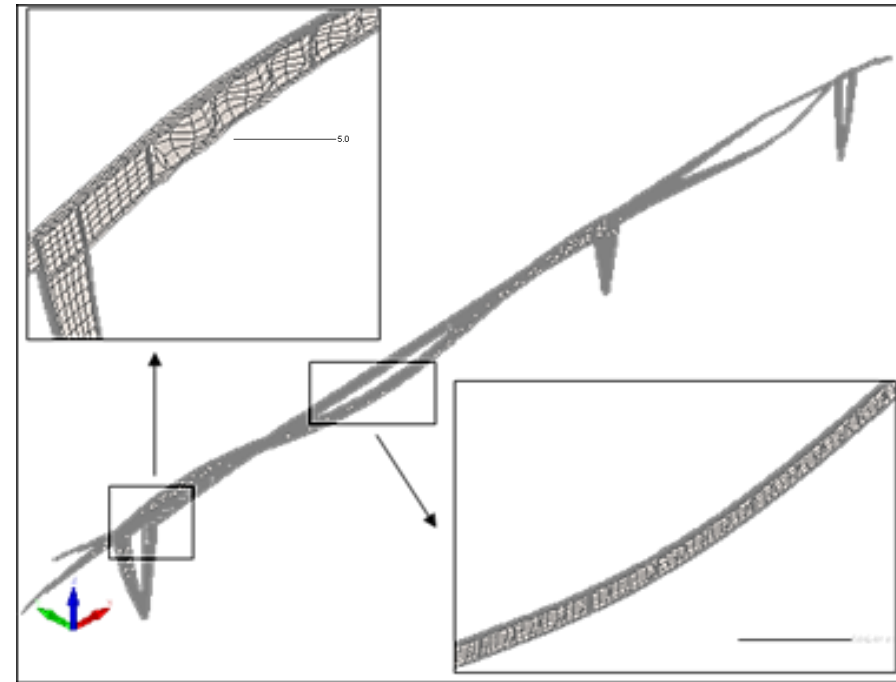


3D beam FE

Structures with shell finite elements

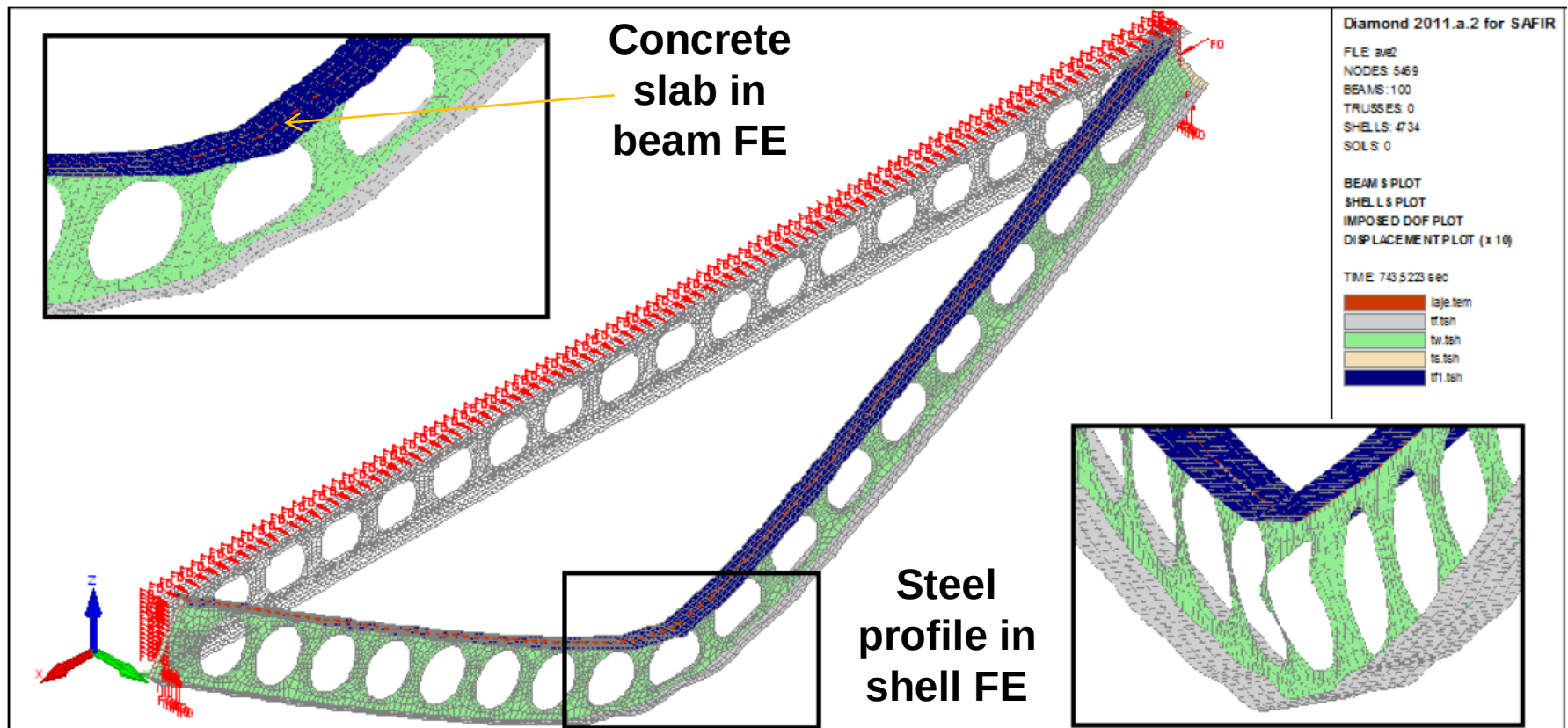


Class 4 steel sections (local buckling)



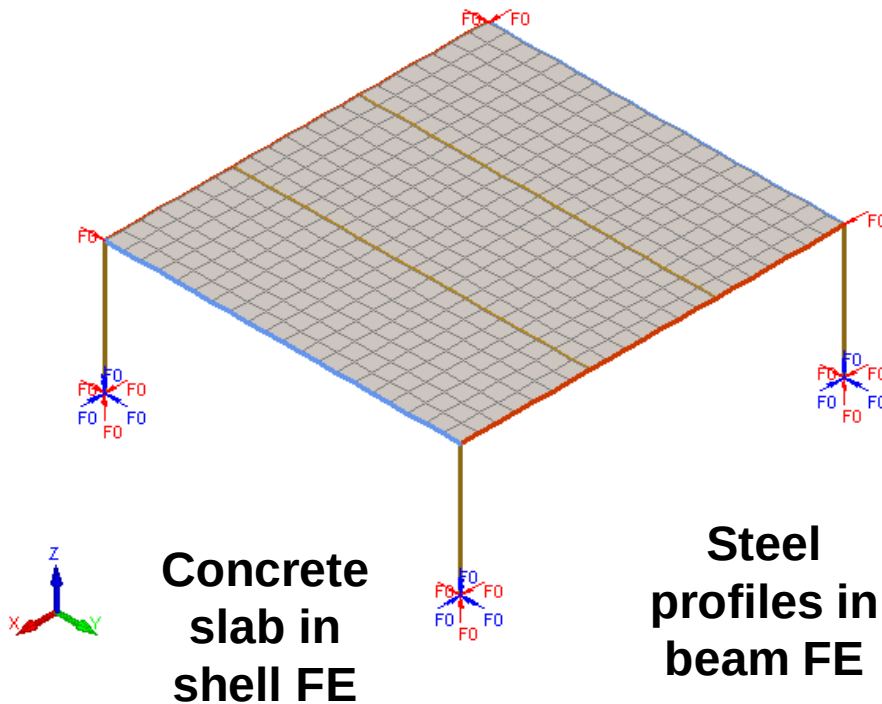
Structures with both beam and shell finite elements

Composite beam with cellular steel profile



Structures with both beam and shell finite elements

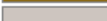
Concrete slab supported by steel beams and columns



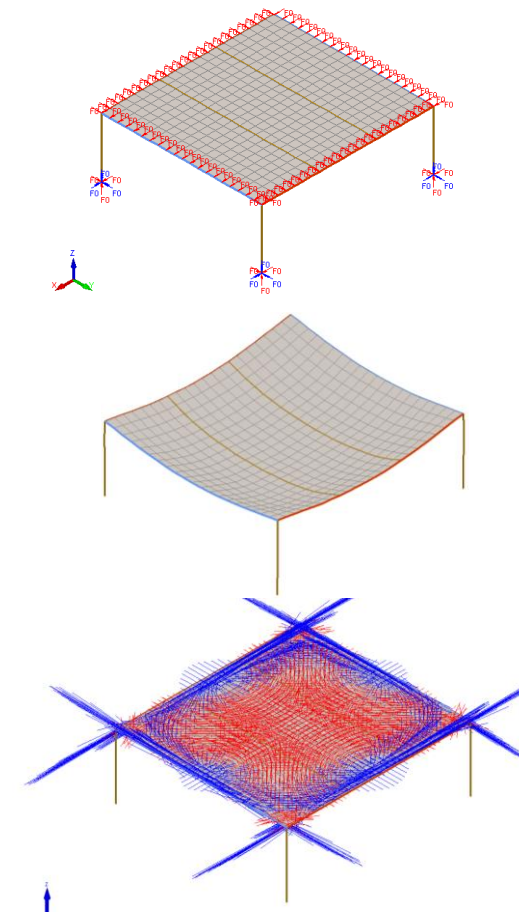
Diamond 2011.a.2 for SAFIR

FILE: PA0
 NODES: 630
 BEAMS: 142
 TRUSSES: 0
 SHELLS: 420
 SOILS: 0

BEAMS PLOT
SHELLS PLOT
IMPOSED DOF PLOT

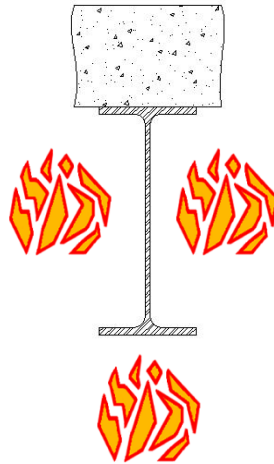
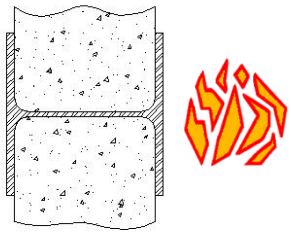
	he260a.tem
	ipe240.tem
	ipe220.tem
	he260aCold.tem
	slab.tsh

Membrane effect



Outcome of a structural analysis for fire resistance

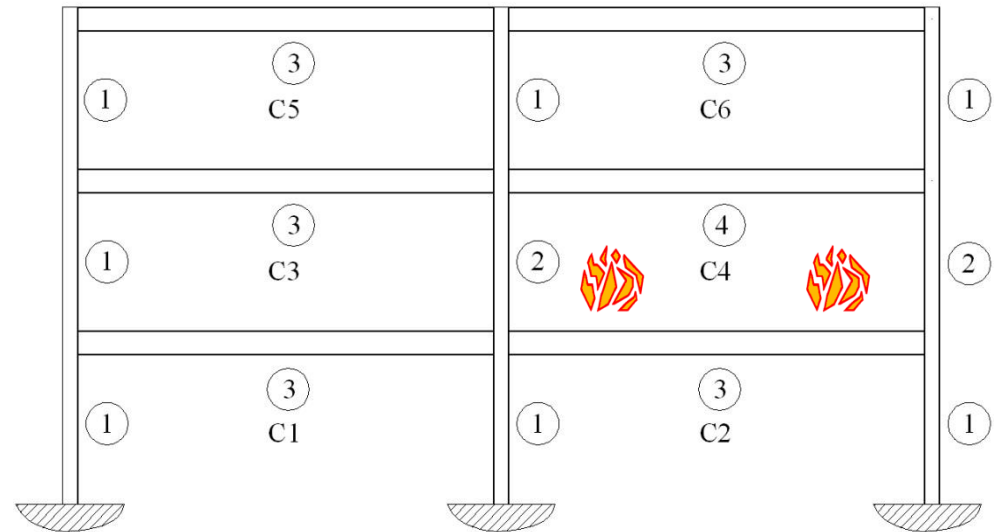
Example: office building portal frame



Cross-sections

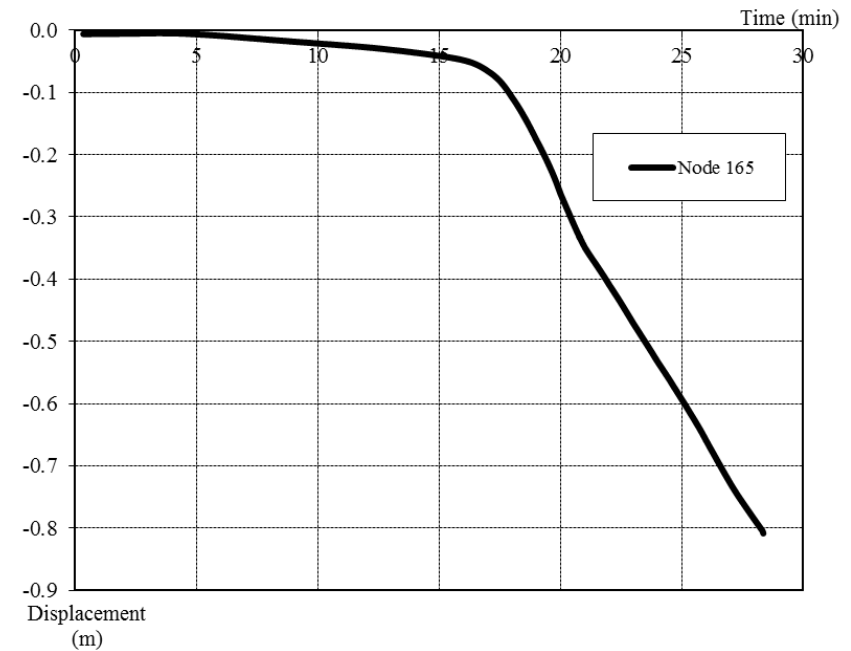
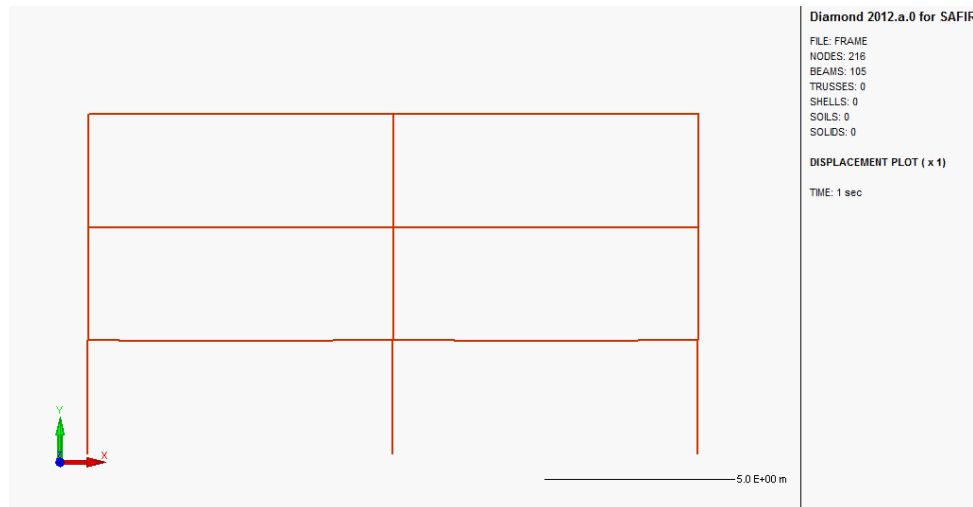
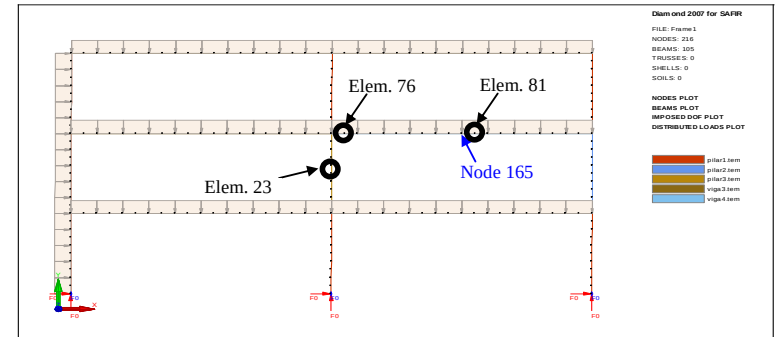
Beams - IPE 450

Columns - HEA 300

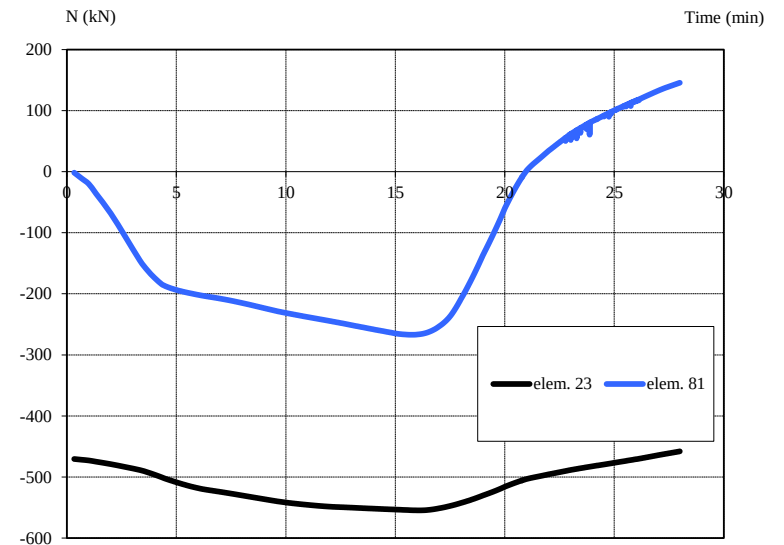
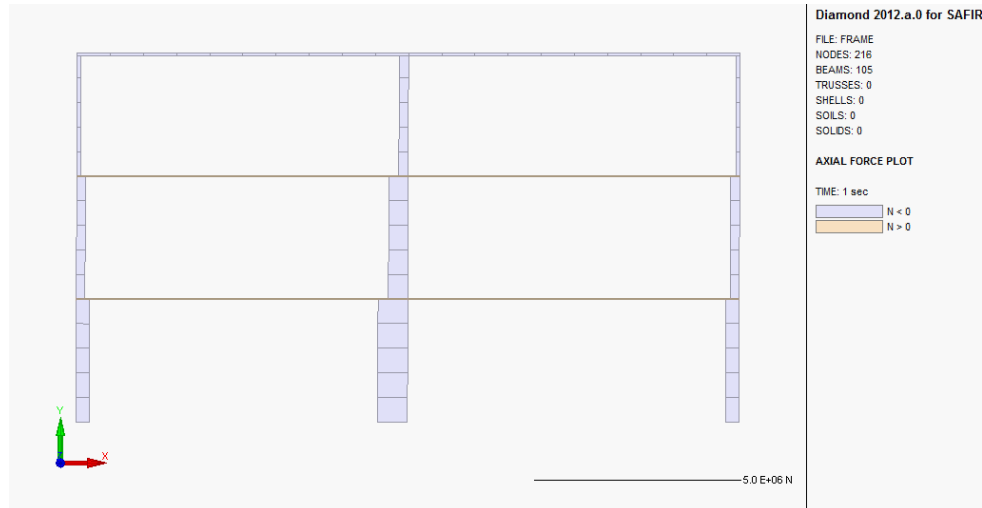
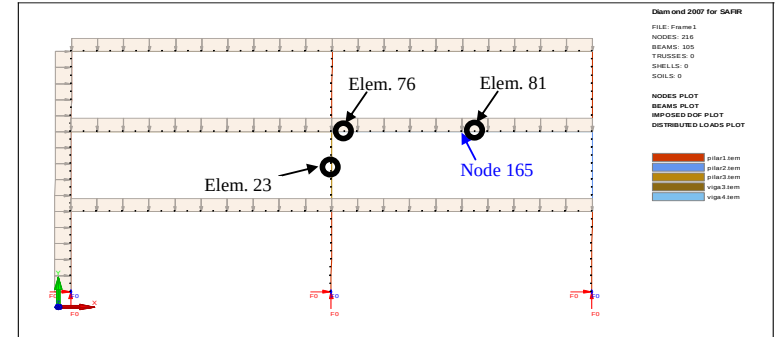


Required fire resistance - R30

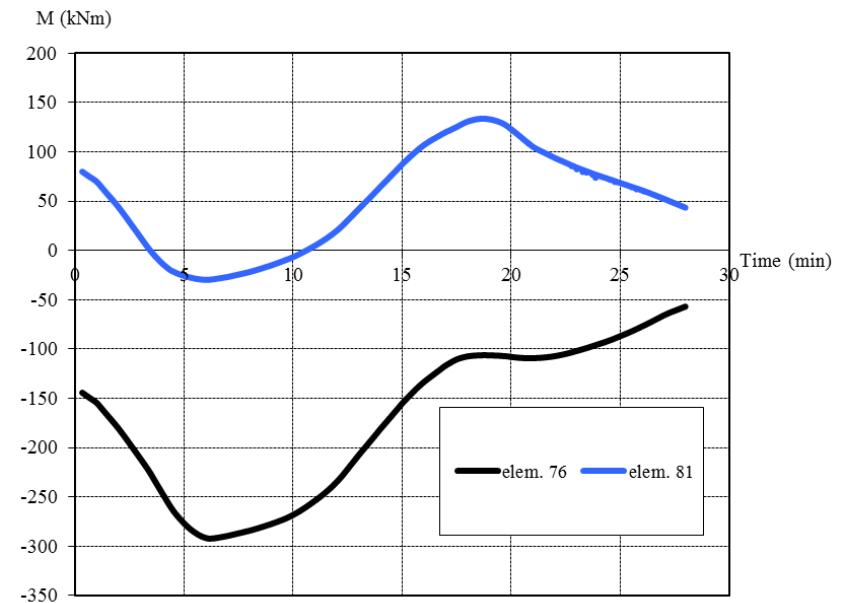
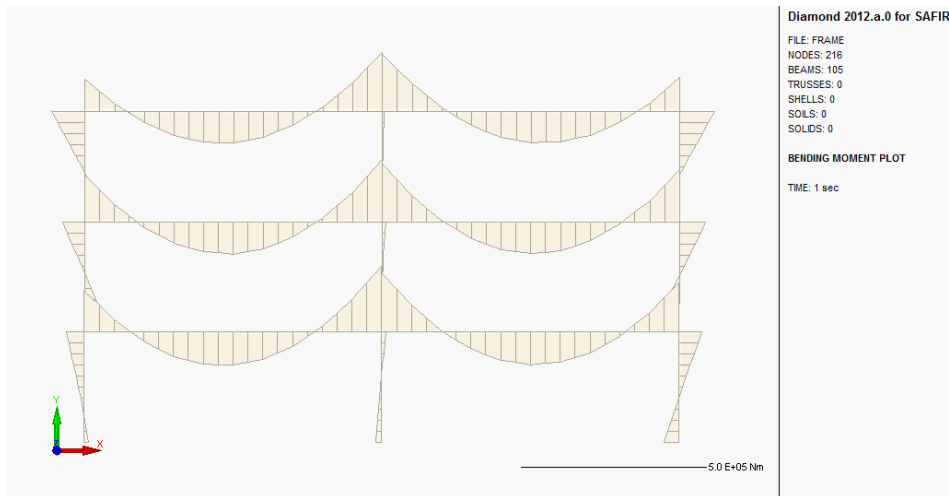
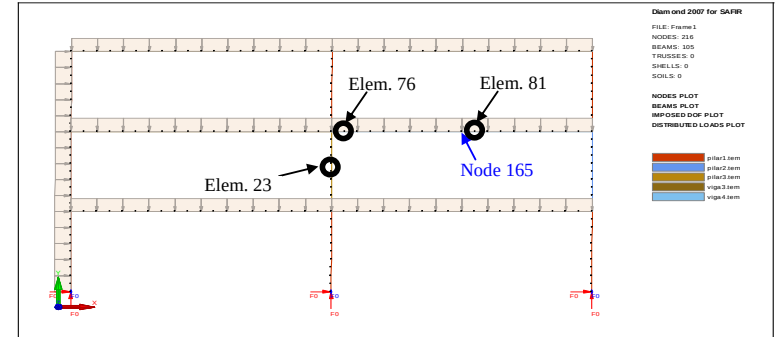
Displacements



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



Application examples of fire safety engineering

Fire resistance of the Shopping Centre Dolce Vita steel roof in Braga, Portugal

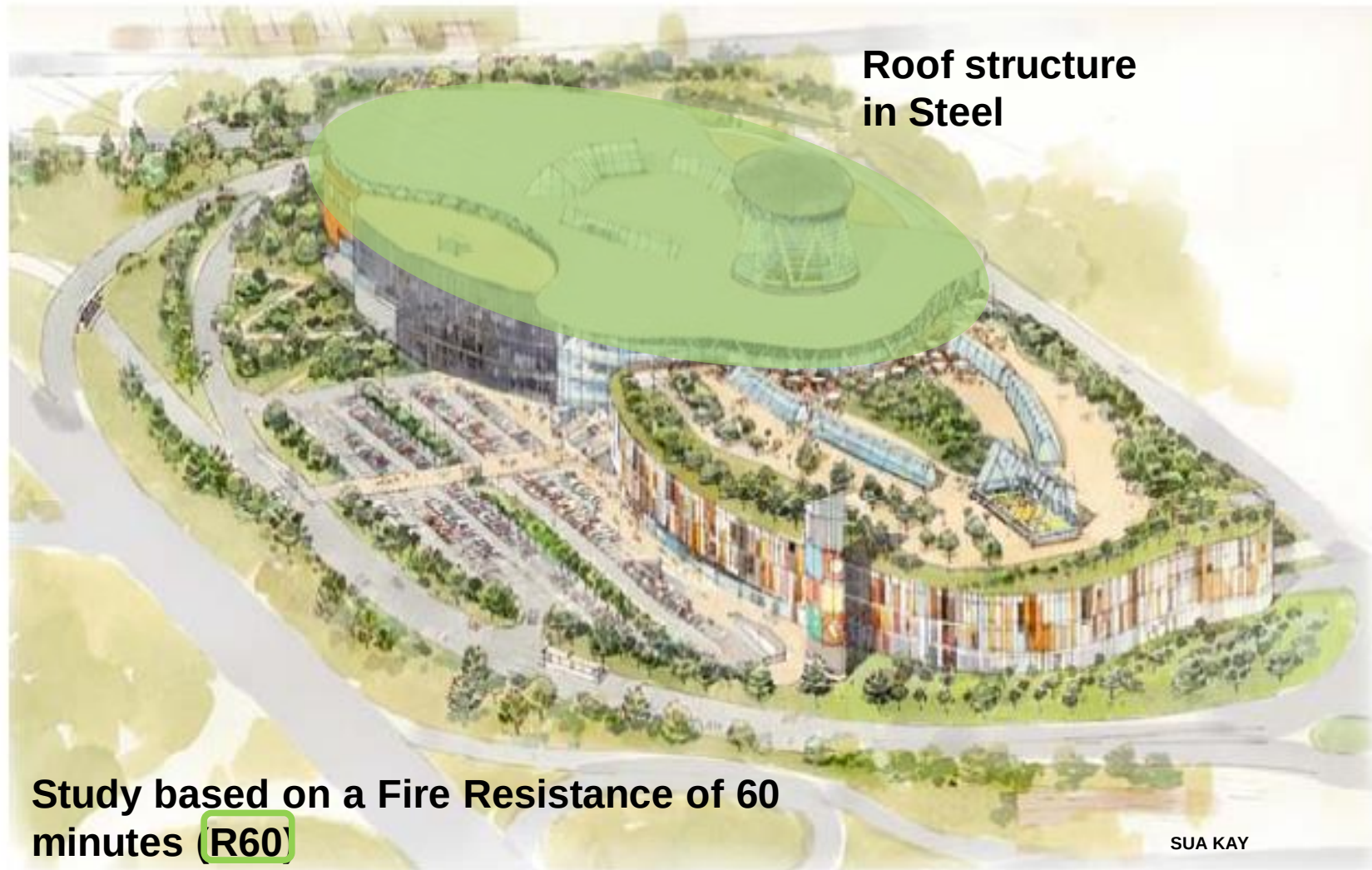
- ✓ **Main data**
- ✓ **Fire scenarios**
 - ✓ **Fire in the compartments**
 - ✓ **Localized fires**
- ✓ **Thermal analysis**
 - ✓ **Commercial sections**
 - ✓ **Built-up sections**
- ✓ **Structural analysis**
- ✓ **Final results**

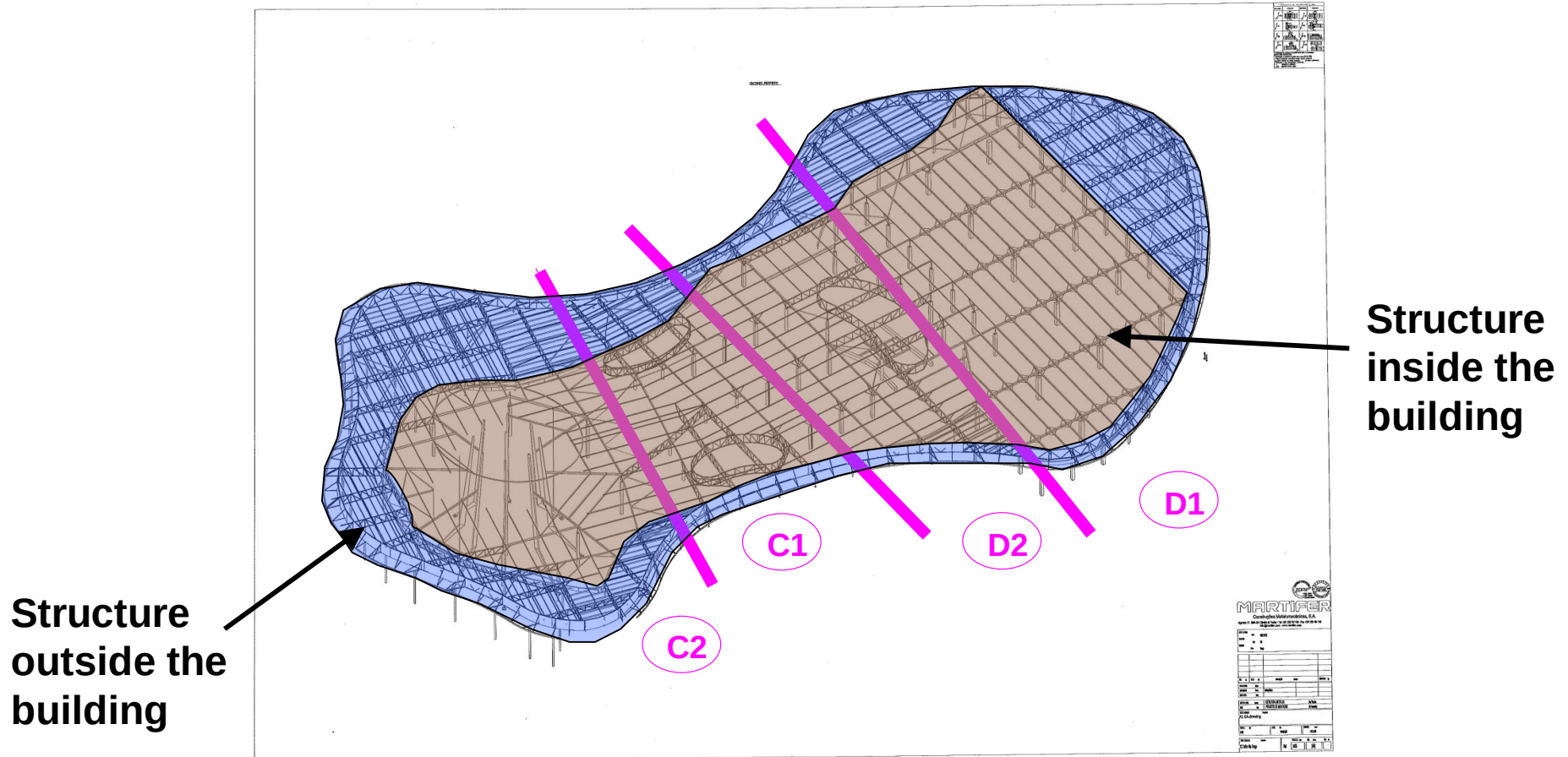
- **Owner: Chamartin Imobiliária**
- **Location: Braga, Portugal**
- **Erection: May, 2010**
- **Architect: SUA KAY**
- **Designer: GAPRES – Gabinete de Projectos, Engenharia e Serviços, SA**
- **Contractor for the steel structure: MARTIFER SA**
- **Building: 3 storey shopping centre**
- **Dimensions: 75000 m²**
- **Structure: mainly reinforced concrete portal frame, and a part with a steel roof**

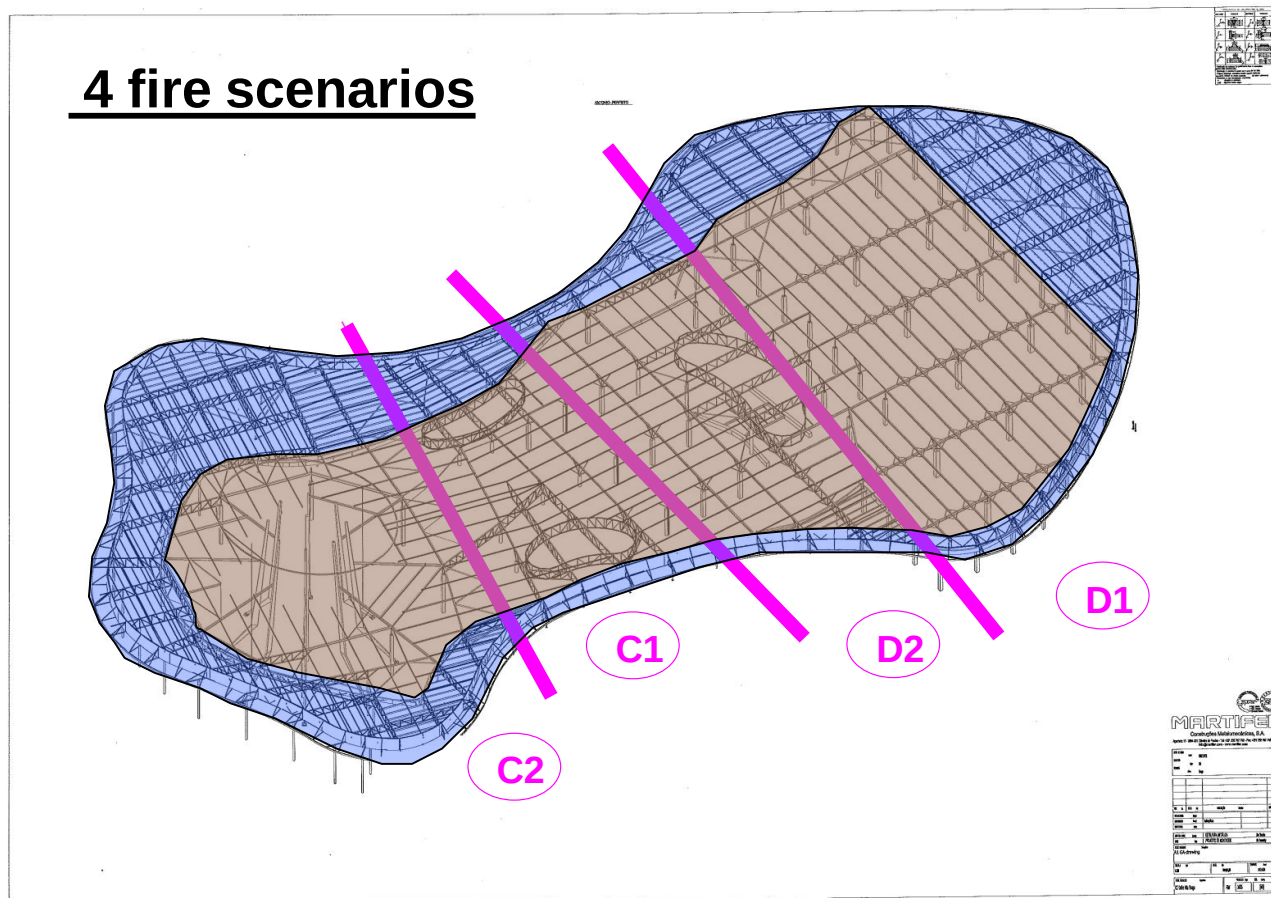
Steel roof structure:

- **Very irregular**
- **Several cross-sections from SHS, HE, IPE, UB and box welded sections**
- **Steel grade S275**
- **Mainly concrete columns**
- **Client: MARTIFER SA**
- **Steel consumption: 600 Ton**



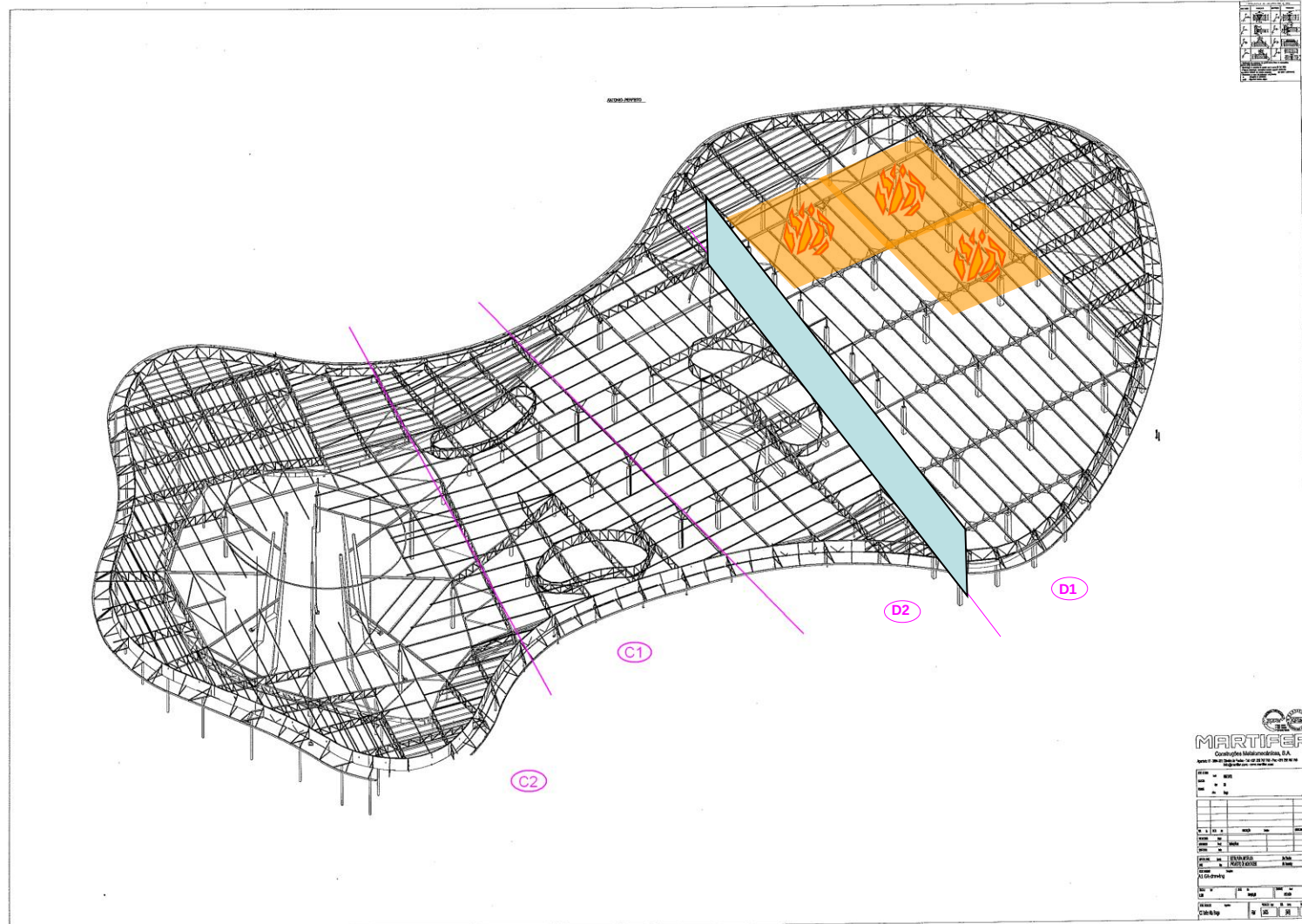






Scenario 1

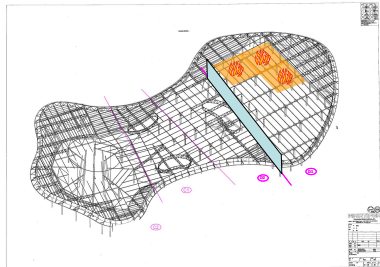
Fire in the
compartment
in 3 cinemas



I was assumed that a maximum of 3 cinemas would be simultaneous subjected to fire.

Scenario 1

Fire in the
compartment
in 3 cinemas



Maximum area: $A_{f,max} = 3960 \text{ m}^2$

Fire area: $A_{fi} = 960 \text{ m}^2$ (3 cinemas area)

Openings: the openings area was 237.6 m^2 , located at 10.50 m above the floor level, plus an area of 203.2 m^2 in the separation between the part D1 and parts C1, C2 and D2. It was assumed that 10% of the openings would be opened, most severe case.

Compartment height: 12.67 m

Walls: concrete blocks

Ceiling: Sandwich panels with 0.75 mm thickness steel plate and rock wool of 40 mm thickness and 125 kg/m^3 density.

Rate of Heat Release: $RHR_f = 250 \text{ kW/m}^2$

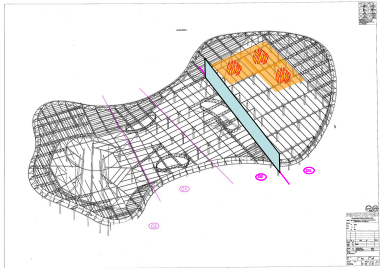
Fire growth rate: high, $t_\alpha = 150 \text{ s}$

Fire load density: $q_{f,k} = 730 \text{ MJ/m}^2$

Combustion factor: $m = 1.0$

Scenario 1

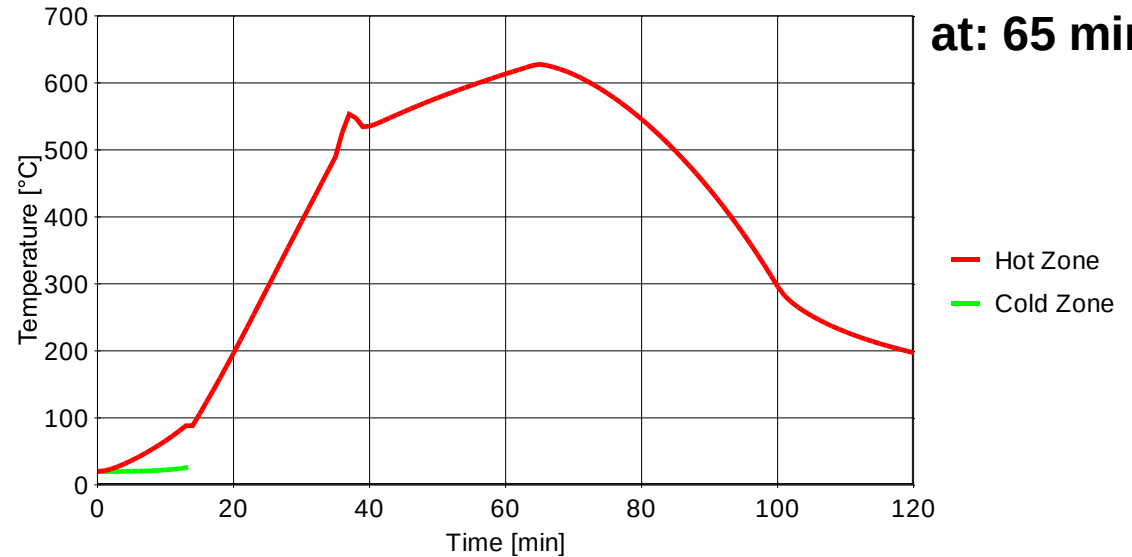
Fire in the
compartment
in 3 cinemas



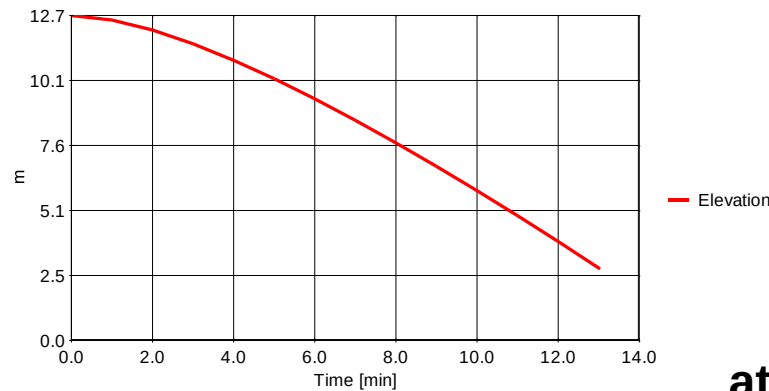
OZONE

Gas Temperature

**Peak: 628 °C
at: 65 min**



Zones Interface Elevation



**$h = 2.82 \text{ m}$
at: 13.00 min**

Fire in the compartment D2, C1 and C2



It was assumed that the fire would developed in all the 3 parts D2, C1 and C2.

Scenario 2

Fire in the compartment D2, C1 and C2



Maximum area: $A_{f,max} = 7560 \text{ m}^2$

Fire area: $A_{fi} = 7560 \text{ m}^2$

Openings: the openings area was 554.4 m^2 , at 10.50 m above the floor level, plus an area of 762 m^2 in a glass façade.

It was assumed that 10% of the openings would be opened until 400°C , 50% between 400°C and 500°C and 100% for temperatures higher 500°C (stepwise variation).

Compartment height: 12.67 m

Walls: concrete blocks

Ceiling: Sandwich panels with 0.75 mm thickness steel plate and rock wool of 40 mm thickness and 125 kg/m^3 density.

Rate of Heat Release: $RHR_f = 250 \text{ kW/m}^2$

Fire growth rate: high, $t_\alpha = 150 \text{ s}$

Fire load density: $q_{f,k} = 730 \text{ MJ/m}^2$

Combustion factor: $m = 1.0$

Scenario 2

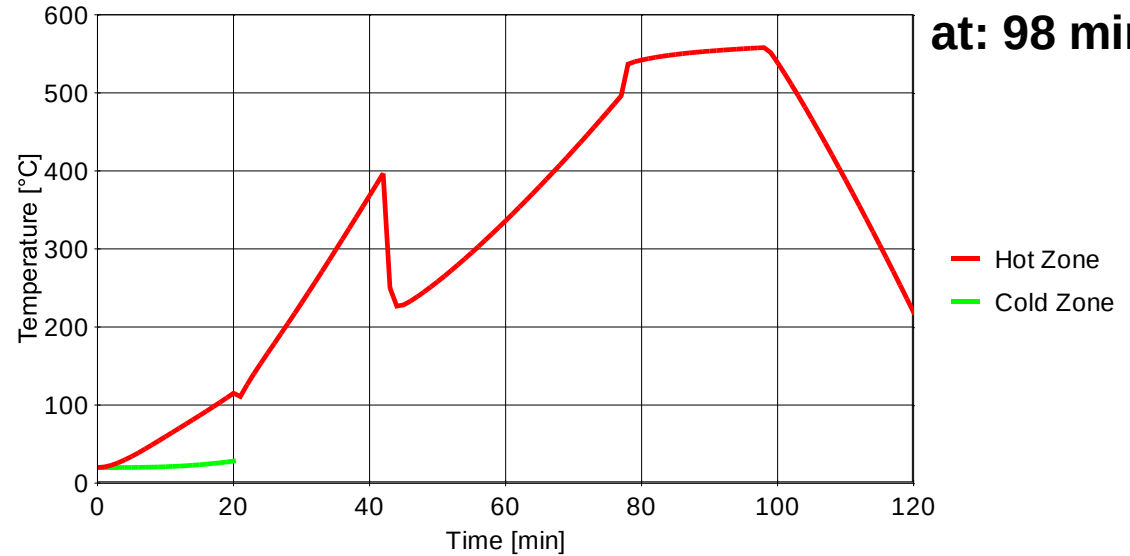
Fire in the compartment D2, C1 and C2



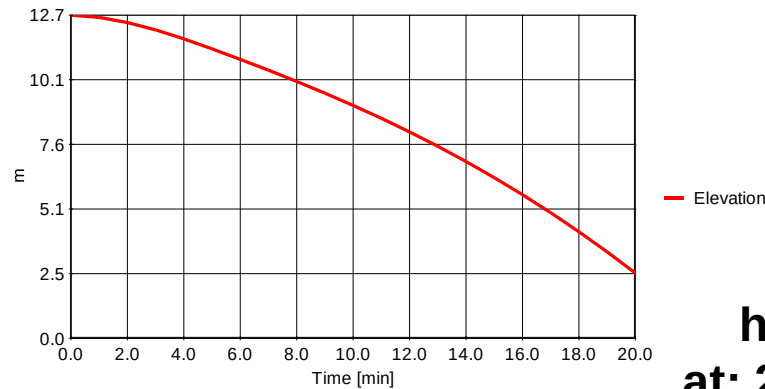
OZONE

Gas Temperature

**Peak: 558 °C
at: 98 min**



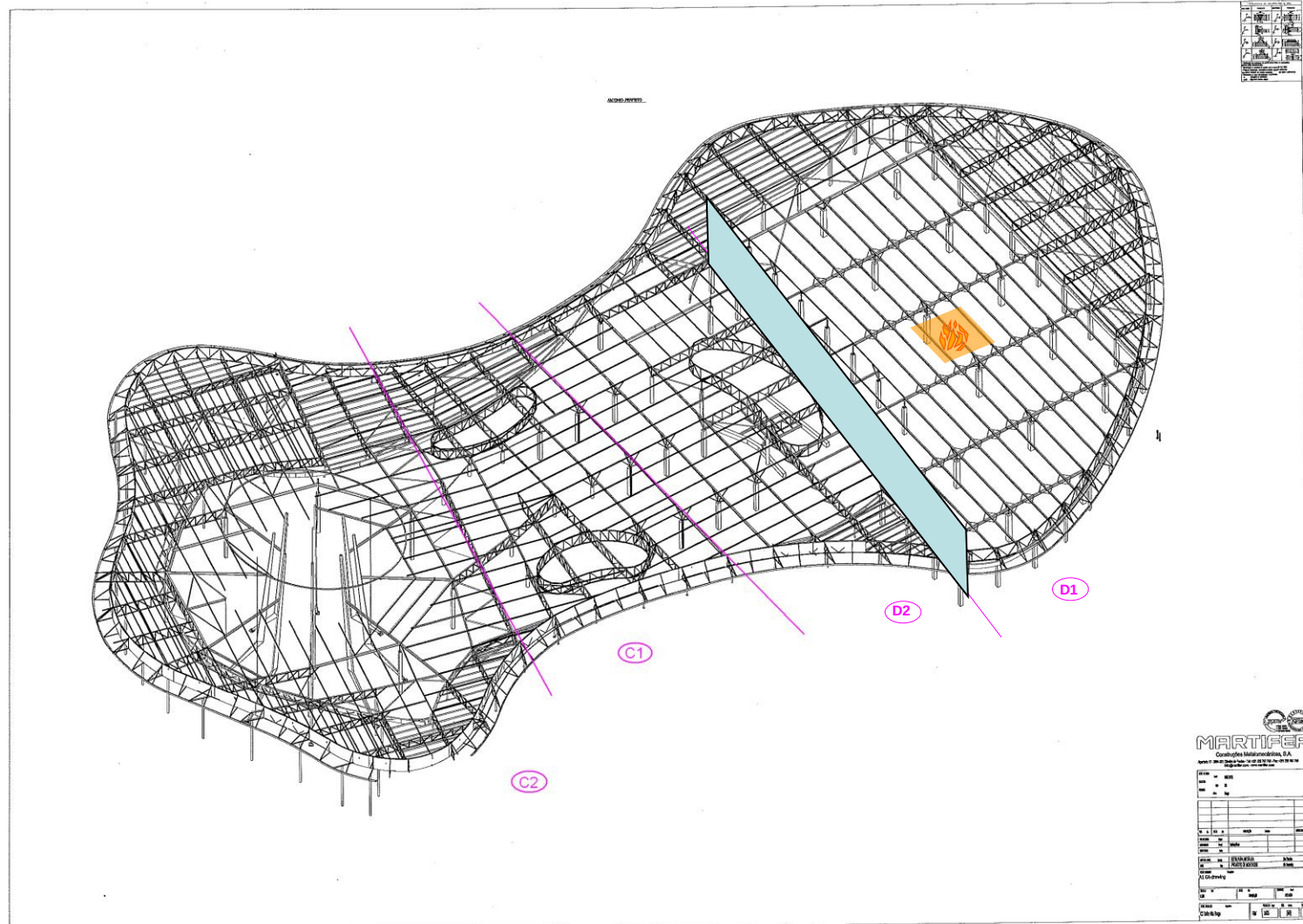
Zones Interface Elevation



**h = 2.55 m
at: 20.00 min**

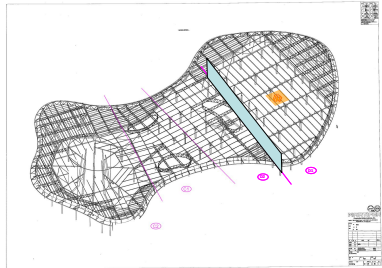
Scenario 3

Localised fire in the roof structure



Scenario 3

**Localised fire
in the roof
structure**



I was considered a localise fire in the beams of the steel roof structure.

Fire area: $A_{fi} = 36 \text{ m}^2$ (corresponded to 6.8 m of diameter)
Temperature calculated at 12.67 m above the floor level

Compartment height: 12.67 m

Rate of Heat Release: $RHR_f = 250 \text{ kW/m}^2$

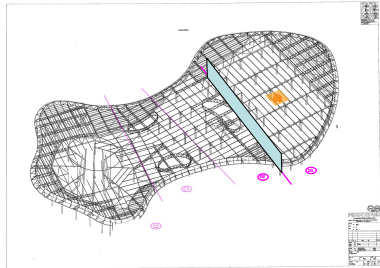
Fire growth rate: high, $t_\alpha = 150 \text{ s}$

Fire load density: $q_{f,k} = 730 \text{ MJ/m}^2$

Combustion factor: $m = 1.0$

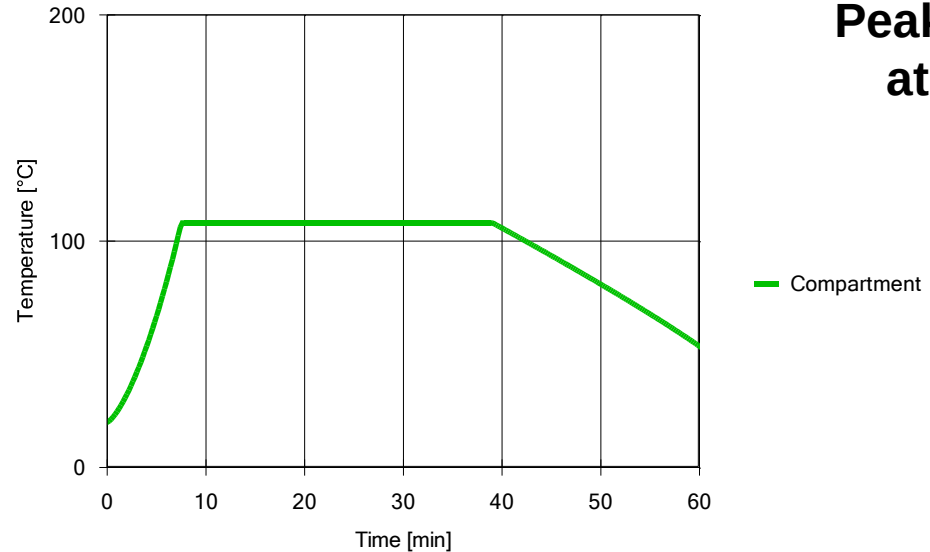
Scenario 3

Localised fire in the roof structure

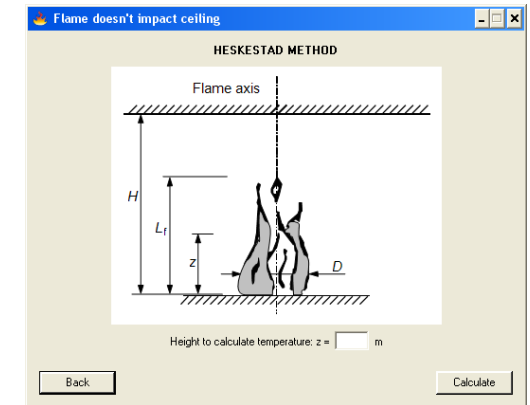
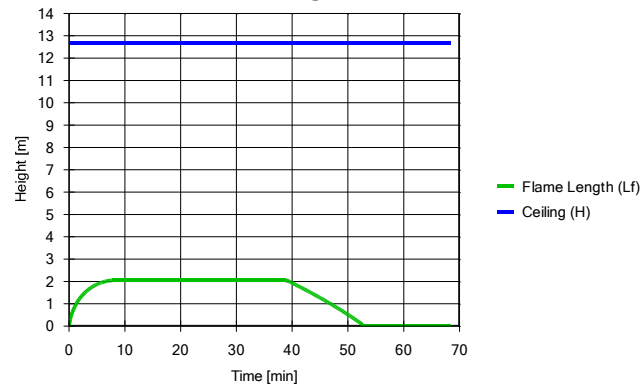


ELEFIR-EN

FIRE TEMPERATURE



Flame length



$$h_{\max} = 2.05 \text{ m}$$

Scenario 4

Localised fire
at floor level 1
of part C2



I was considered a localise fire at the floor level 1 of part C2.

Scenario 4

Localised fire
at floor level 1
of part C2



Fire diameter: $d_{fi} = 10 \text{ m}$

Temperature calculated at different heights

Compartment height: 36 m

Rate of Heat Release: $RHR_f = 250 \text{ kW/m}^2$

Fire growth rate: high, $t_\alpha = 150 \text{ s}$

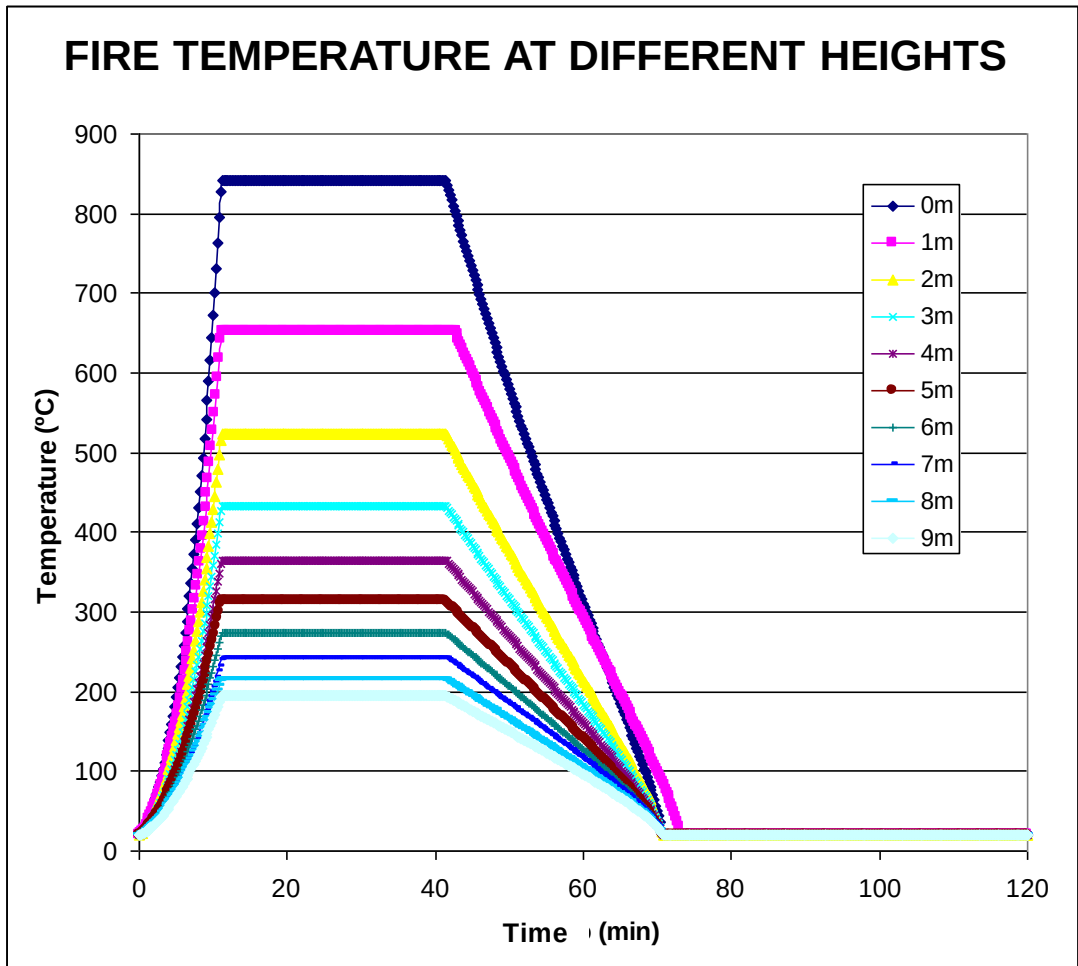
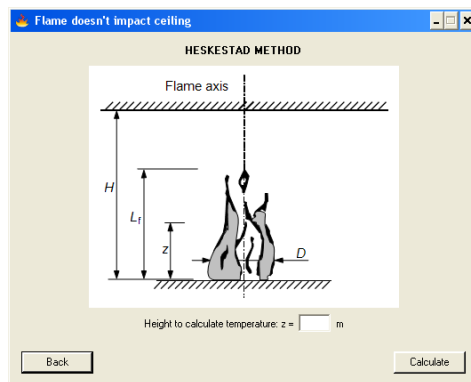
Fire load density: $q_{f,k} = 730 \text{ MJ/m}^2$

Combustion factor: $m = 1.0$

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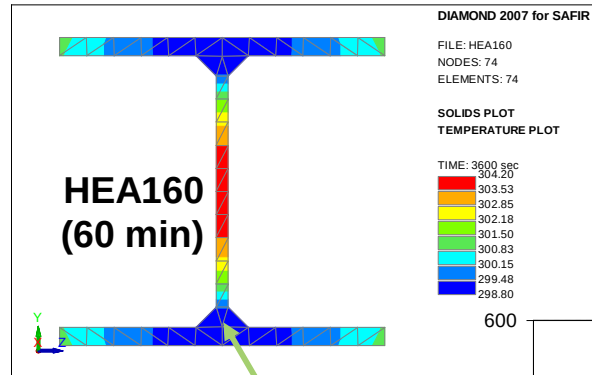
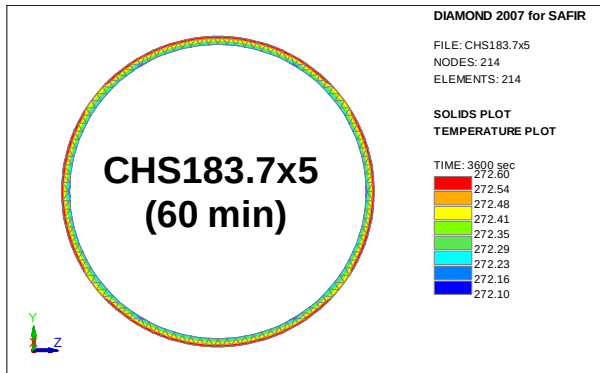
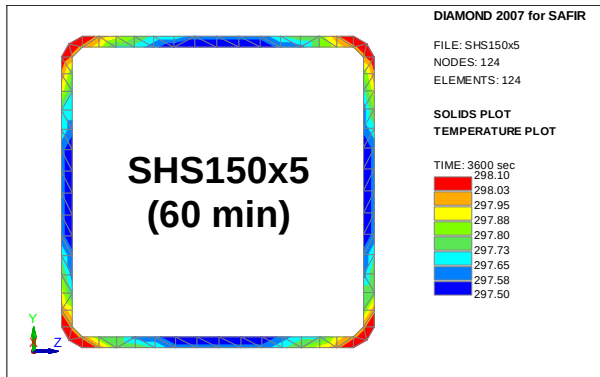
Scenario 4

Localised fire
at floor level 1
of part C2

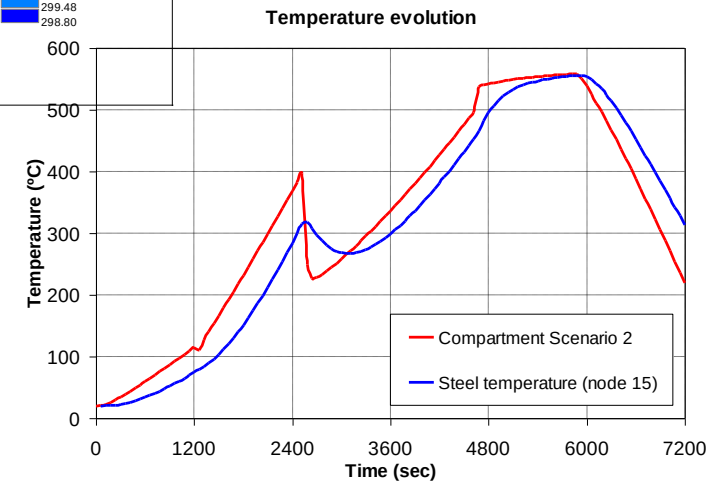
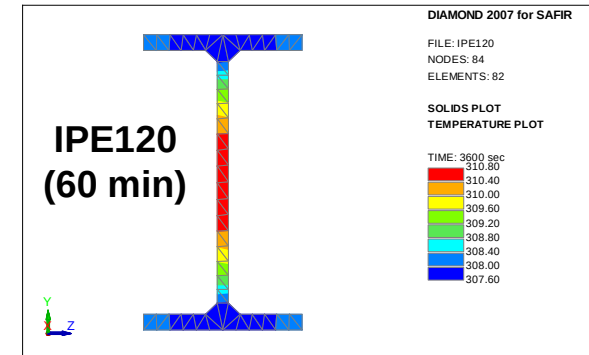


Commercial profiles

SAFIR

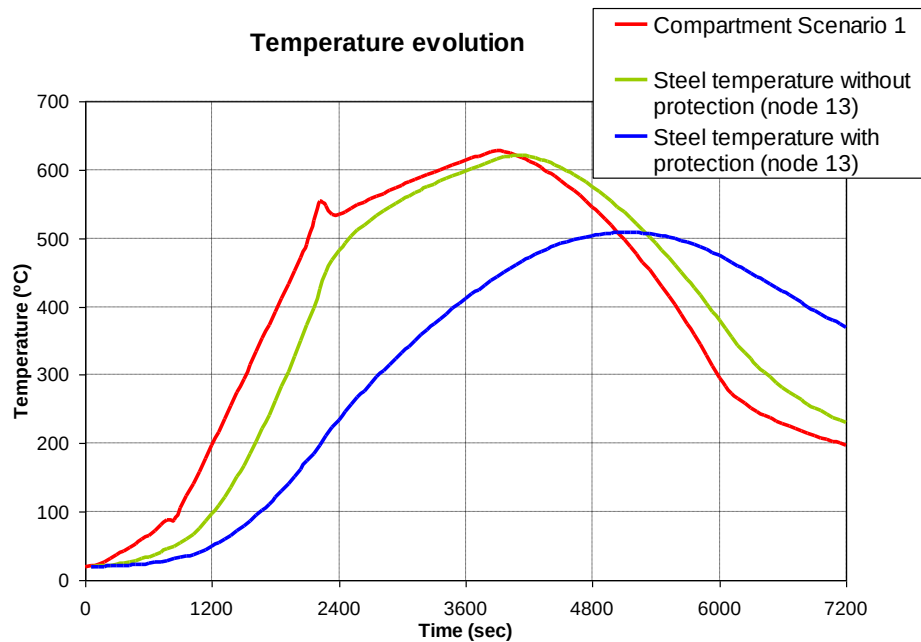


node 15

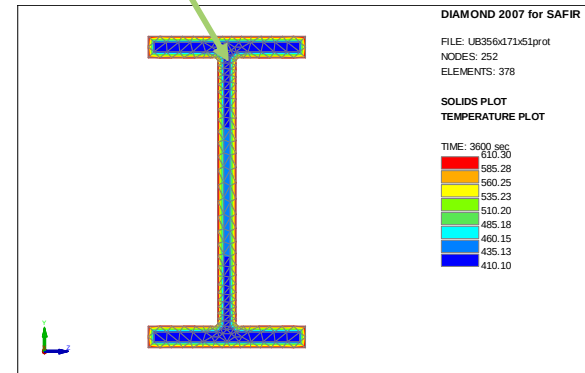
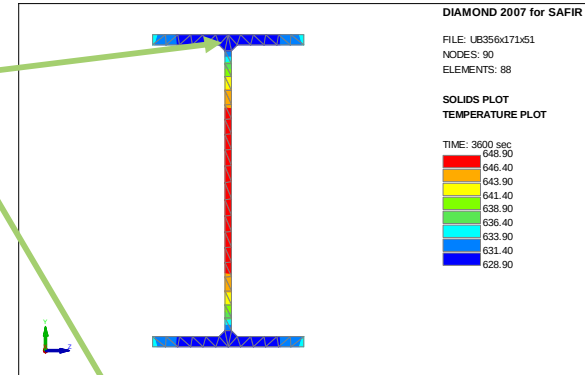


Commercial profiles

SAFIR

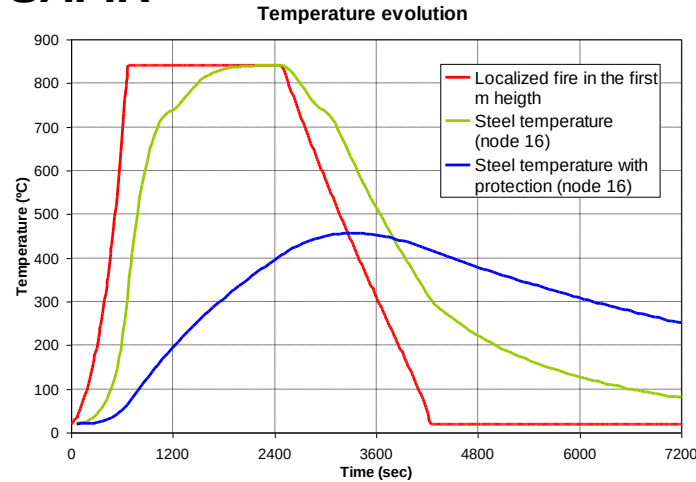


node 13

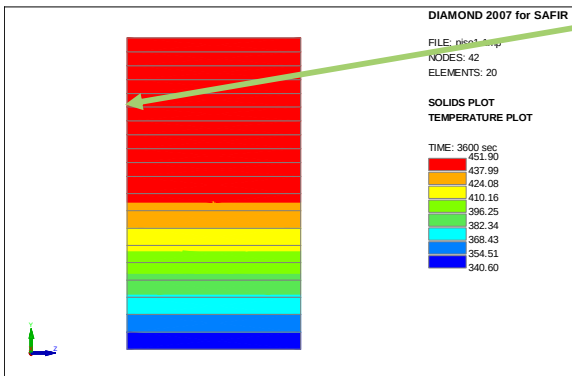


Built-up section profiles

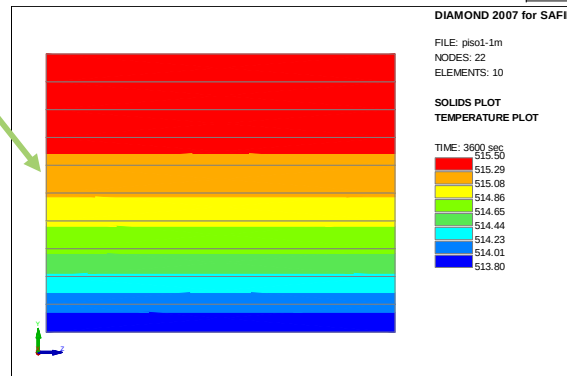
SAFIR



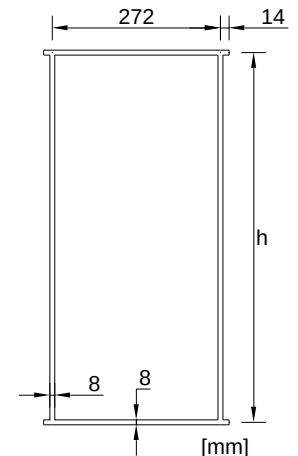
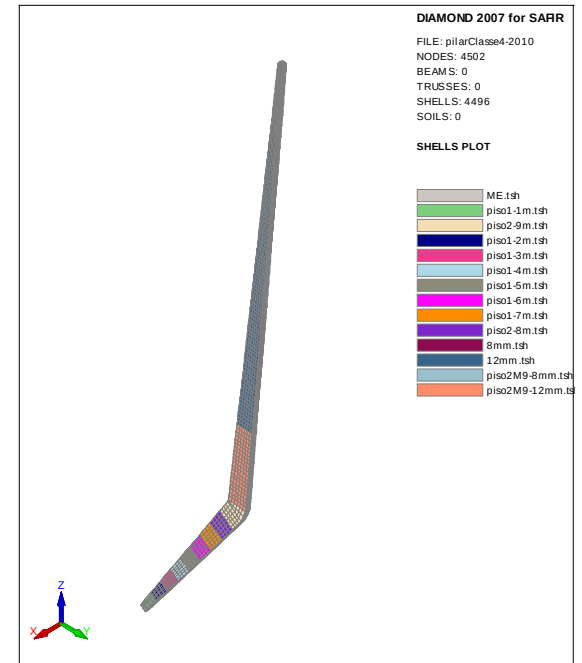
Steel plate section node 16



Steel shell element with
protection for R60
(60min)



Steel shell element
(60min)



Mechanical actions

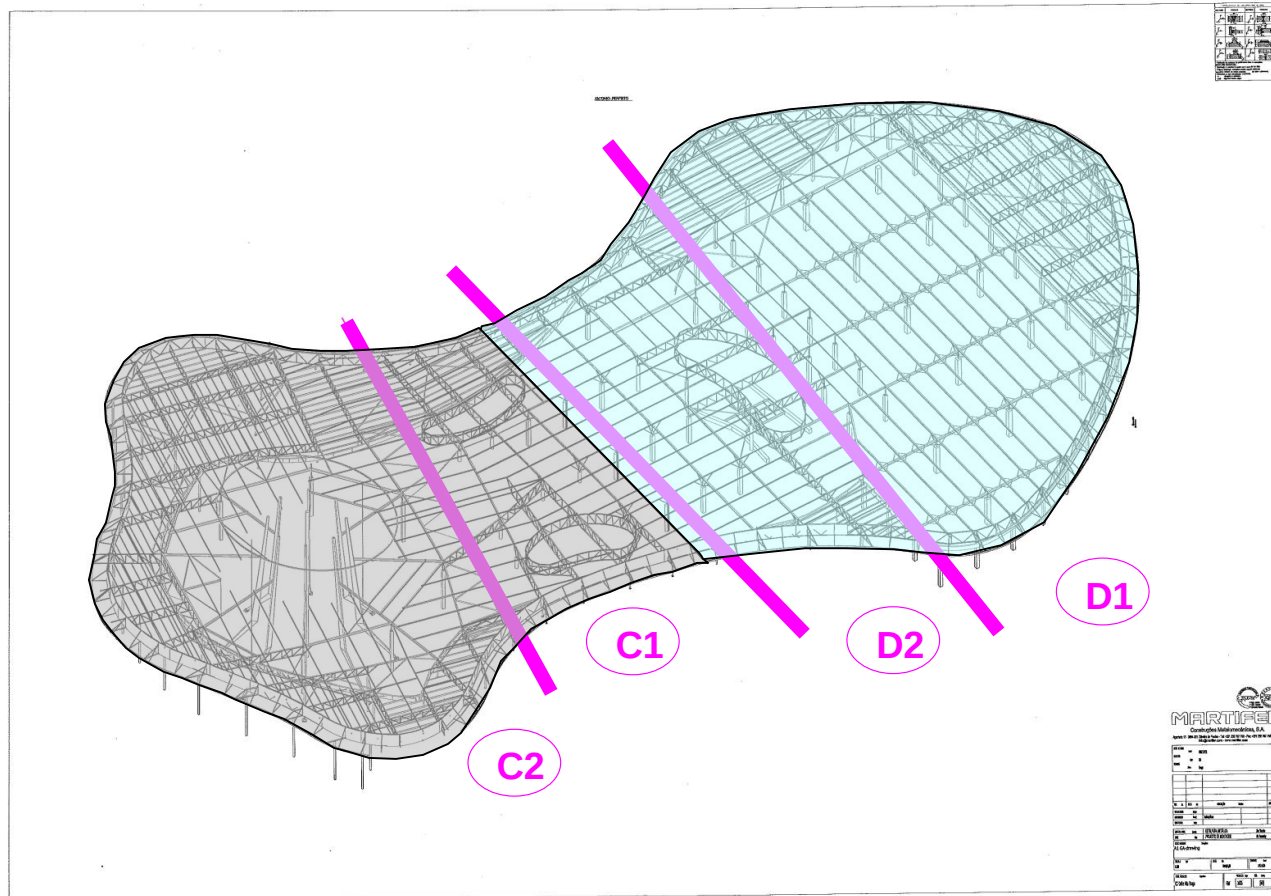
$$1.0G_k + \psi_{1,1}Q_{k,1} = 1.0G_k + 0.7Q_{k,1}$$

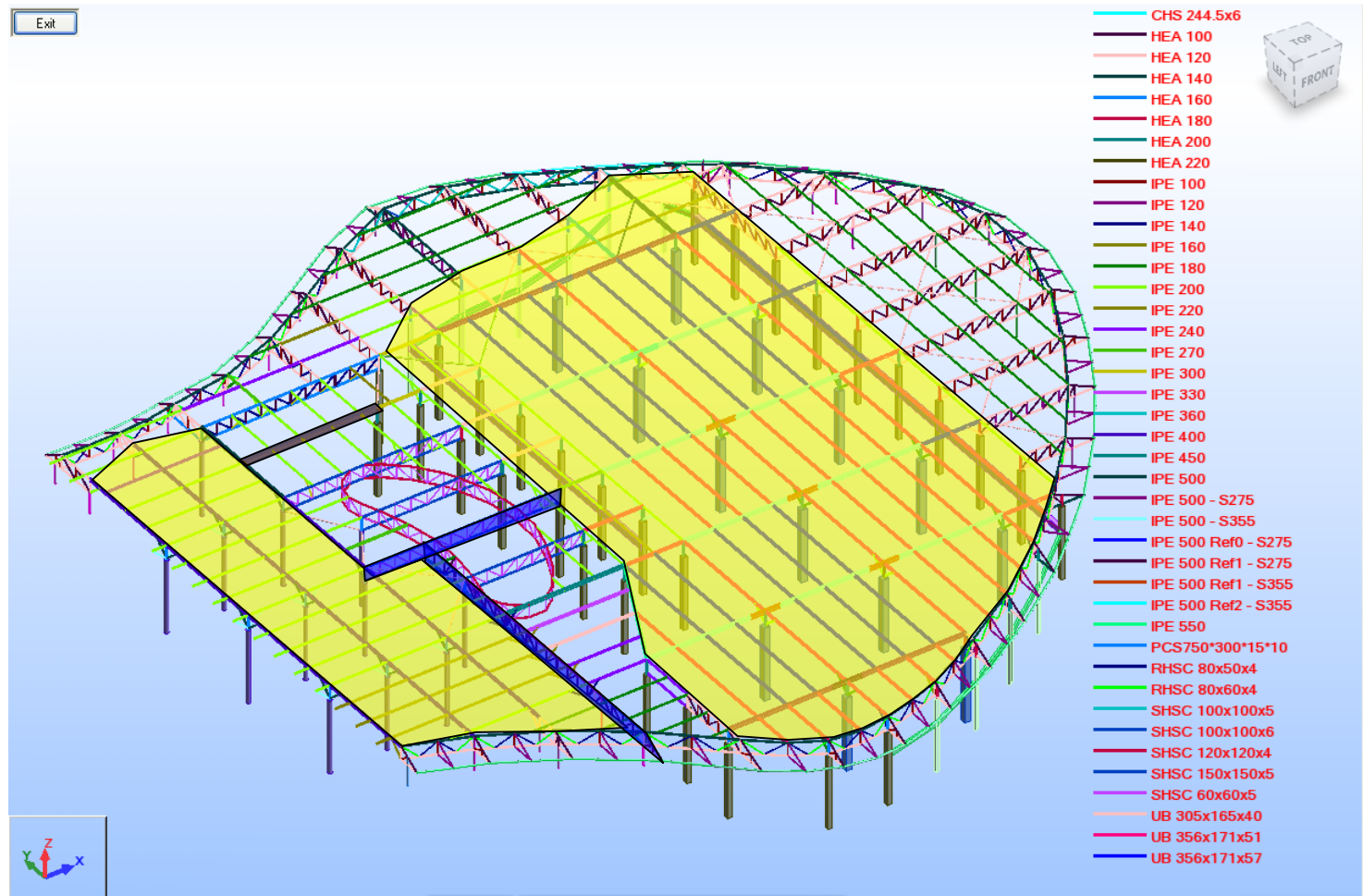
Permanent loads:

- **77 kN/m³ - dead weight of the steel profiles;**
- **0.5 kN/m² - dead weight of the roof;**
- **0.3 kN/m² - others permanent loads.**

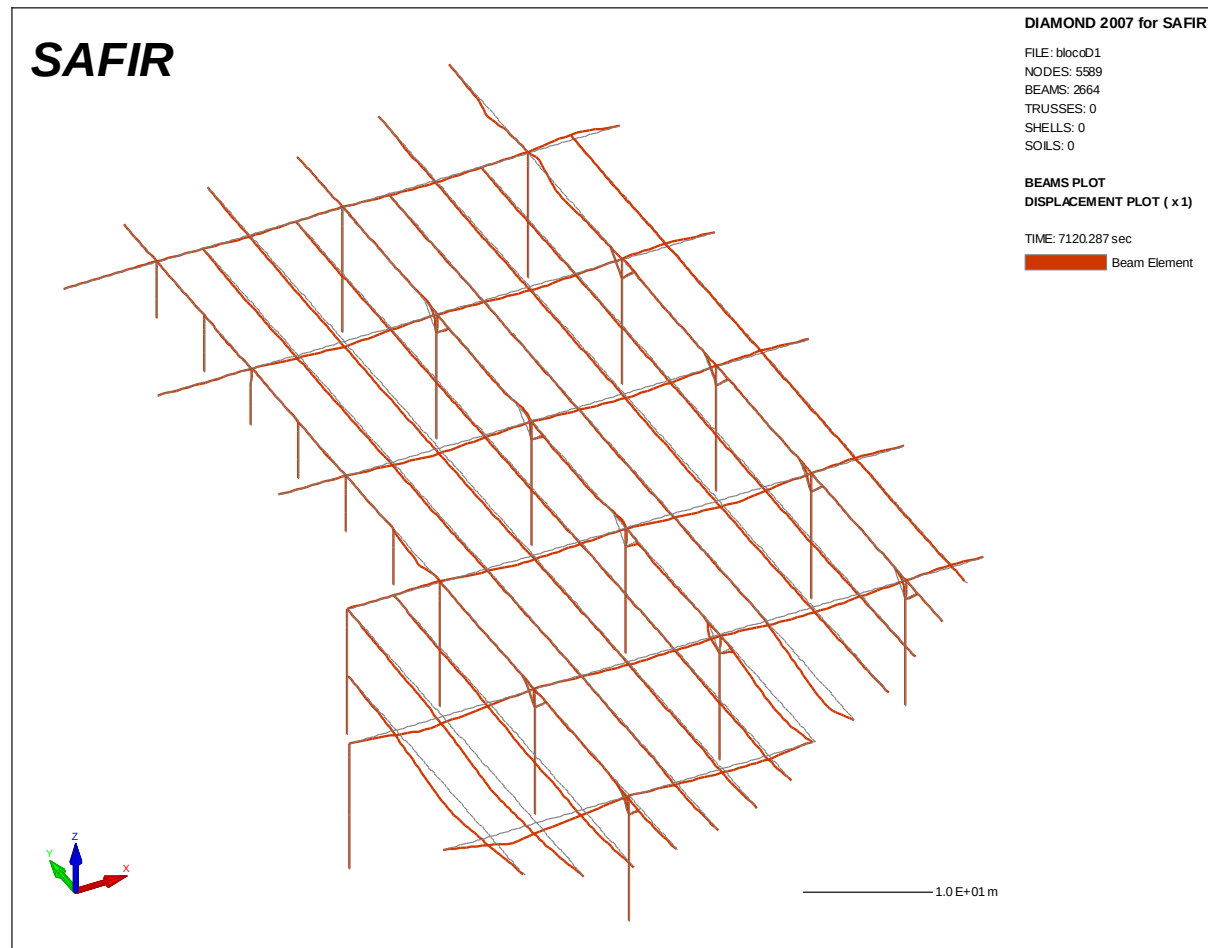
Imposed load:

- **0.5 kN/m² - publicity panels and other suspended objects from the ceiling.**





Part D1 with the Fire scenario 1

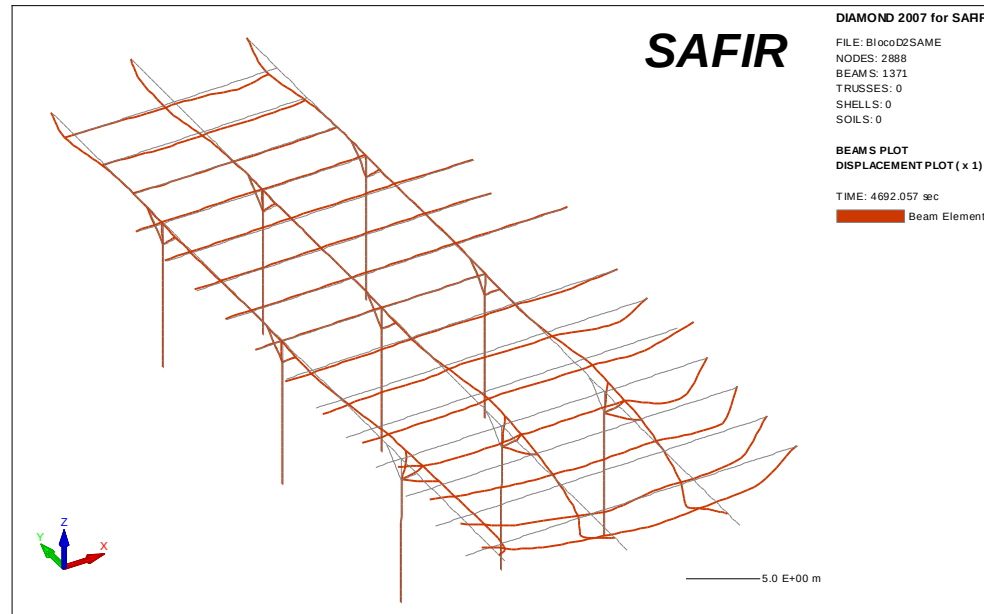


Without protection - collapse at 53 min

With protection of the purlins of R30 – no collapse



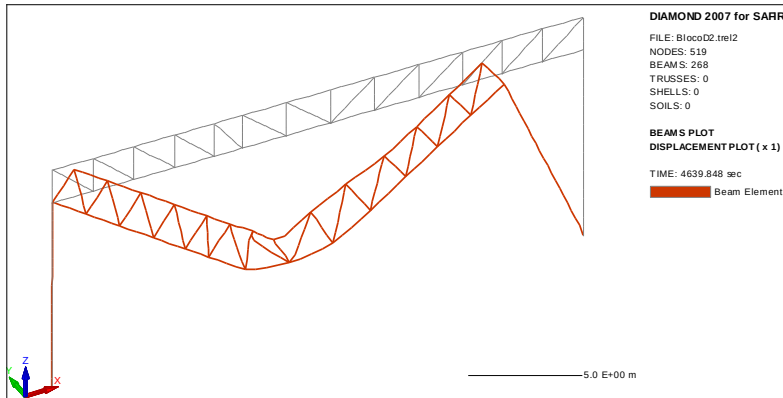
Frame of part D2 with the Fire scenario 2



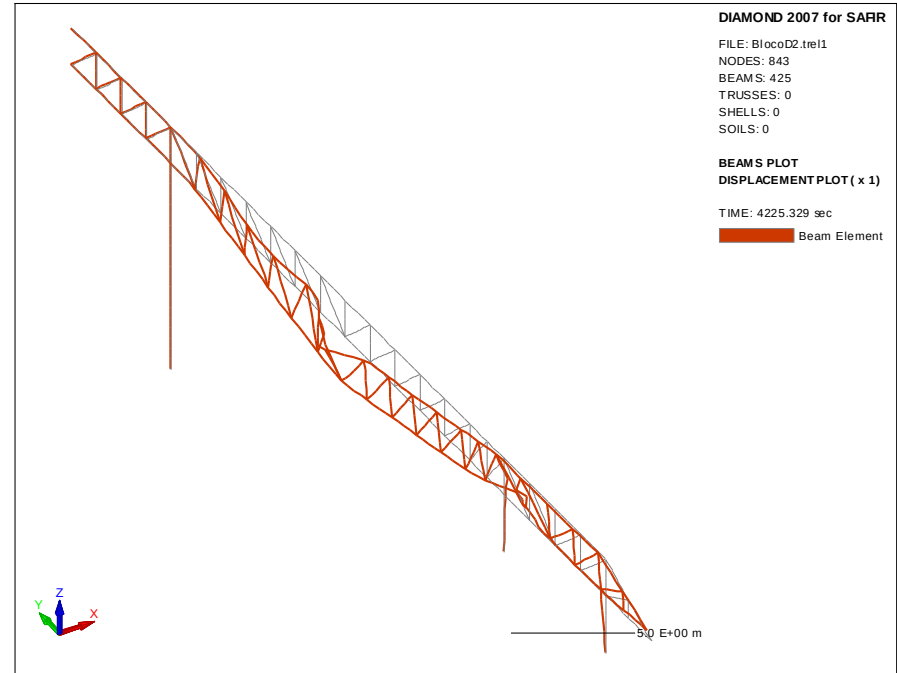
Collapse at 78 min

Part D2 with the Fire scenario 2

SAFIR



Truss structure 2
Collapse at 77 min

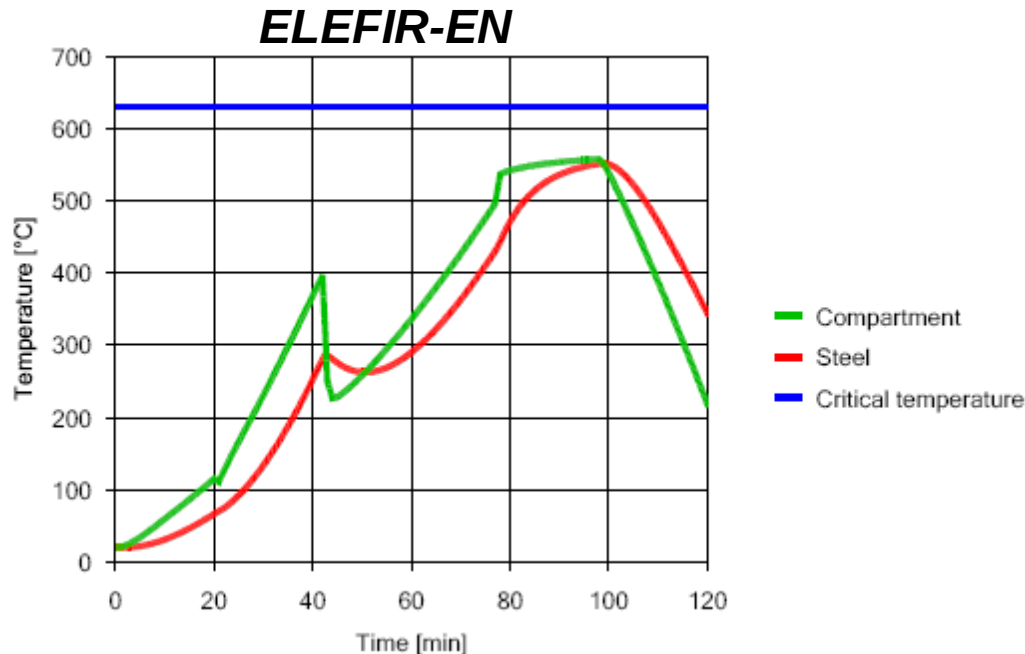


Truss structure 1
Collapse at 70 min

**Simplified method
(on the safe side)**

Built-up I-steel beam section of class 3 of Part D2

Fire scenario 2



No collapse

[Maximum temperature]

Compartment: 558.0 °C at 98.00 min

Steel: 551.9 °C at 98.92 min

ELEFIR-EN REPORT

Project name:
Date: 15-04-2009

Temperature evaluated using interpolation on the table 3.1 from EN 1993-1-2.

PROFILE

Other (Class 3)

$h = 750 \text{ mm}$
 $b = 300 \text{ mm}$
 $t_w = 10 \text{ mm}$
 $t_f = 15 \text{ mm}$
 $r = 3 \text{ mm}$
 $A = 16208 \text{ mm}^2$
 $P = 2.675 \text{ m}^2/\text{m}$

$W_{el,y} = 4073900 \text{ mm}^3$
 $W_{pl,y} = 4606276 \text{ mm}^3$
 $I_z = 67560251 \text{ mm}^4$
 $I_t = 917078 \text{ mm}^4$
 $I_w = 9116296875000 \text{ mm}^6$

ELEMENT SUBMITTED TO BENDING ABOUT THE MAJOR AXIS

Critical temperature function of design moment: $M_{fi,Ed} = 446 \text{ kNm}$
Is lateral torsional buckling allowed? No

Adaptation factors:

Non-uniform temperature across the cross-section: $k_1 = 1.0$
Non-uniform temperature along the beam: $k_2 = 1.0$

EXPOSURE

Fire exposure: Fire on all sides
Fire protection: No protection

RESULTS

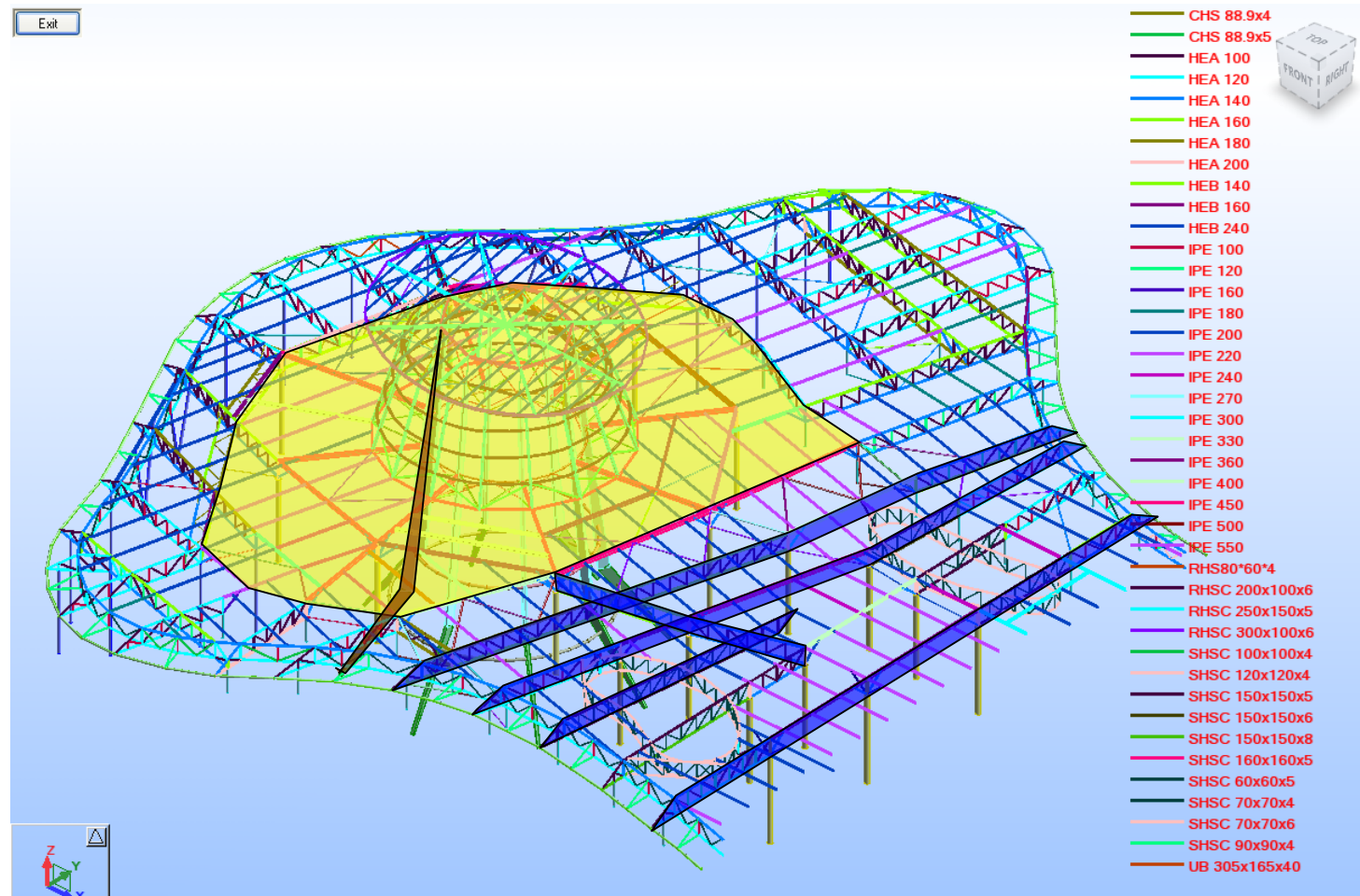
Section factor: $[A_m/V] = 165.0 \text{ m}^{-1}$
Modified section factor: $k_{sh} [A_m/V] = 129.6 \text{ m}^{-1}$

Fire compartment

Maximum temperature: 558.0 °C
Time to reach maximum temperature: 98.00 min

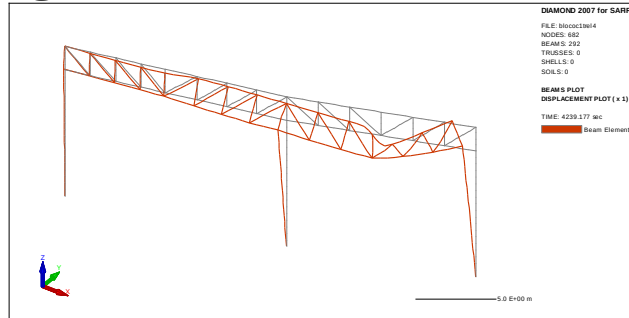
Steel

Maximum temperature: 551.9 °C
Time to reach maximum temperature: 98.92 min
The critical temperature is not reached during the fire.



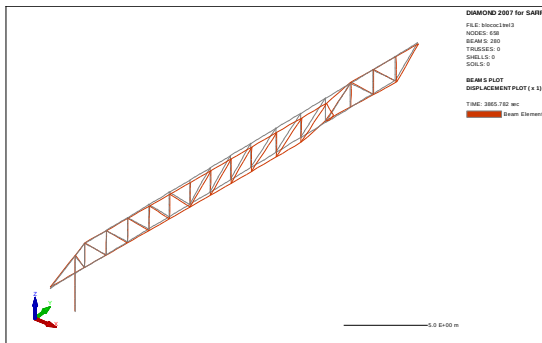
Part C1 with the Fire scenario 2

SAFIR



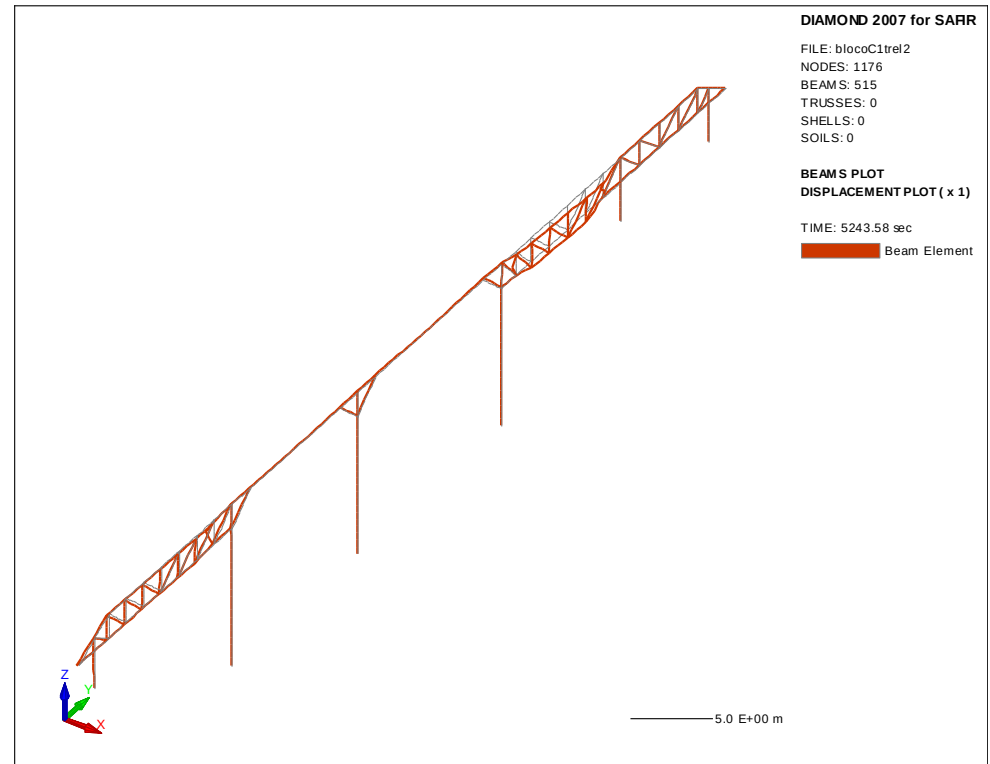
Truss structure 4

Collapse at 71 min



Truss structure 3

Collapse at 65 min

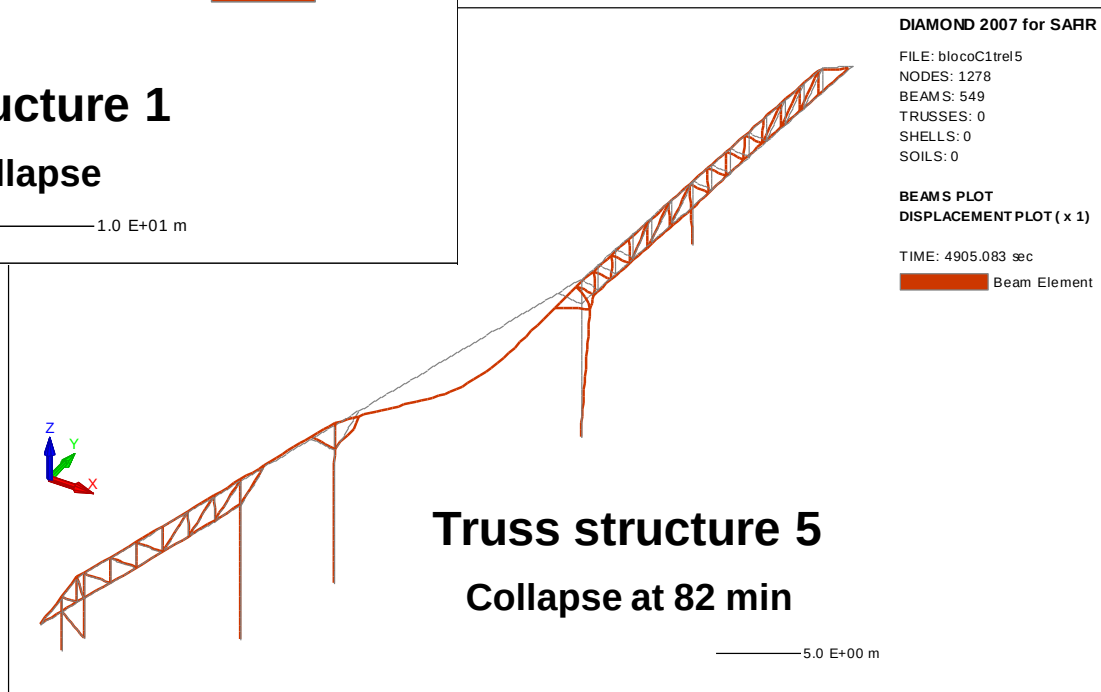
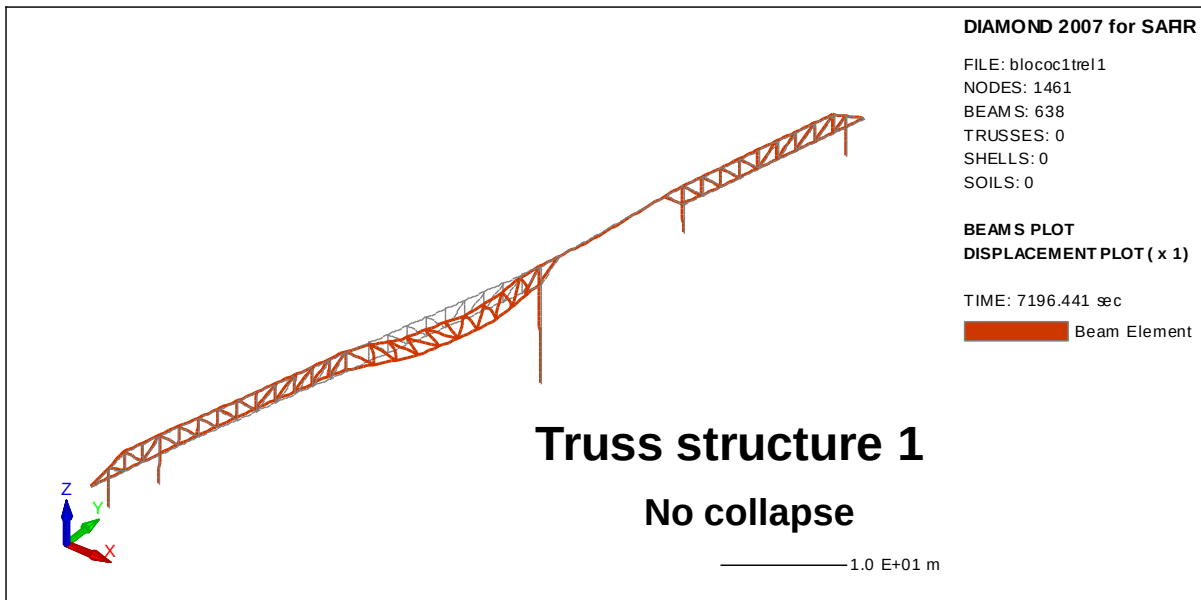


Truss structure 2

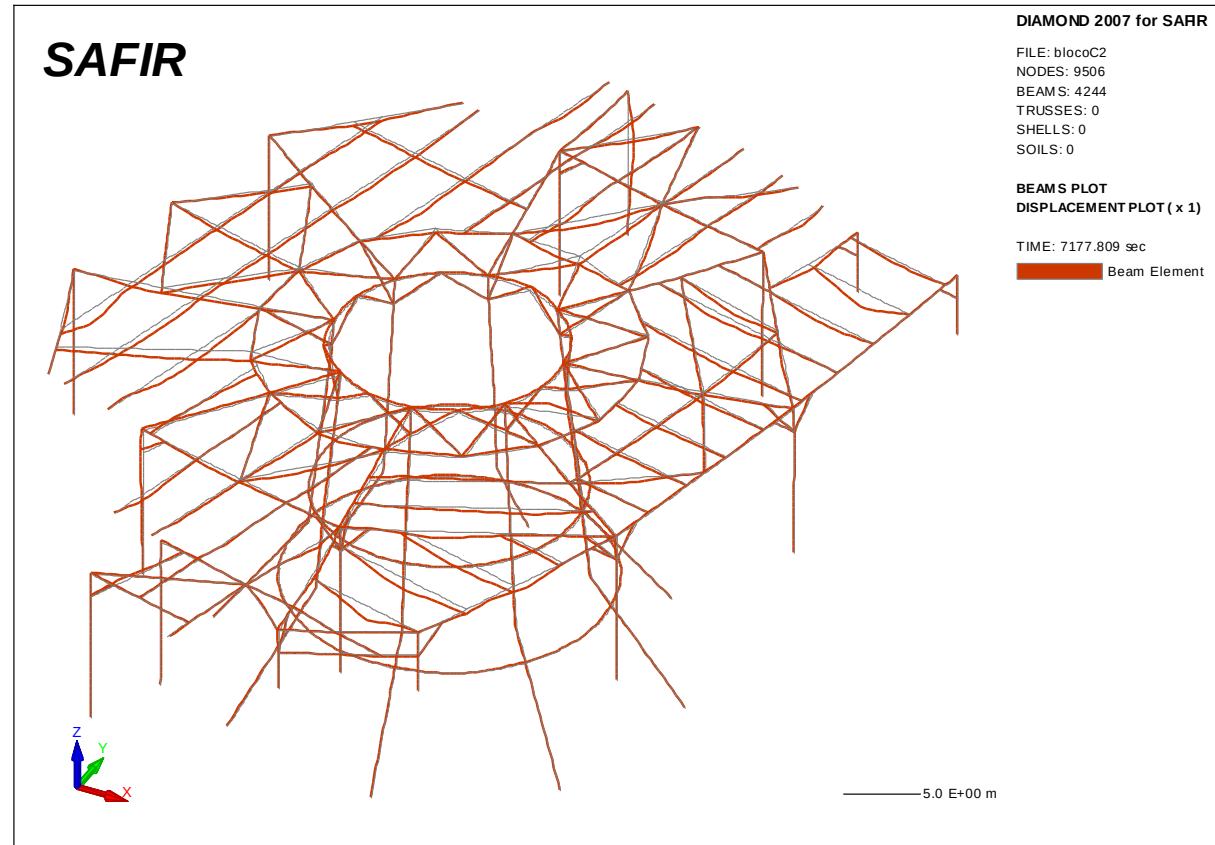
Collapse at 87 min

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Part C1 with the Fire scenario 2



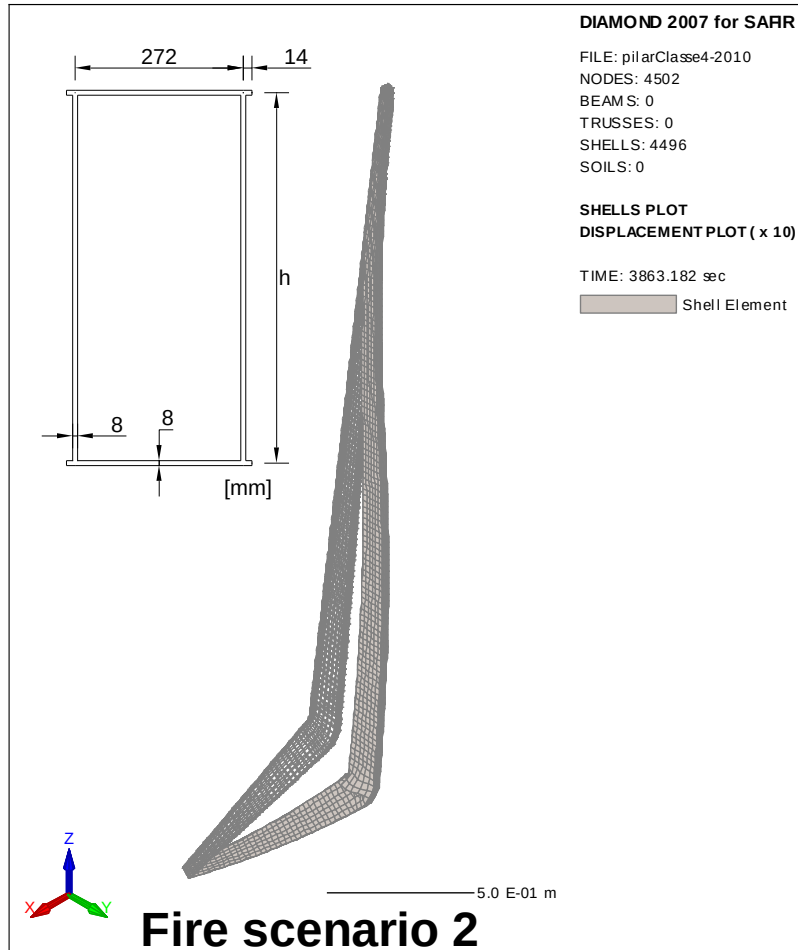
Frame of Part C2 with the Fire scenario 2



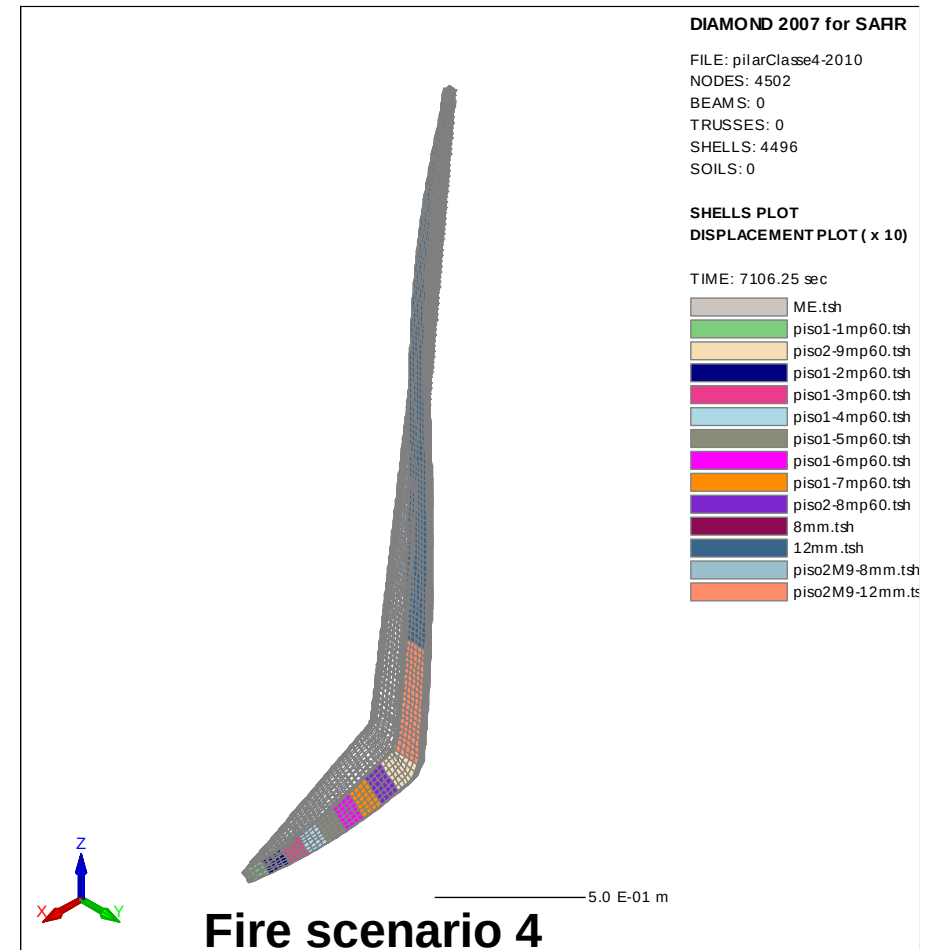
No collapse

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Class 4 column with non-uniform cross-section



Collapse at 64 min



Without protection - collapse at 14 min

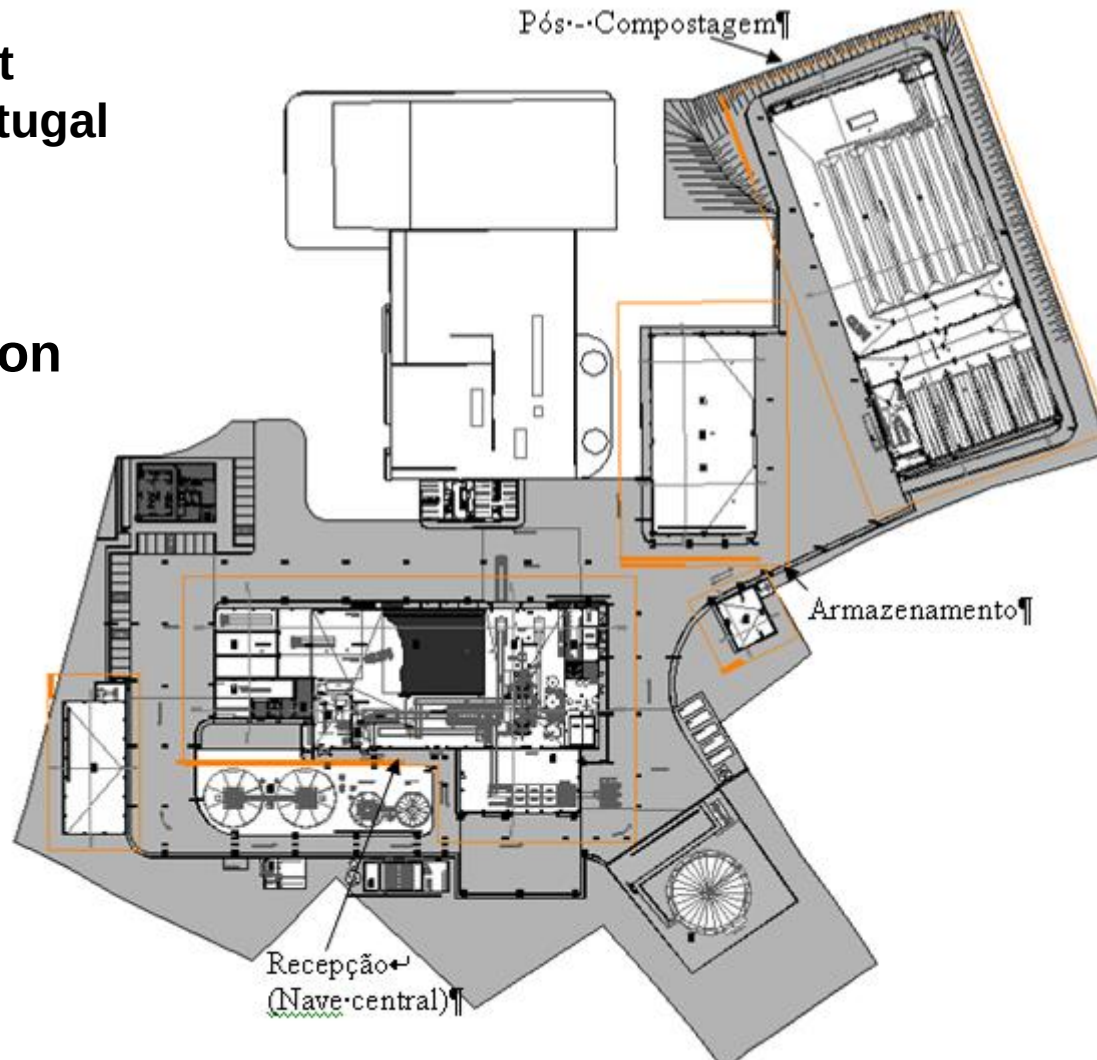
With protection of R60 in the first 9 m height - no collapse

Parts of the structure / fire scenarios	Result
Part D1 without protection under fire scenario 1	$t_{collapse} = 53 \text{ min}$
Part D1 with protection in the purlins of R30 under fire scenario 1	No collapse
Frame of part D2 under fire scenario 2	$t_{collapse} = 78 \text{ min}$
Truss structure 1 of part D2 under fire scenario 2	$t_{collapse} = 70 \text{ min}$
Truss structure 2 of part D2 under fire scenario 2	$t_{collapse} = 77 \text{ min}$
Beam of part D2 under fire scenario 2	No collapse
Truss structure 1 of part C1 under fire scenario 2	No collapse
Truss structure 2 of part C1 under fire scenario 2	$t_{collapse} = 87 \text{ min}$
Truss structure 3 of part C1 under fire scenario 2	$t_{collapse} = 65 \text{ min}$
Truss structure 4 of part C1 under fire scenario 2	$t_{collapse} = 71 \text{ min}$
Truss structure 5 of part C1 under fire scenario 2	$t_{collapse} = 82 \text{ min}$
Frame of part C2 under fire scenario 2	No collapse
Collumn with non-uniform cross-section without protection under fire scenario 2	$t_{collapse} = 64 \text{ min}$
Collumn with non-uniform cross-section without protection under fire scenario 4	$t_{collapse} = 14 \text{ min}$
Collumn with non-uniform cross-section with protection of R60 in the first 9 m height under fire scenario 4	No collapse

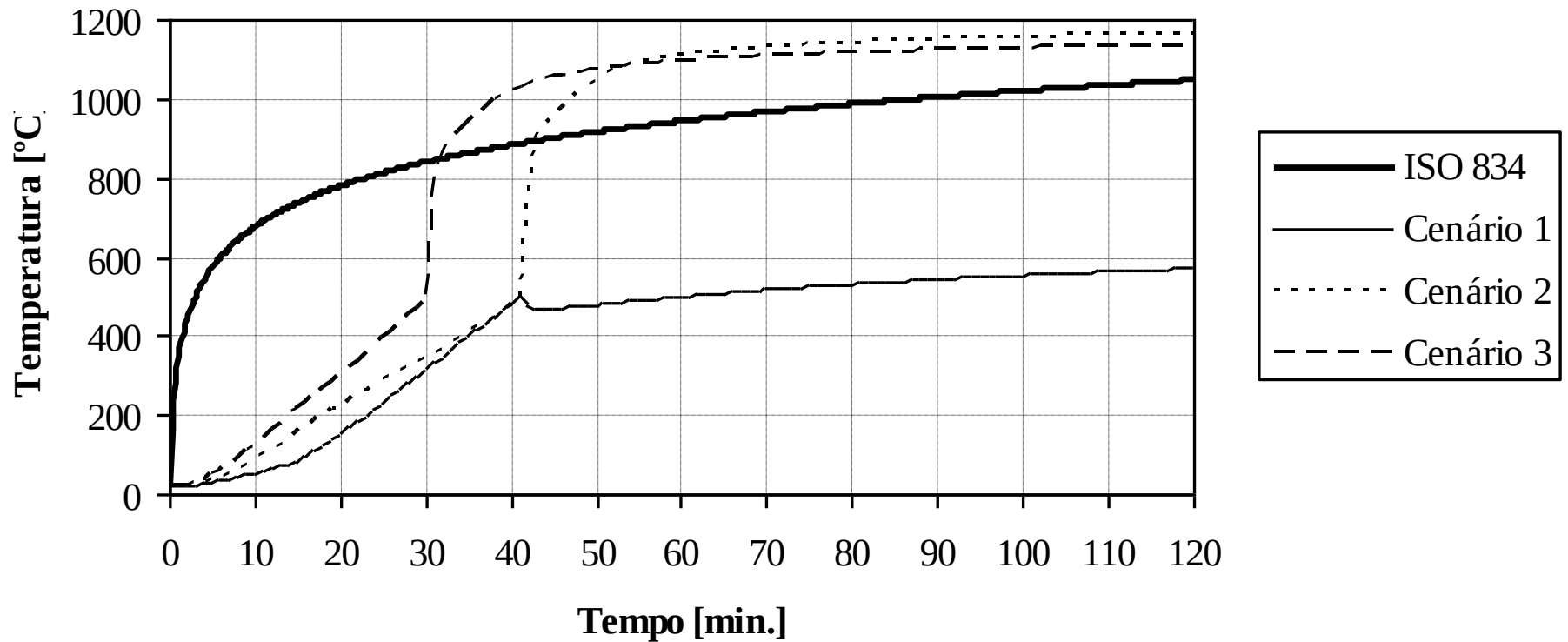
- It can be concluded that, the purlins in part D1 of the structure should be protected, with fire passive protection for 30 min (calculated with a critical temperature of 500°C), in order to achieve a fire resistance of 60 min.
- In parts D2 and C1 it is not necessary any protection material to assure a fire resistance of 60 min.
- In part C2 it is necessary, only in first the 9 m of the columns with non-uniform built-in cross-section (floor 1 of the building), passive fire protection that guarantees a fire resistance 60 minutes for a critical temperature of 500 °C (considered in the calculation).
- It can also be concluded, that in accordance with the deformed shape of all the analyzed structural systems, the collapse, when it occurs, is for inside of the building, thus not resulting in danger for the intervention of fire brigades.

Waste treatment plant, Gaia, Portugal

Implantation



Fire scenarios



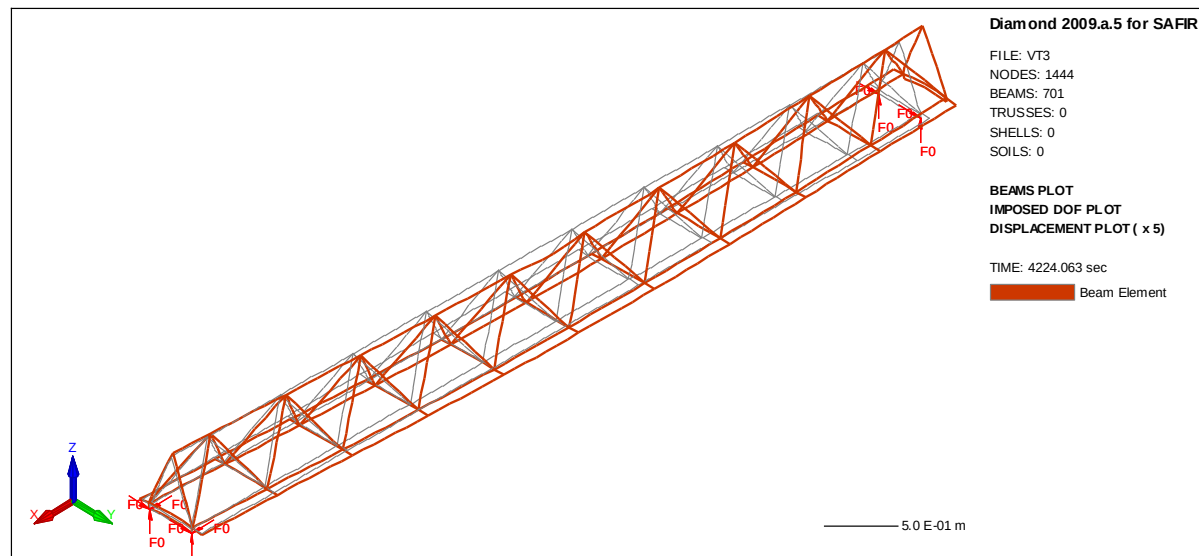
Structural analysis

Reception hall (central) subjected to scenario 1

Principal structural truss



SAFIR



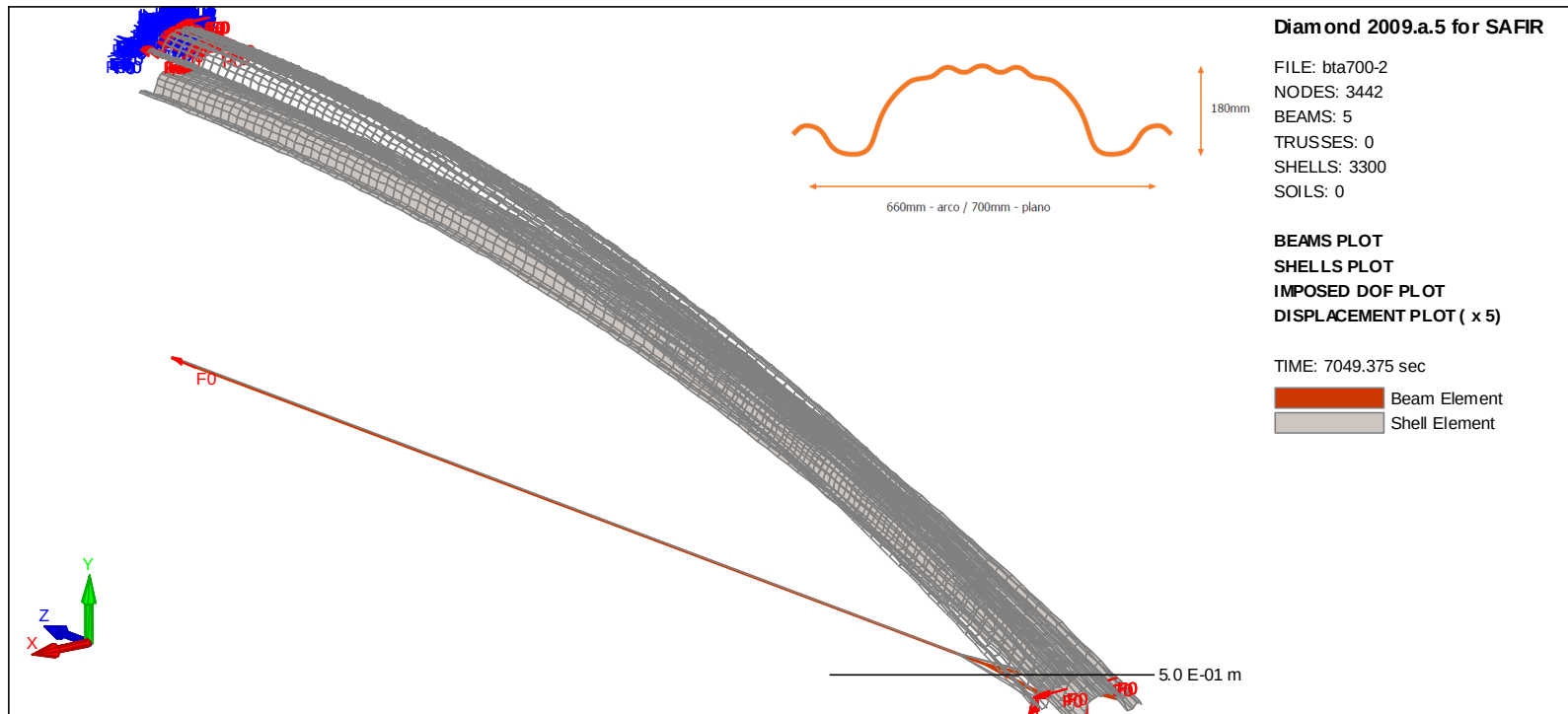
Structural analysis

Reception hall (central) subjected to scenario 1

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



SAFIR



✓ Networks:

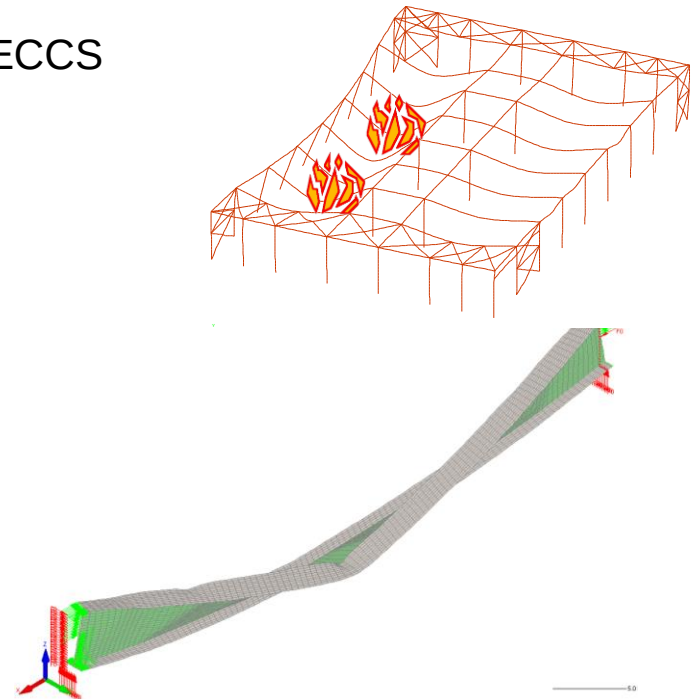
- ✓ Paulo Vila Real is member of the Steering committee of the SiF movement (<http://structuresinfire.com/>)
- ✓ Paulo Vila Real is project team leader for the development of the new generation of EC3 part 1-2
- ✓ Paulo Vila Real is the Chairman of the TC3 (fire) of ECCS (European Convention for constructional Steelwork)

✓ Transfer of knowledge:

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

✓ European research projects:

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



- ✓ CEN, Eurocodes:
EN1991-1-2, EN1992-1-2, EN1993-1-2, 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/>)



Finite element modelling of steel
structures in case of fire

Thank you for your attention

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