REPUBLIKA SLOVENIJA
MINISTRSTVO ZA IZOBRAŽEVANJE, ZNANOST IN ŠPORT

Univerza v Ljubljani

EVROPSKA UNIJA
EVROPSKI SOCIALNI SKLAD
NALOŽBA V VAŠO PRIHODNOST

STUCTURAL FIRE DESIGN
Considerations in fire design of steel structures

Ioan Both, PhD. Eng

Politehnica University of Timisoara
Department of Steel Structures and Structural Mechanics

Ljubljana, 24 Oct - 3 Nov 2017

Naložbo sofinancirata Evropska unija iz Evropskega socialnega sklada in Republika Slovenija.

Overview

Context. Why fire design?

Materials

Actions on structures

Basic design considerations

Fire design considerations

Examples

Context. Why?

- Source of energy and heat

Fire effect 1

Fire effect 2

- The cause of material and life loss

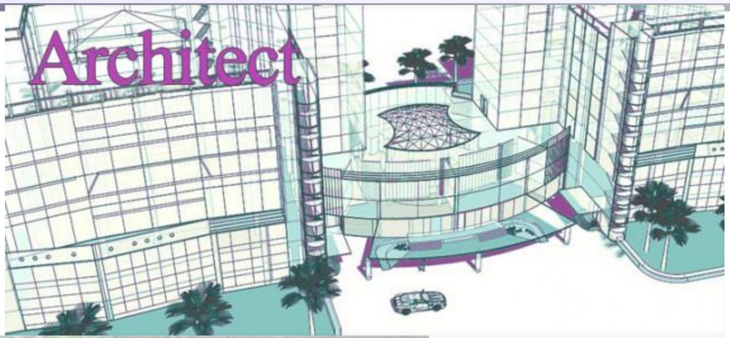
Fire effect 3

Fire effect 4

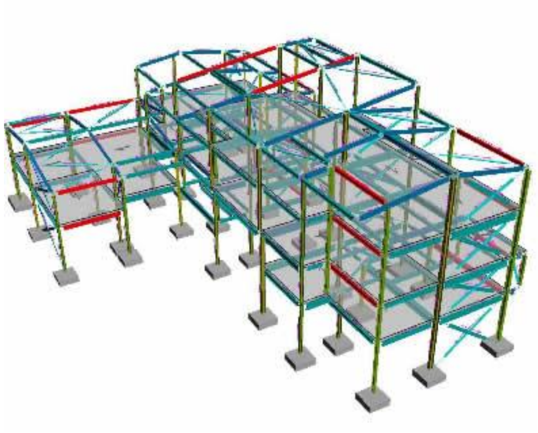
Fire effect 5

Fire effect 6

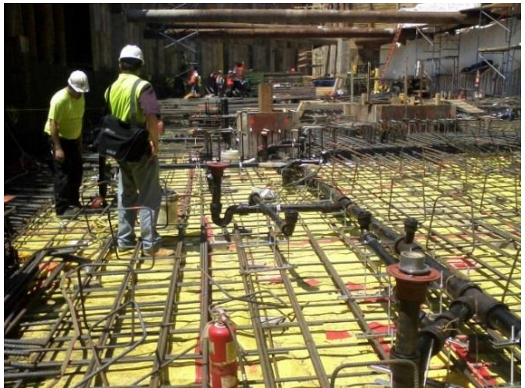
Context



Architects



Structural Engineers

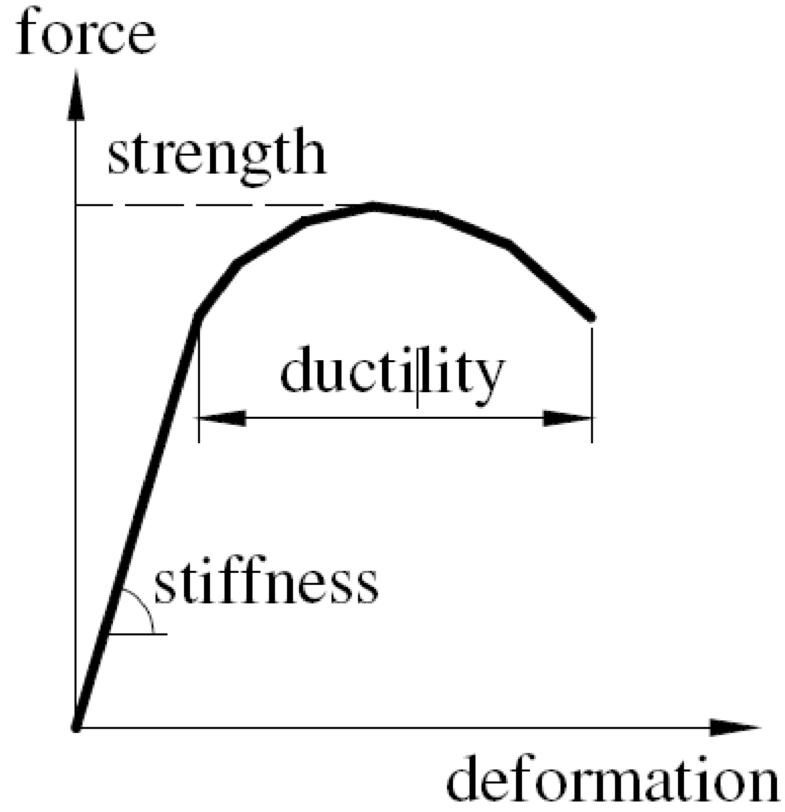


Service Engineers

Materials

Structural materials

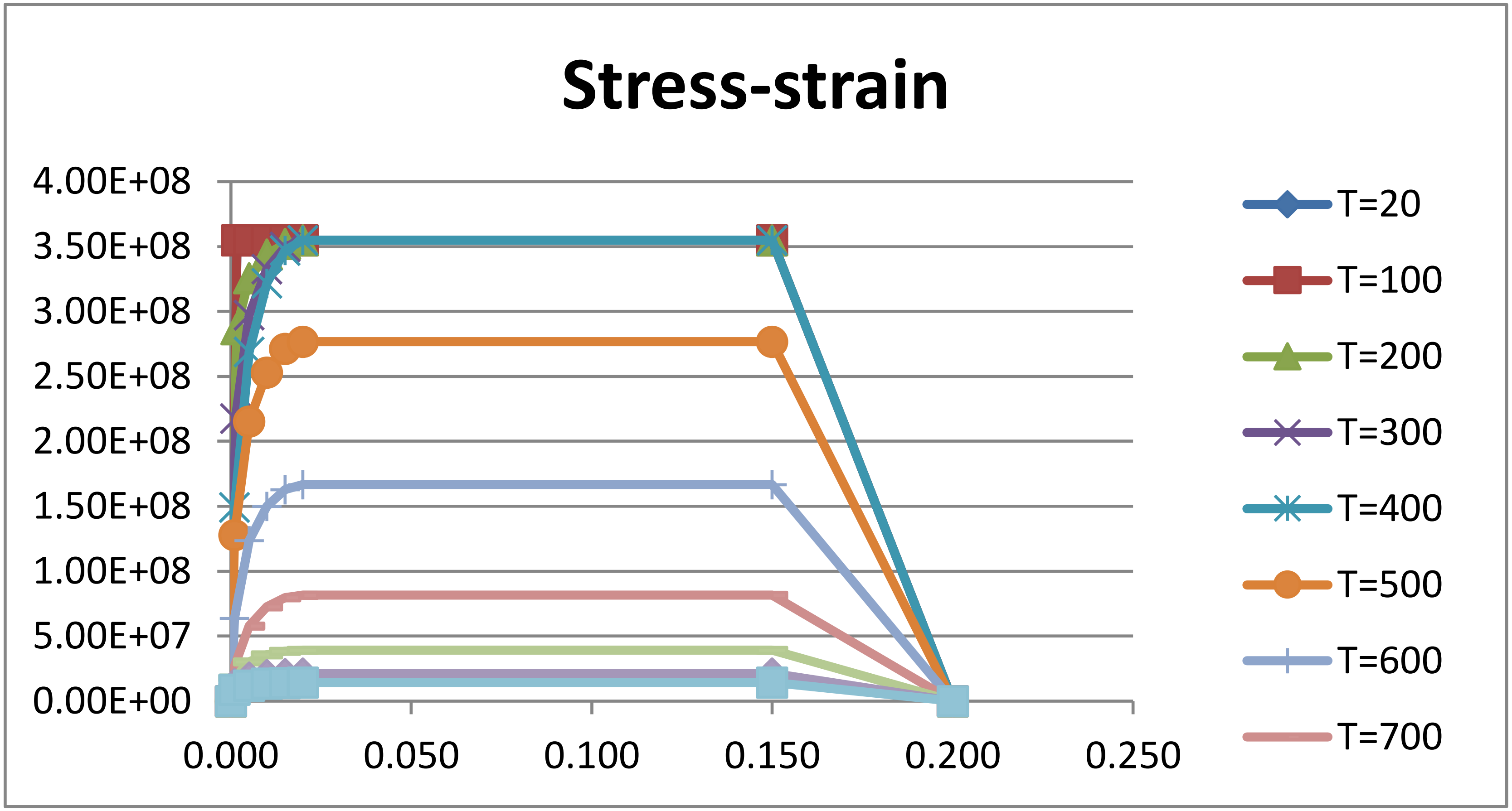
- Structural material is the one which is used in those parts of the structure which carry loads and give it strength and stiffness
- Properties of structural materials:
  - strength
  - stiffness
  - ductility



Materials

Structural materials: ductility

Ductile materials: able to deform significantly into the inelastic range



Design considerations

Actions are classified by their variation in time as follows:

– permanent actions (G), e.g. self-weight of structures, fixed equipment and road surfacing, and indirect actions caused by shrinkage and uneven settlements;

– variable actions (Q), e.g. imposed loads on building floors, beams and roofs, wind actions or snow loads;

– accidental actions (A), e.g. explosions, or impact from vehicles

FIRE

Several loads ➔ load combinations

Actions on structures

Based on codes

EUROPEAN STANDARD EN 1990:2002+A1

EUROPEAN STANDARD EN 1991-1-1

EUROPEAN STANDARD EN 1991-1-3

EUROPEAN STANDARD EN 1991-1-4

NORME EUROPÉENNE EN 1991-1-5

EUROPÄISCHE NORM

EUROPEAN STANDARD

Novembre 2003

ICS 91.010.30

Version Française

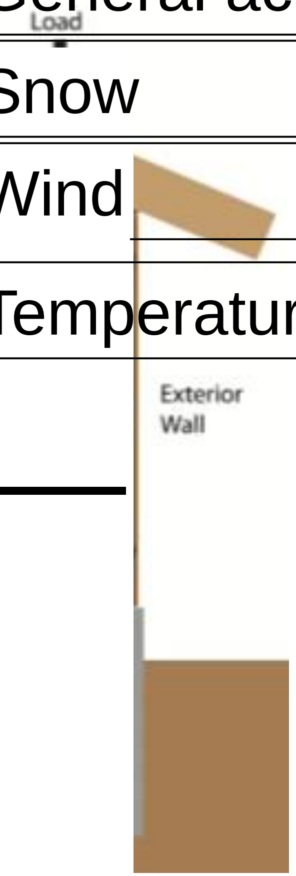
Eurocode 1: - Actions sur les structures - Partie 1-5: Actions générales - Actions thermiques

General actions

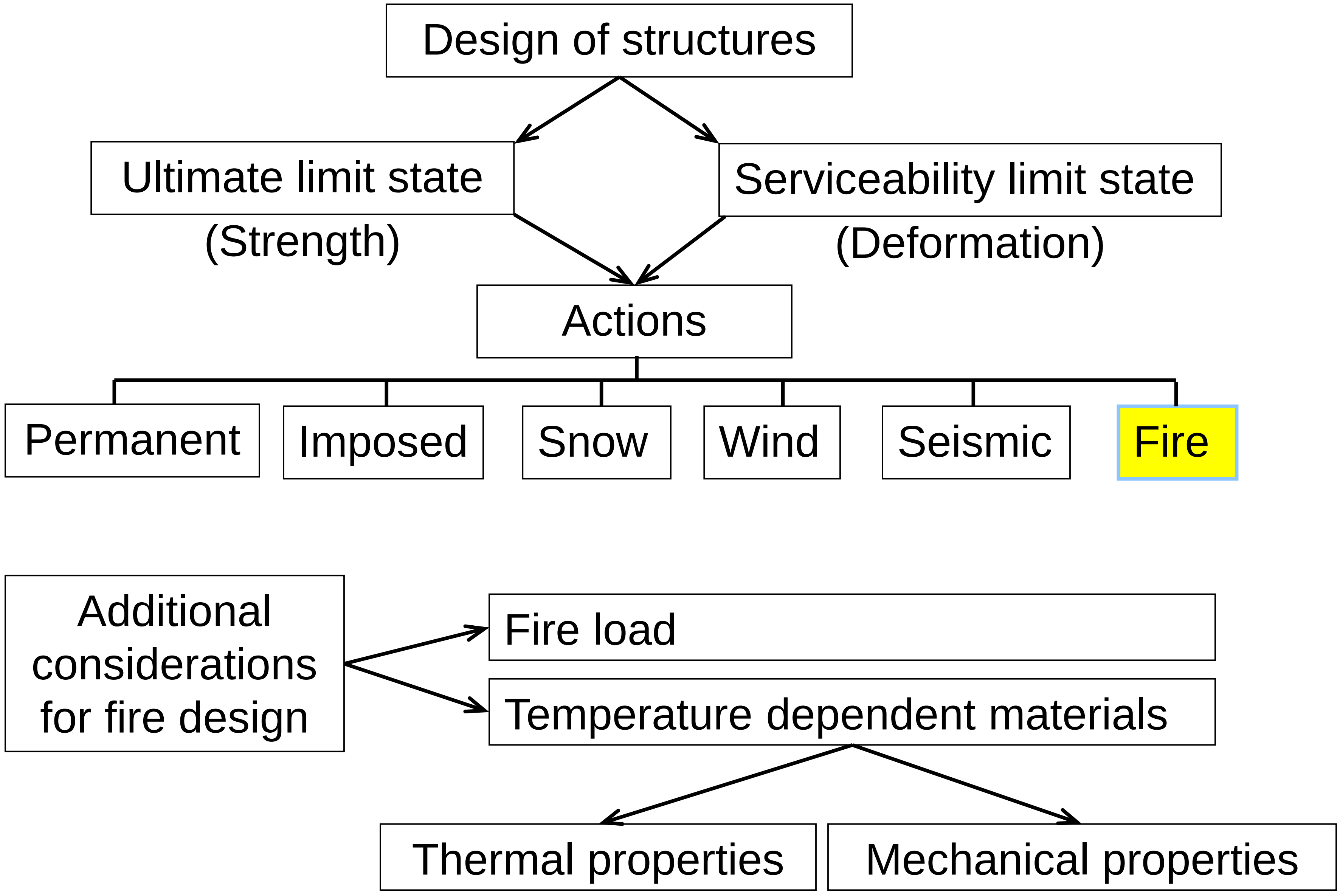
Snow

Wind

Temperature



Design considerations

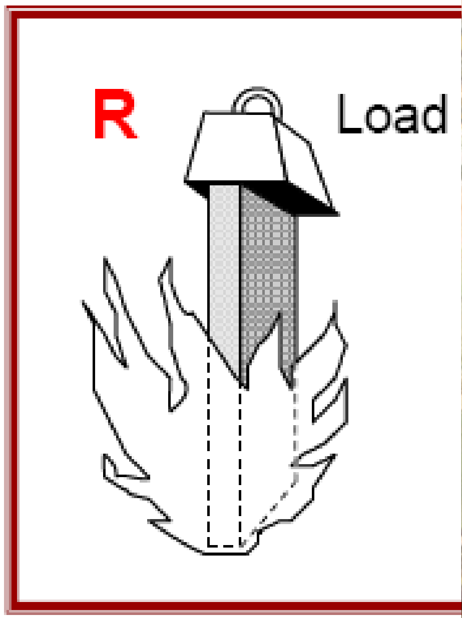


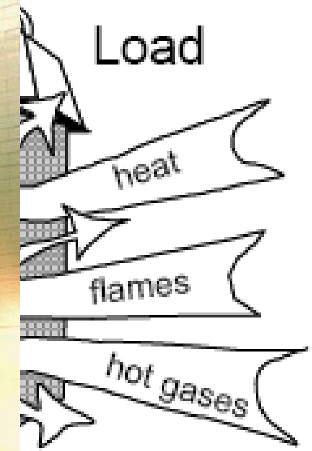
Fire action in design codes

Eurocode	Normal temperature	Elevated temperature
0: Basis of design	EN 1990	---
1: Actions	EN 1991-1-1	EN 1991-1-2
2: Concrete	EN 1992-1-1	EN 1992-1-2
3: Steel	EN 1993-1-1	EN 1993-1-2
4: Composite	EN 1994-1-1	EN 1994-1-2
5: Timber	EN 1995-1-1	EN 1995-1-2
6: Masonry	EN 1996-1-1	EN 1996-1-2
7: Foundations	EN 1997-1-1	-
8: Earthquake	EN 1998-1-1	-
9: Aliminium	EN 1999-1-1	EN 1999-1-2

Design considerations

Resista





Design considerations

The aim of fire design codes

- The Eurocodes covers the Resistance criterion - the load bearing capacity of elements and structures. It gives information that allows calculating whether or how long a structure is able to withstand the applied loads during a fire. The design is performed in the ultimate limit state.
- The EN fire design codes **DO NOT** relate to the insulation or integrity criteria of structural elements (E or I).

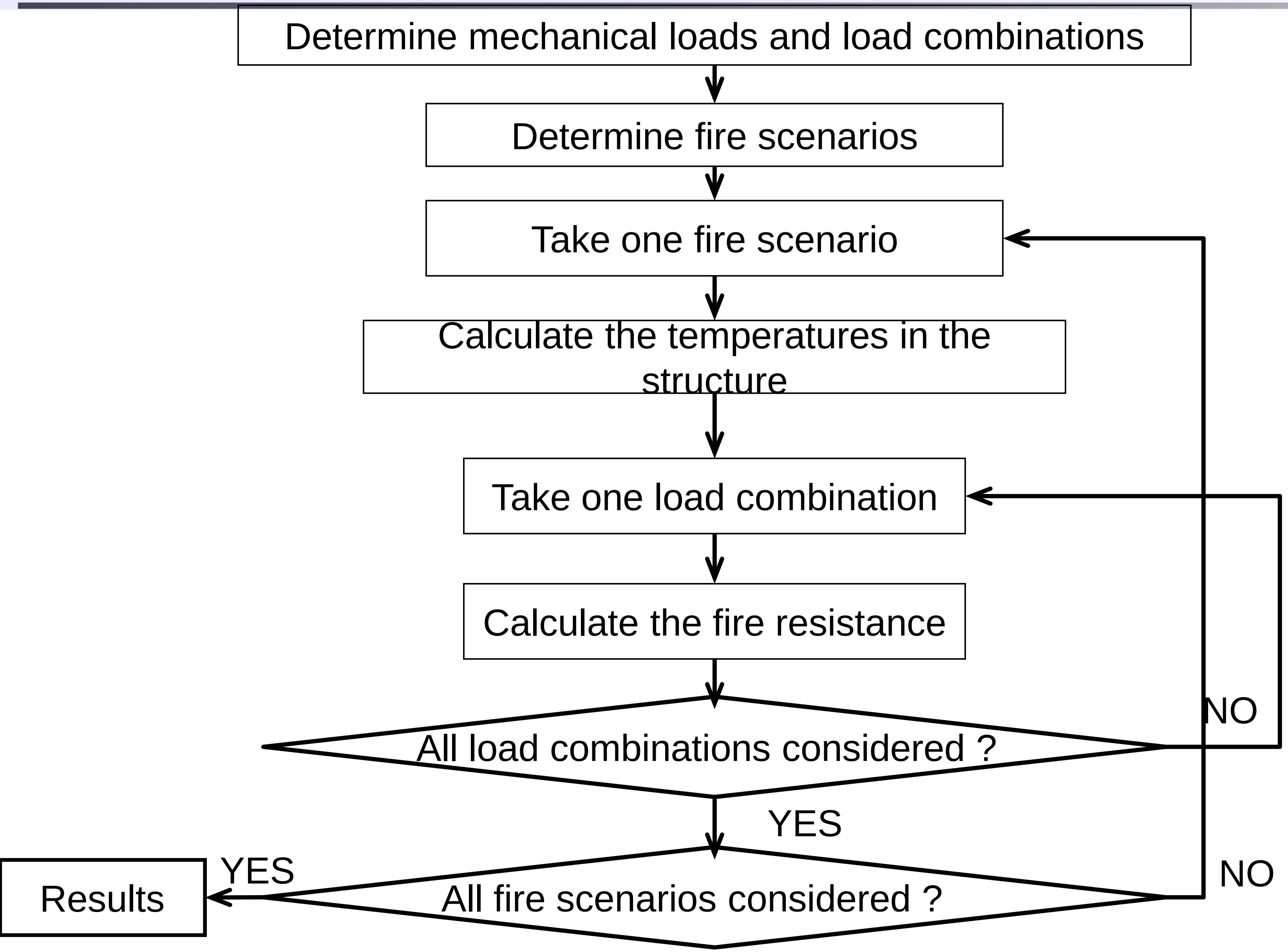
The aim of fire design codes

- There is no deformation criteria explicitly mentioned in the Eurocode.
- Deformation criteria should be applied in two cases:

1. When the fire protection may loose its efficiency in case of excessive deformations.
2. When separating elements, for example a separating wall, supported by or located under a structural element may suffer from excessive deformations of this member

Fire design considerations

Steps of an analysis



Fire design considerations

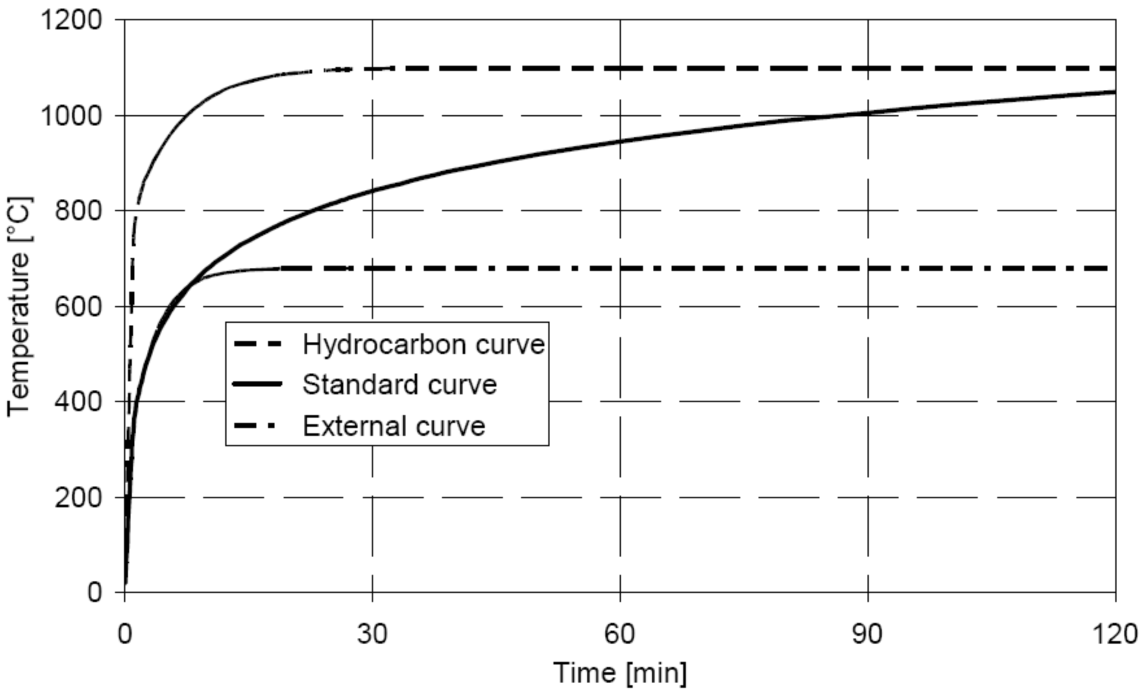
Thermal action

the fire is represented by a temperature-time curve, i.e. an equation describing the evolution with time of the unique temperature that is supposed to represent the environment in which the structure is located.

1. Standard fire (ISO 834)

2. External curve

3. Hydrocarbon curve



Fire design considerations

Mechanical actions

The design against the ultimate limit state is based on the comparison between the **RESISTANCE OF THE STRUCTURE** calculated with the design values of material properties, and the **EFFECTS OF ACTIONS** calculated with design value of actions.

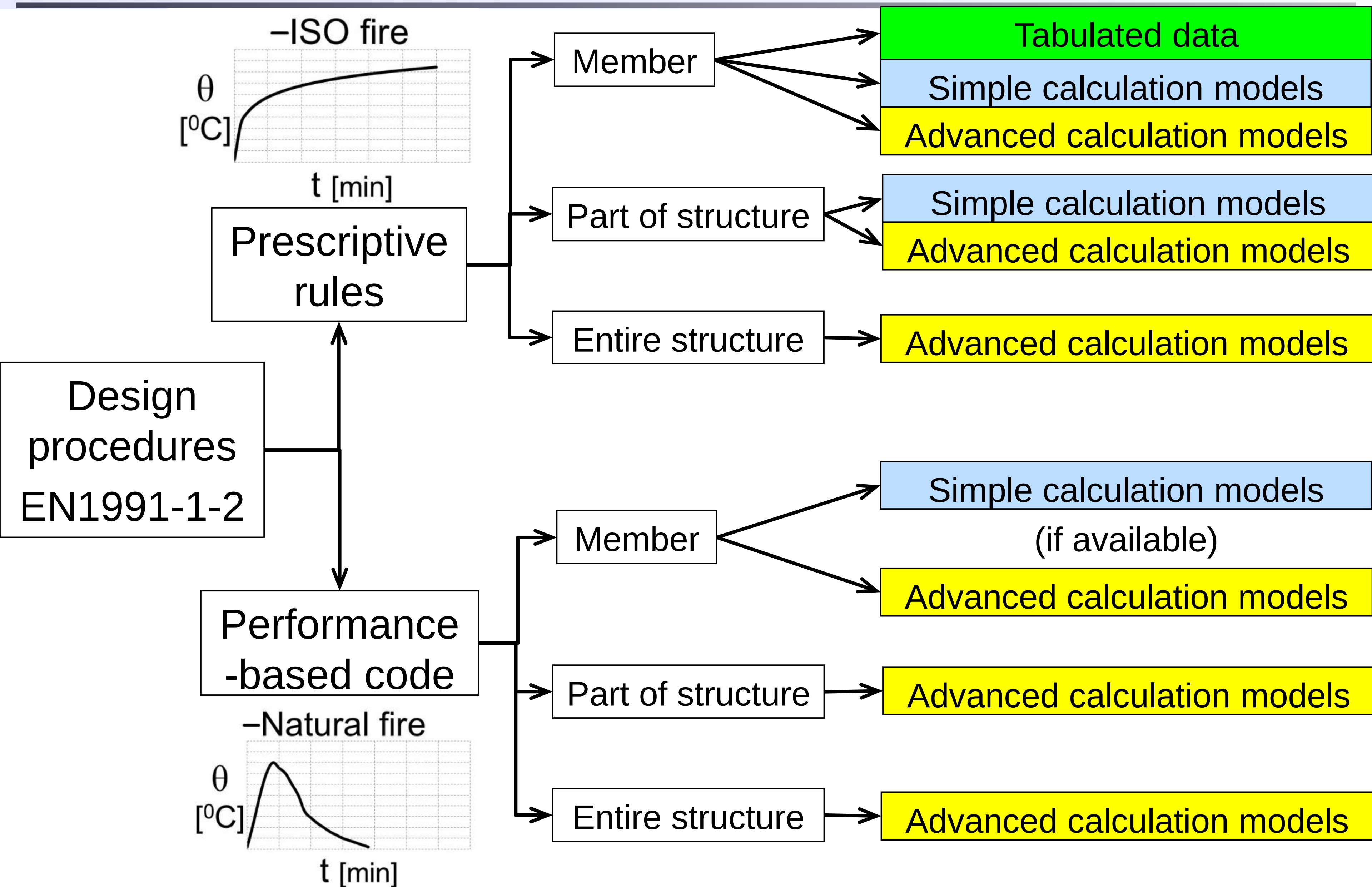
$$R_{fi,d,t}(X_{d,fi}) > E_{fi,d}(F_{fi,d})$$

$$E_{fi,d} = G_k + P_k + \psi_{1,1}\, Q_{k1} + \sum_{i>1} \psi_{2,i}\, Q_{ki}$$

$$E_{fi,d} = G_k + P_k + \sum_{i=1} \psi_{2,i}\, Q_{ki}$$

Action	ψ_1	ψ_2
Imposed load in buildings		
category A: domestic, residential	0.5	0.3
category B: offices	0.5	0.3
category C: congregation areas	0.7	0.6
category D: shopping	0.7	0.6
category E: storage	0.9	0.8
Traffic loads in buildings		
category F: vehicle weight ≤ 30kN	0.7	0.6
category G: 30kN < vehicle weight < 160kN	0.5	0.3
category H: roofs	0.0	0.0
Snow loads		
for sites located at altitude H ≤ 1000 m	0.2	0.0
for sites located at altitude H > 1000 m	0.5	0.2
Wind loads	0.5	0.0

Fire design considerations



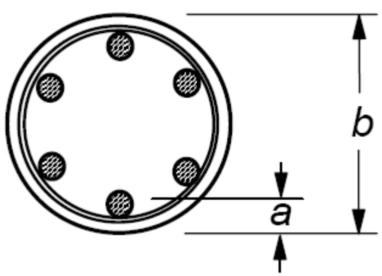
Fire design considerations

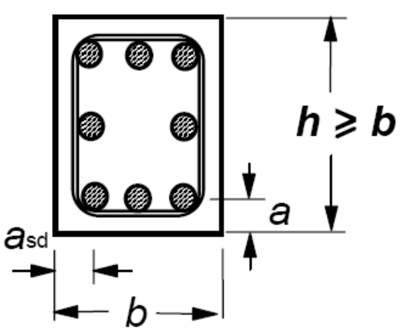
Tabulated data:

recognised design solutions for the standard fire exposure

Columns

$\mu_{fi} = N_{Ed.fi} / N_{Rd}$





Standard fire resistance	Minimum dimensions (mm) Column width b_{min}/axis distance a of the main bars			
	Column exposed on more than one side			Exposed on one side
	$\mu_{fi} = 0.2$	$\mu_{fi} = 0.5$	$\mu_{fi} = 0.7$	$\mu_{fi} = 0.7$
1	2	3	4	5
R 30	200/25	200/25	200/32 300/27	155/25
R 60	200/25	200/36 300/31	250/46 350/40	155/25
R 90	200/31 300/25	300/45 400/38	350/53 450/40**	155/25
R 120	250/40 350/35	350/45** 450/40**	350/57** 450/51**	175/35
R 180	350/45**	350/63**	450/70**	230/55
R 240	350/61**	450/75**	-	295/70

**
Minimum 8 bars
For prestressed columns the increase of axis distance according to 4.2.2. (4) should be noted.

Fire design considerations

Simple calculatin models:

- The resistance is based on analytical relations

$$R_{fi,d,t}(X_{d,fi}) > E_{fi,d}(F_{fi,d})$$

Introduction

Advanced calculation models

- Dedicated FE programs

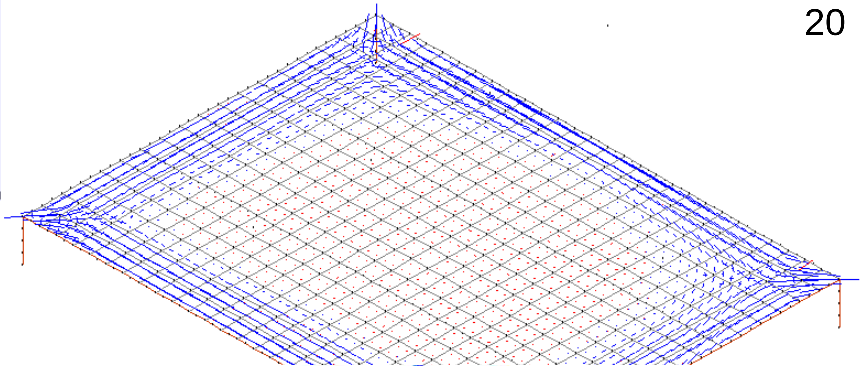
Computational environment is predefined

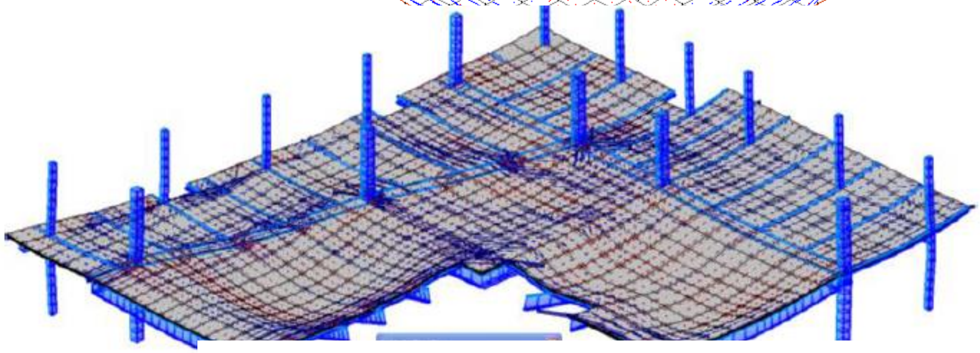
- SAFIR
- VULCAN
- etc.

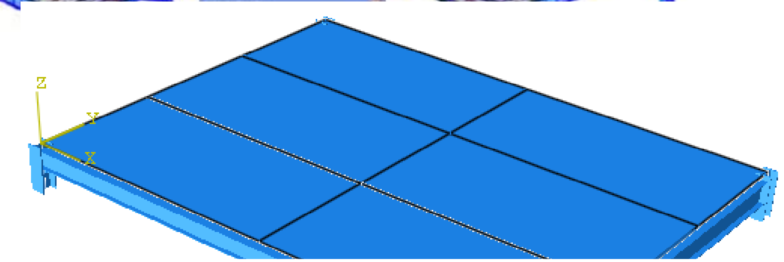
- General purpose FE programs

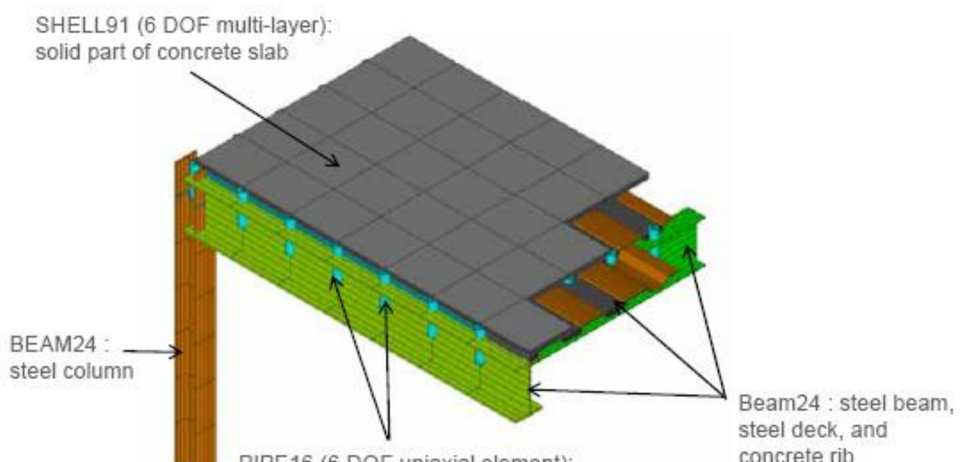
Specific settings should be defined

- ABAQUS [4]
- ANSYS
- etc.









Fire design considerations

Validate the calculation model

Compare the results to a real test

Modify the input data

- Your analysed case

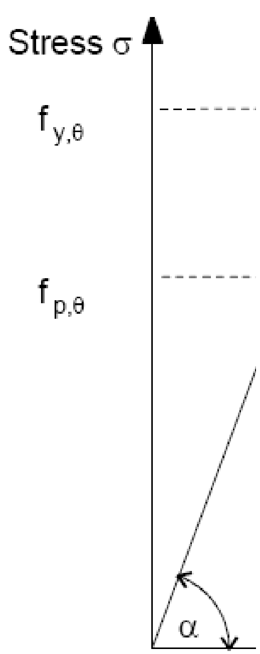
Present the results

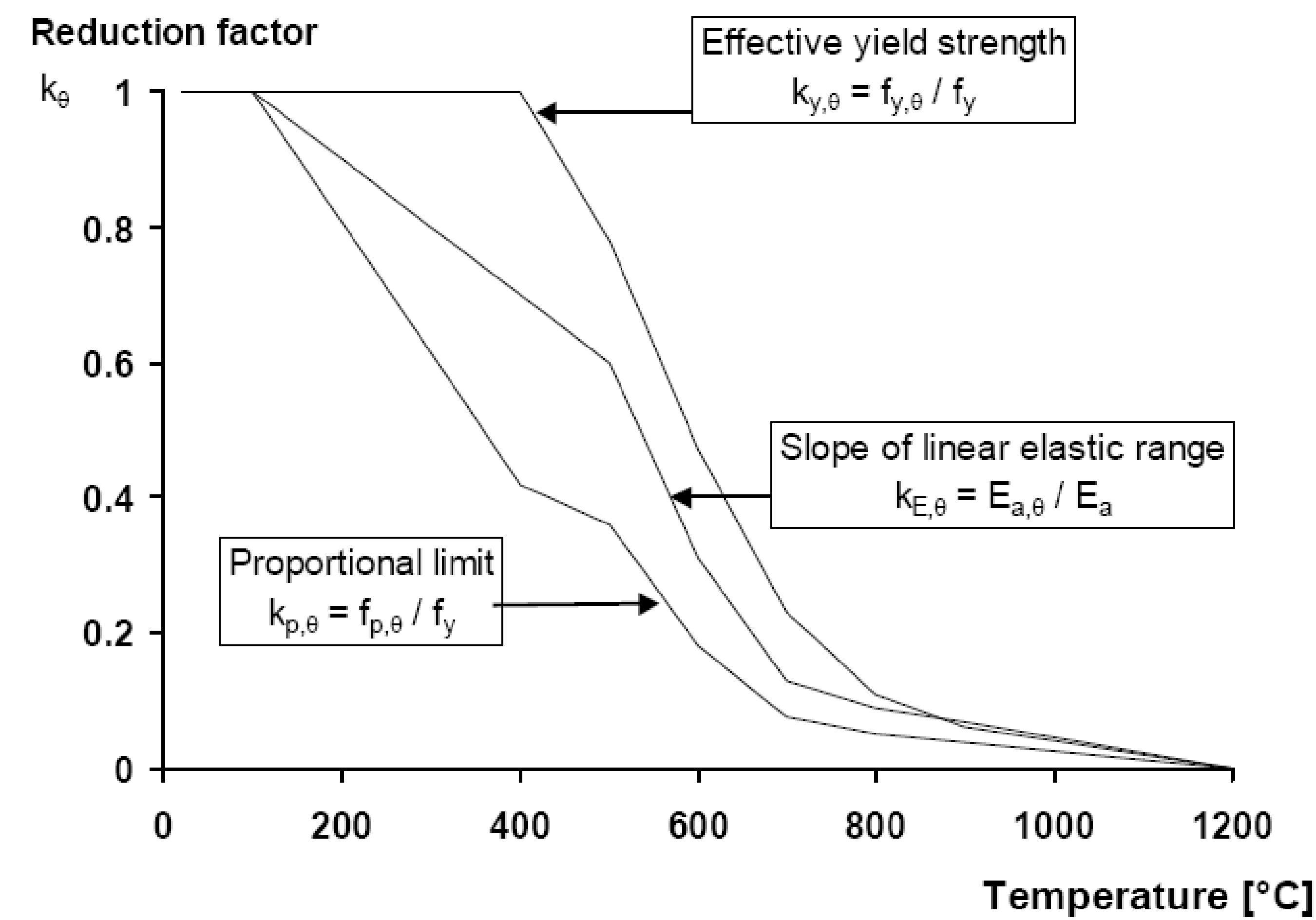
- R / E / I ???

Fire design considerations

ALL CALCULATION MODELS ARE BASED ON THE MATERIAL PROPERTIES DEGRADATION CAUSED BY ELEVATED TEMPERATURE

Mecha





...tive to the value of f_y or E_a

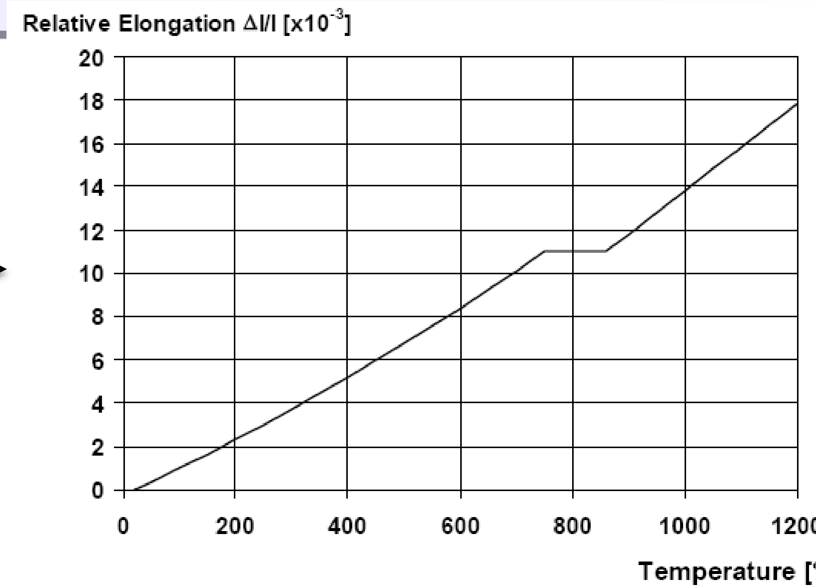
Reduction factor (relative to E_a) for the slope of the linear elastic range $k_{E,\theta} = E_{a,\theta}/E_a$
1,000
1,000
0,900
0,800
0,700
0,600
0,310
0,130
0,090
0,0675
0,0450
0,0225
0,0000

...ture, linear interpolation may

Fire design considerations

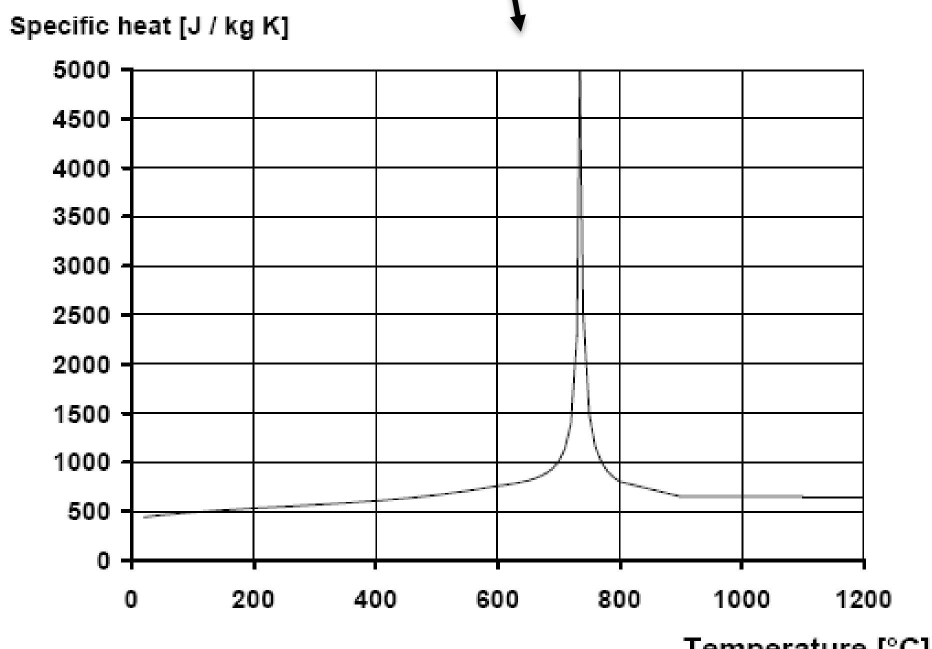
Thermal properties of steel

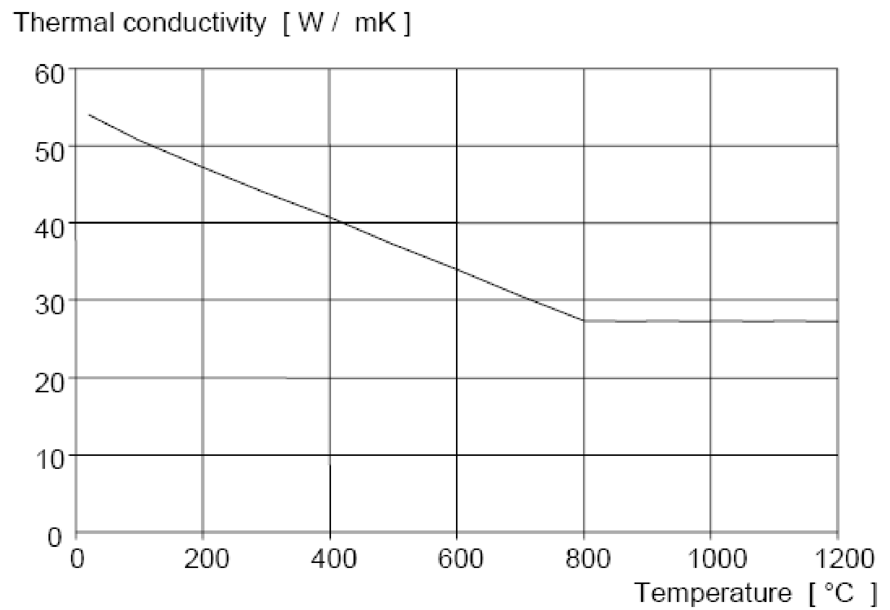
Thermal elongation



Conductivity

Specific heat

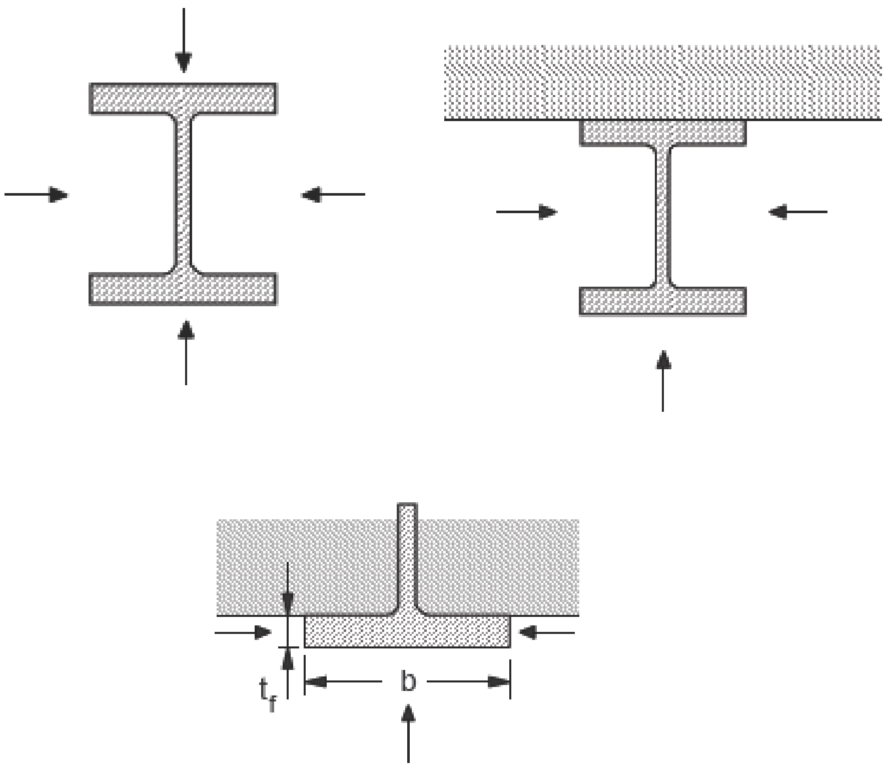




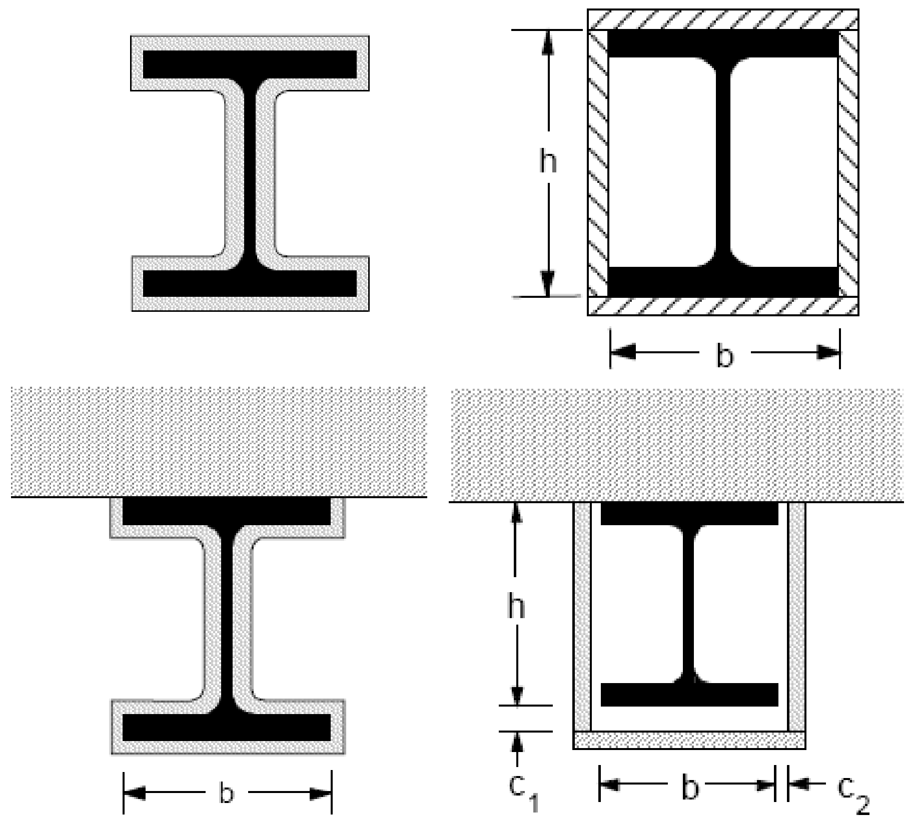
Fire design considerations

Temperature in structural elements

Unprotected steelwork



Protected steelwork

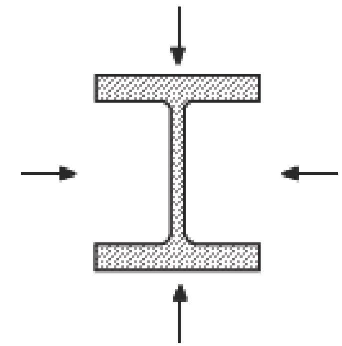


Fire design considerations

Unprotected steelwork temperature development

$$\Delta\theta_{s,t} = k_{sh} \frac{A_m/V}{c_a \, \rho_a} \dot{h}_{net,d} \, \Delta t$$

$$\frac{A_m}{V} = \frac{\text{perimeter}}{\text{cross-section area}}$$



$\Delta\theta_{s,t}$ is the steel temperature increase from time t to time $t+\Delta t$,

k_{sh} is the correction factor for the shadow effect, see below,

A_m is the surface area of the member per unit length,

V is the volume of the member per unit length,

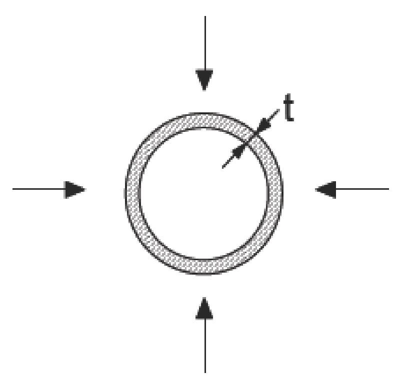
c_a is the specific heat of steel,

ρ_a is the unit mass of steel,

$\dot{h}_{net,d}$ is the design value of the net heat flux per unit area,

Δt is the time interval.

Am/V = 1/t

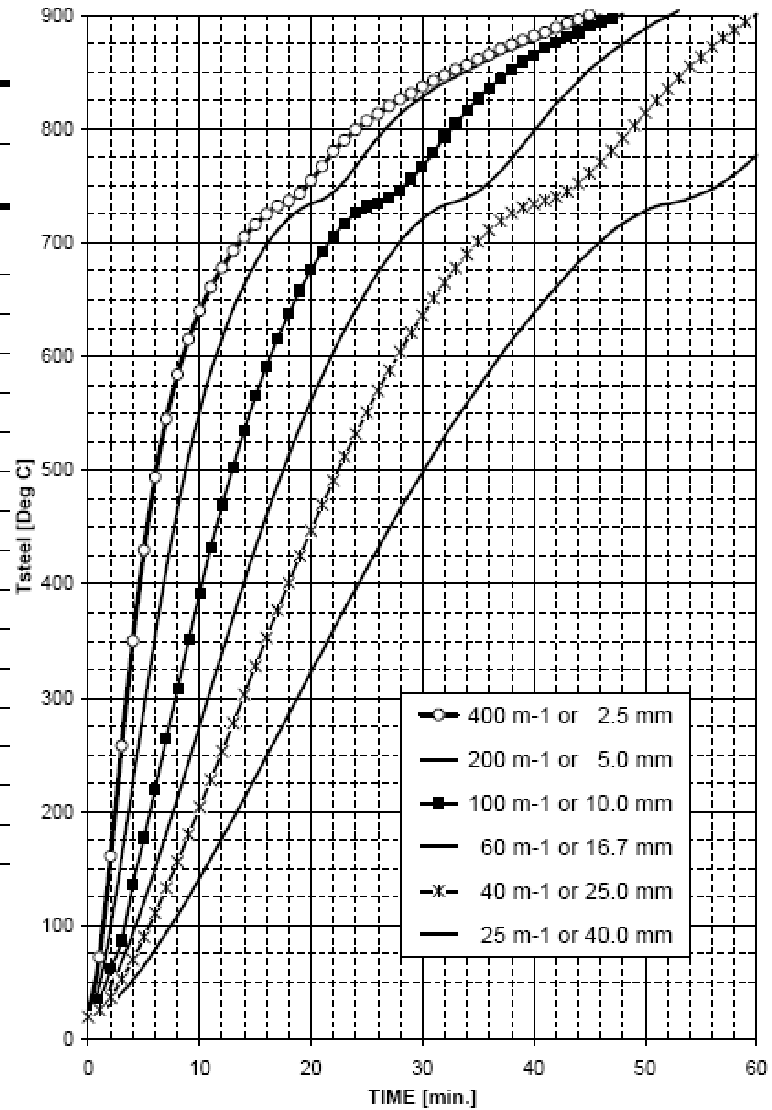


Am/V : section factor

Fire design considerations

Unprotected steelwork temperature development

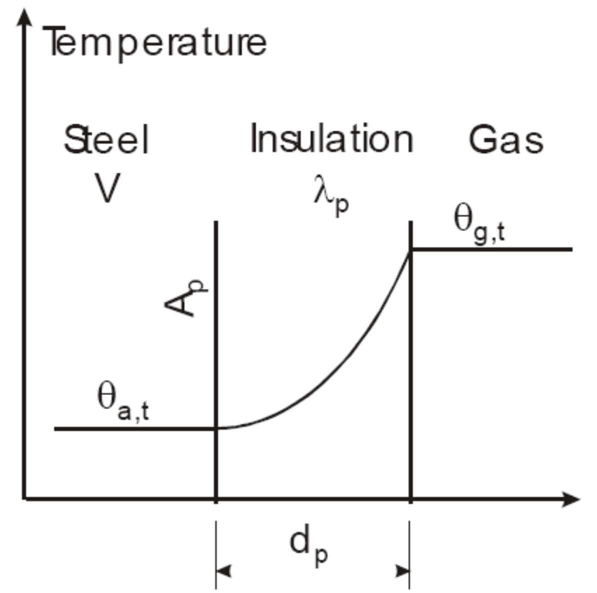
A^*_m/V [m^{-1}]	400	200	100	60	40	25
V/A^*_m [mm]	2.5	5.0	10.0	16.7	25.0	40.0
Time [min.]	Steel temperature in °C					
0	20	20	20	20	20	20
5	430	291	177	121	90	65
10	640	552	392	276	204	142
11	661	587	432	308	228	159
12	678	616	469	340	253	177
13	693	642	503	371	278	194
14	705	663	535	402	303	212
15	716	682	565	432	328	230
16	725	698	591	460	353	249
17	732	711	616	487	377	267
18	736	721	638	513	401	286
19	743	729	658	538	425	304
20	754	734	676	561	447	323
21	767	738	692	583	470	341
22	780	744	706	604	491	360



Fire design considerations

Protected steelwork temperature development

$$\Delta\theta_{a,t} = \frac{\lambda_p A_p/V}{d_p c_a \rho_a} \frac{(\theta_{g,t} - \theta_{a,t})}{(1+\phi/3)} \Delta t \; - \; (e^{\phi/10} - 1)\,\Delta\theta_{g,t}$$

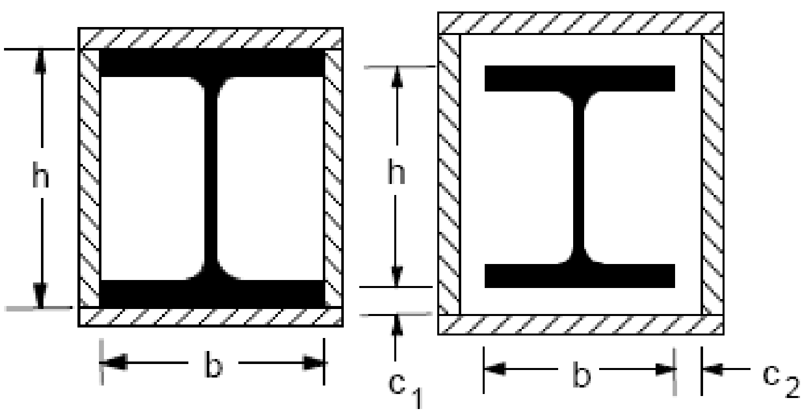


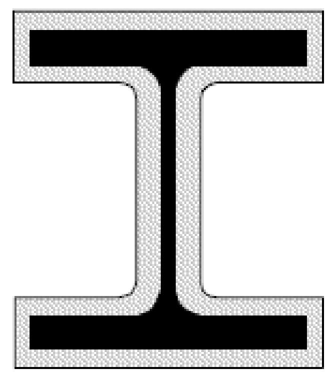
λ_p	is the thermal conductivity of the fire protection material,
A_p/V	is the section factor for steel members insulated by fire protection material,
A_p	is the appropriate area of fire protection material per unit length of member,
V	is the volume of the member per unit length,
$\theta_{g,t}$	is the ambient gas temperature at time t,
$\theta_{a,t}$	is the steel temperature at time t,
d_p	is the thickness of the fire protection material,
c_a	is the temperature dependant specific heat of steel,
ρ_a	is the unit mass of steel,
Δt	is the time interval,
$\Delta\theta_{g,t}$	is the increase of the ambient gas temperature during the time interval Δt,
c_p	is the temperature independent specific heat of the fire protection material,
ρ_p	is the unit mass of the fire protection material,

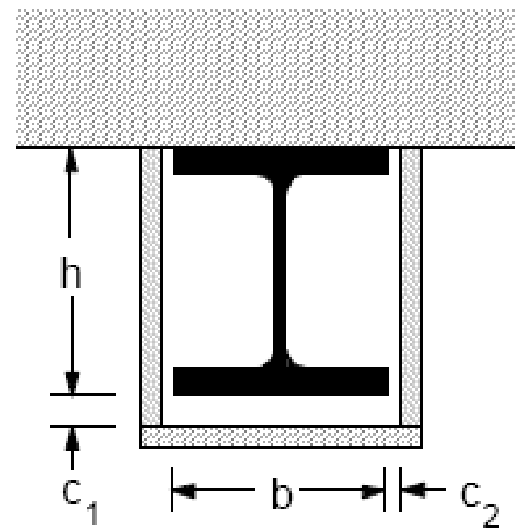
Fire design considerations

Protected steelwork temperature development

$$\frac{2(b+h)}{\text{steel cross-section area}} \qquad \frac{\text{steel perimeter}}{\text{steel cross-section area}} \qquad \frac{2h+b}{\text{steel cross-section area}}$$





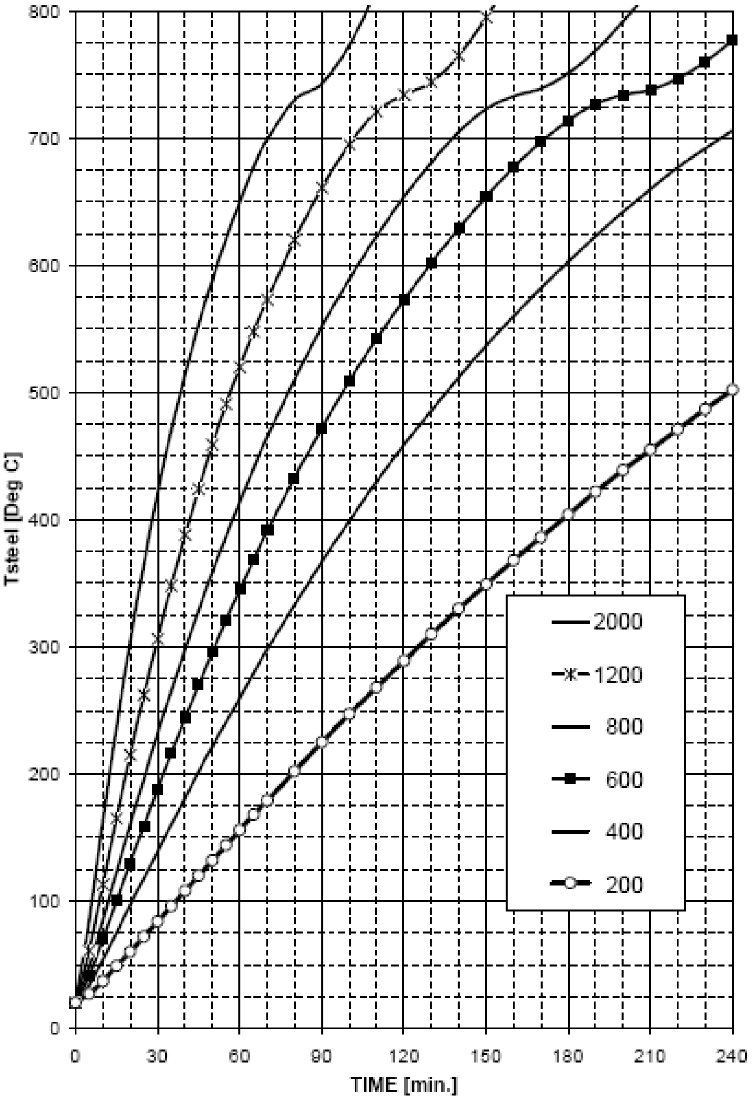


Fire design considerations

Protected steelwork temperature development

$$k_p = \frac{\lambda_p}{d_p}\frac{A_p}{V}$$

k_p [W/m³K]	200	400	600	800	1200	2000
Time [min.]	Steel temperature in °C					
0	20	20	20	20	20	20
10	37	54	70	85	113	163
20	60	97	130	160	215	304
30	84	139	188	232	306	421
40	108	181	244	298	388	514
50	132	222	296	359	459	589
60	156	260	345	414	520	650
70	179	298	391	465	573	699
80	202	333	433	510	620	730
90	225	367	472	552	661	743
100	247	399	509	589	695	773
110	268	430	542	623	721	816
120	289	459	573	654	734	859



Neglecting the specific heat of insulation

Fire design considerations

$$R_{fi,d,t}(X_{d,fi}) > E_{fi,d}(F_{fi,d})$$

Simple calculatin models:

- The resistance is based on analytical relations

Tensioned members

$$N_{fi,\theta,Rd} = k_{y,\theta} N_{R,d} \left[\gamma_{M,1} / \gamma_{M,fi} \right]$$

N_{Rd} - the plastic design resistance of the cross-section for normal temperature design
$k_{y\theta}$ - the reduction factor giving the effective yield strength of steel at temperature θ reached at time t

Compressed members

$$N_{b,fi,\theta,Rd} = \chi_{fi} A k_{y,\theta} f_y / \gamma_{M,fi}$$

χ_{fi} – buckling coefficient
A – cross-section area
f_y – yield limit
$k_{y\theta}$ - the reduction factor giving the effective yield strength of steel at temperature θ reached at time t

Fire design considerations

$$R_{fi,d,t}(X_{d,fi}) > E_{fi,d}(F_{fi,d})$$

Simple calculatin models:

- The resistance is based on analytical relations

Resistance in shear

$$V_{fi,t,Rd} = k_{y,\theta,web} V_{RD} \left[\gamma_{M,1}/\gamma_{M,fi}\right]$$

V_{Rd} - the plastic design resistance of the cross-section for normal temperature design
$k_{y\theta, web}$ - the reduction factor giving the effective yield strength of the web, at temperature θ reached at time t

Resistance in bending

$$M_{fi,\theta,Rd} = k_{y,\theta}\left[\gamma_{M,0}/\gamma_{M,fi}\right] M_{Rd}$$

$$M_{fi,\theta,Rd} = k_{y,\theta}\left[f_y/\gamma_{M,fi}\right] W$$

χ_{fi} – buckling coefficient
W – Strength modulus
f_y – yield limit
$k_{y\theta}$ - the reduction factor giving the effective yield strength of steel at temperature θ reached at time t

Summary quiz?

1 What are the basic requirements for a building to hold?

Structural materials and structural elements

2 Which are the main three types of actions?

Permanent, variable and accidental

3 What type of action is fire?

Accidental

4 How is the elevated temperature considered?

By temperature-time curves (Standard, Exterior and Hydrocarbons)

5 How is the fire resistance established from the structural point of view?

Resistance in fire > Load effect in fire

Summary quiz?

6 What are the three methods to evaluate the fire resistance in prescriptive design?

Tabulated data; Simple calculation models; Advanced calculation models

7 What is the basic cause of structural failure in fire?

Degradation of mechanical properties

8 What is the main characteristic that influences the temperature development?

Section factor Am/V

9 What is the principle of temperature increase for unprotected steel ?

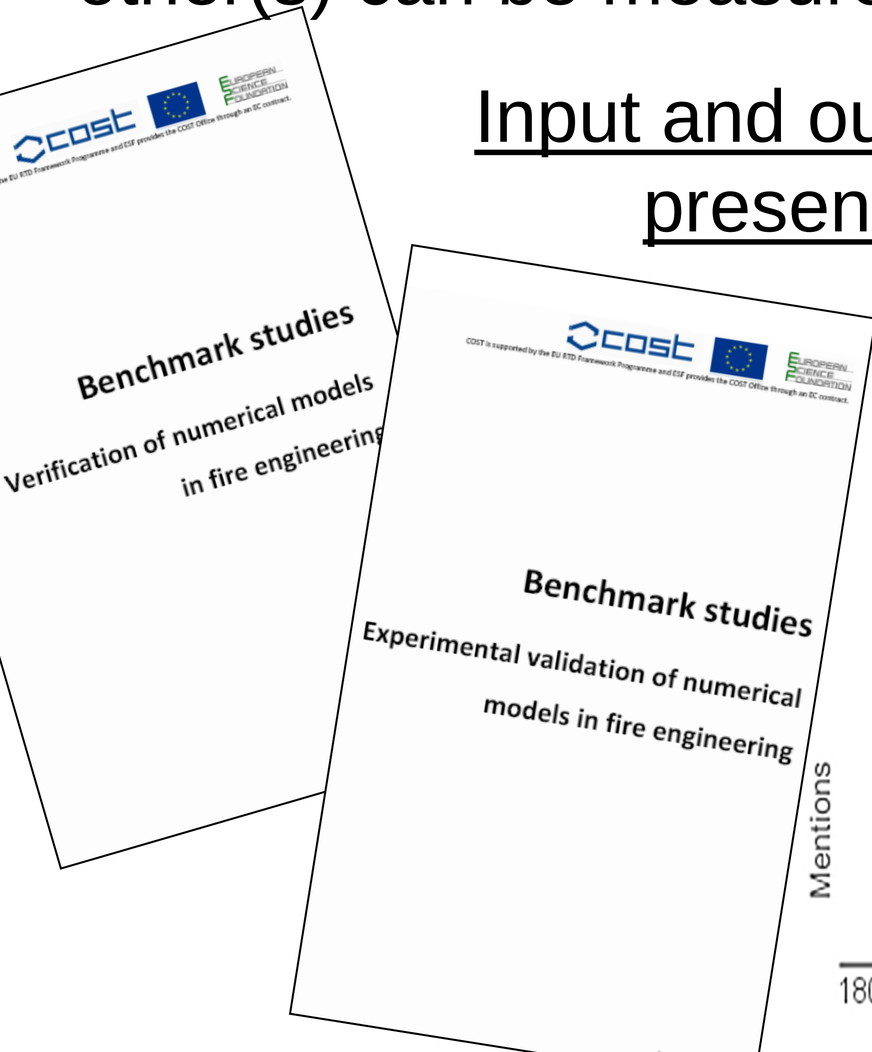
Net heat flux (convection and radiation)

10 What is the principle of temperature increase for protected steel ?

Temperature difference between insulation and steel

FRACOF

Benchmark: a standard or reference by which other(s) can be measured or judged [5]


Benchmark studies
Verification of numerical models in fire engineering

Benchmark studies
Experimental validation of numerical models in fire engineering

Input and output data should be presented in detail [6]

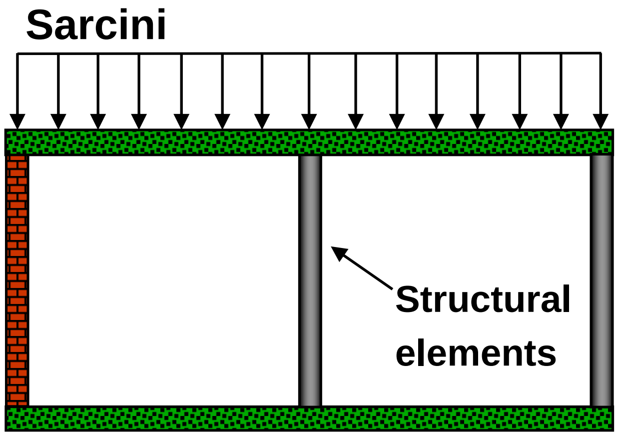
Number of "benchmark" use

[5]

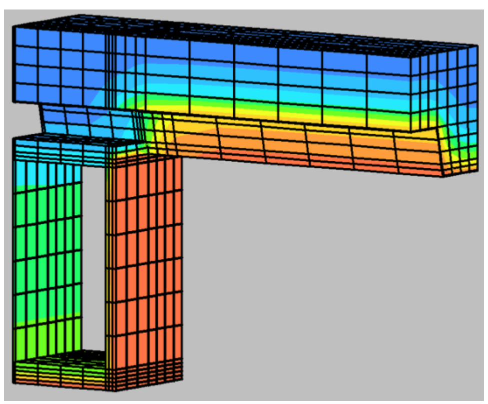
Events during fire

1: Ignition

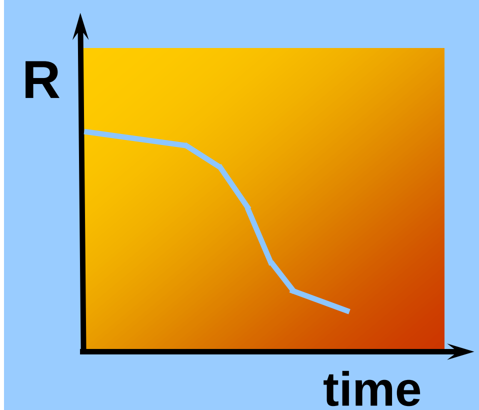
2: Thermal load



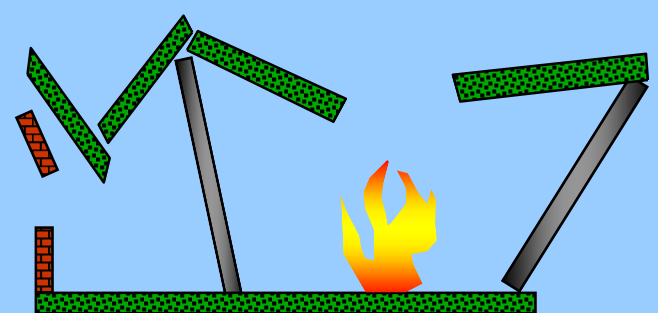
3: Mechanical load



4: Thermal response



5: Structural response



6: Failure ???

Reference case

FRACOF fire test

Objectives:

– To confirm same good performance under long fire duration (at least 90 minutes of ISO fire)

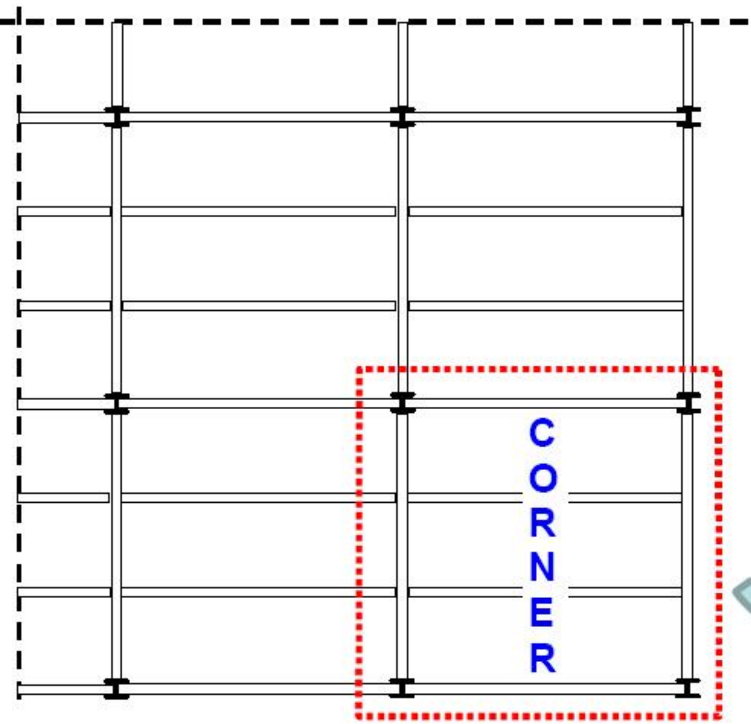
– To investigate the impact of different construction details,such as reinforcing steel mesh and fire protection of edge beams

– To validate different fire safety engineering tools

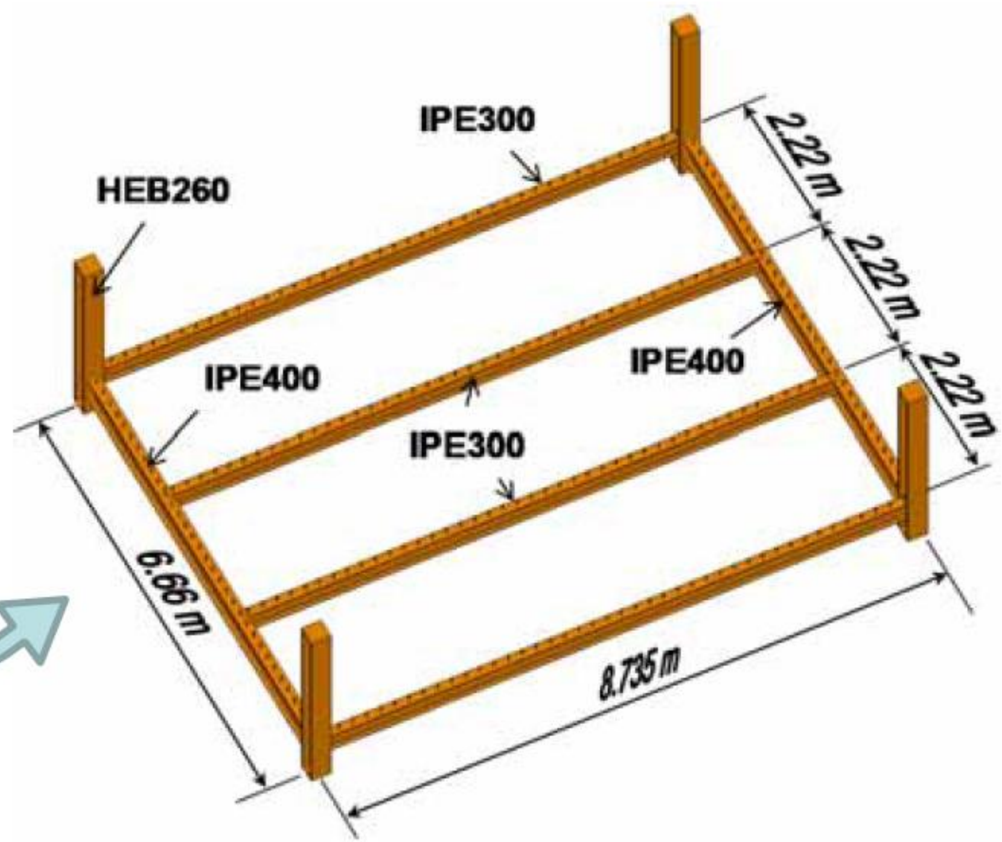
[3]

Reference case

FRACOF fire test - **Setup**



Grid of a real structure

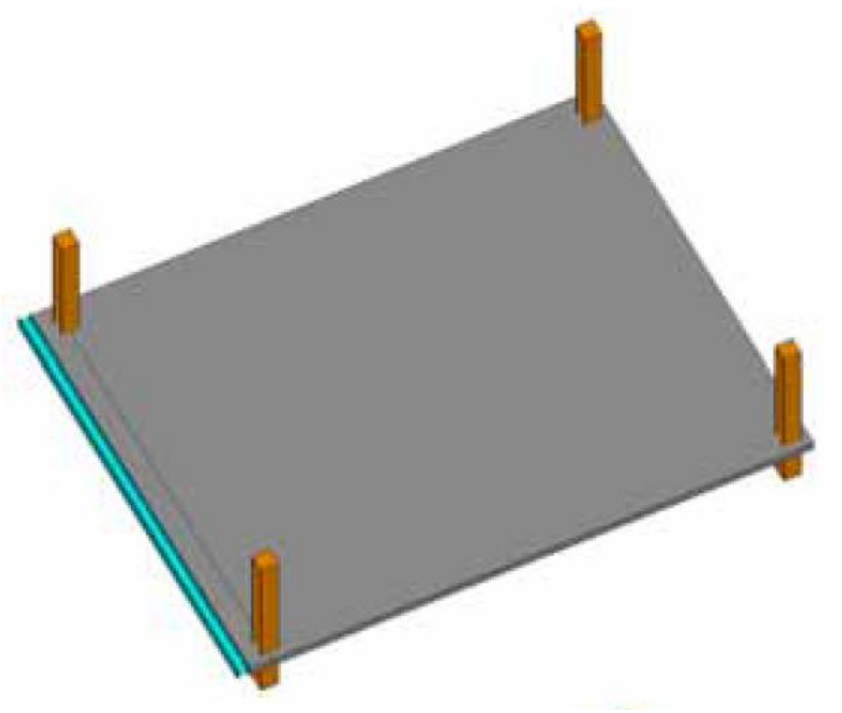


Elements of tested structure

[3]

Reference case

FRACOF fire test - **Setup**



Composite floor

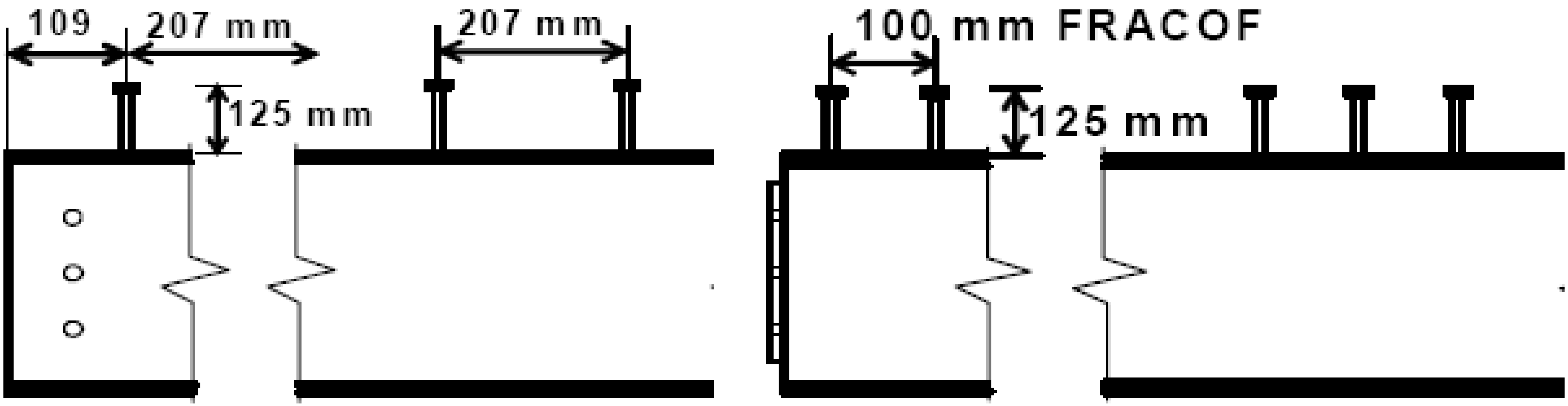
Real-scale specimen

[3]

Reference case

FRACOF fire test

Beam to slab connections



Secondary beams IPE300

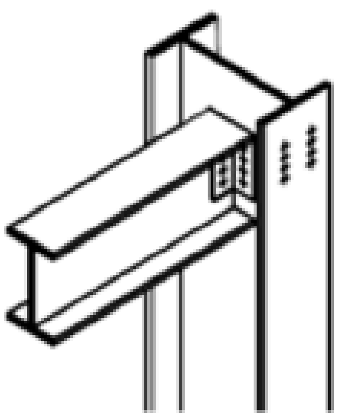
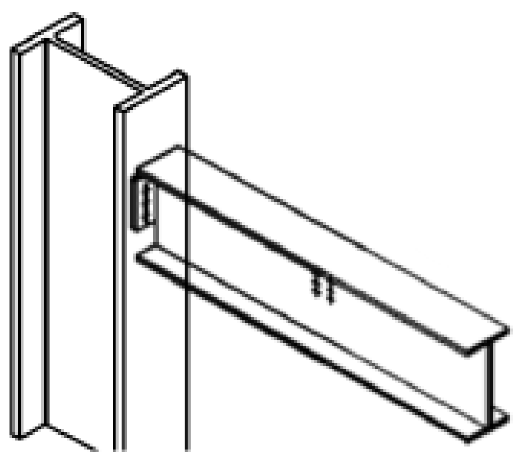
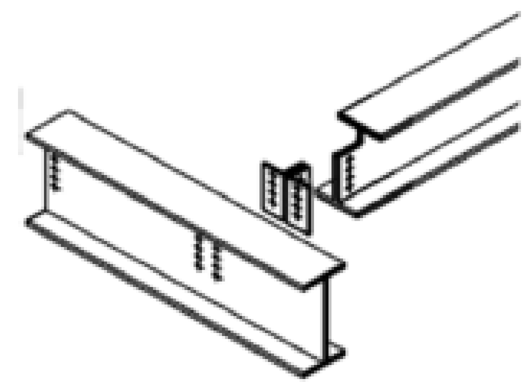
Primary beams IPE400

Full shear connection !

[3]

Reference case

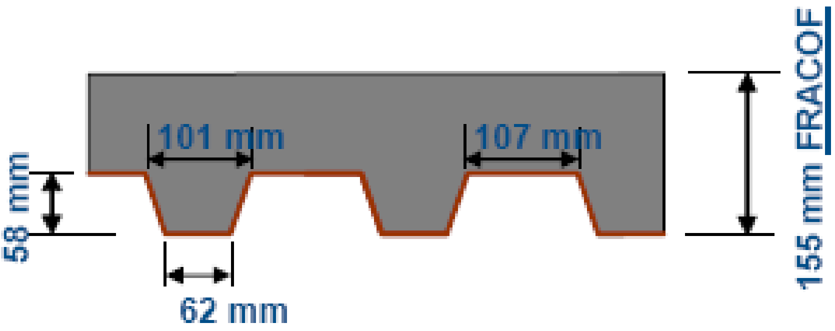
FRACOF fire test - **Connections**

Beam to column		**Beam to beam**
Secondary beam	Primary beam	
Double angle web cleats	Flexible end plate	Double angle web cleats
		

[3]

Reference case

FRACOF fire test - **Materials**



Structural steel: S235

Reinforcing steel mesh:

S500 Ø7 / 150x150

Axis distance from top of the slab:

50mm

Concrete: C30/37

Steel deck: COFRAPLUS60 - 0.75mm

Secondary beams: f_y=311 N/mm^2

Primary beams: f_y=423 N/mm^2

Reinforcing steel mesh: f_y=594 N/mm^2

Concrete cylinder compressive strength: f_c=36.7 N/mm^2

[7]

Reference case

FRACOF fire test - **Loads**

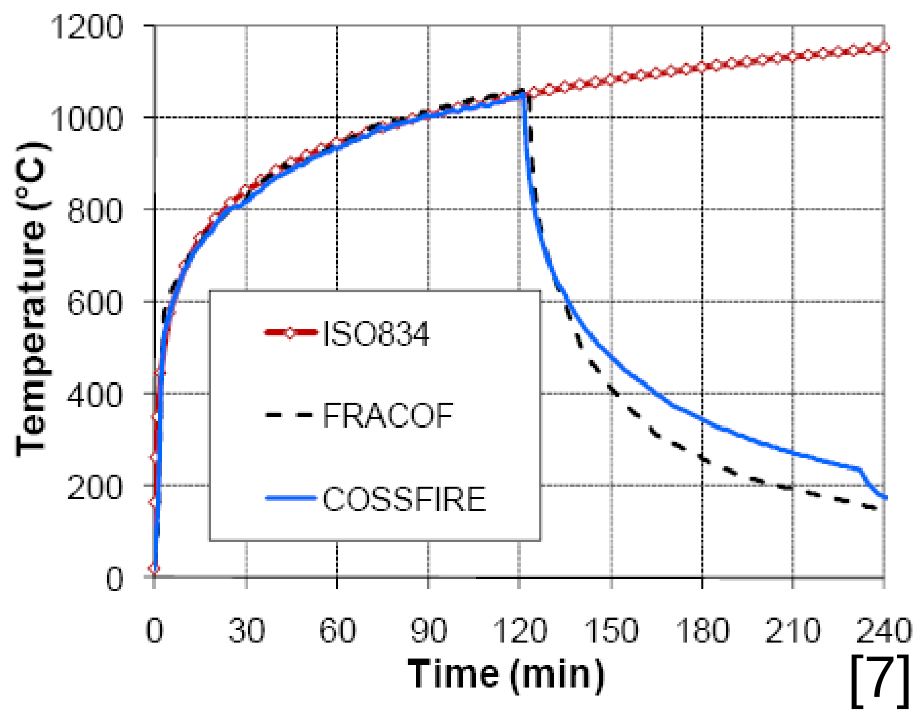
Mechanical load

15 sand bags x 1512 kg

Equivalent uniform load: $390 kg/m^2$

Fire load

120 min of Standard fire curve ISO 834 and a cooling phase



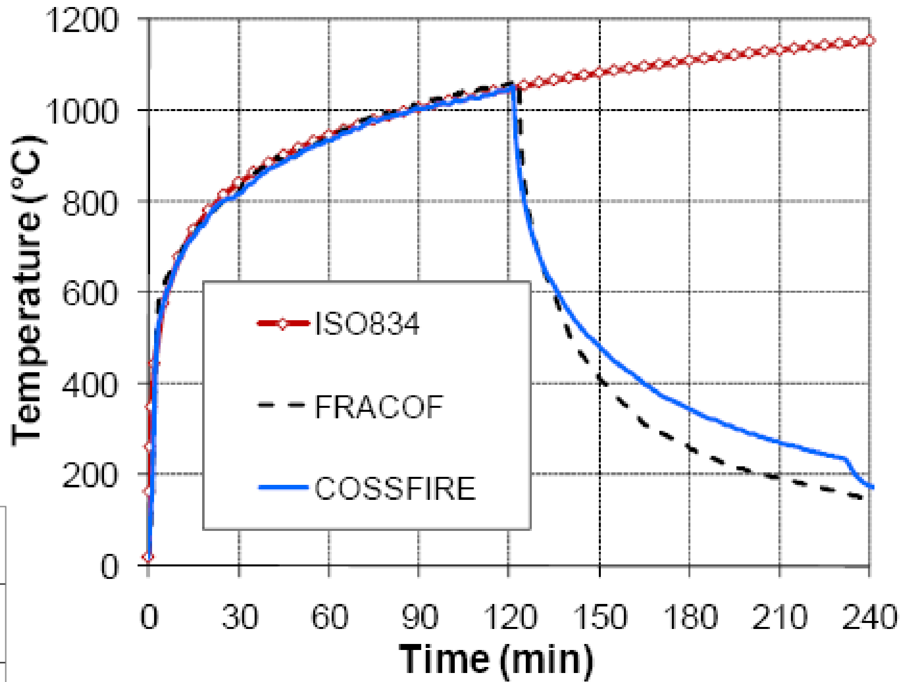
[7]

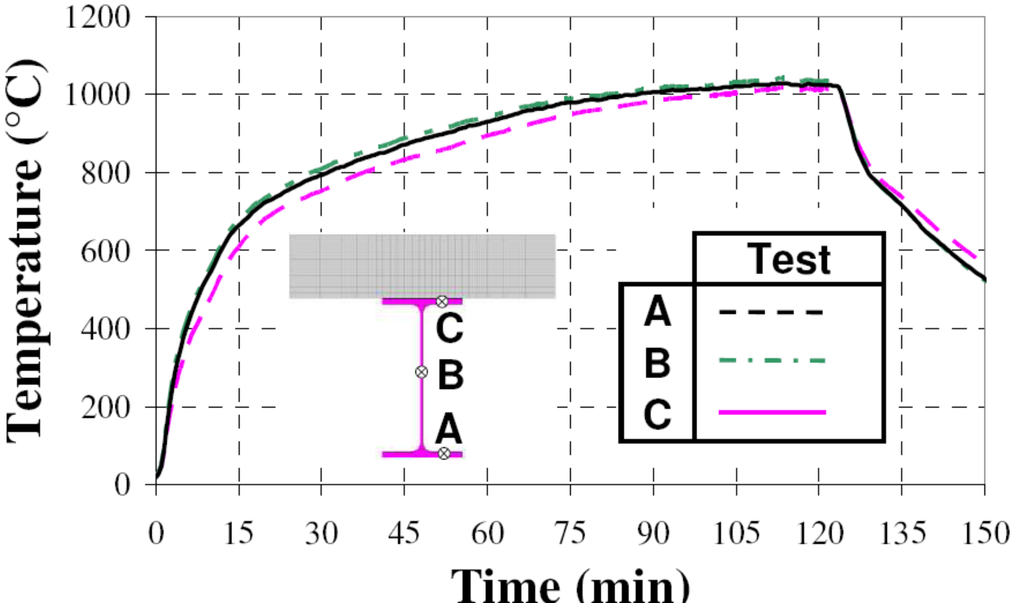
Reference case

Reference case

FRACOF fire test - **Results**

Fire (gas) temperature ⟹





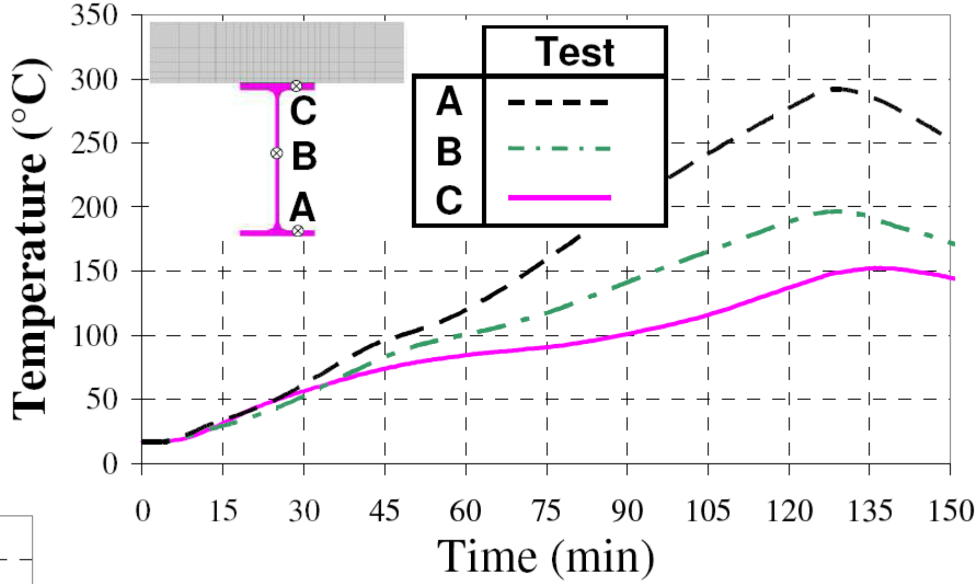
⟸ Heating of unprotected steel beams

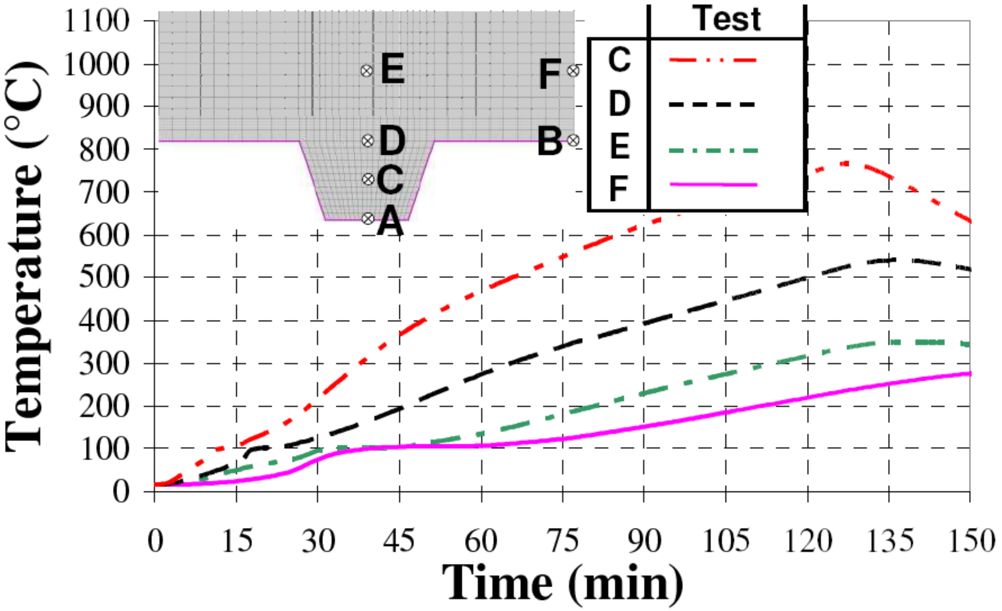
[7]

Reference case

FRACOF fire test - **Results**

Heating of protected steel ⇨





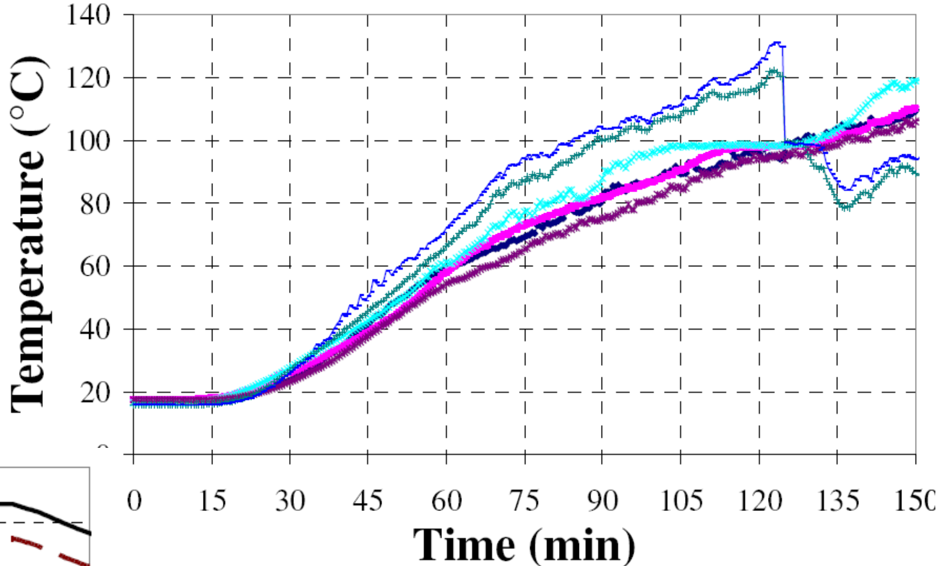
⇦ Heating of composite slab

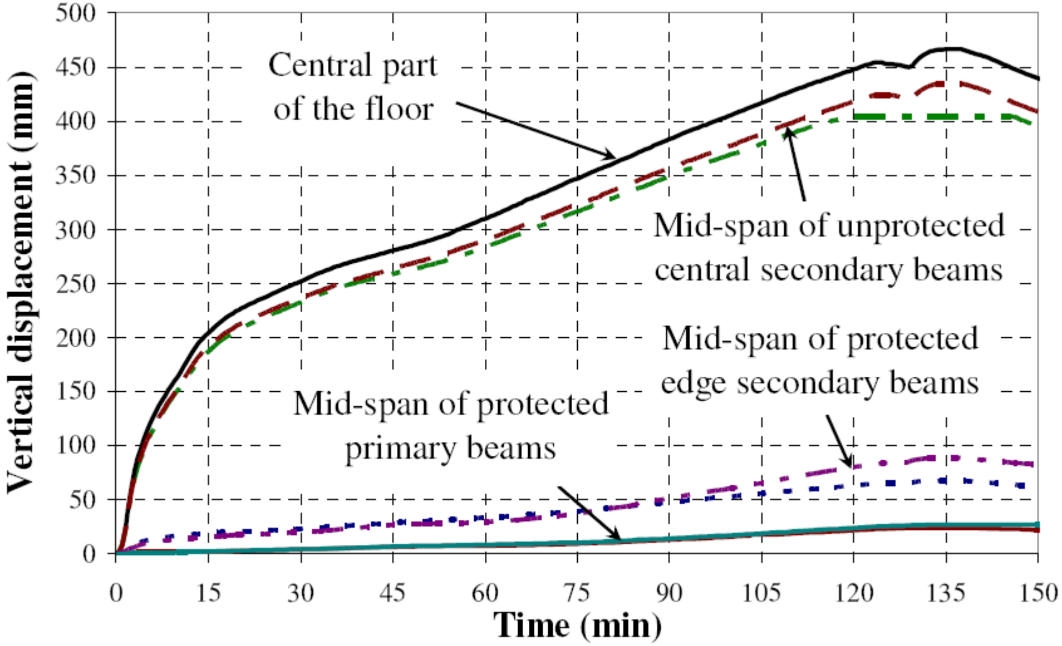
[7]

Reference case

FRACOF fire test - **Results**

Temperatures at the unexposed face of slab ⇨





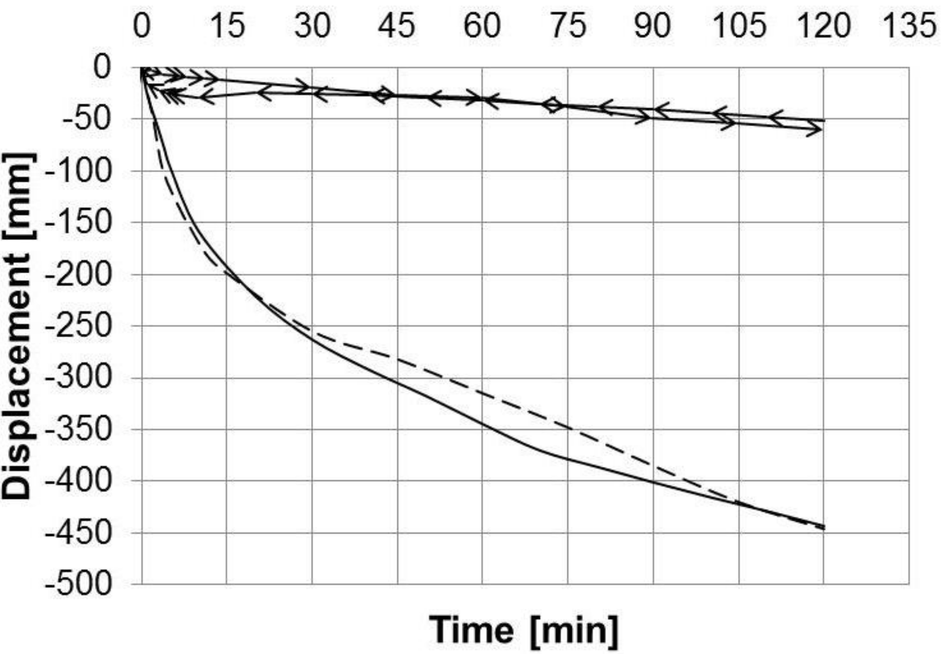
⇦ Deflection of the floor

[7]

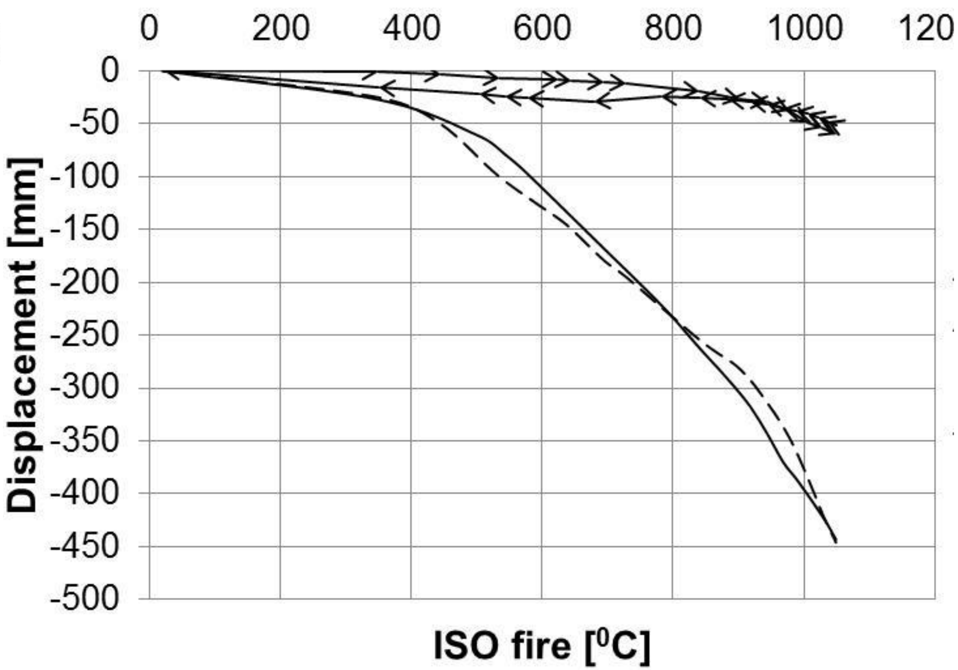
Validation

Displacement

with respect to time



with respect to temperature



Legend:

Central point-numeric

Central Point-test

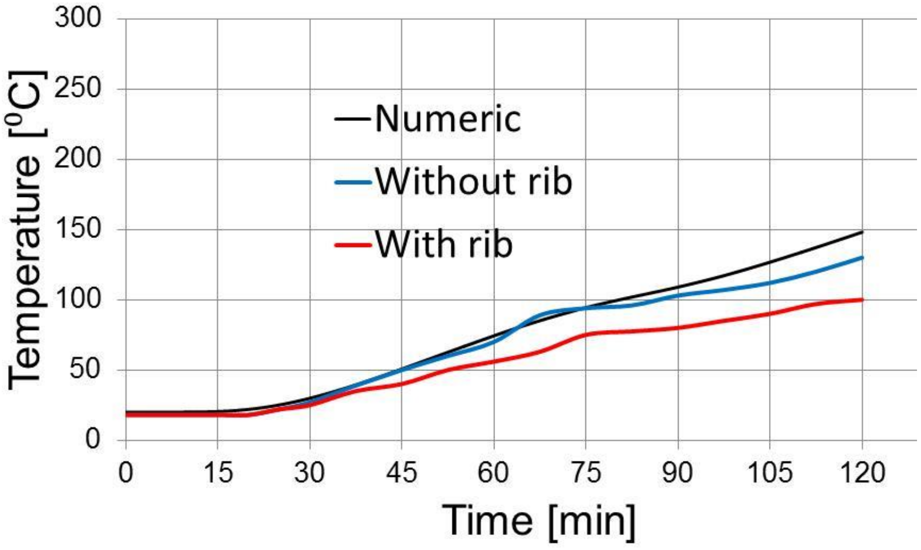
Protected IPE300-numeric

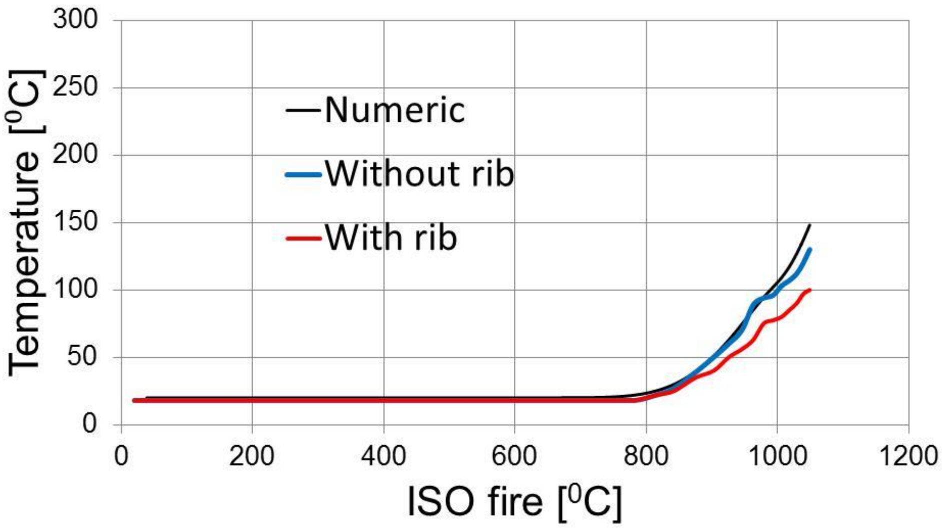
Protected IPE300-test

Validation

Temperature

Unexposed side of the slab





with respect to time

with respect to temperature

Benchmark model

Materials properties

Consideration: only strength of materials is affected by temperature!!! (EN 1994-1-2)

Thermal analysis

Material	Density [kg/m^3]	Conductivity [W/m K]	Specific heat [J/kg K]
Steel	7850	40	550
Concrete	2400	0.9	1050

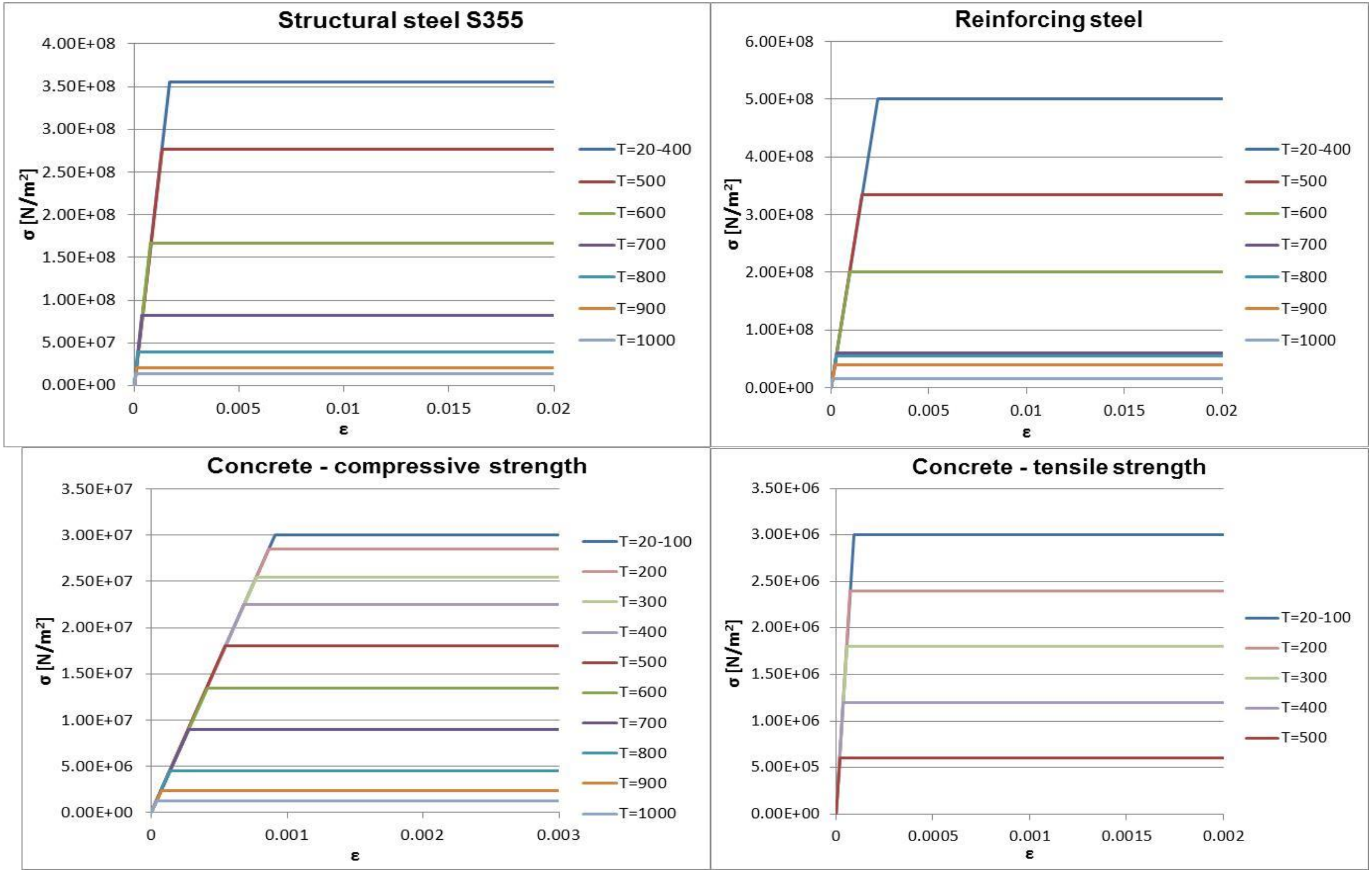
Mechanical ananlysis

Steel	E [N/m^2]	ν	σ_y [N/m^2]	α [1/C]
S235	2.1e11	0.3	235.0e6	1.4e-5
S355	2.1e11	0.3	355.0e6	1.4e-5
S500	2.1e11	0.3	500.0e6	1.4e-5

Concrete	E [N/m^2]	ν	f_c [N/m^2]	f_t [N/m^2]	α [1/C]
C30/37	3.3e10	0.2	30.0e6	3.0e6	1.0e-5

Benchmark model

Materials properties

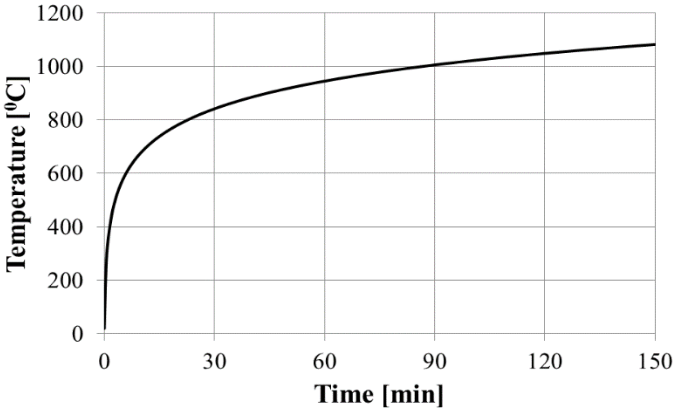


Benchmark model

Loads

Thermal load:

- constant temperature for unprotected beams,
- gradients through protected beams section,
- imported temperature field for slab



Standard fire curve

Mechanical load:

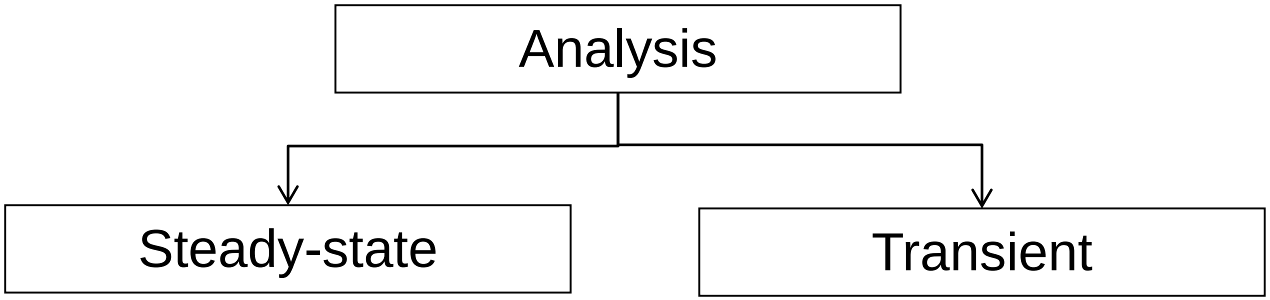
- sand bags: 3870 N/m^2
- selfweight: 3280 N/m^2

7150 N/m^2 – uniform pressure on the slab

Numerical model - Basics

Heat transfer analysis in Abaqus summary

- uncoupled heat transfer analysis
- sequentially coupled thermal-stress analysis
- fully coupled thermal-stress analysis,
- fully coupled thermal-electric-structural analysis,
- adiabatic analysis,
- coupled thermal-electrical analysis
- cavity radiation



[4]

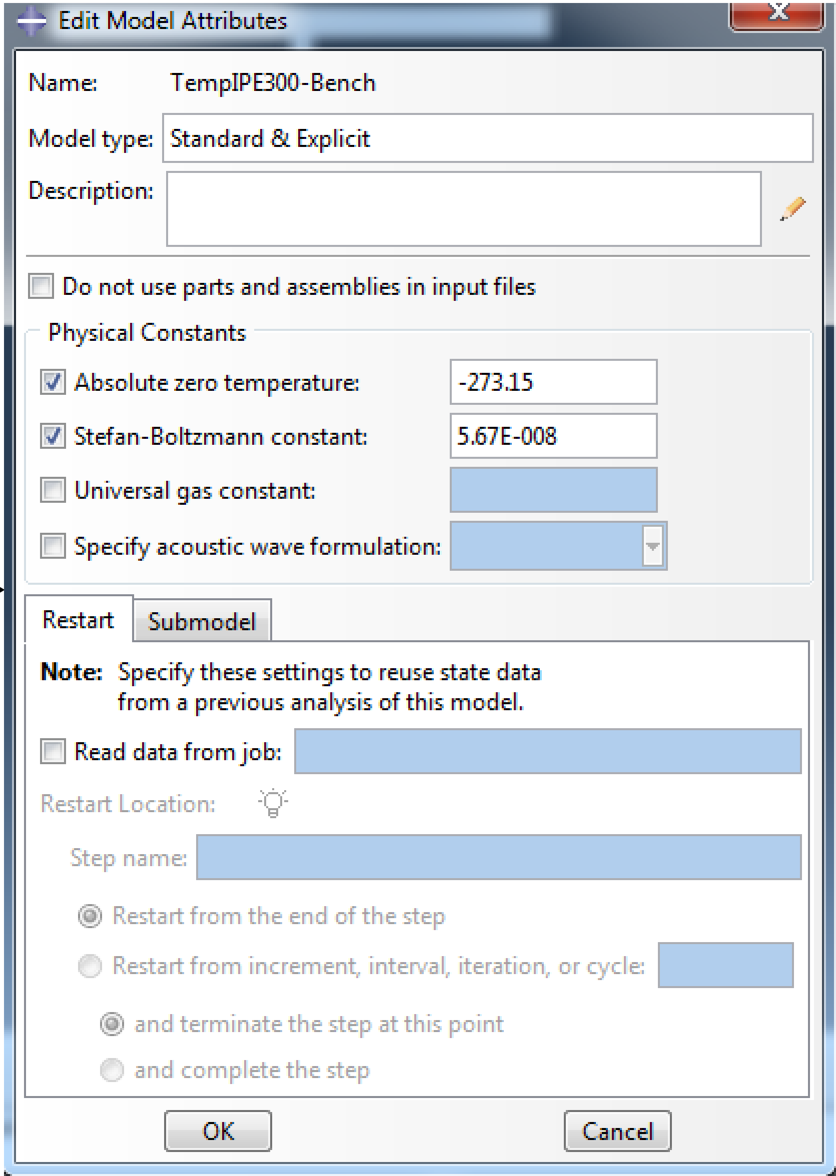
Numerical model - Basics

Settings

ABAQUS has no settings for units system

Measurement units are chosen by the user and should be consistent throughout all model(s)

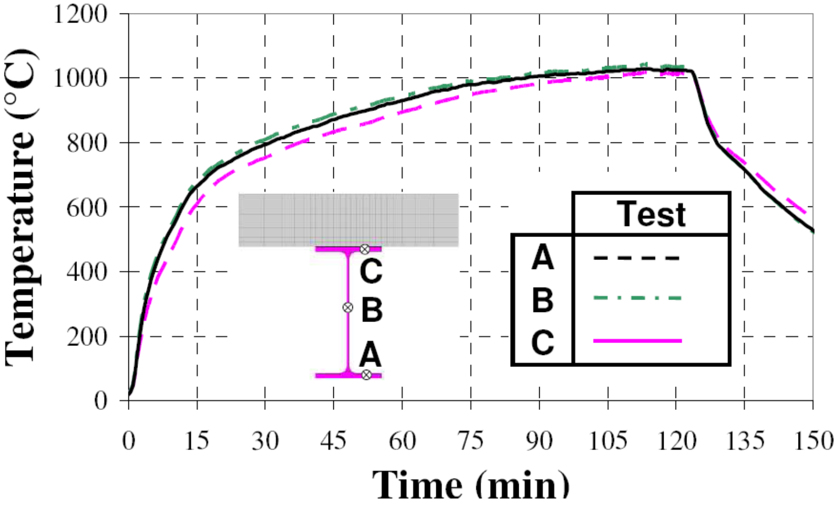
For the benchmark the units are:
N, m, s, ^{0}C



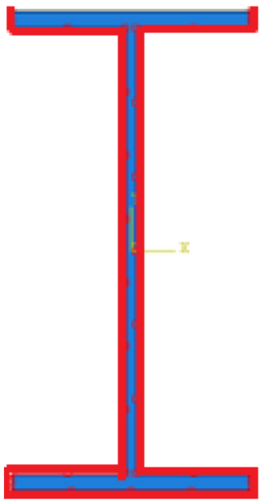
Numerical model

Temperature field for secondary, unprotected beams

From test➔ uniform temperature



Create a 2D heat transfer model for the IPE300 section



Define interactions to the environment:

- convection
- radiation

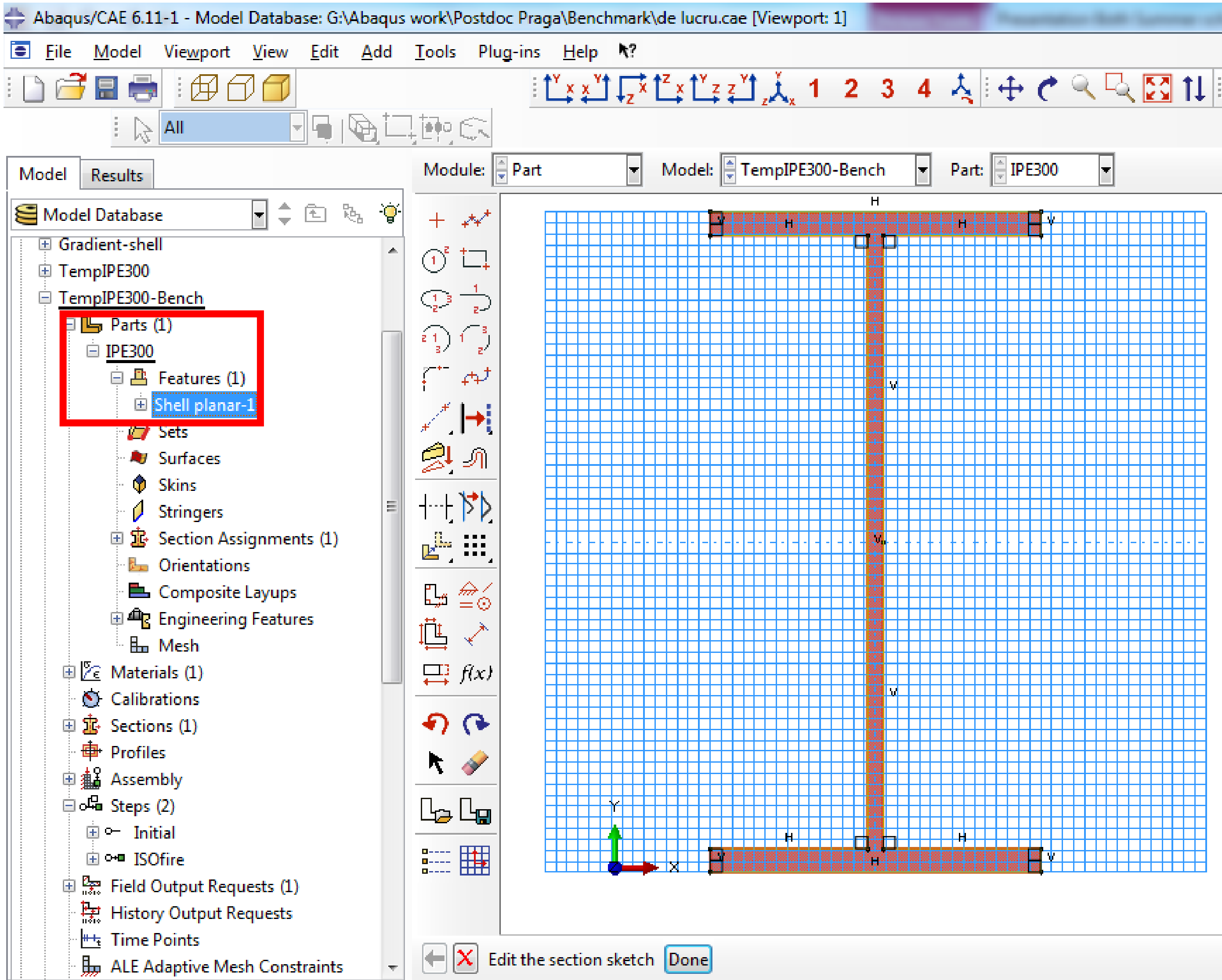
Obtain temperature field which will be used in the composite slab model

Numerical model

Temperature field for secondary, unprotected beams

Create part:

2D shell planar

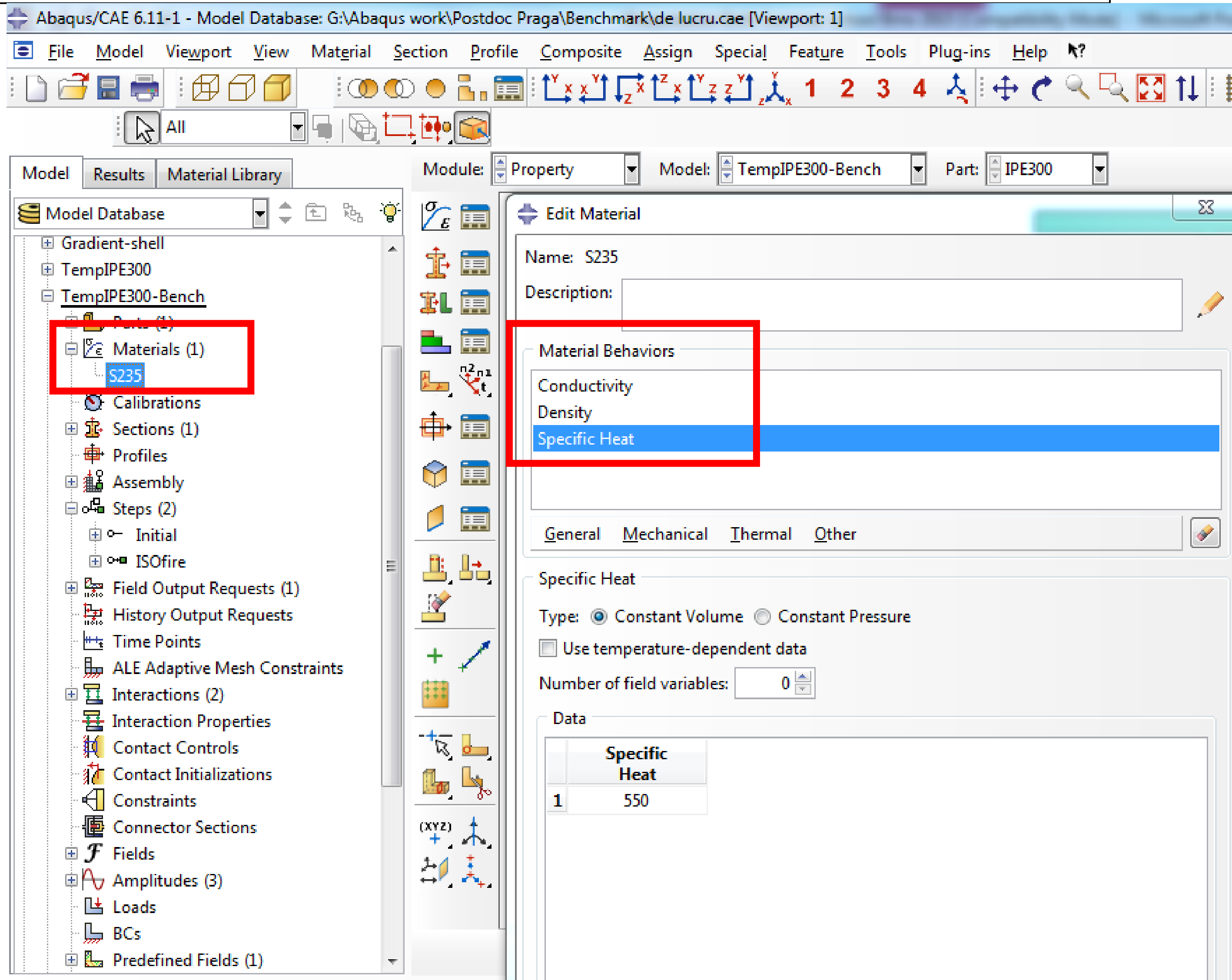


Numerical model

Temperature field for secondary, unprotected beams

Define material:

- conductivity
- specific heat
- density

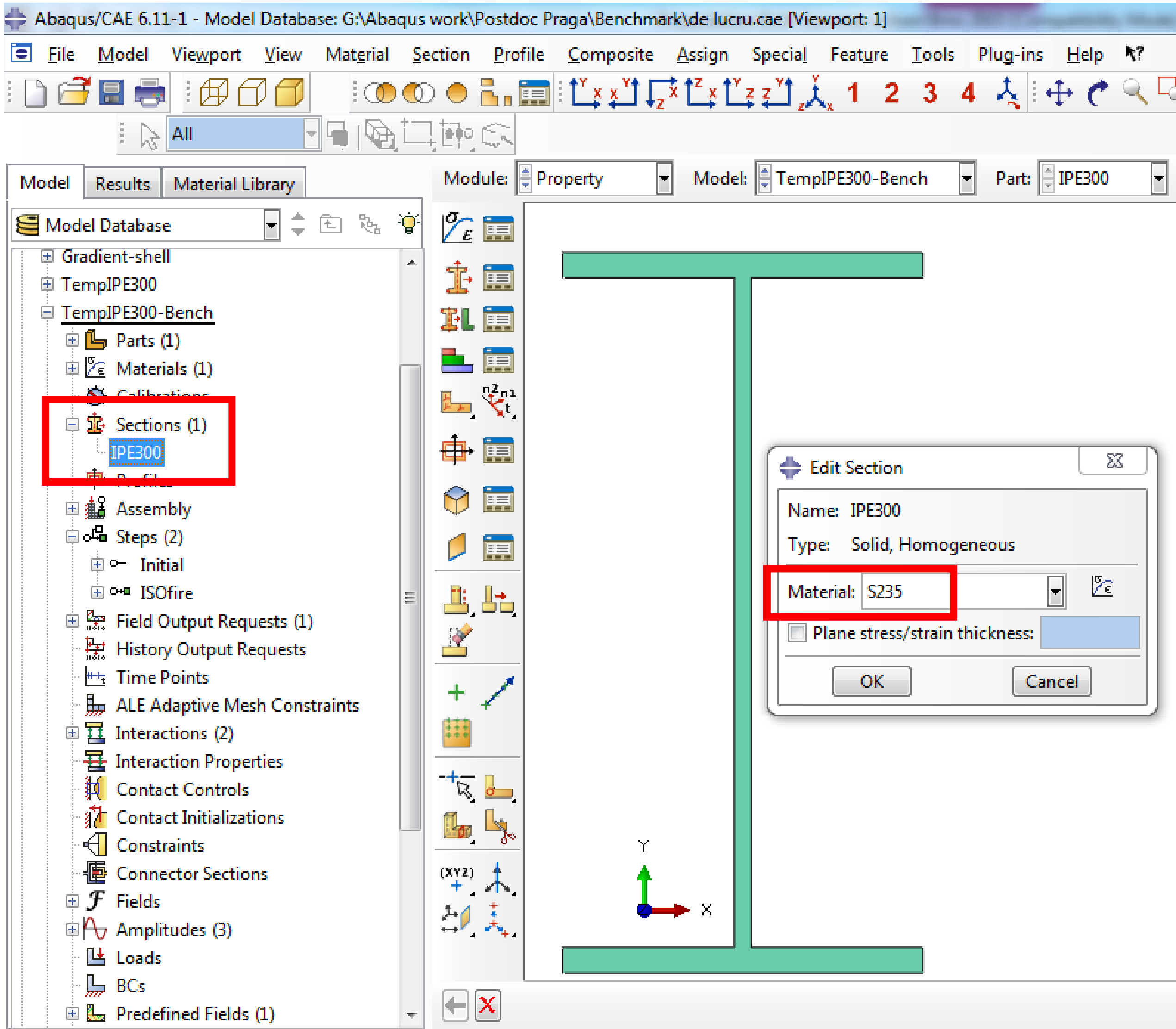


Numerical model

Temperature field for secondary, unprotected beams

Define section property:

- Solid homogeneous

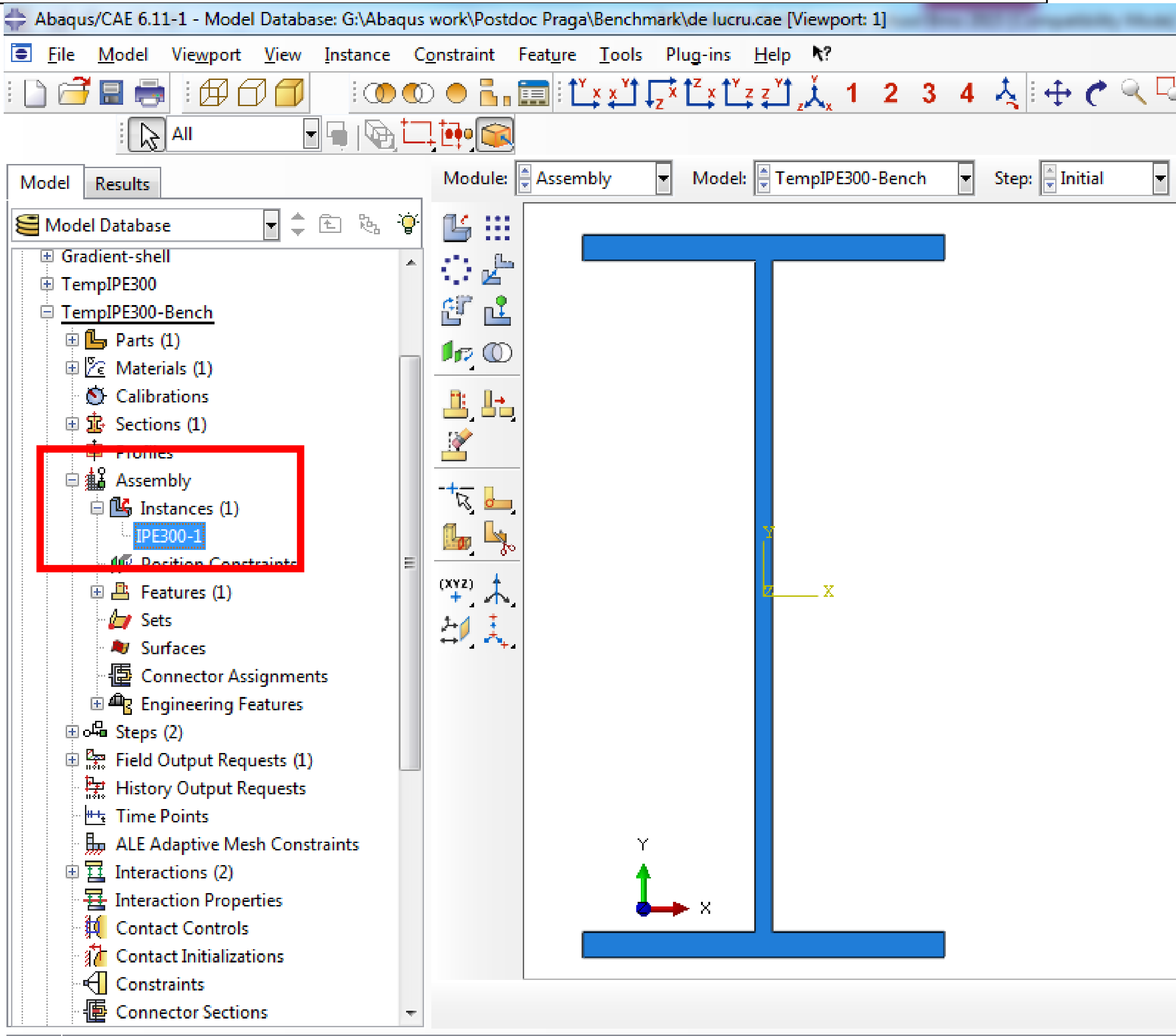


Numerical model

Temperature field for secondary, unprotected beams

Create instances:

- IPE300

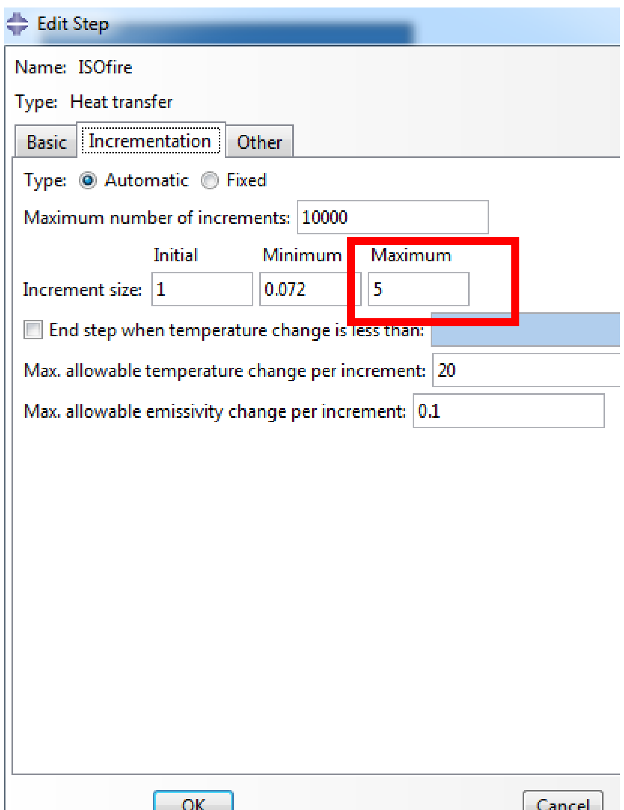


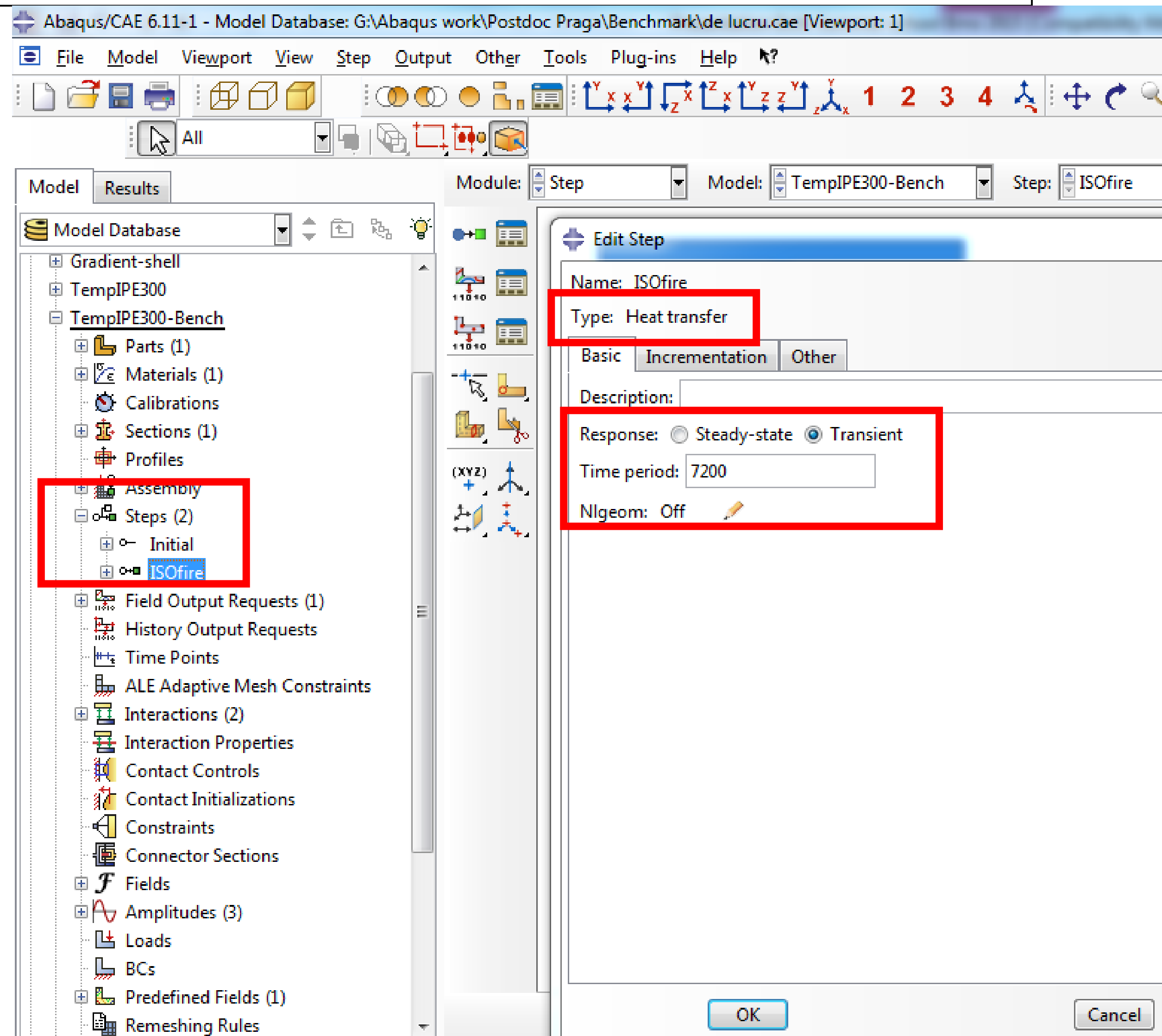
Numerical model

Temperature field for secondary, unprotected beams

Define steps:

- Heat transfer



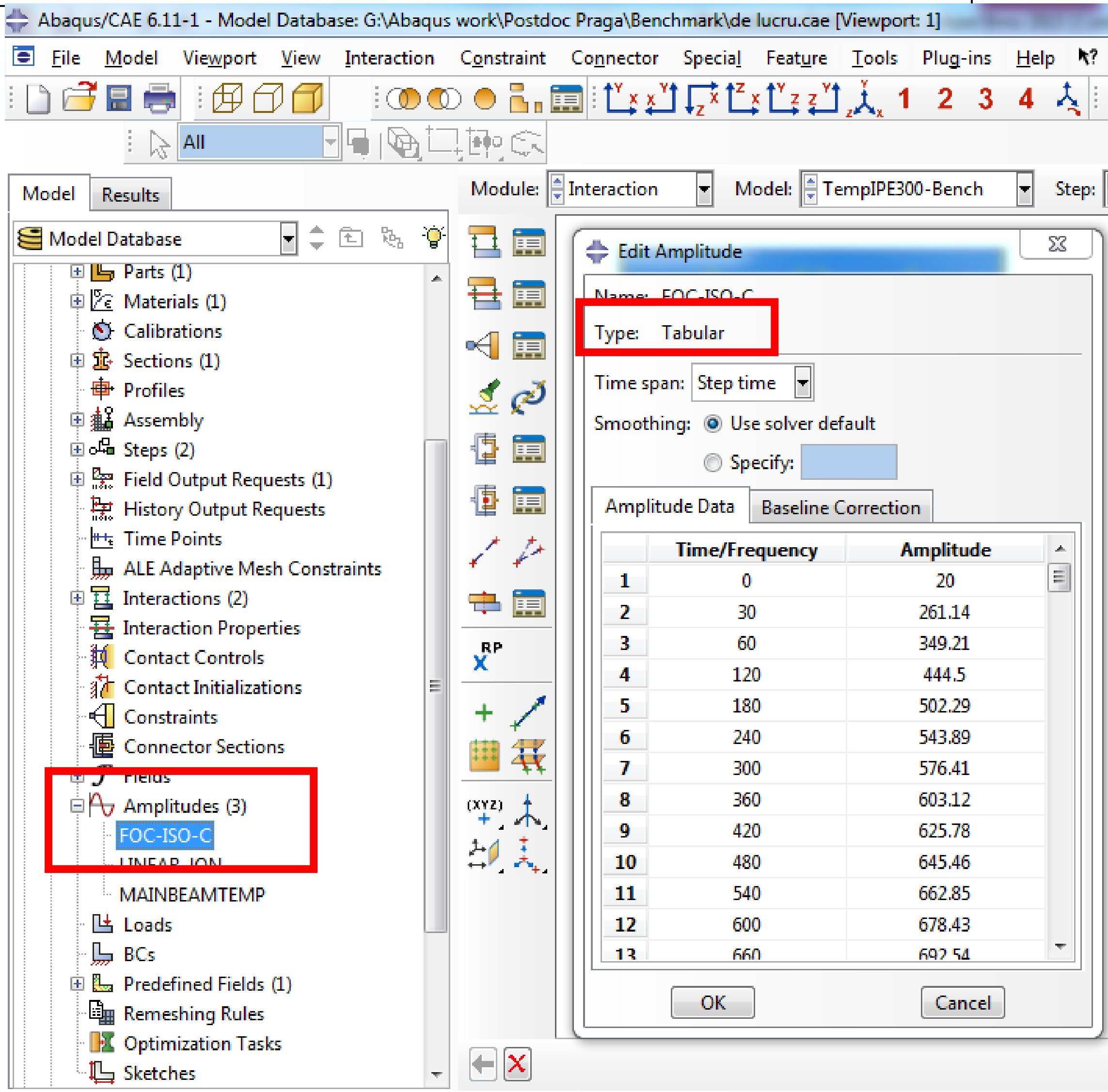


Numerical model

Temperature field for secondary, unprotected beams

Define fire curve:

- Amplitude

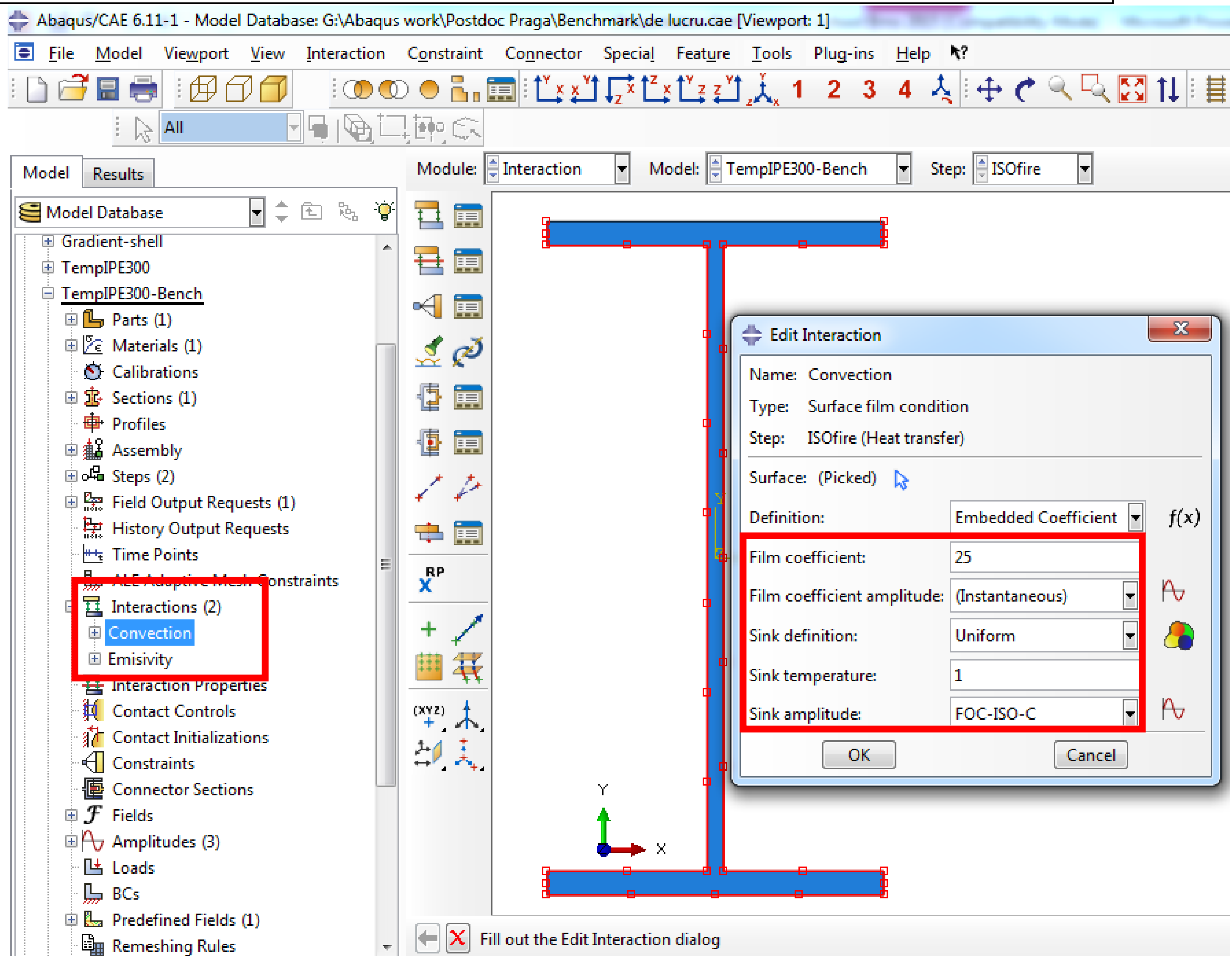


Numerical model

Temperature field for secondary, unprotected beams

Define interactions:

- Convection (surface film condition)

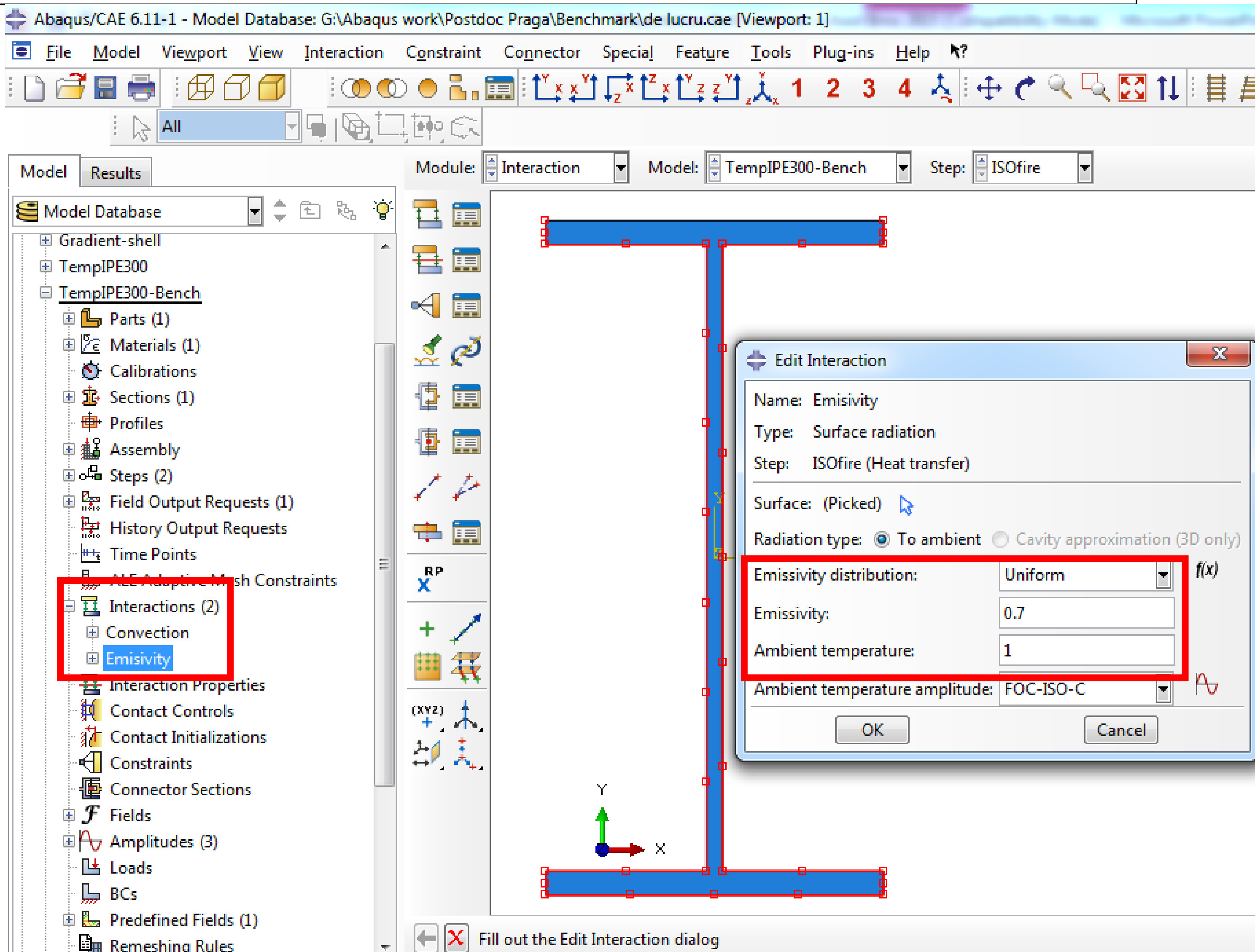


Numerical model

Temperature field for secondary, unprotected beams

Define interactions:

- Radiation (surface radiation)

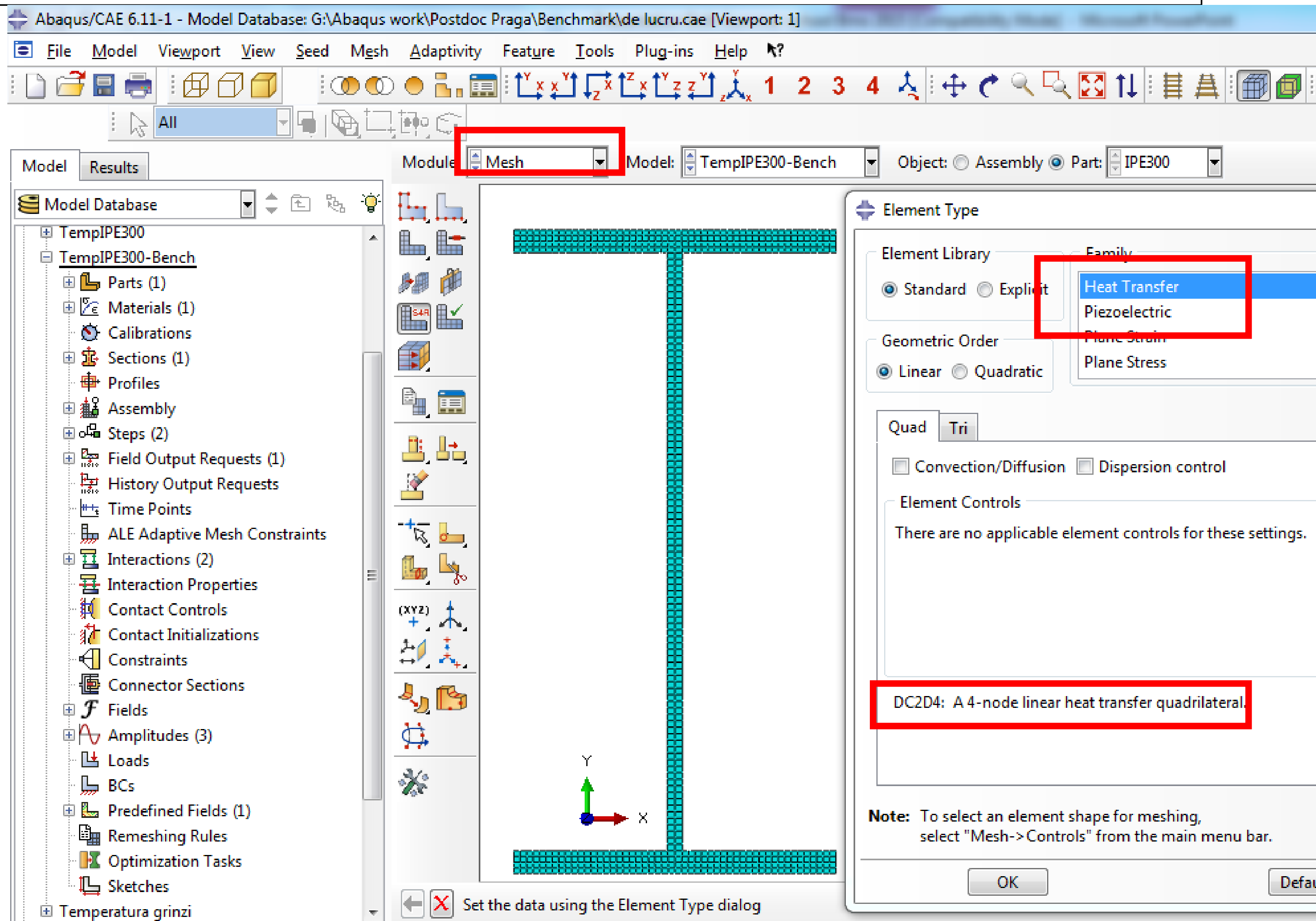


Numerical model

Temperature field for secondary, unprotected beams

Define mesh:

-DC2D4

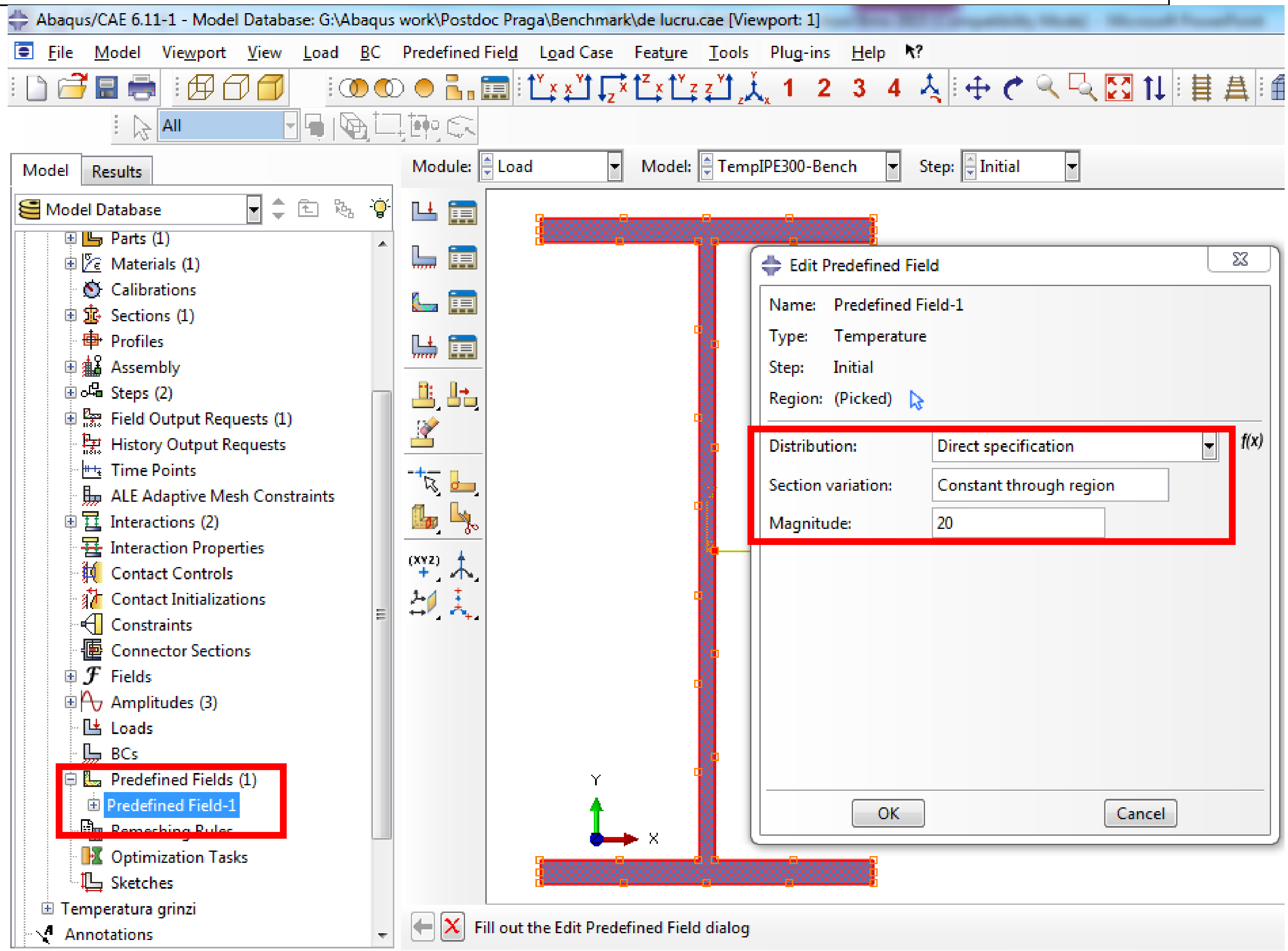


Numerical model

Temperature field for secondary, unprotected beams

Define initial temperature:

- Predefined field

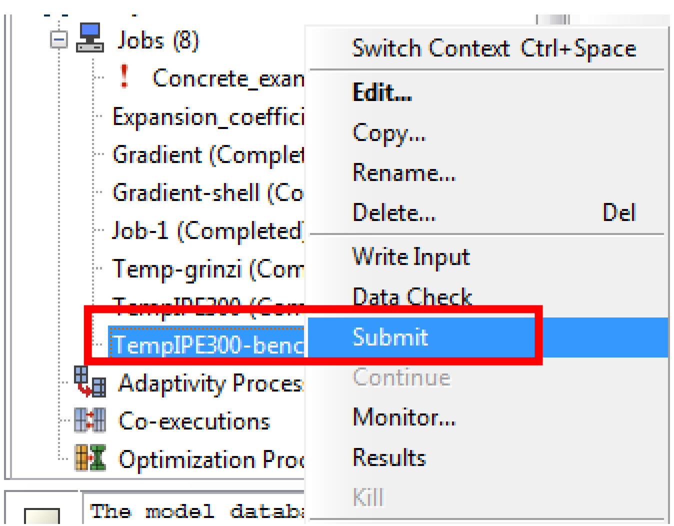


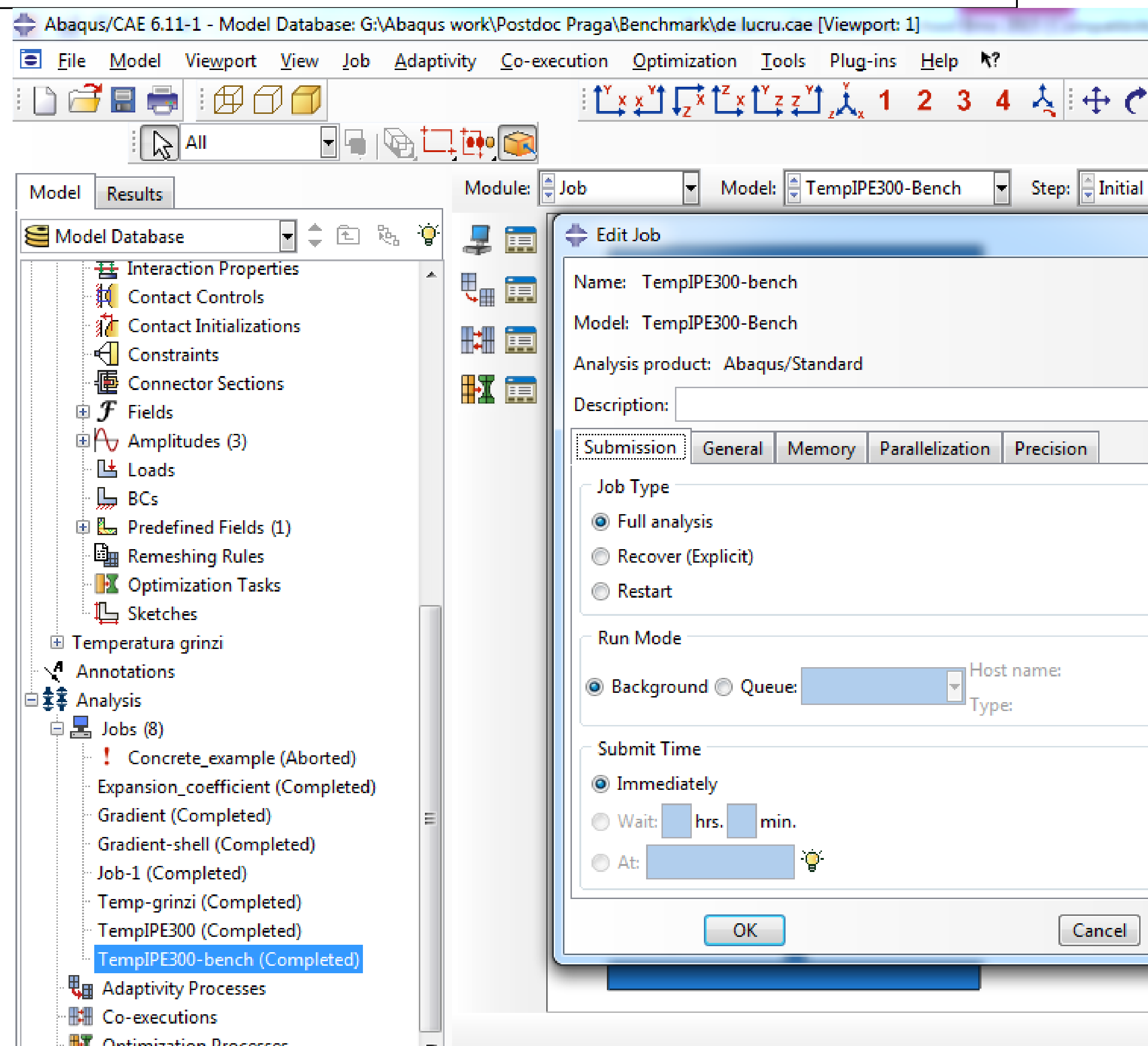
Numerical model

Temperature field for secondary, unprotected beams

Create job and run analysis:

- Jobs
- Submit



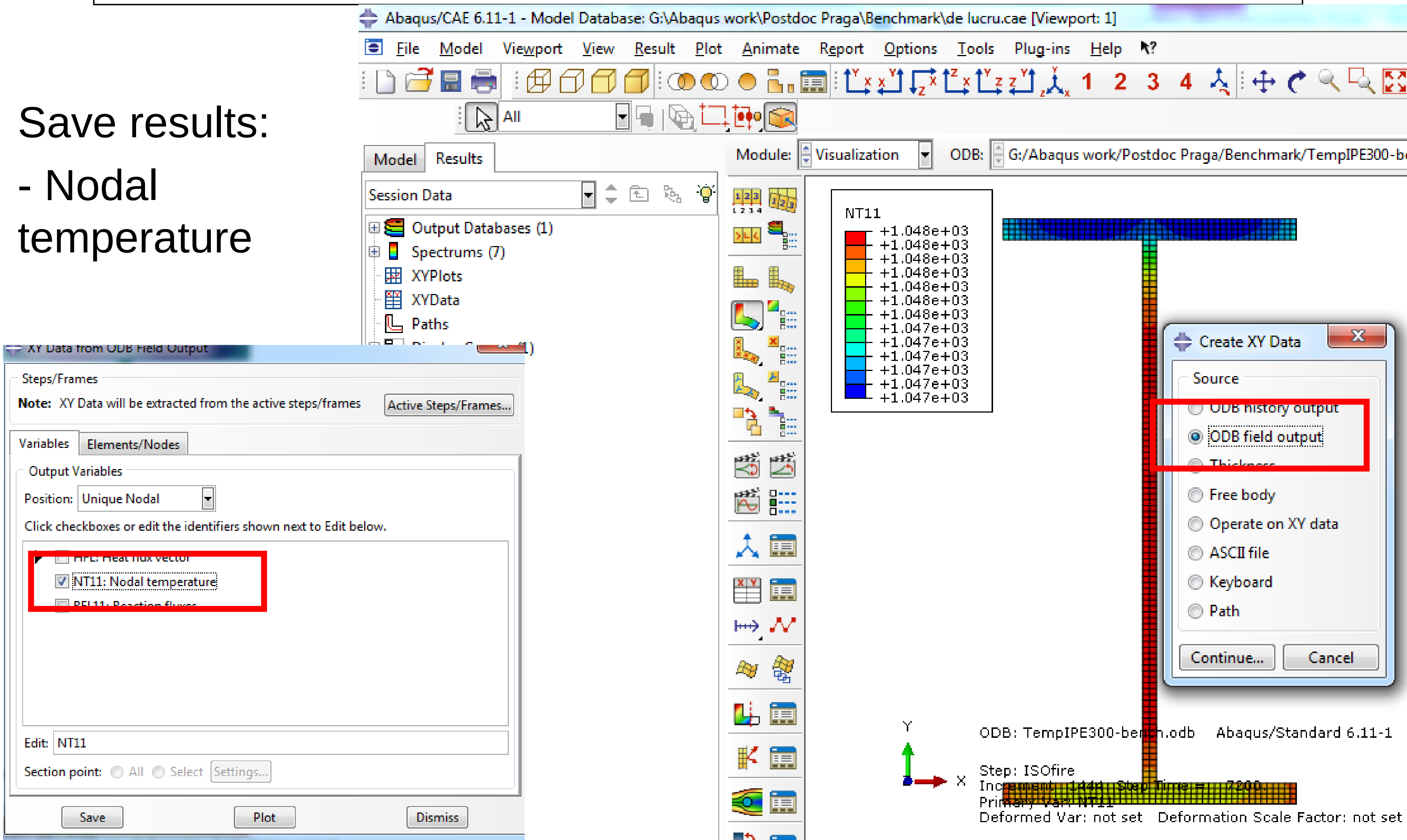


Numerical model

Temperature field for secondary, unprotected beams

Save results:

- Nodal temperature

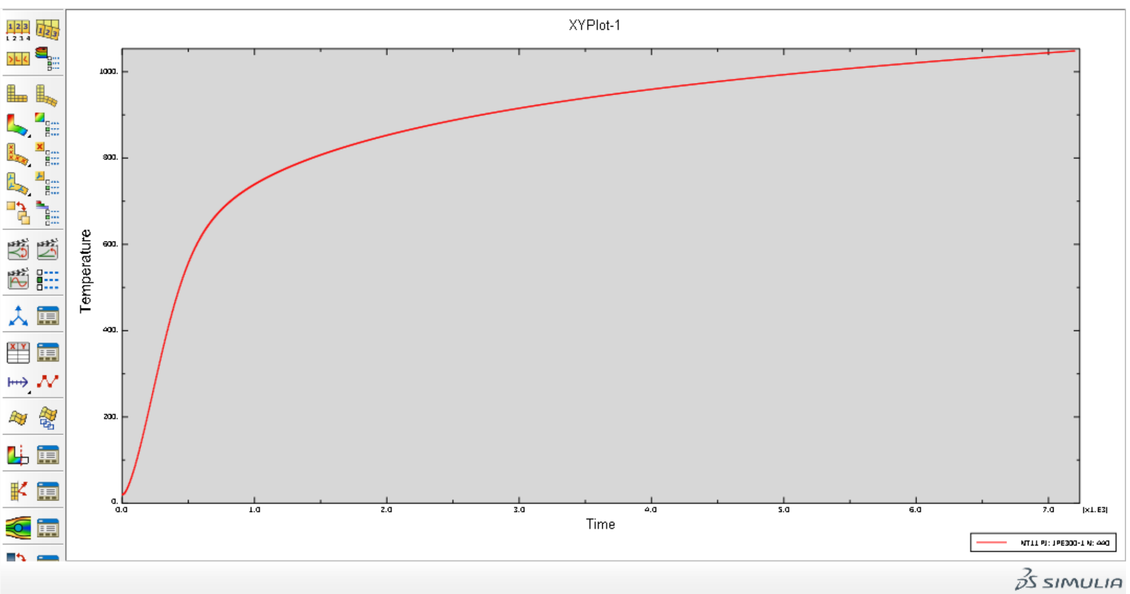


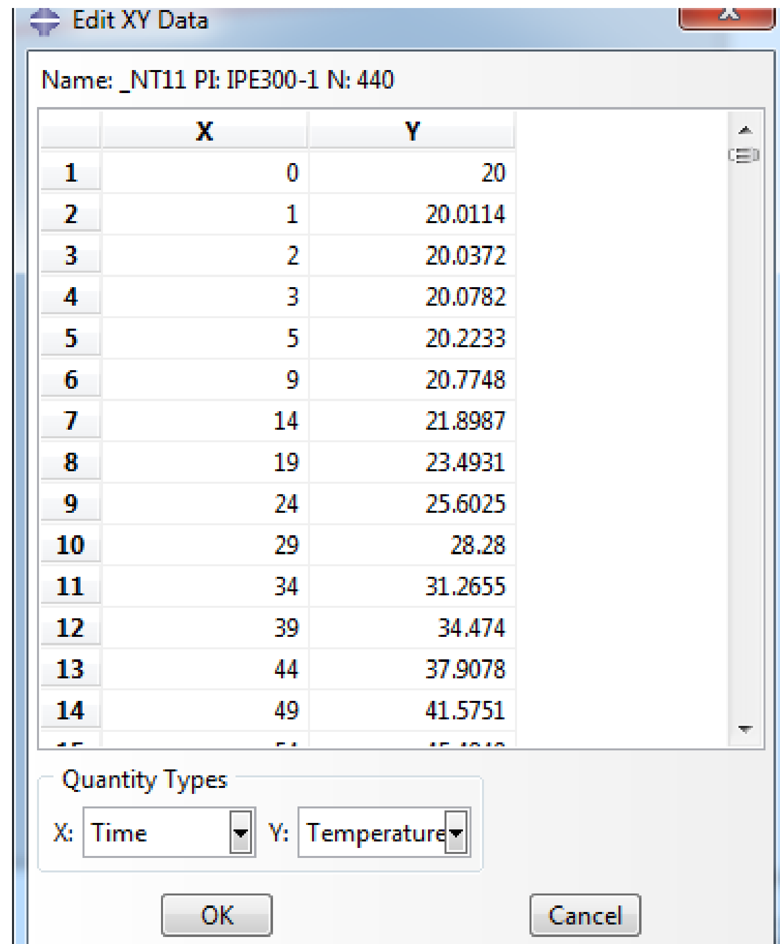
Numerical model

Temperature field for secondary, unprotected beams

Save results:

- Nodal temperature



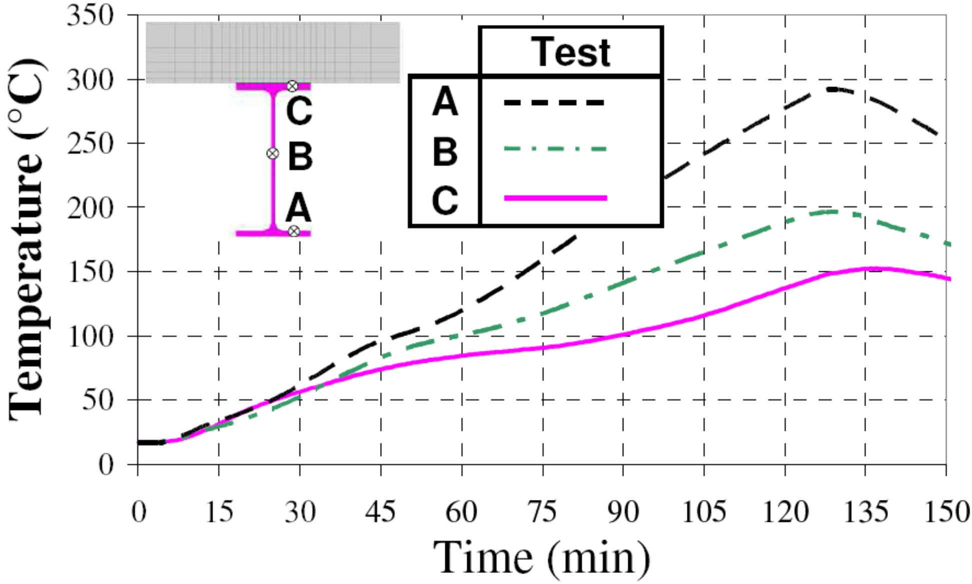


	X	Y
1	0	20
2	1	20.0114
3	2	20.0372
4	3	20.0782
5	5	20.2233
6	9	20.7748
7	14	21.8987
8	19	23.4931
9	24	25.6025
10	29	28.28
11	34	31.2655
12	39	34.474
13	44	37.9078
14	49	41.5751

Numerical model

Temperature field for protected beams

Temperature from test: difference between top and bottom flange

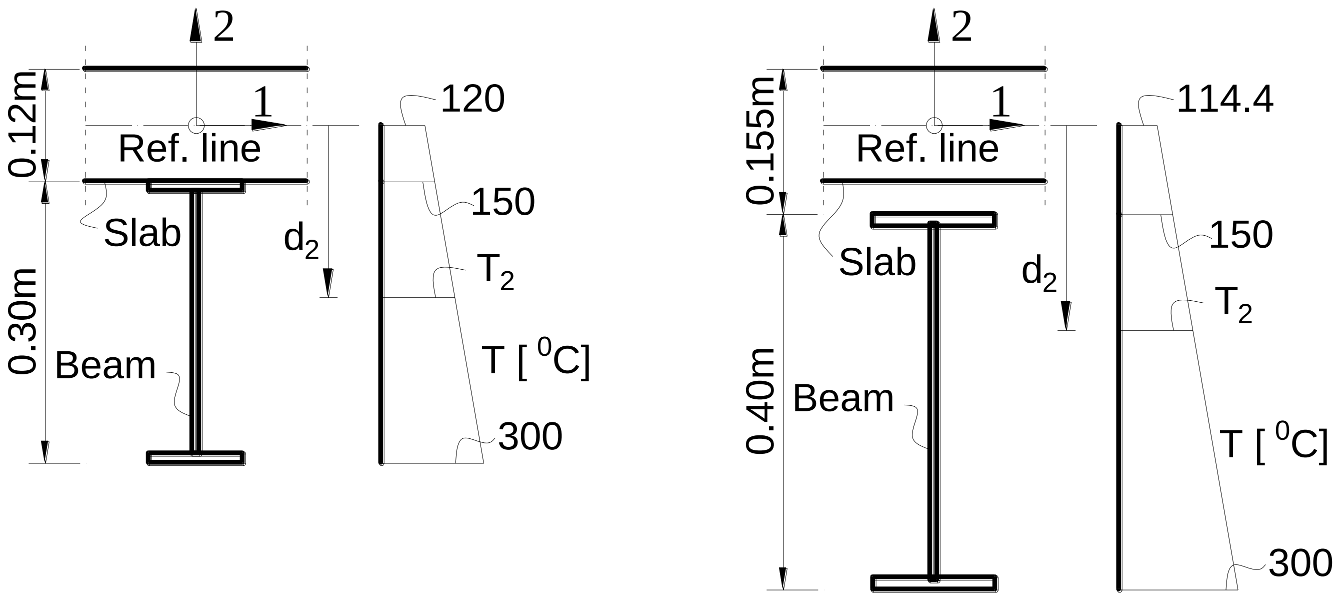


It is defined as a *predefined field* gradient through beam section in the composite slab model (no need for an additional model)

Numerical model

Temperature field for protected beams

Beam elements sections are defined function of a reference line

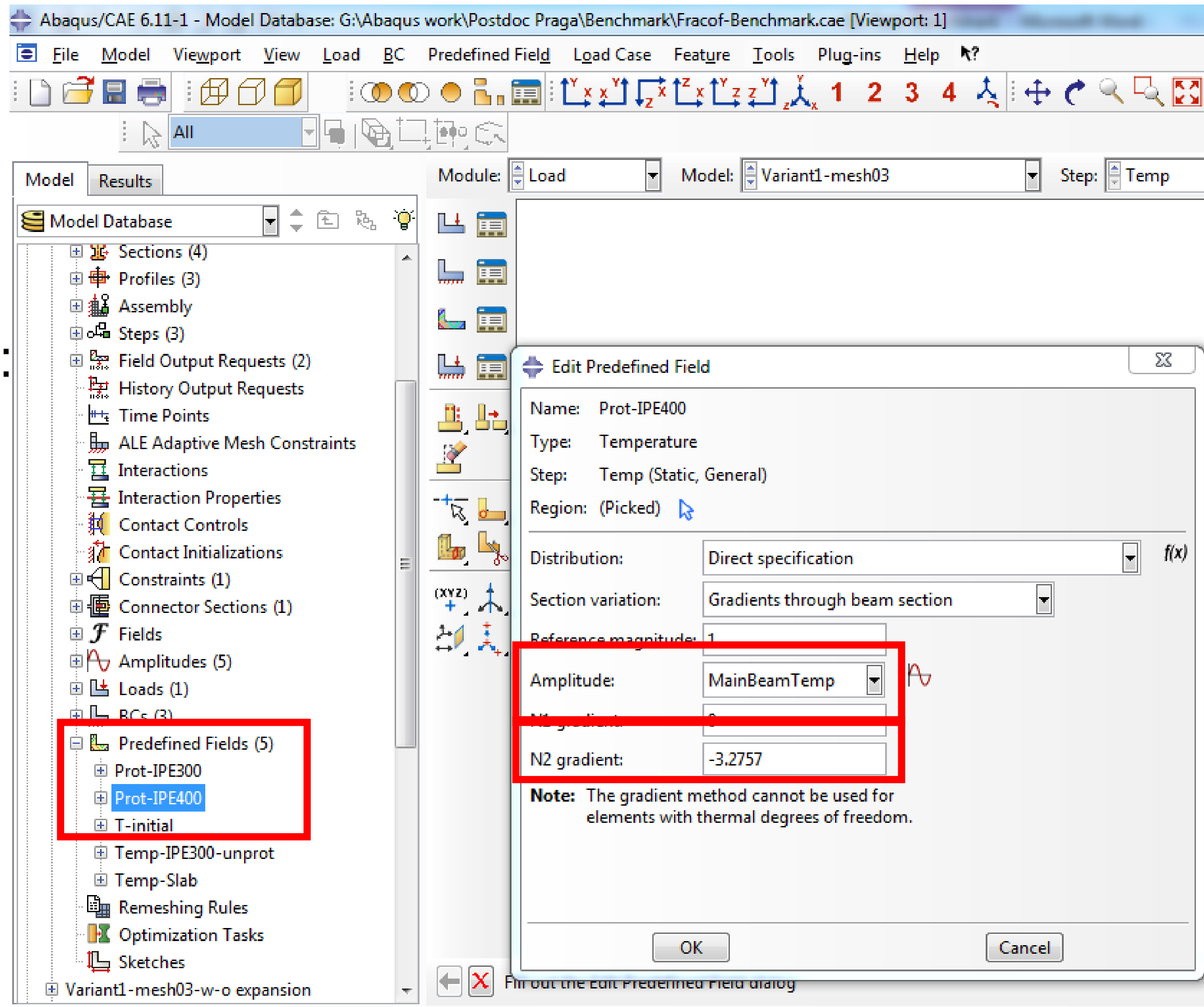


Numerical model

Temperature field for protected beams

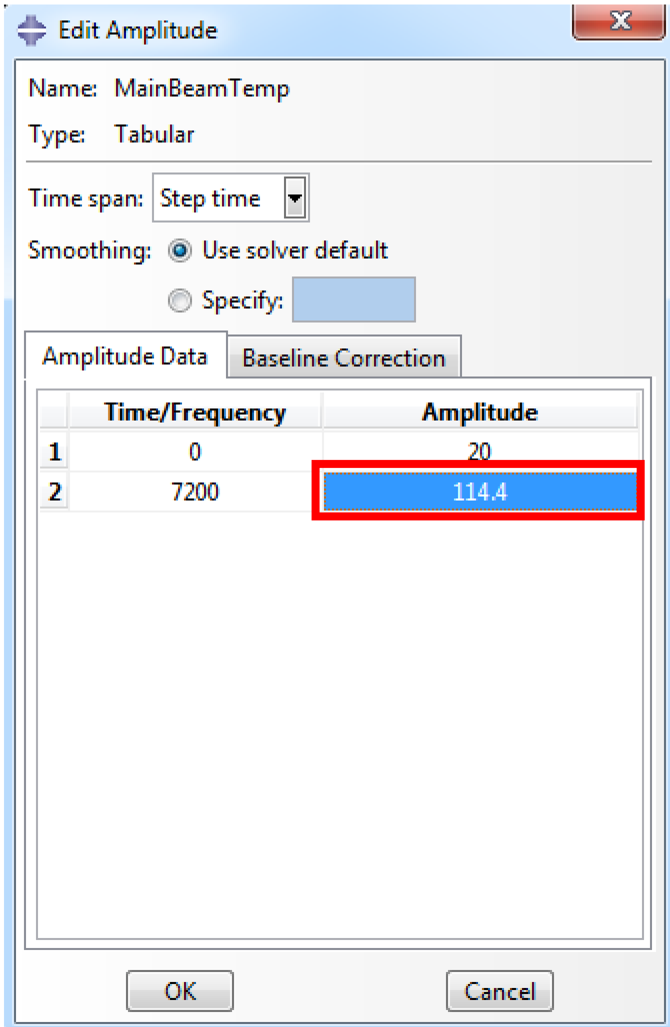
Input for *predefined field* of gradient through beam section:

- amplitude
- gradient

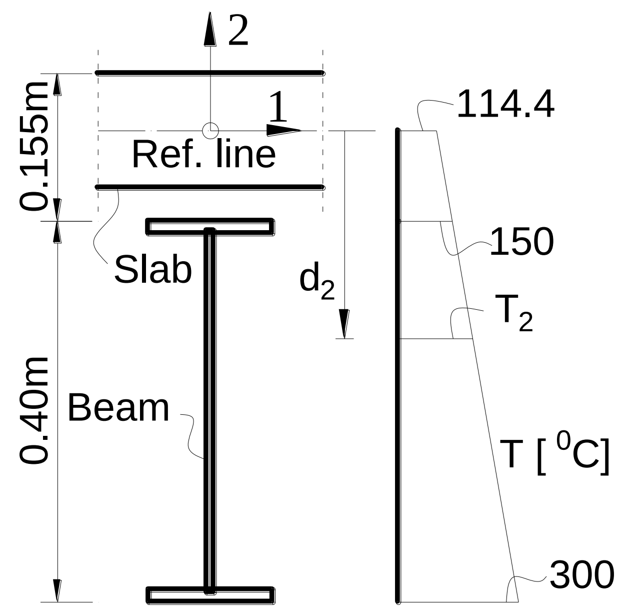


Numerical model

Temperature field for protected beams



Amplitude is function of reference line temperature obtained by linear interpolation

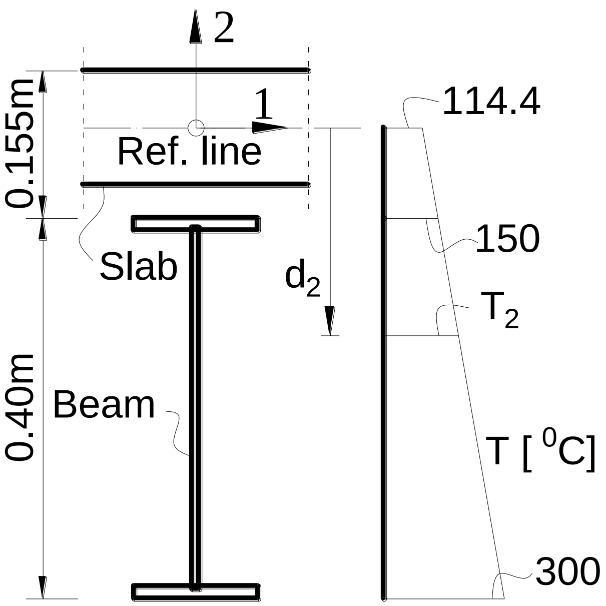


Numerical model

Temperature field for protected beams

Determination of gradient

$$\theta_{ref}\left(1+d_2\cdot x\right)=\theta_2$$



x – *gradient*

θ_{ref} – temperature at reference line level,

d_2 – distance from reference line to a point along direction 2;

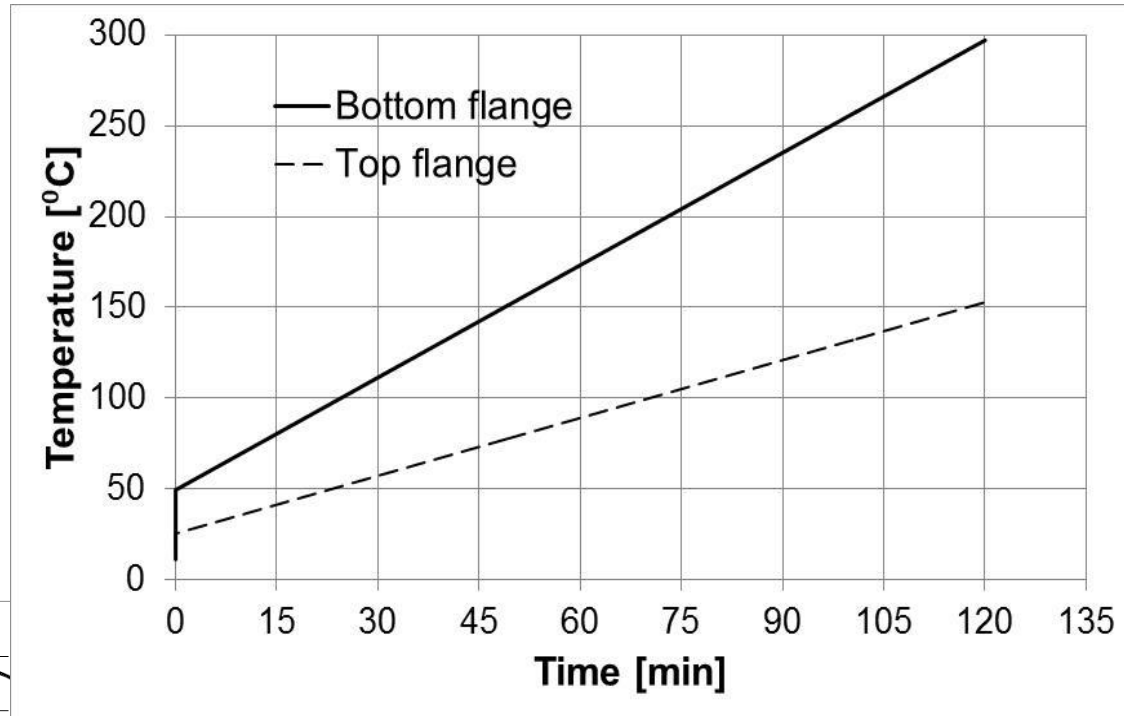
θ_2 – temperature at distance d_2

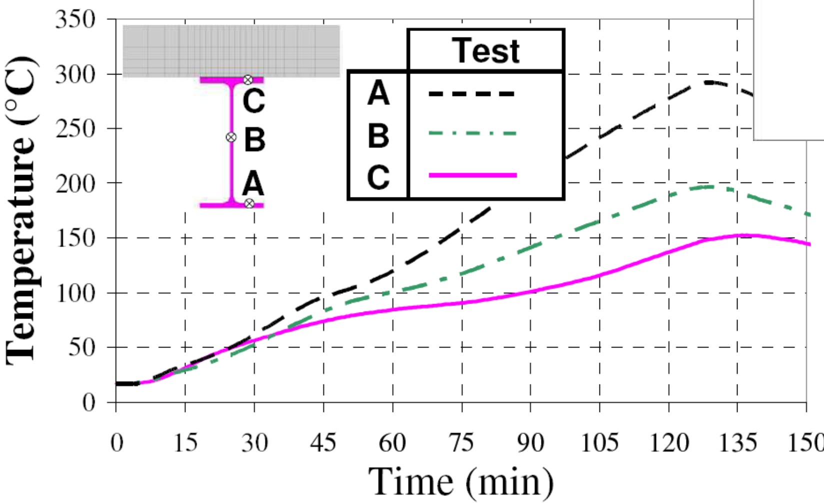
x ➔ -3.2757

Numerical model

Temperature field for protected beams

Results



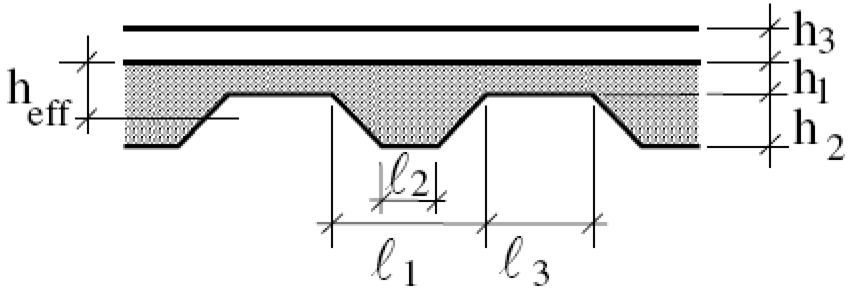


Numerical model

Temperature field for concrete slab

Sequentially coupled thermal-displacement analysis ➔ Create a separate heat transfer model (initial model for mechanical analysis – similar coordinates of slab)

It is considered an equivalent thickness of slab according to EN1994-1-2 Annex D



$$h_{eff} = h_1 + 0{,}5\, h_2 \left(\frac{\ell_1 + \ell_2}{\ell_1 + \ell_3} \right)$$ for $h_2/h_1 \leq 1{,}5$ and $h_1 > 40$ mm

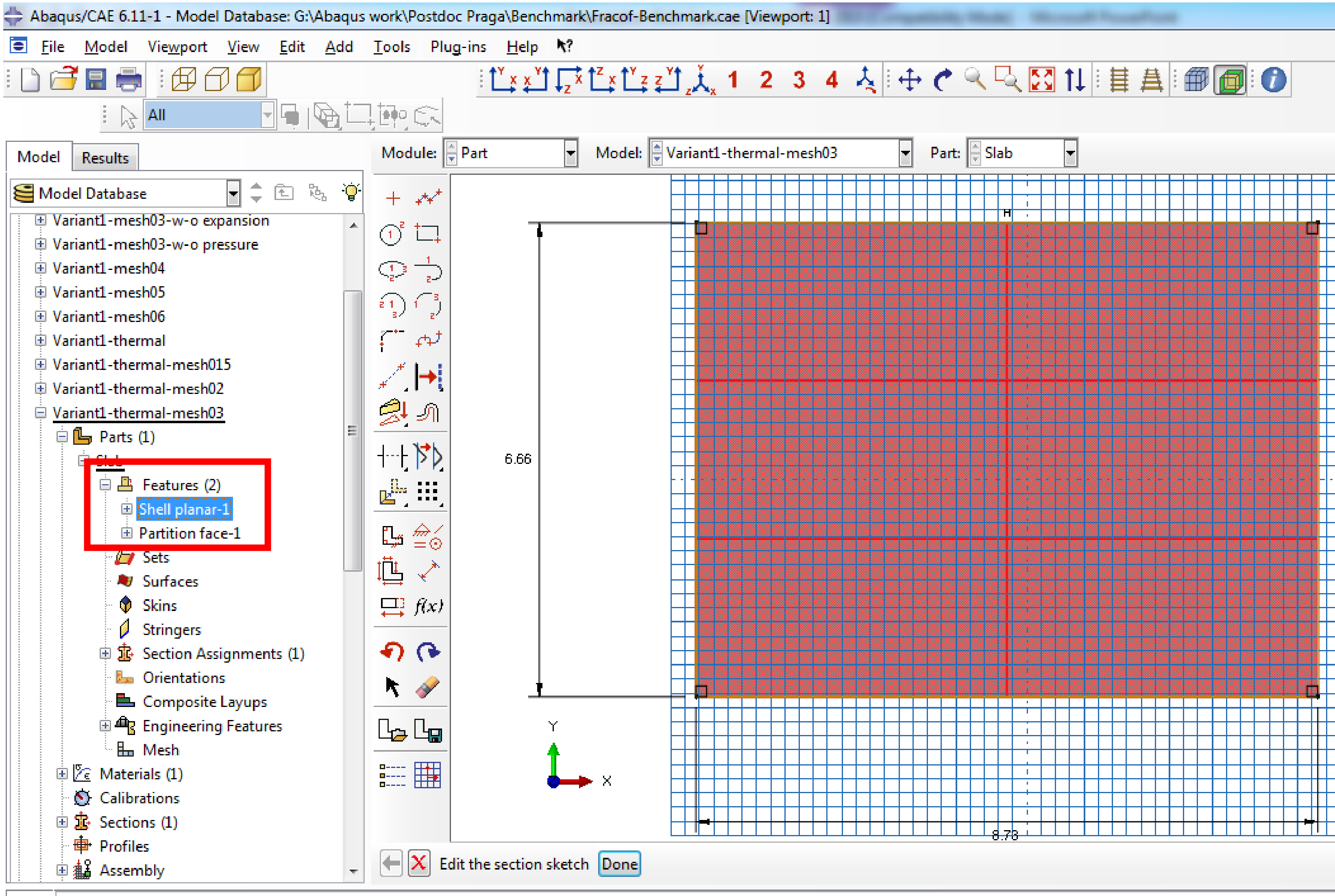
$$h_{eff} = h_1 \left[1 + 0{,}75 \left(\frac{\ell_1 + \ell_2}{\ell_1 + \ell_3} \right) \right]$$ for $h_2/h_1 > 1{,}5$ and $h_1 > 40$ mm

Numerical model

Temperature field for concrete slab

Create the part and partition:

-3D shell planar



Numerical model

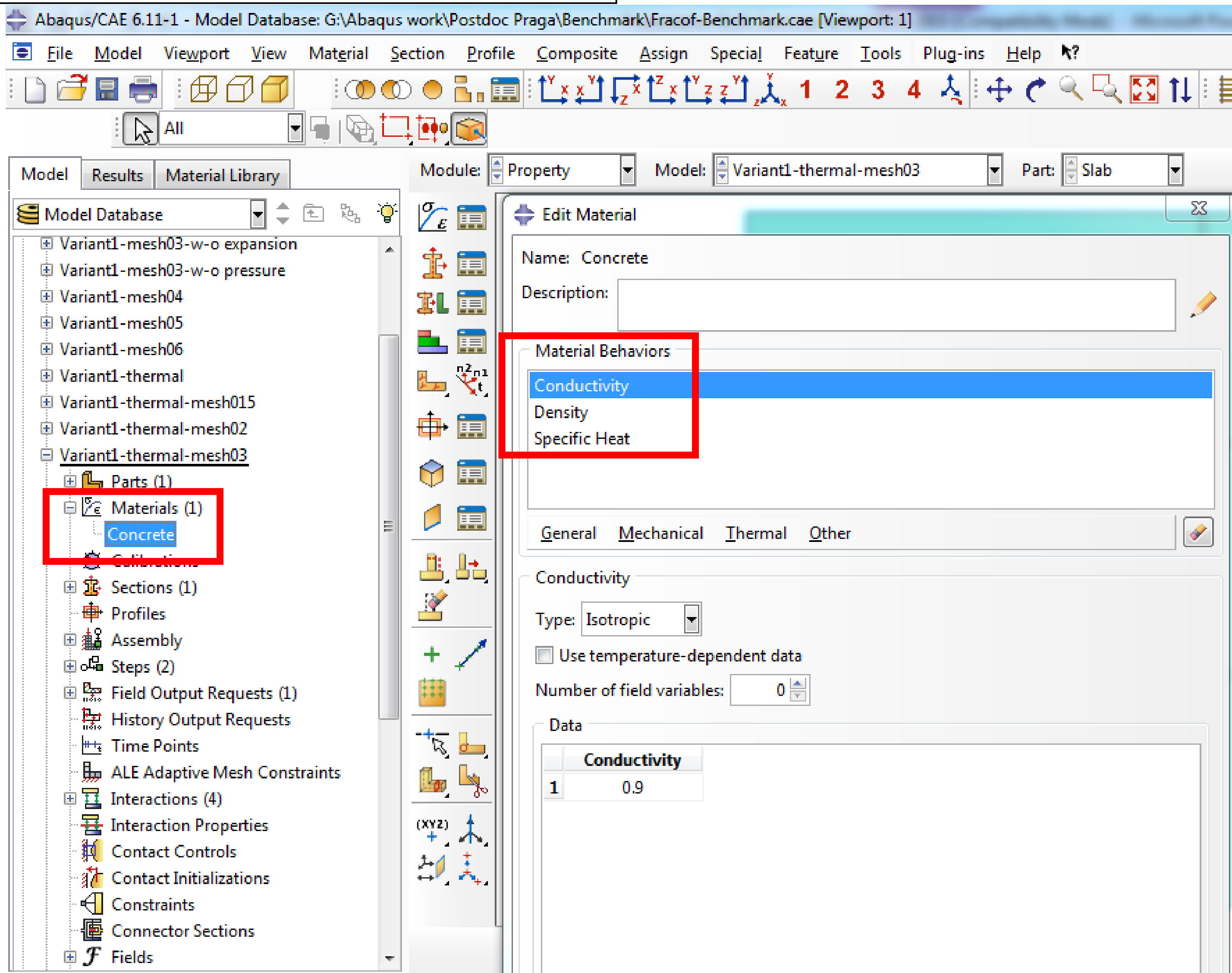
Temperature field for concrete slab

Define material:

-conductivity

-specific heat

-density



Numerical model

Temperature field for concrete slab

Define section:

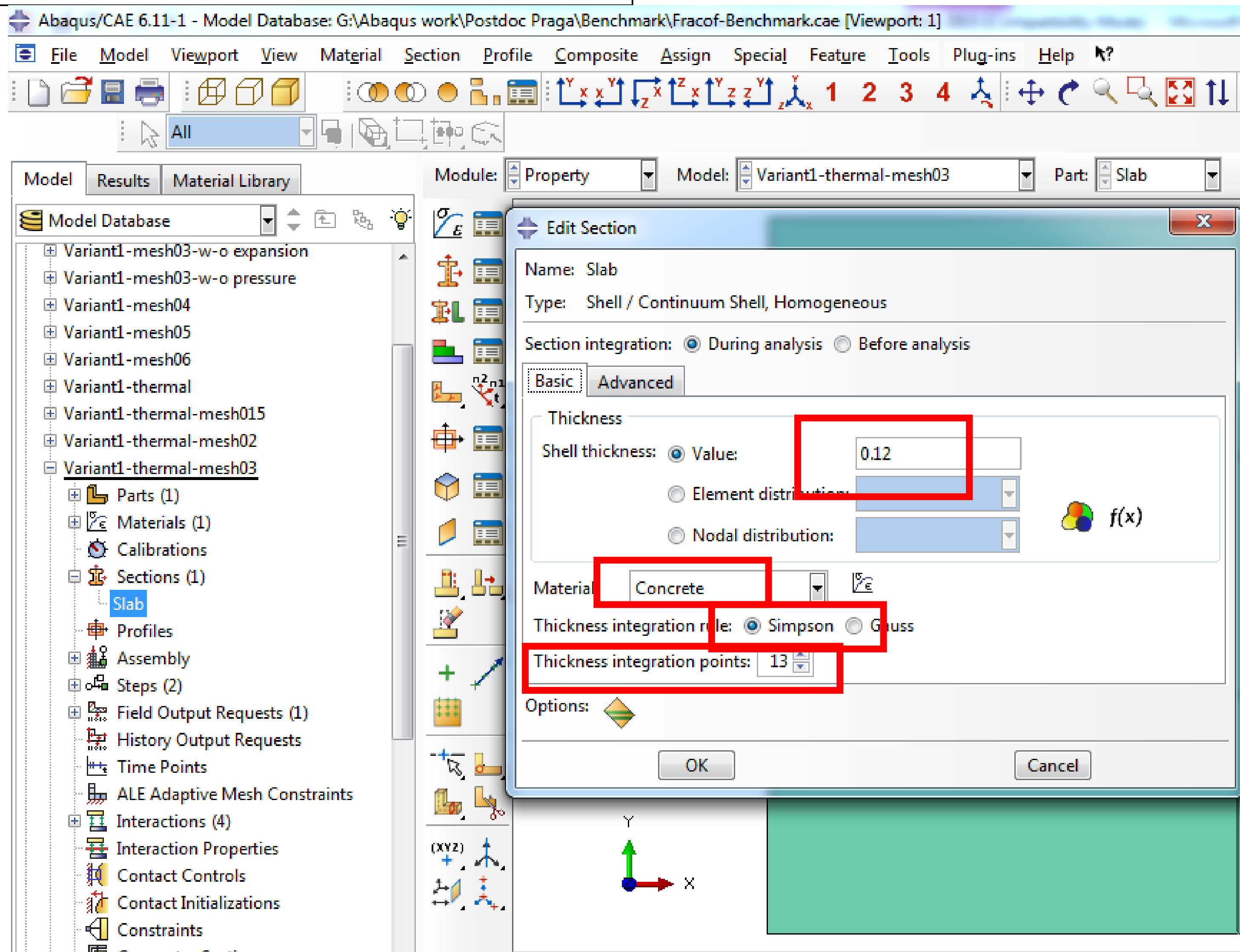
-thickness

-material

-integration rule

-integration points

(without reinforment, yet)

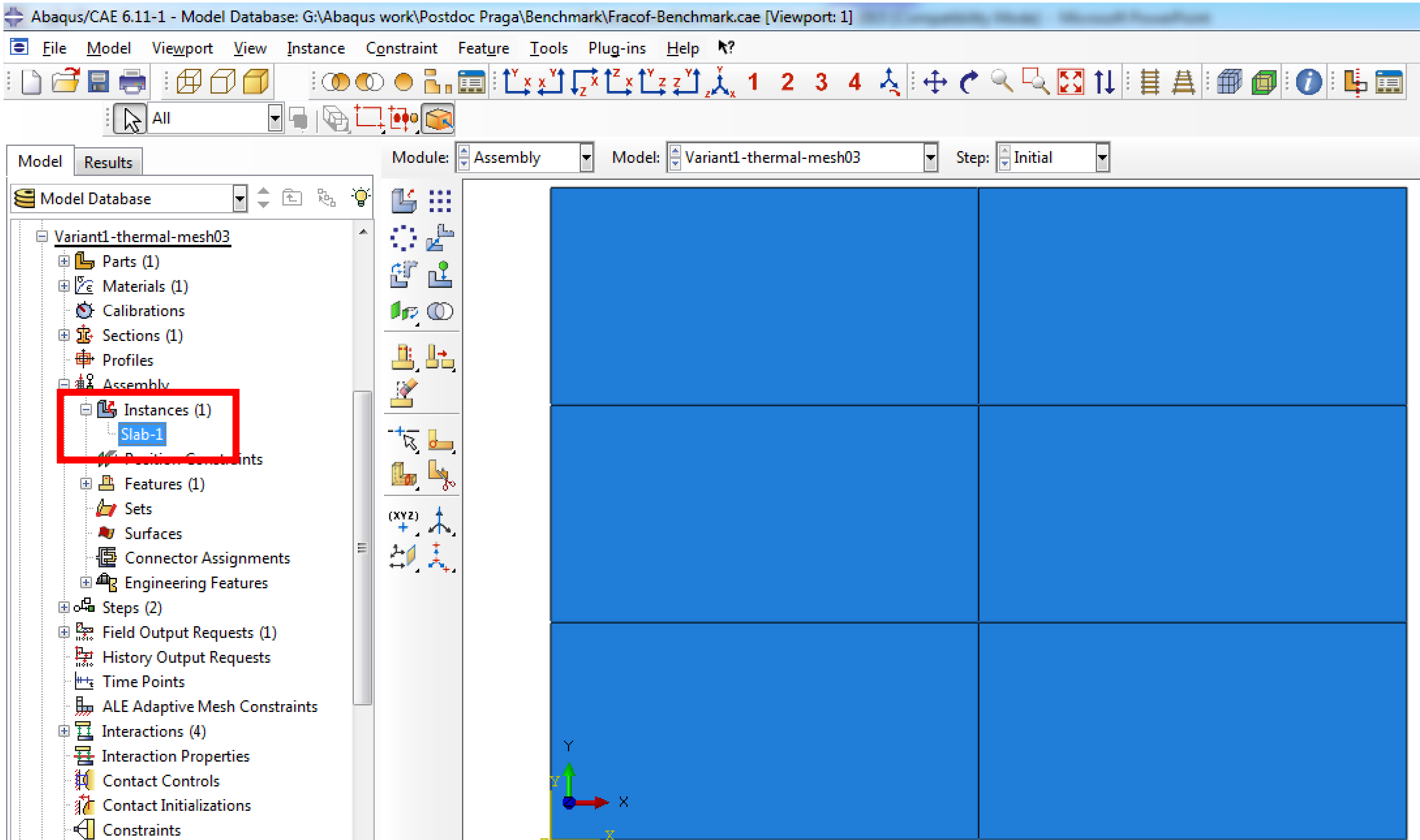


Numerical model

Temperature field for concrete slab

Create instances:

-slab



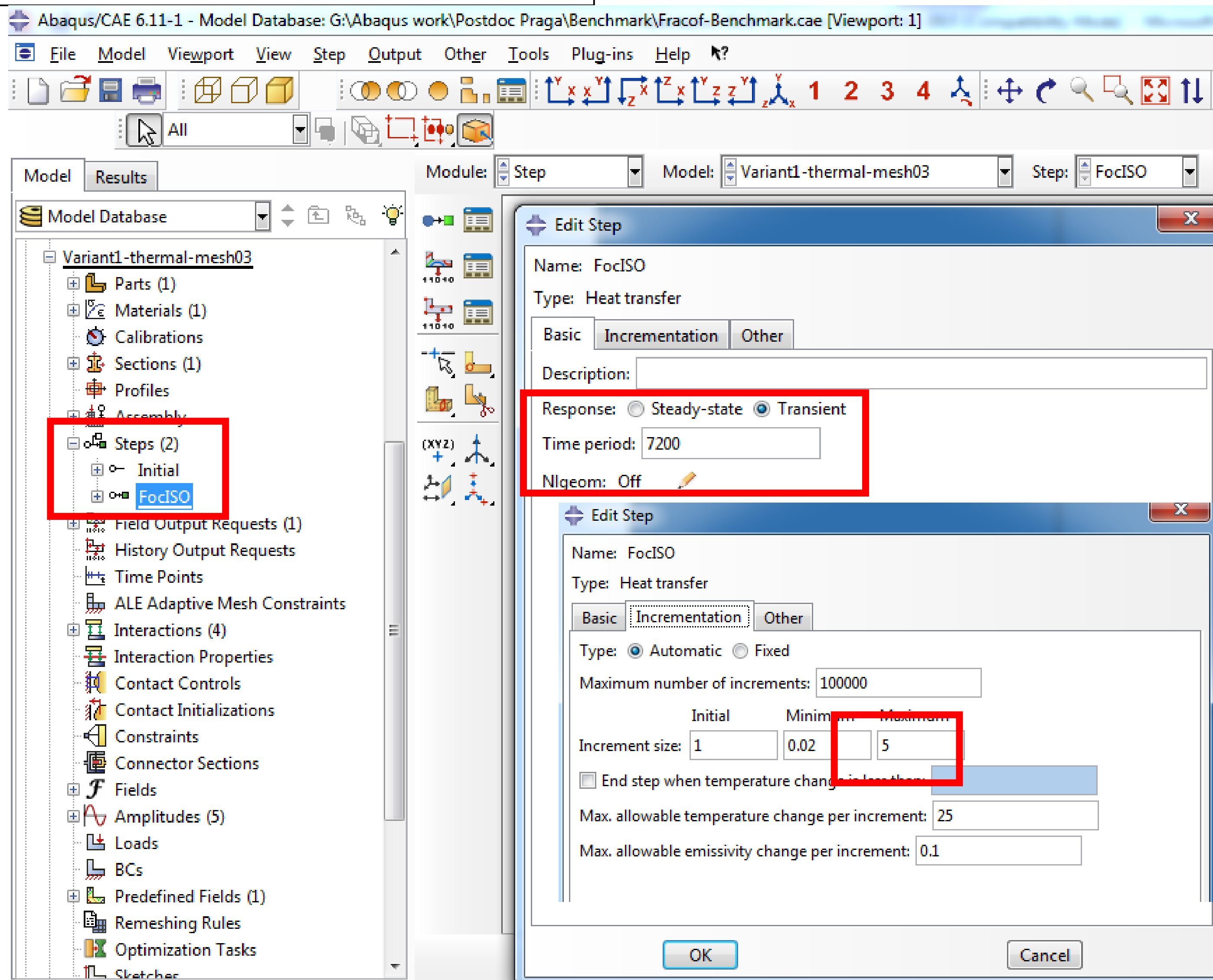
Numerical model

Temperature field for concrete slab

Define heat transfer step:

-transient

-time



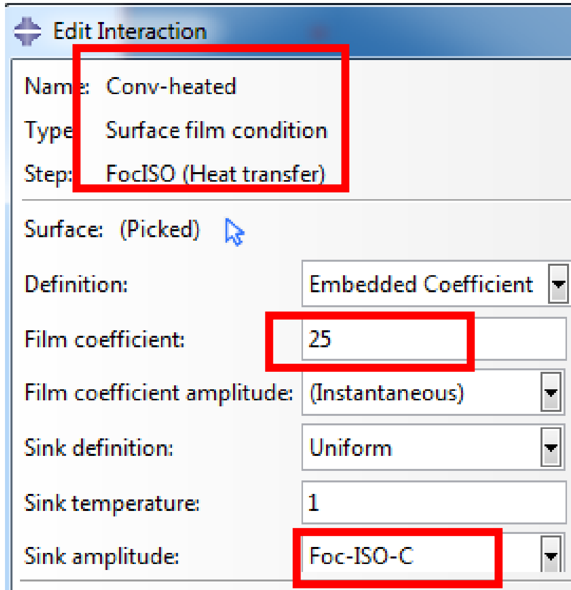
Numerical model

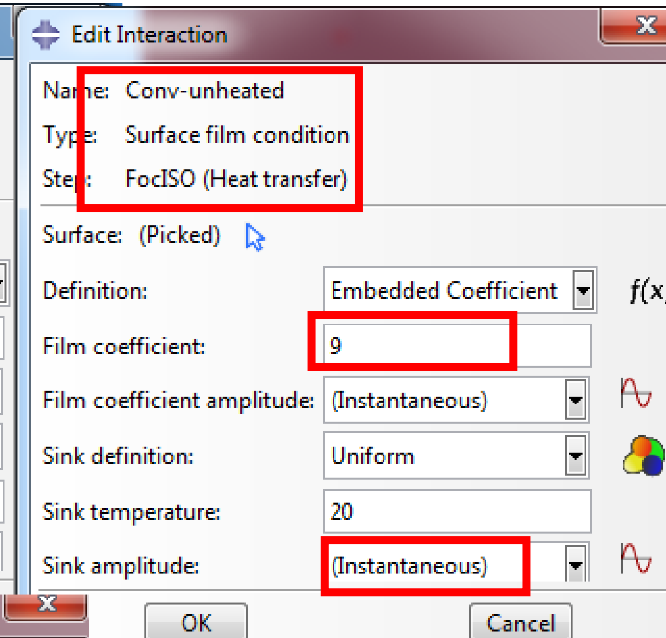
Temperature field for concrete slab

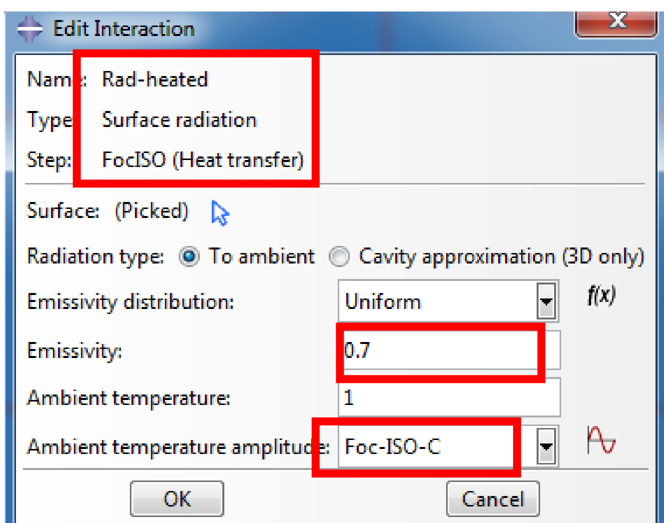
Define interactions:

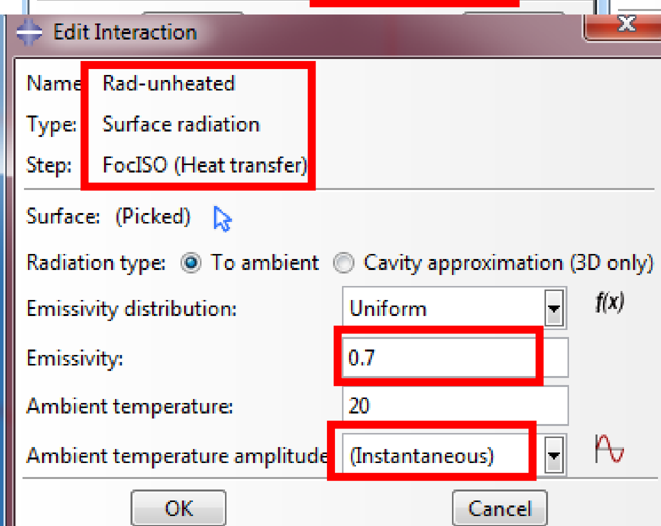
-convection for heated and unheated sides

-radiation for heated and unheated side







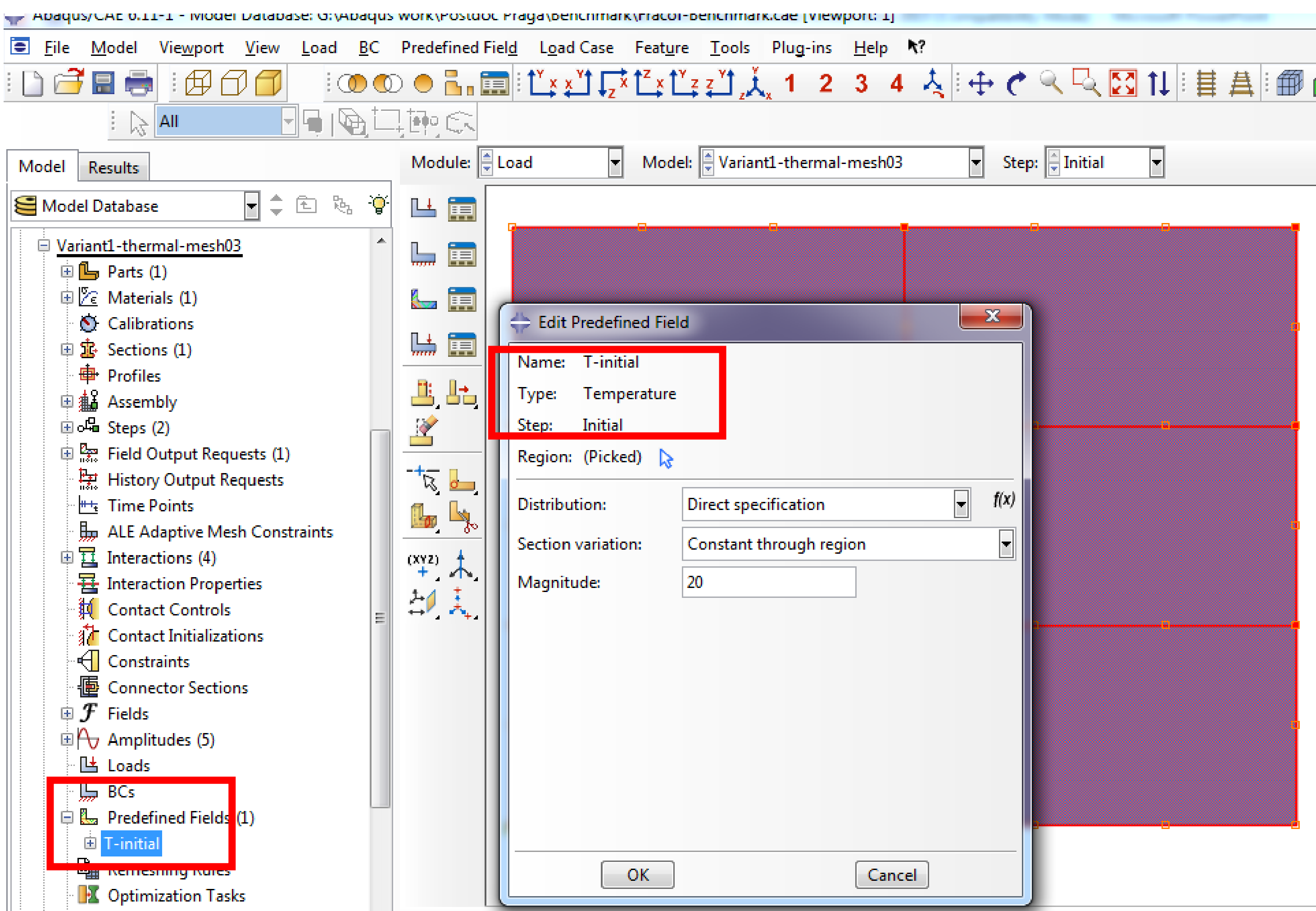


Numerical model

Temperature field for concrete slab

Define initial temperature:

-predefined field – constant through region

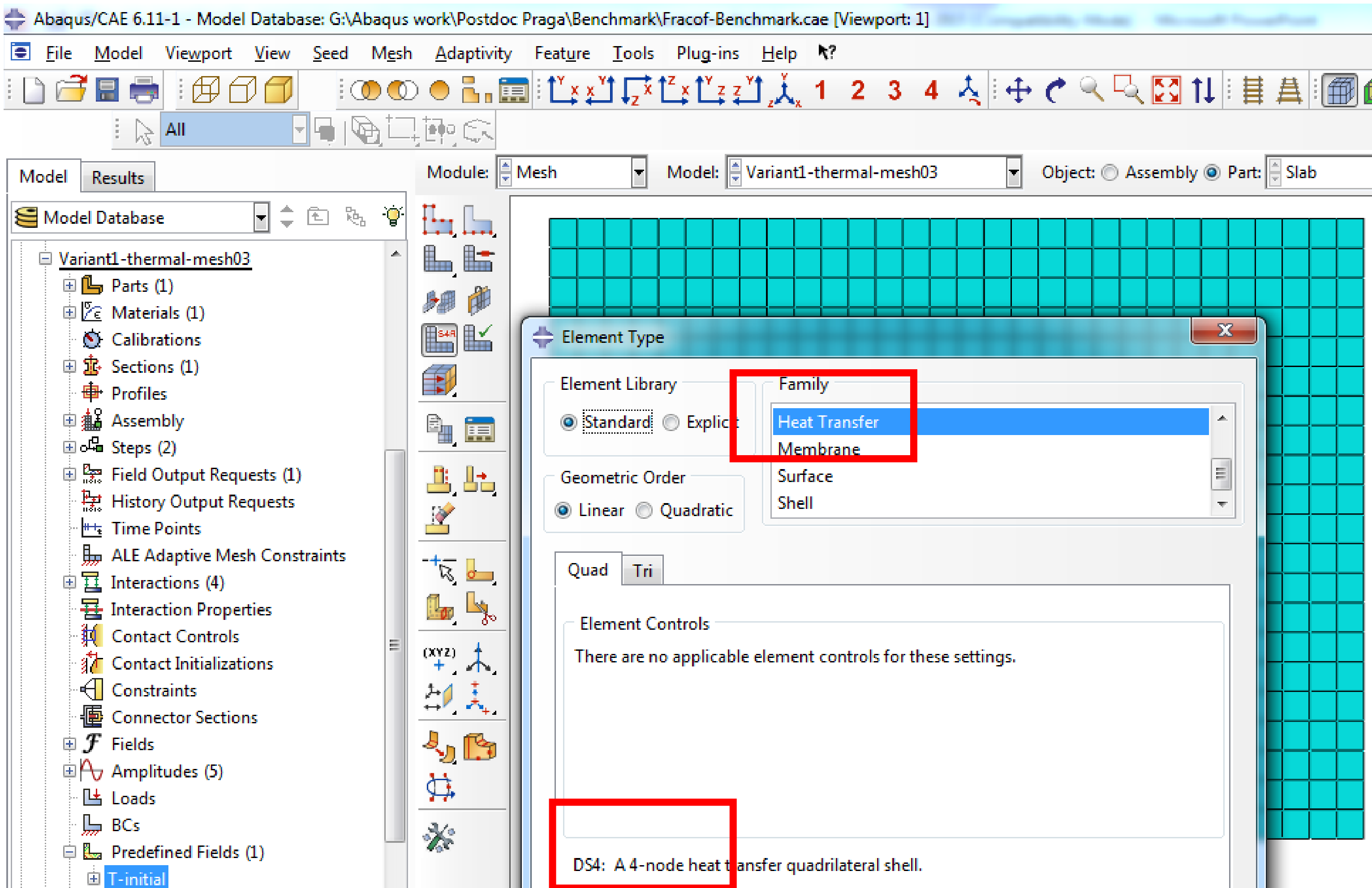


Numerical model

Temperature field for concrete slab

Define mesh and finite elements:

DS4 (0.3 m)

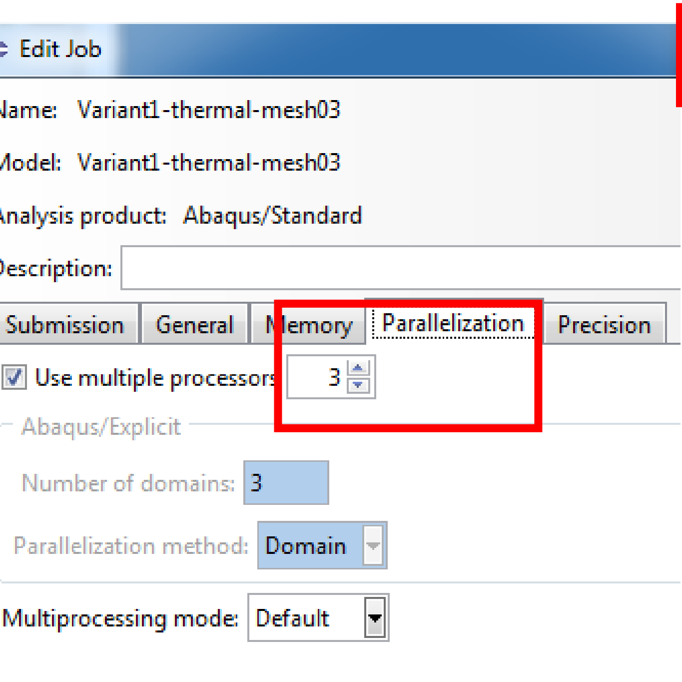


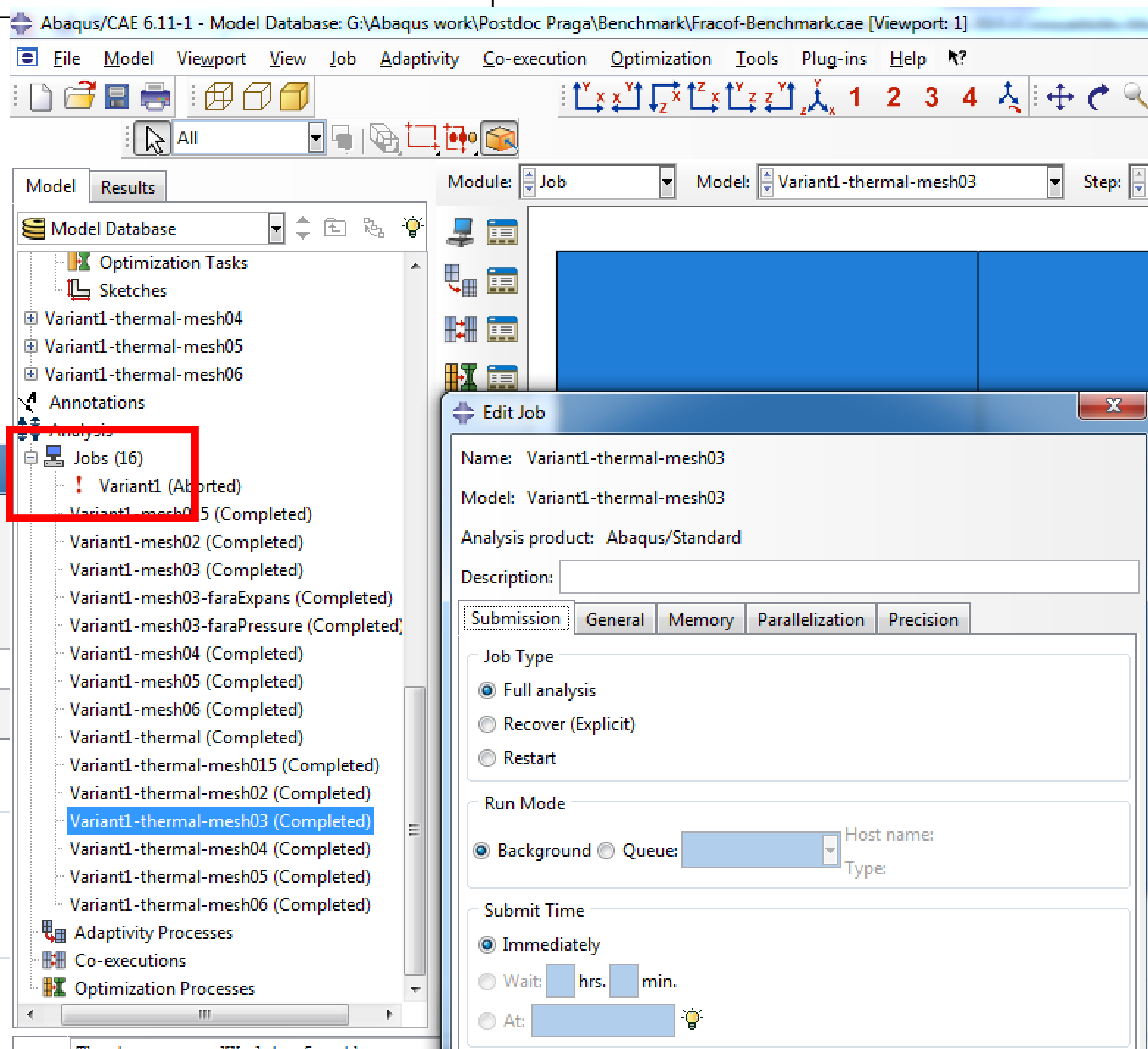
Numerical model

Temperature field for concrete slab

Run analysis:

Create job and submit



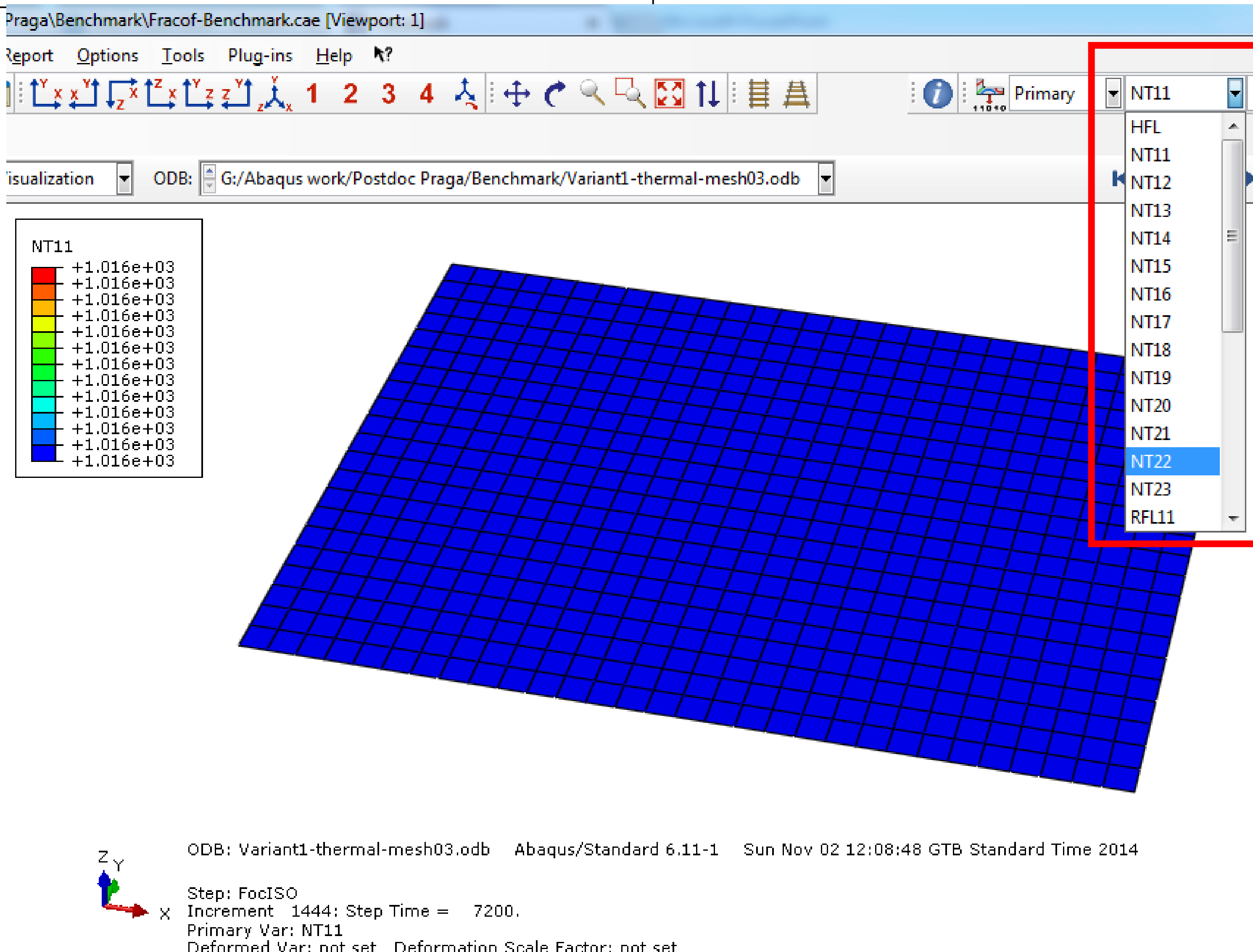


Numerical model

Temperature field for concrete slab

Results:

Nodal temperatures

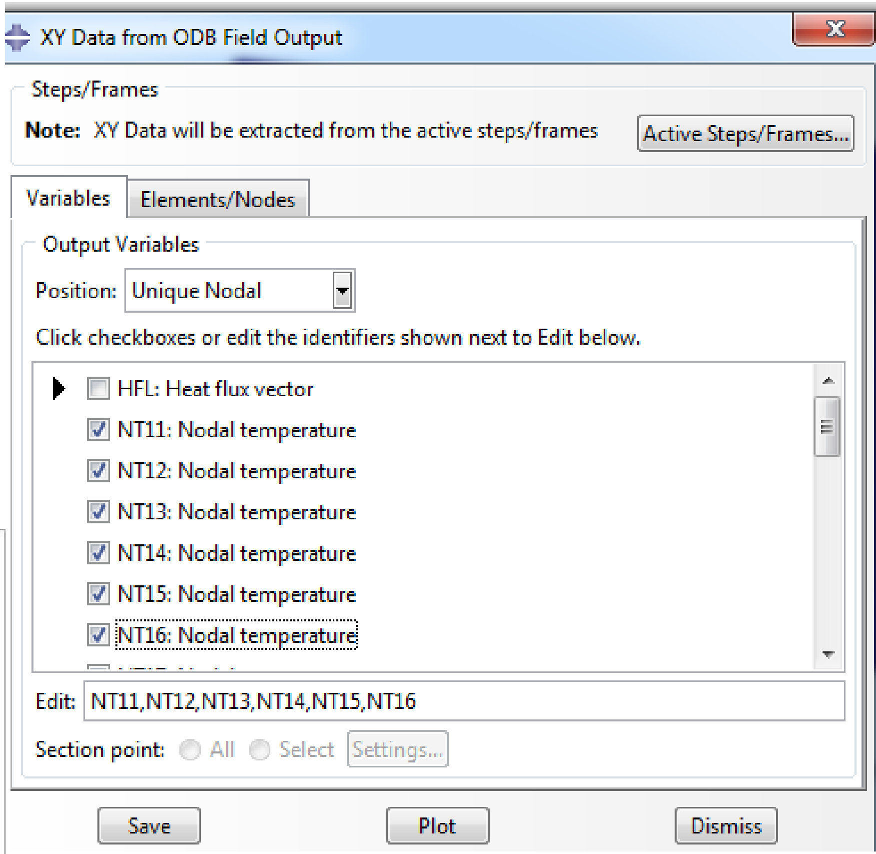


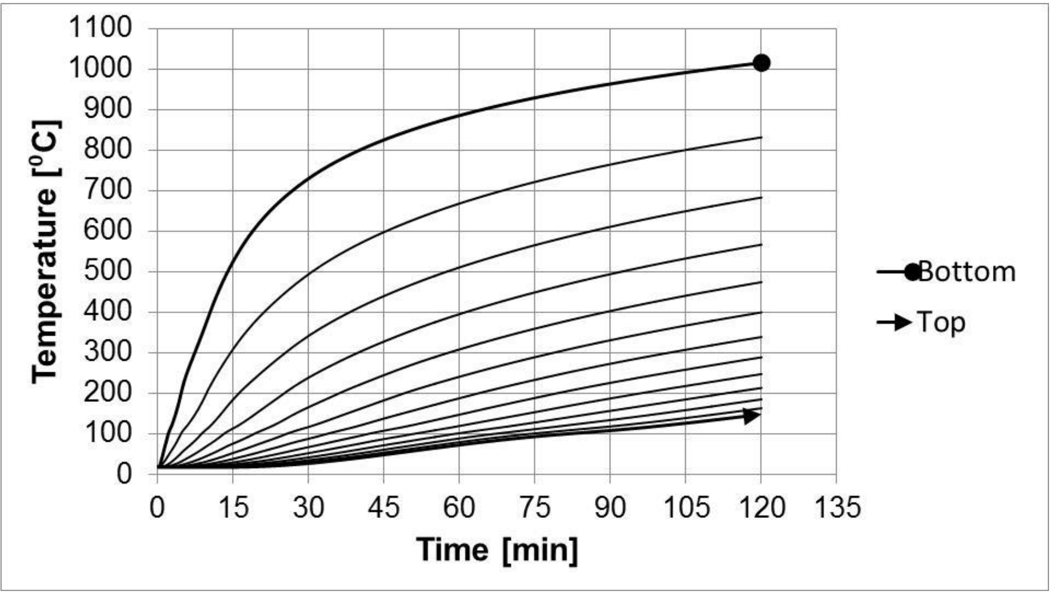
Numerical model

Temperature field for concrete slab

Results:

Nodal temperatures





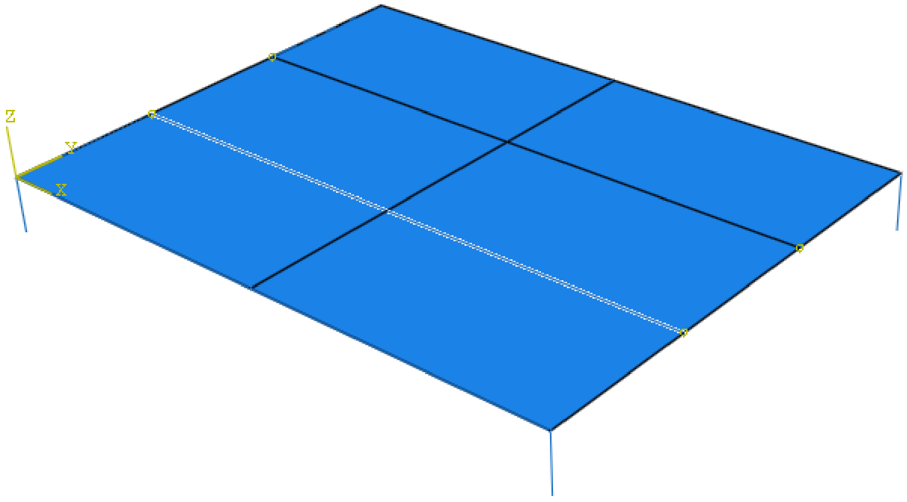
Numerical model

Structural analysis of composite slab

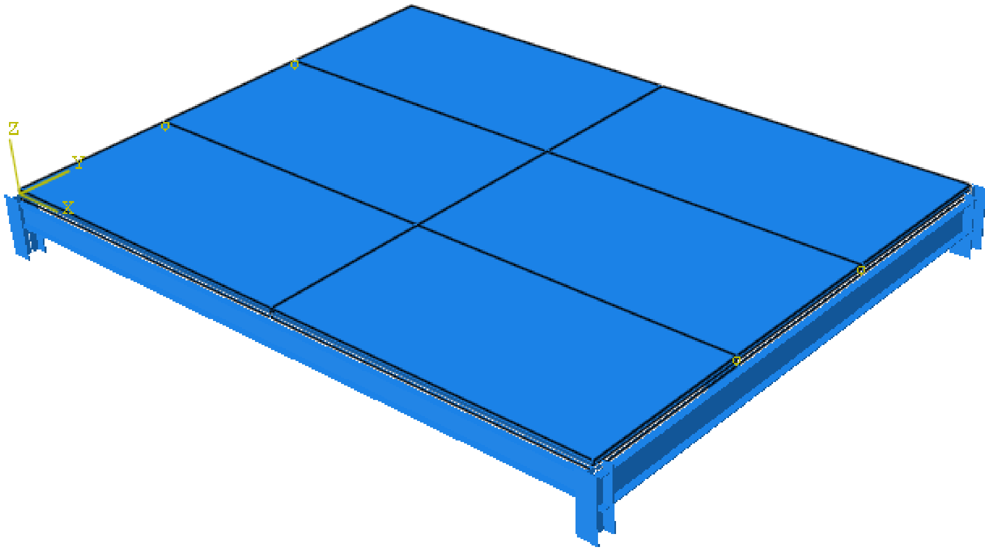
Starts from a saved as model of thermal analysis of concrete slab

All structural elements, beams and columns, are defined as linear *wire element*

Wireframe



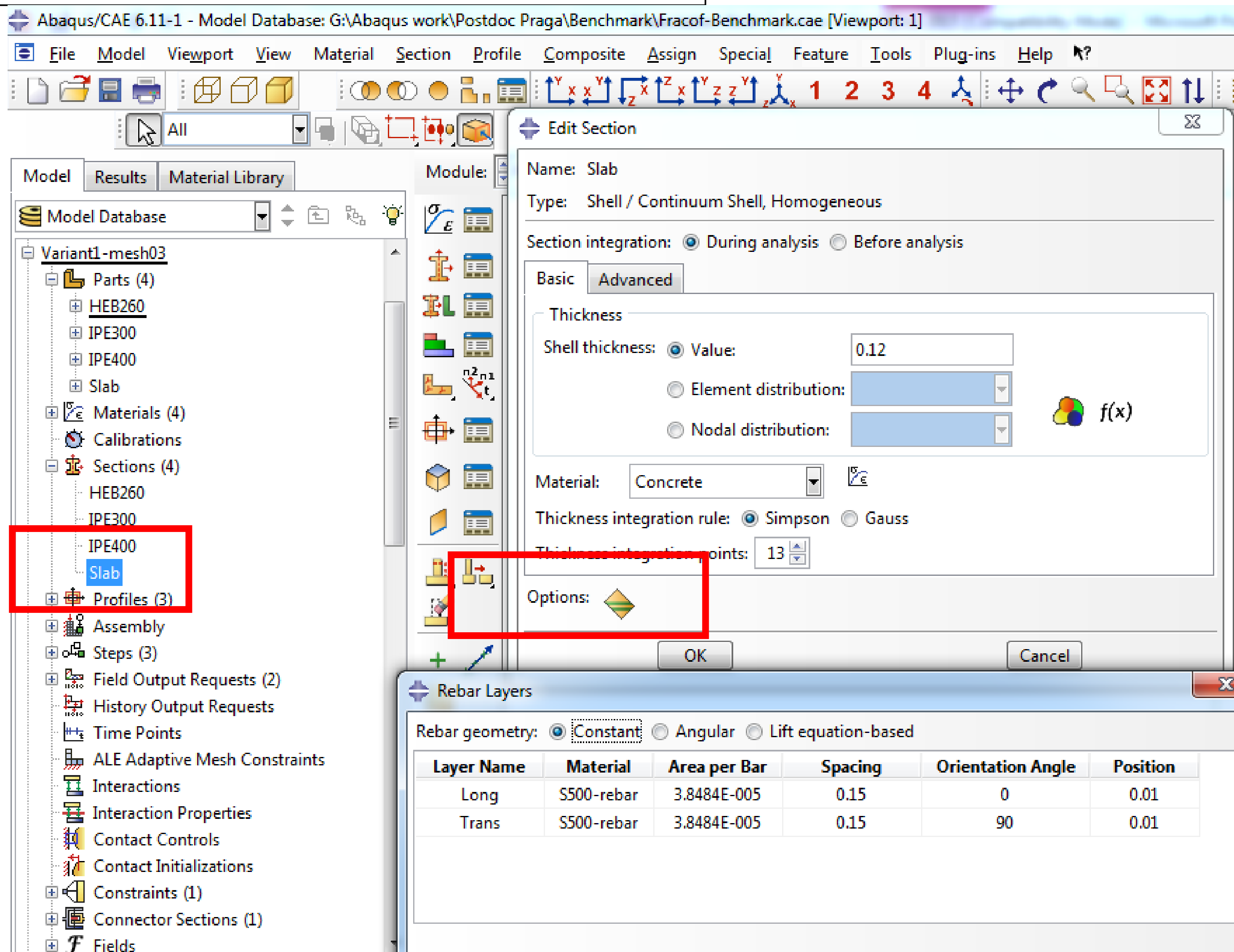
Rendered view



Numerical model

Structural analysis of composite slab

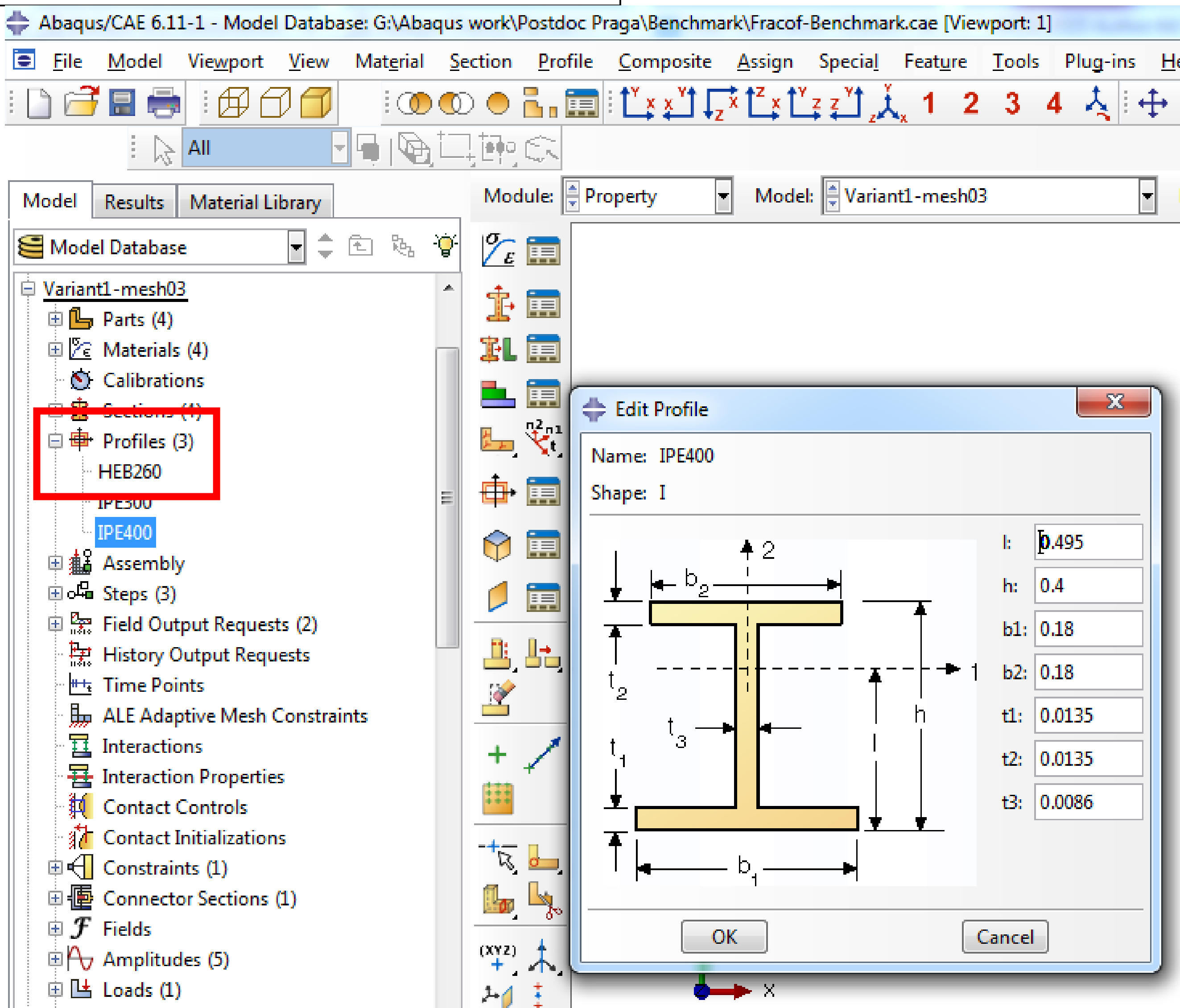
Add the reinforcement of the concrete slab



Numerical model

Structural analysis of composite slab

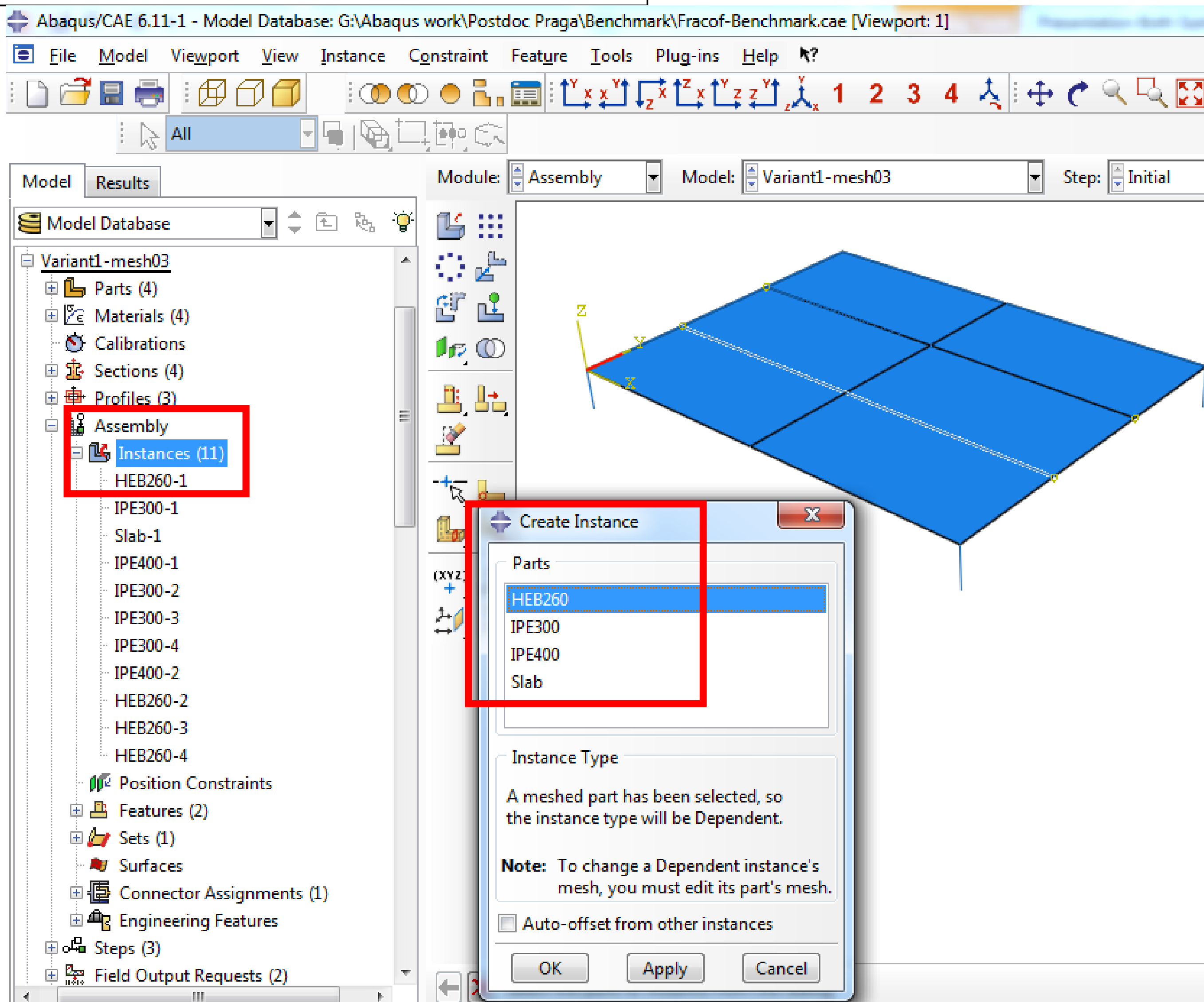
Define “profiles” for the wire elements and orientation



Numerical model

Structural analysis of composite slab

Create "instances" from parts for all elements and "construct" the structure



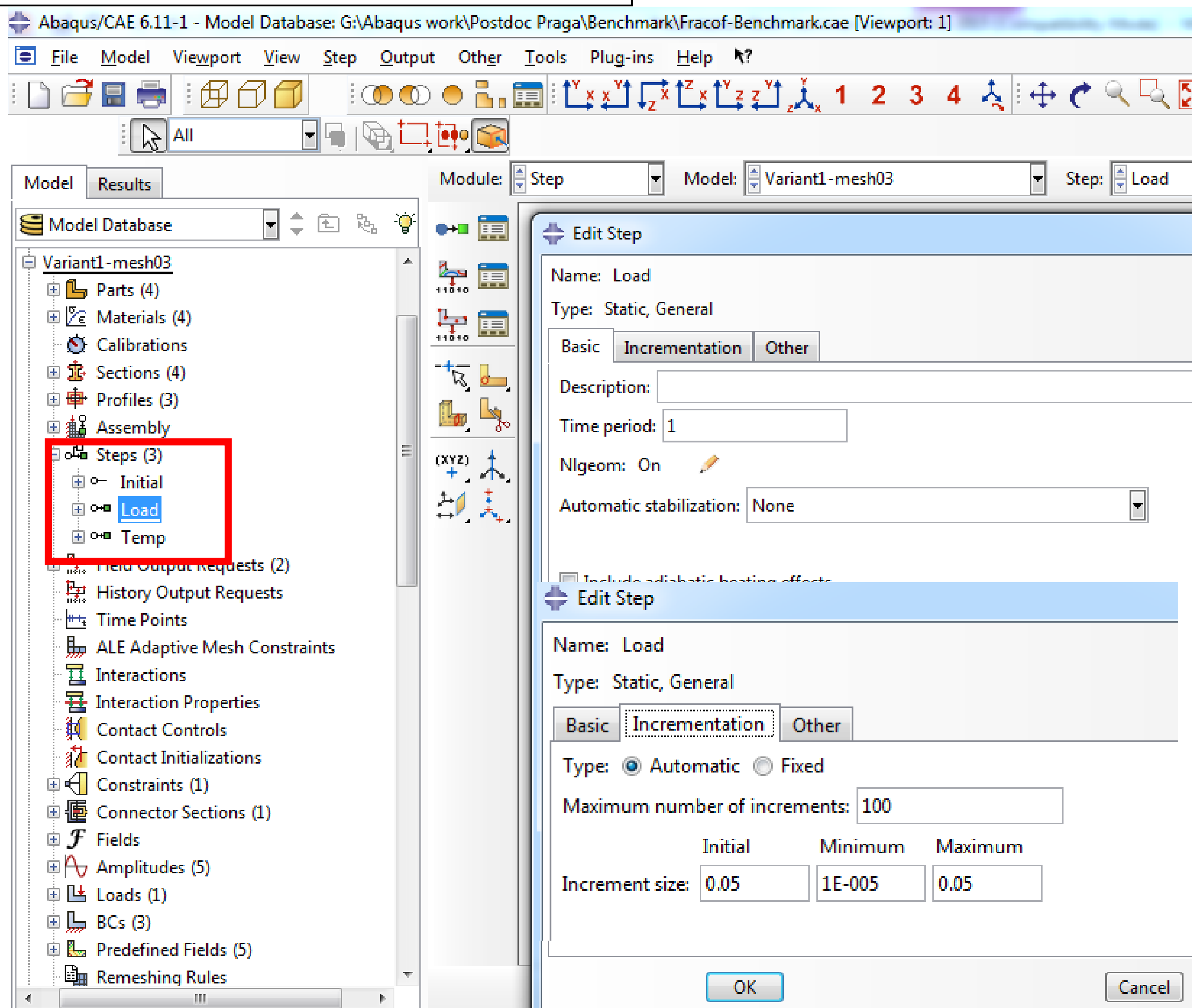
Numerical model

Structural analysis of composite slab

Define steps for analysis:

-for mechanical loading

-for temperature influence



Both steps are "Static, General"

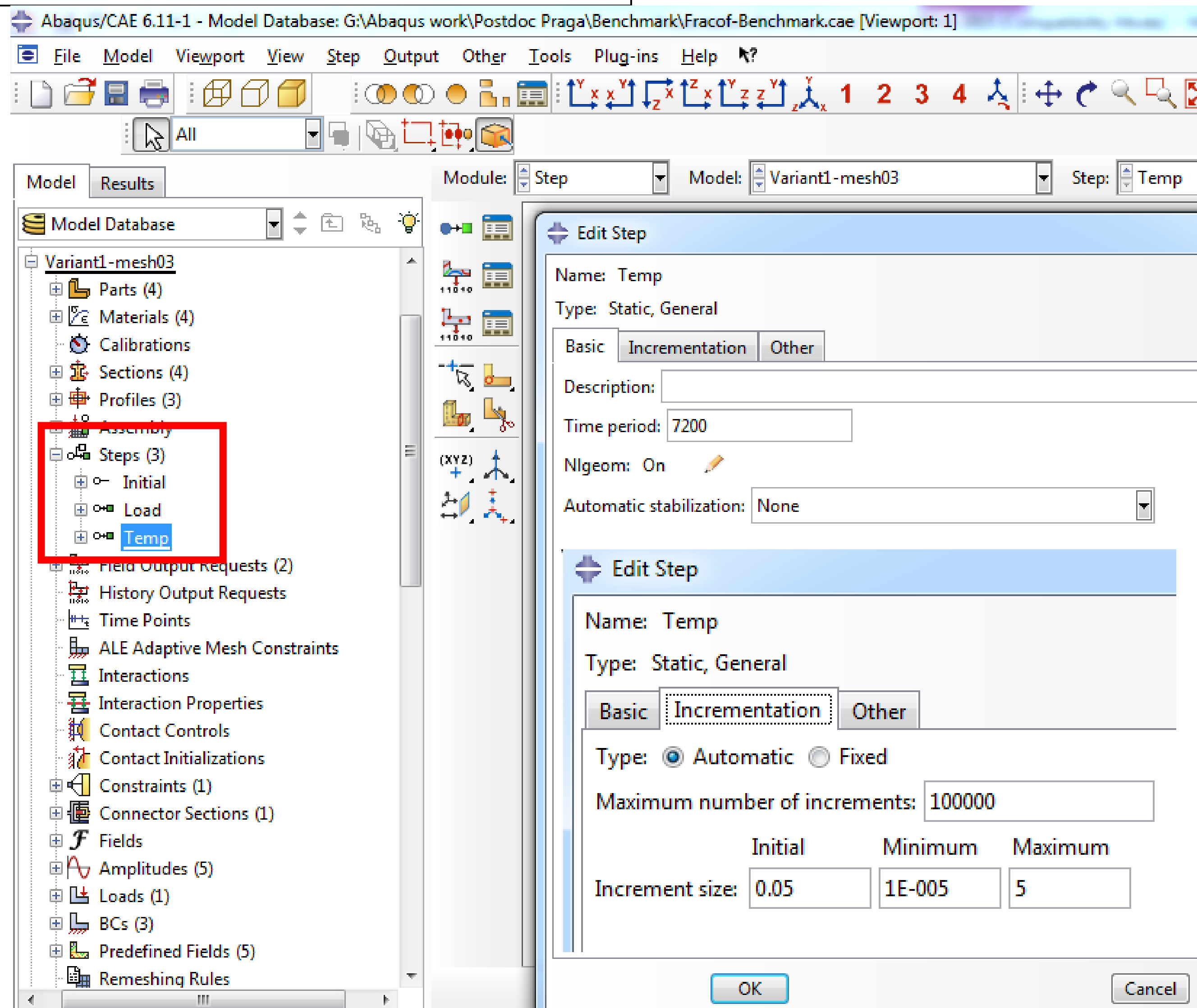
Numerical model

Structural analysis of composite slab

Define steps for analysis:

-for mechanical loading

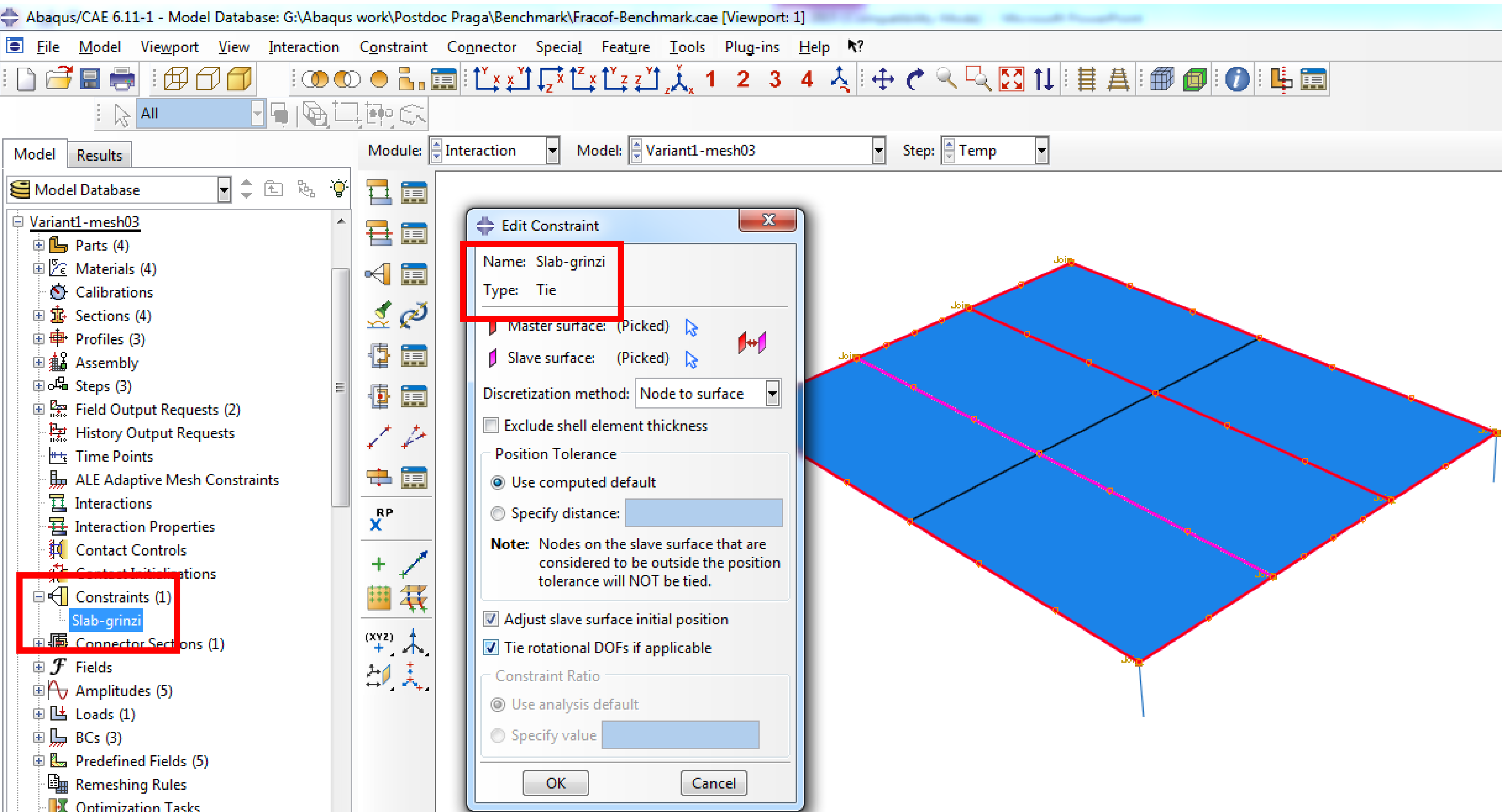
-for temperature influence



Numerical model

Structural analysis of composite slab

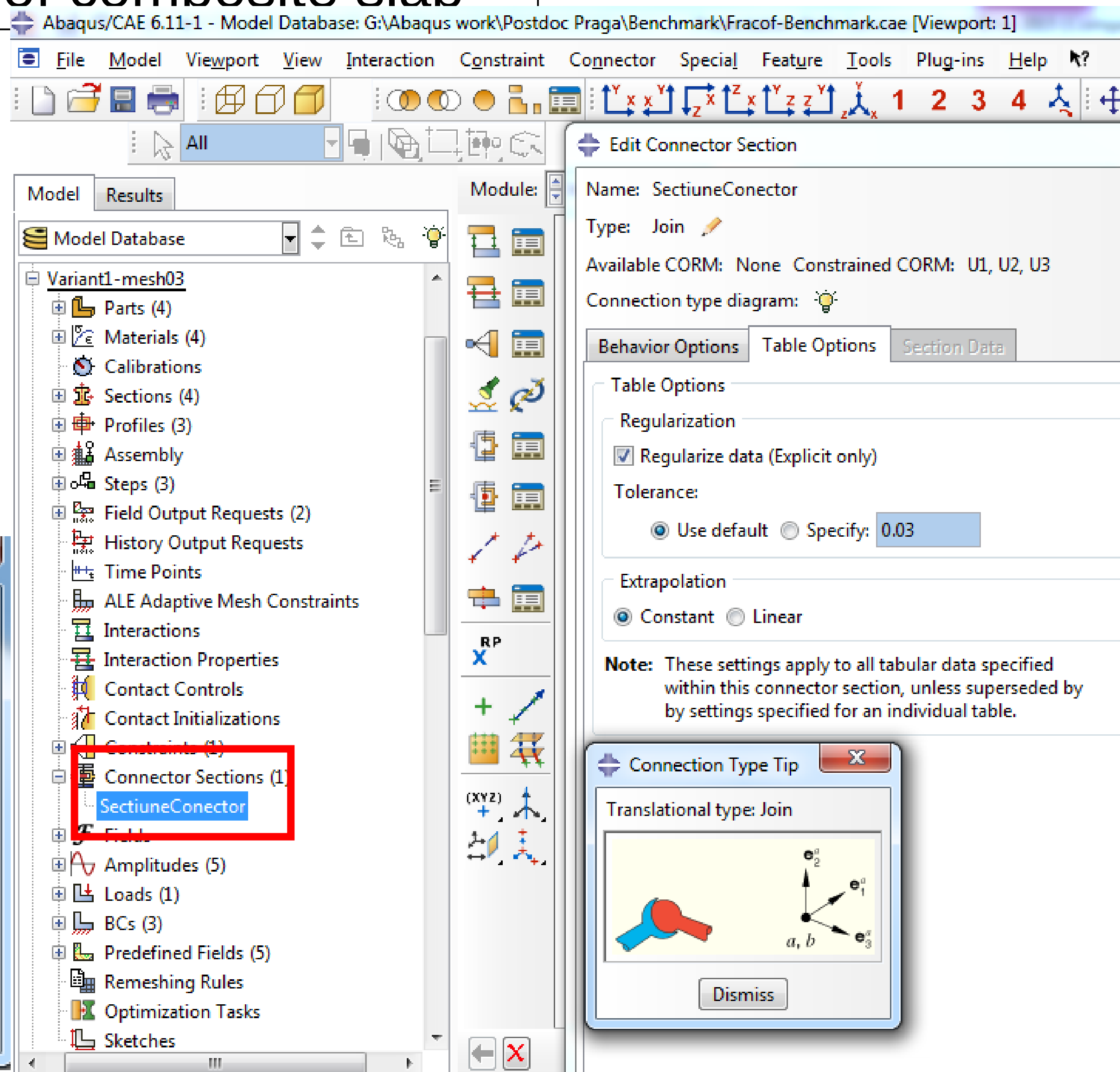
Define mechanical interactions between slab and beams: *constraints*

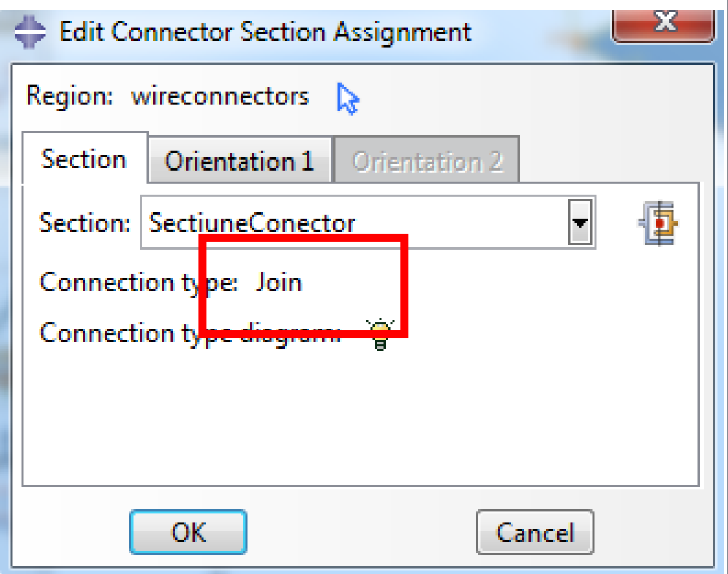


Numerical model

Structural analysis of composite slab

Define mechanical interactions of connections: *connector section "join"*





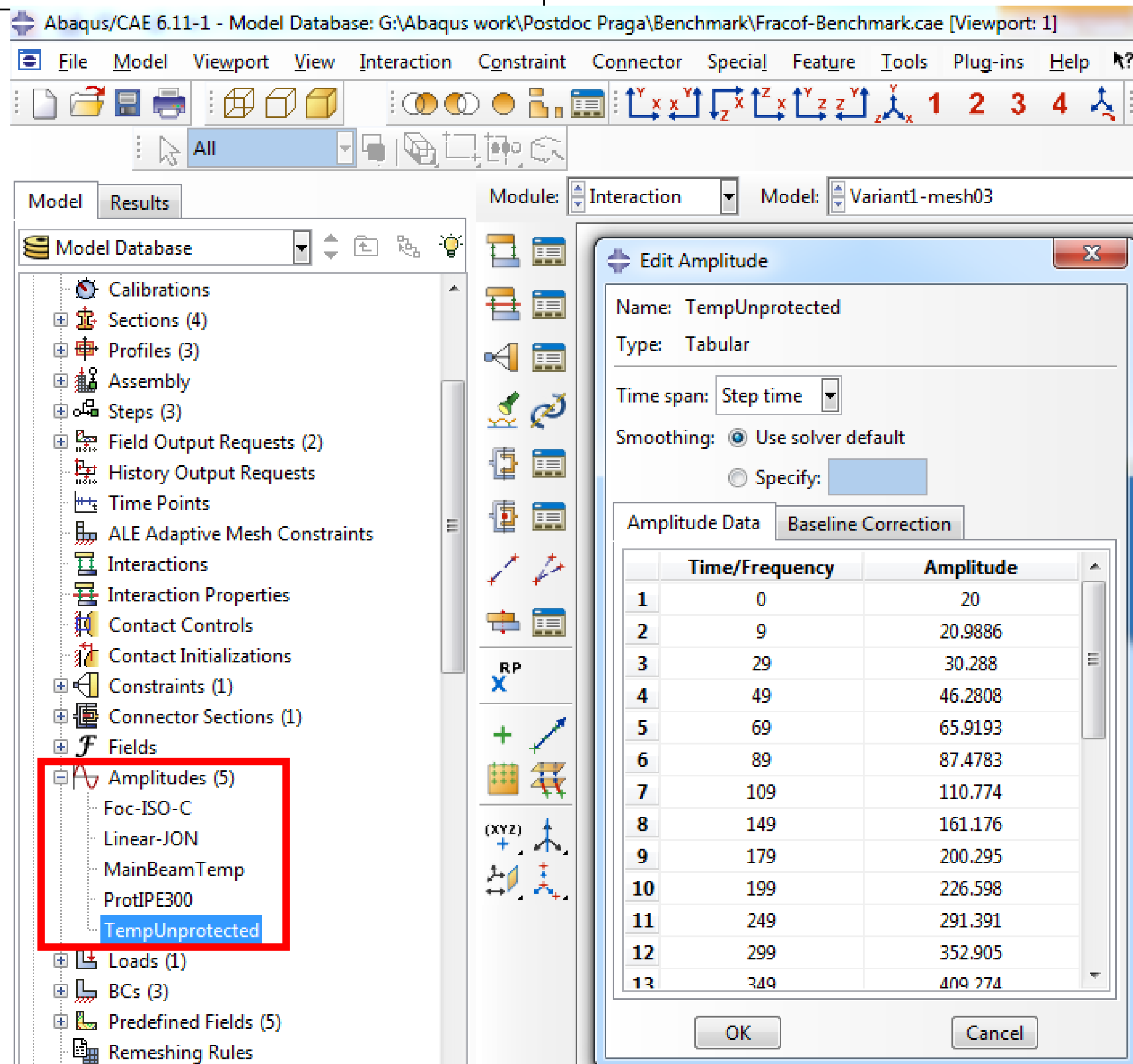
Numerical model

Structural analysis of composite slab

Define *Amplitudes* :

-temperature of unprotected beams,

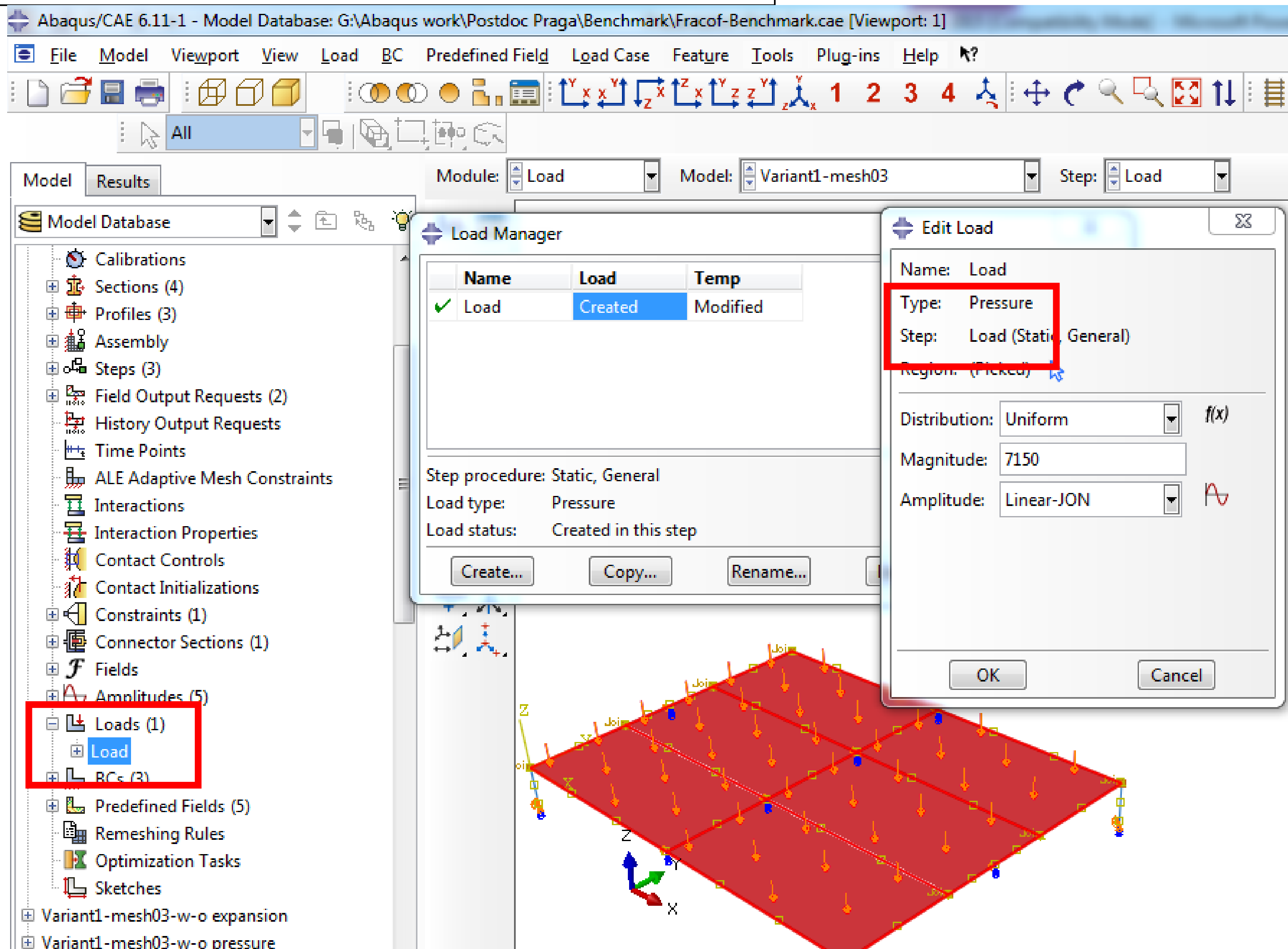
-variation of reference lines for protected primary and secondary beams.



Numerical model

Structural analysis of composite slab

Define *Loads* -Pressure.



Numerical model

Structural analysis of composite slab

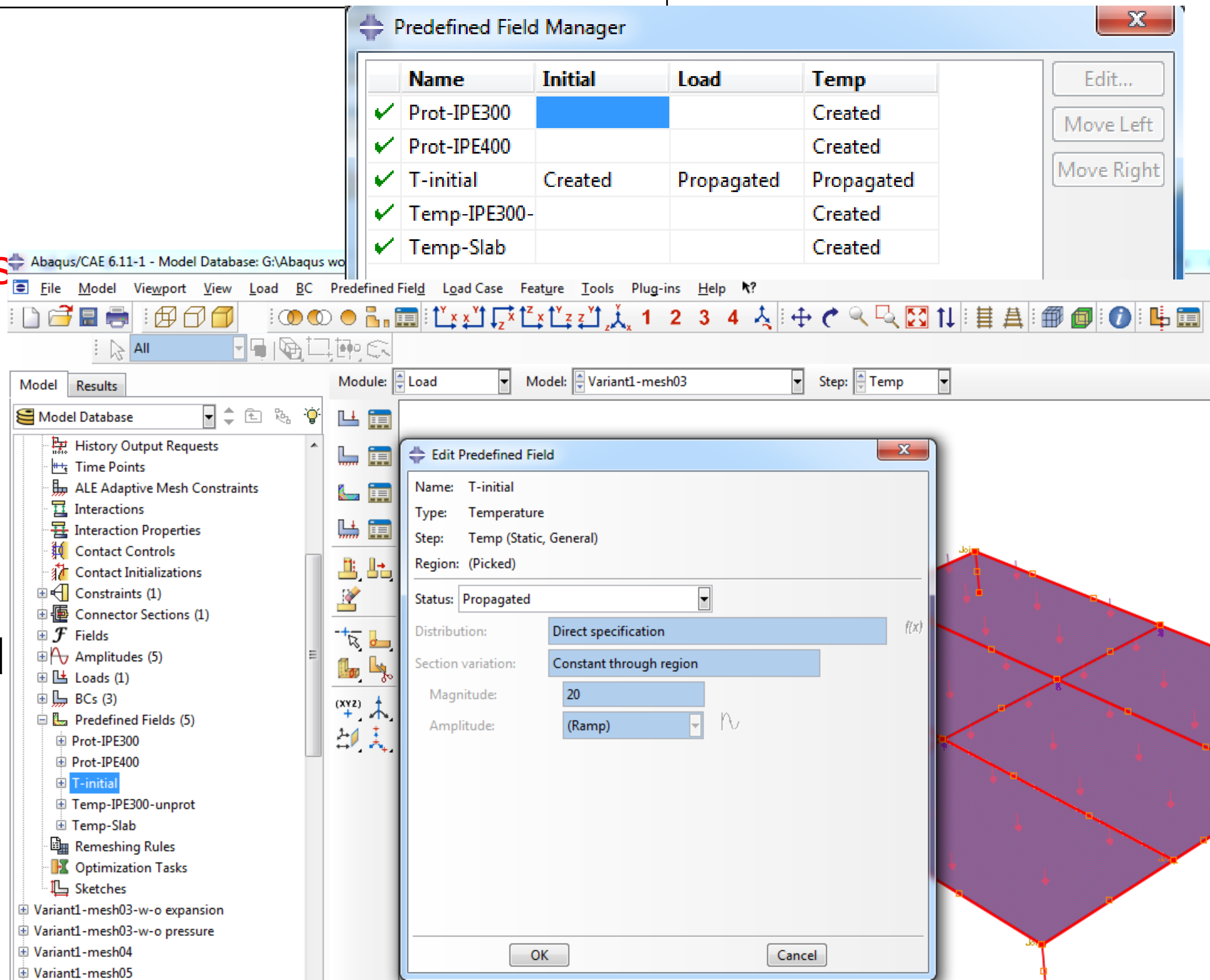
Predefined fields:

-Initial temperatures (entire structure)

-Gradients through beam section (protected beams)

-Constant through region (unprotected beam)

-From thermal analysis data base (slab)



Numerical model

Structural analysis of composite slab

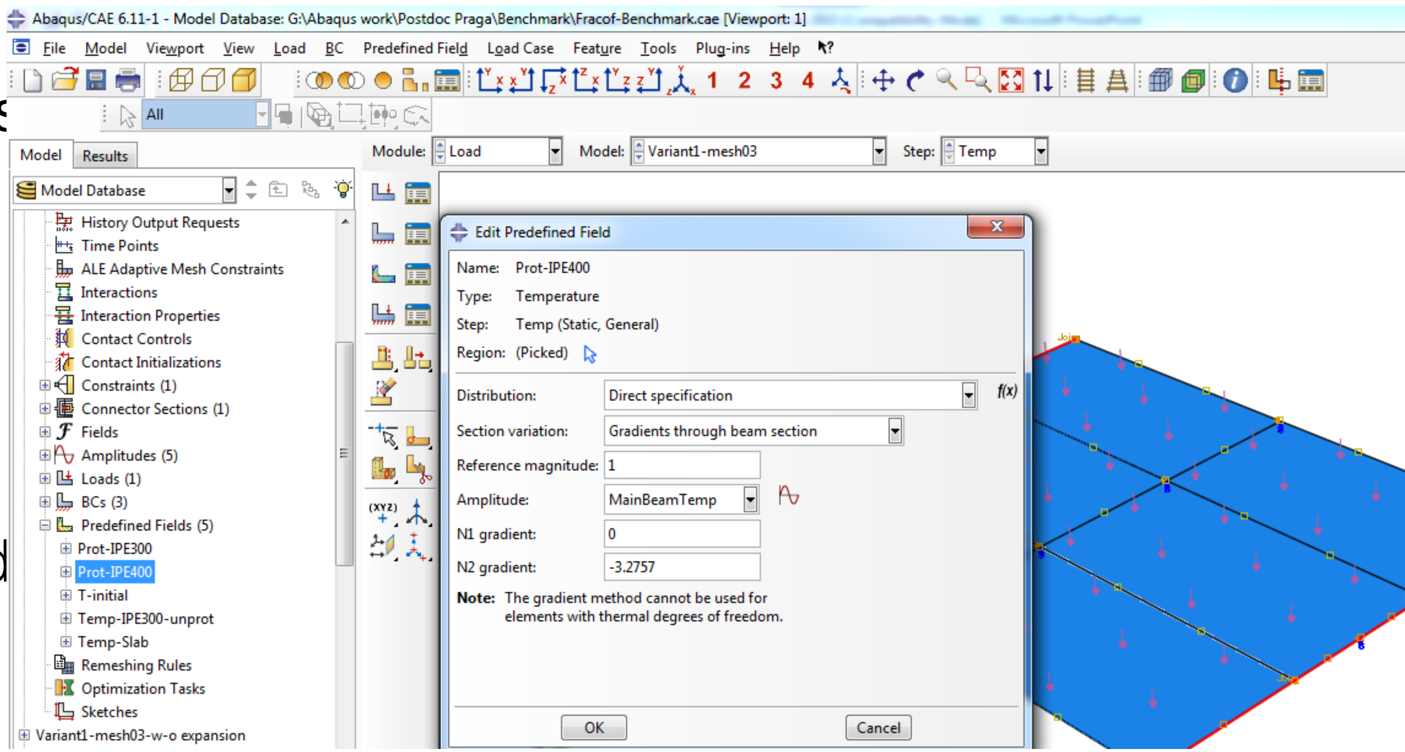
Predefined fields:

-Initial temperatures (entire structure)

-Gradients through beam section (protected beams)

-Constant through region (unprotected beam)

-From thermal analysis data base (slab)



Numerical model

Structural analysis of composite slab

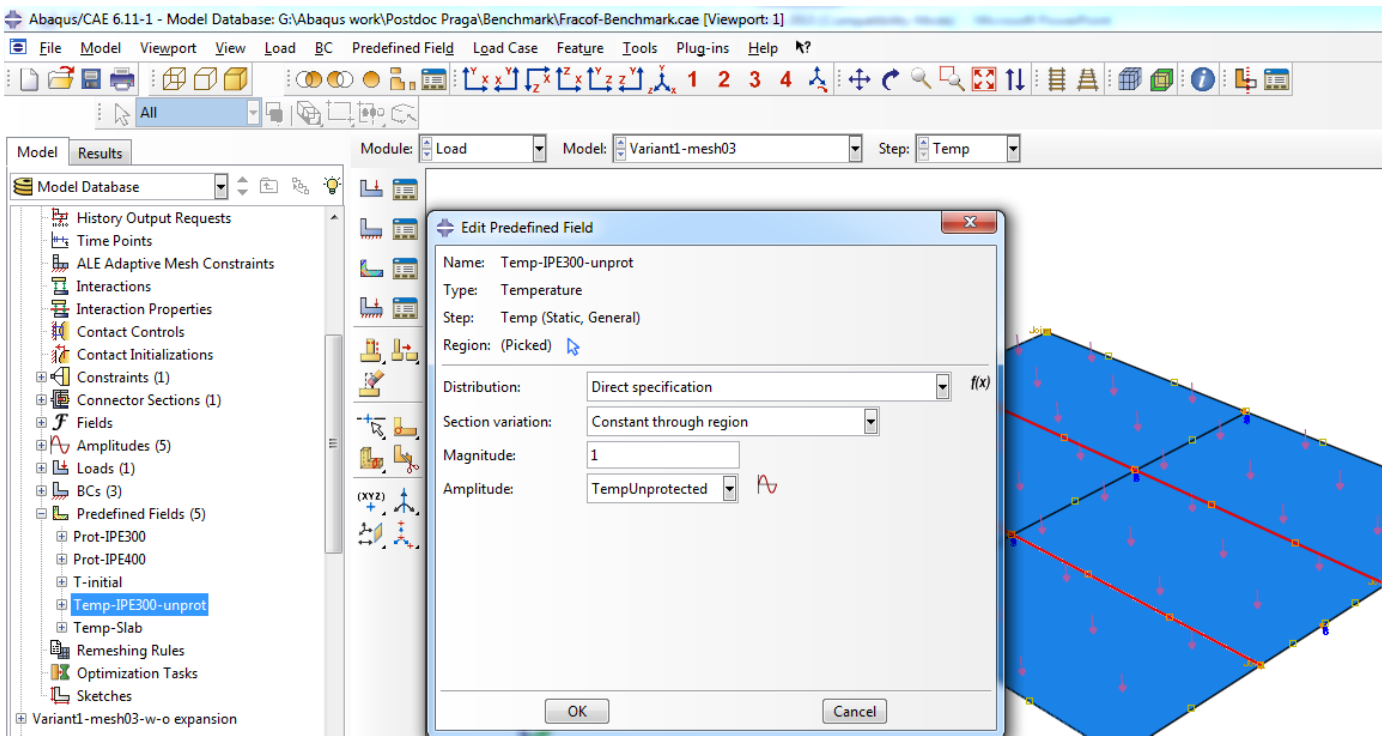
Predefined fields:

-Initial temperatures (entire structure)

-Gradients through beam section (protected beams)

-Constant through region (unprotected beam)

-From thermal analysis data base (slab)



Numerical model

Structural analysis of composite slab

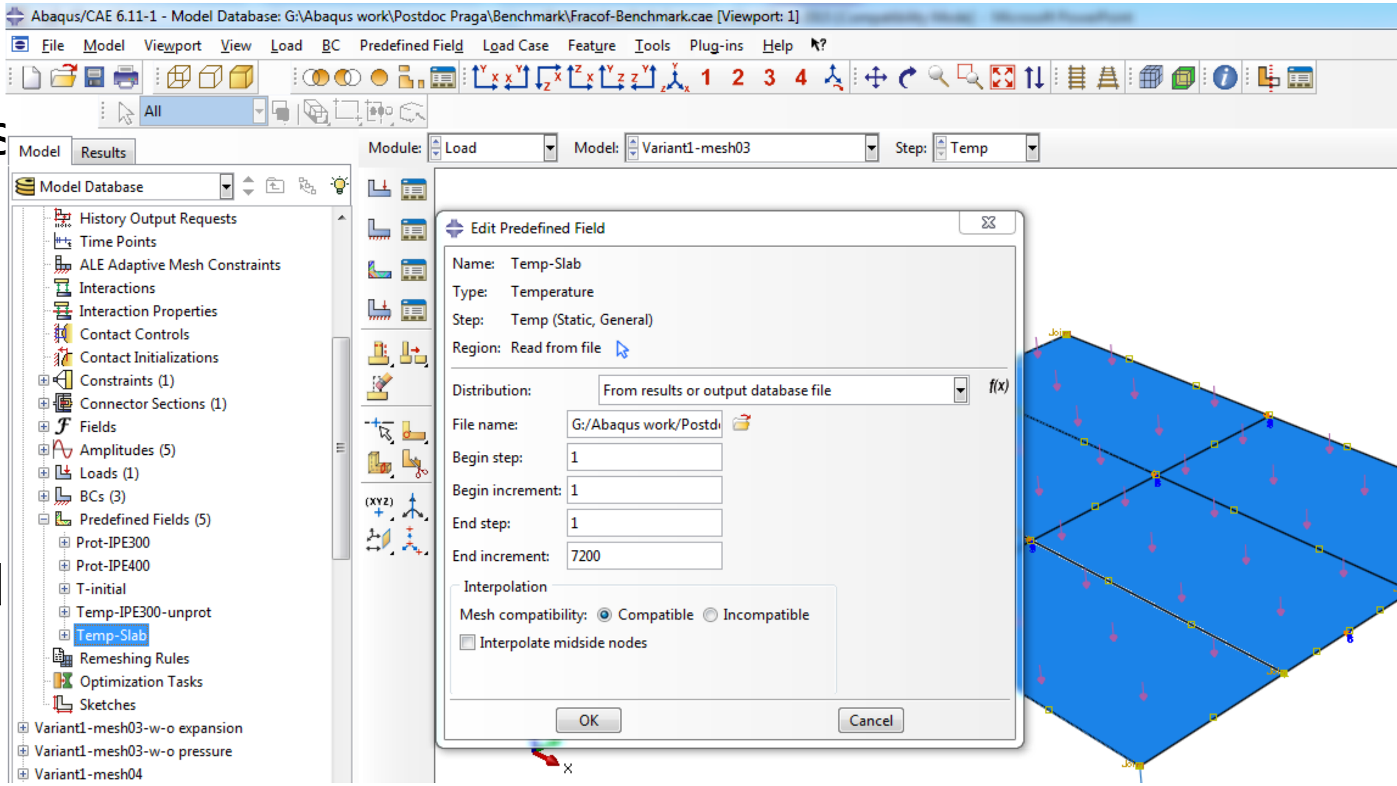
Predefined fields:

-Initial temperatures (entire structure)

-Gradients through beam section (protected beams)

-Constant through region (unprotected beam)

-From thermal analysis data base (slab)



Numerical model

Structural analysis of composite slab

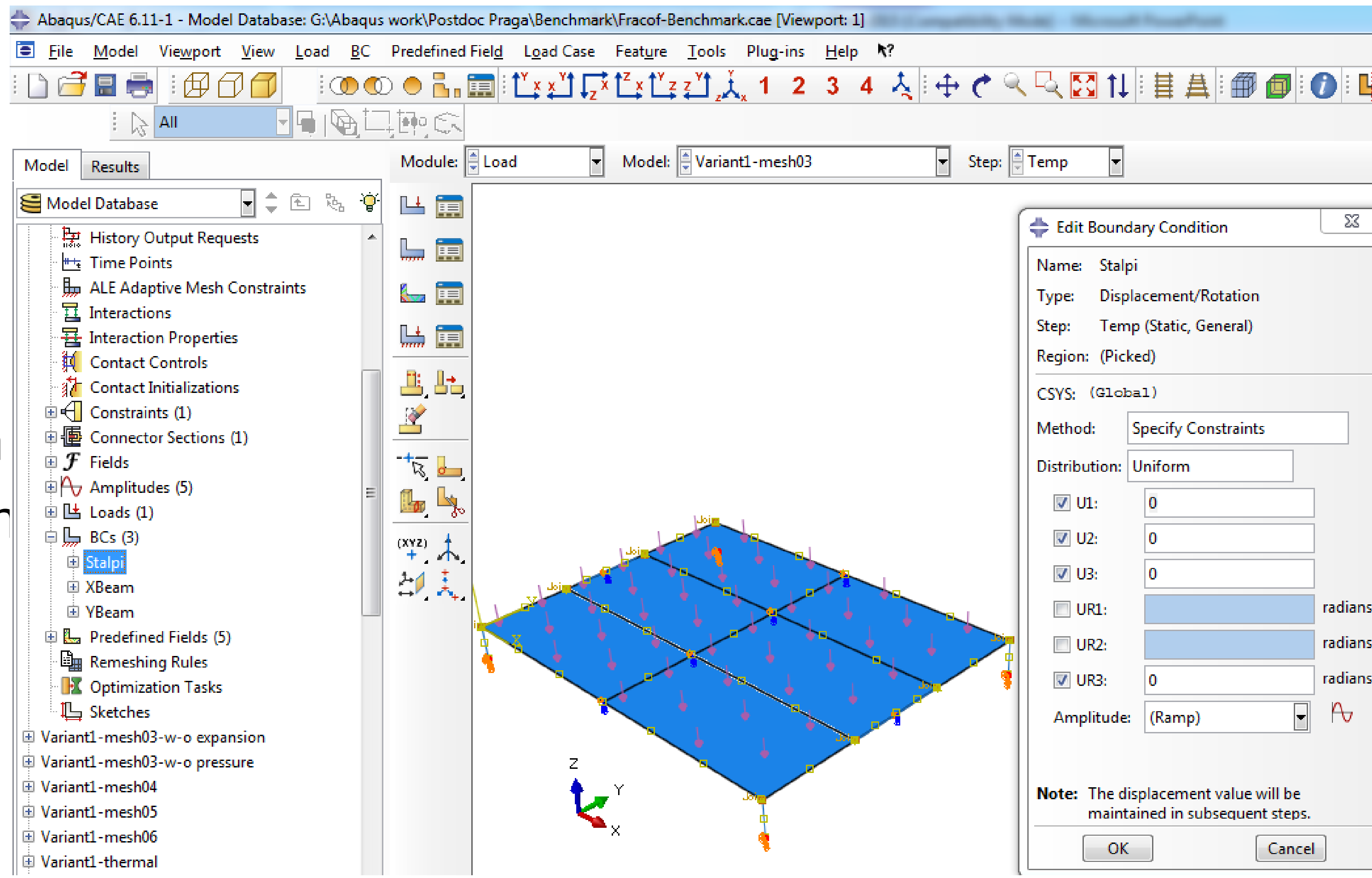
Support conditions:

Boundary conditions:

- columns

-longit. direction

-transv. direction



Numerical model

Structural analysis of composite slab

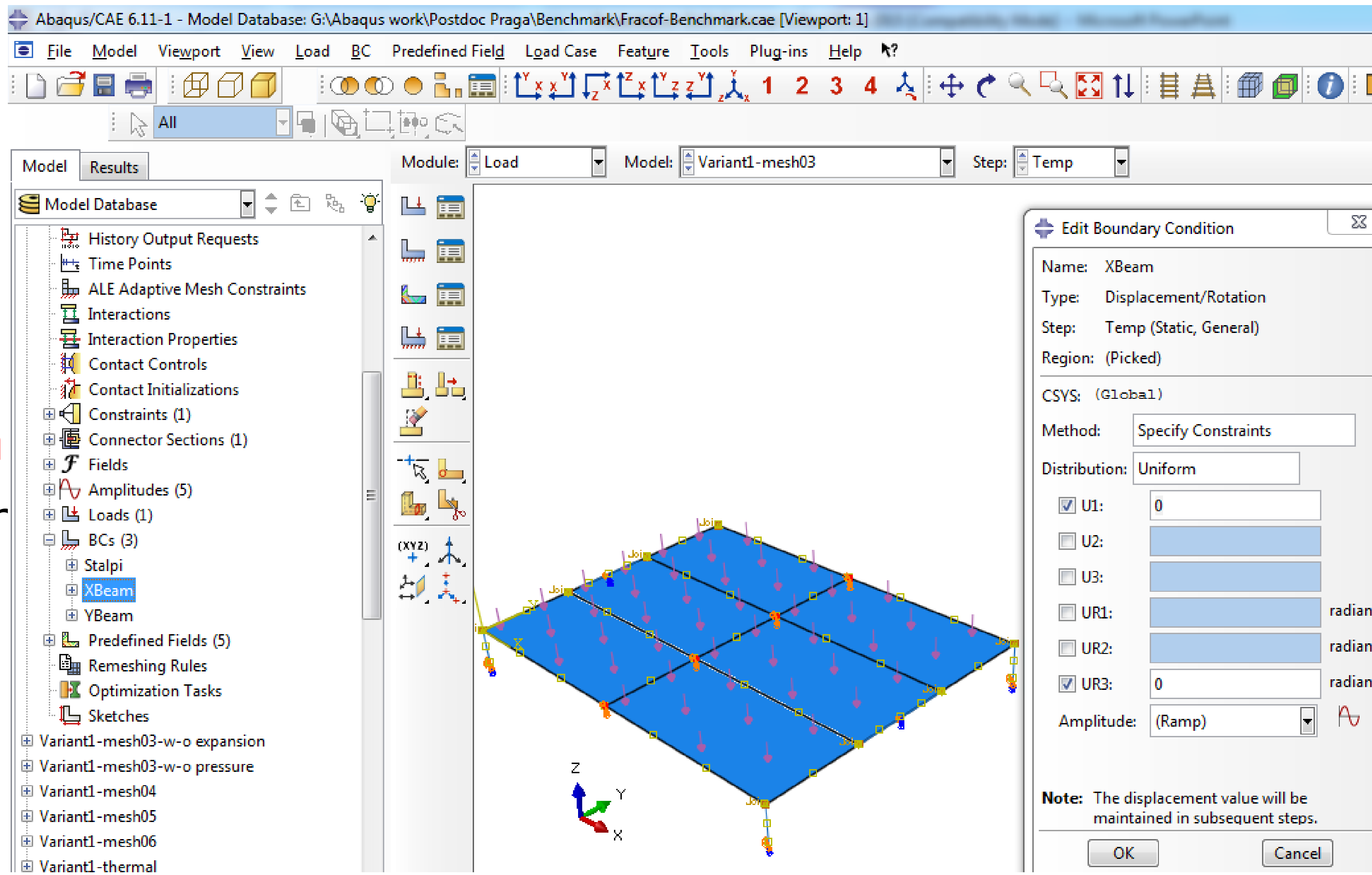
Support conditions:

Boundary conditions:

- columns

-longit. direction

-transv. direction



Numerical model

Structural analysis of composite slab

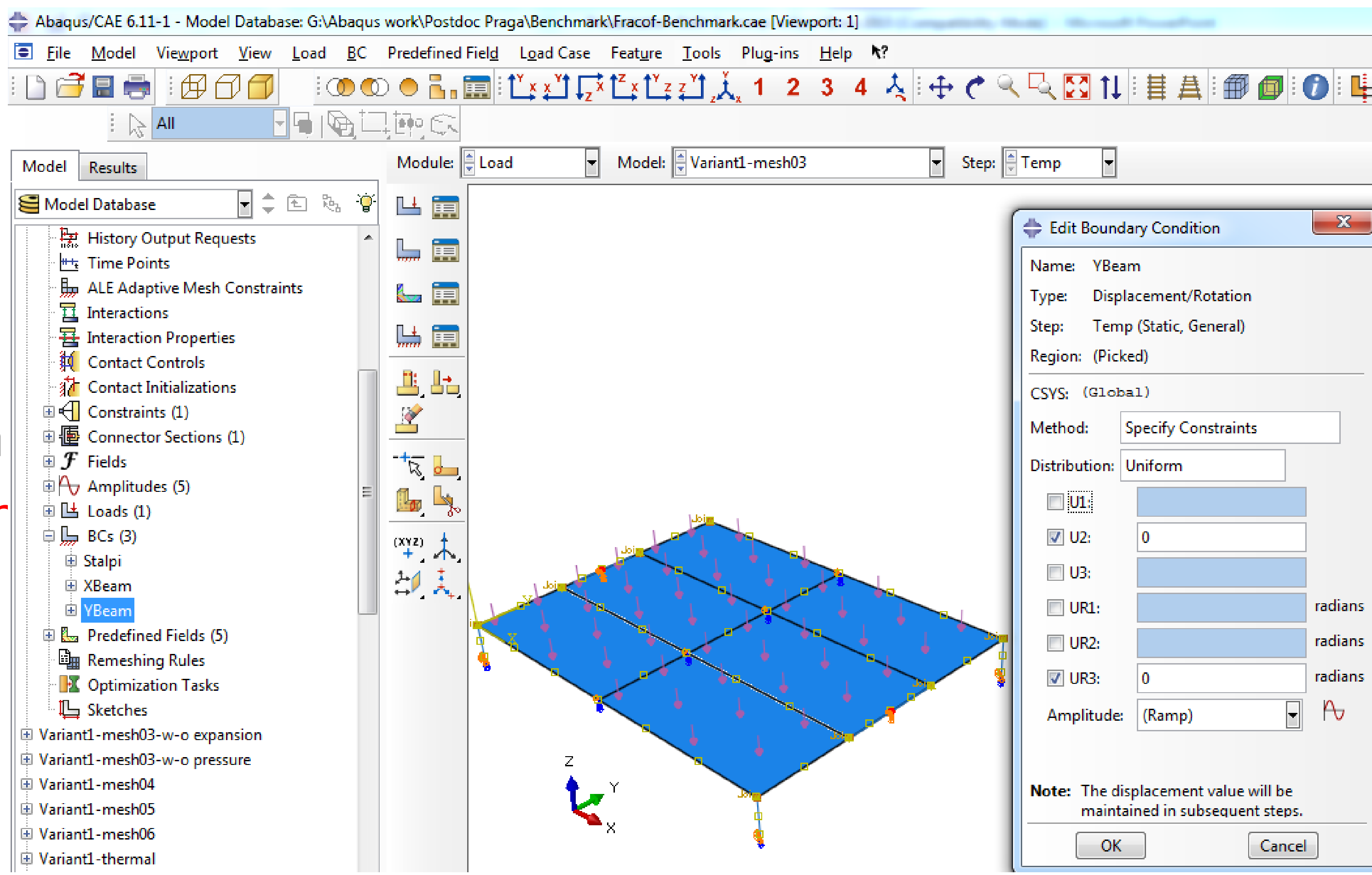
Support conditions:

Boundary conditions:

- columns

-longit. direction

-transv. direction

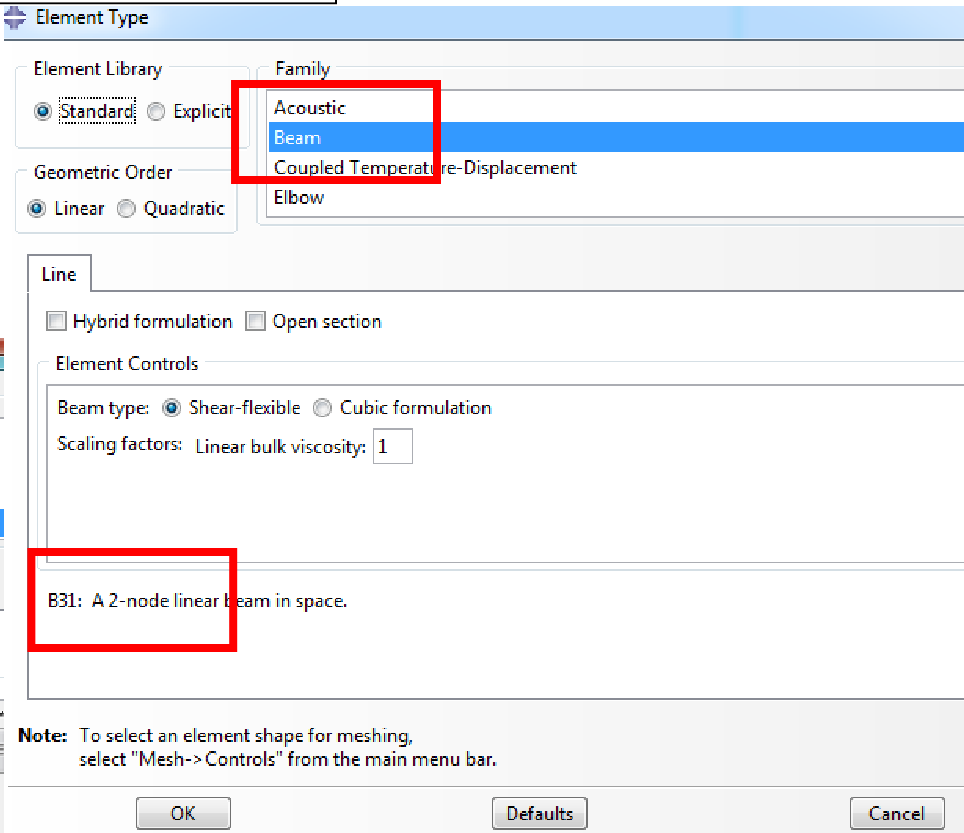


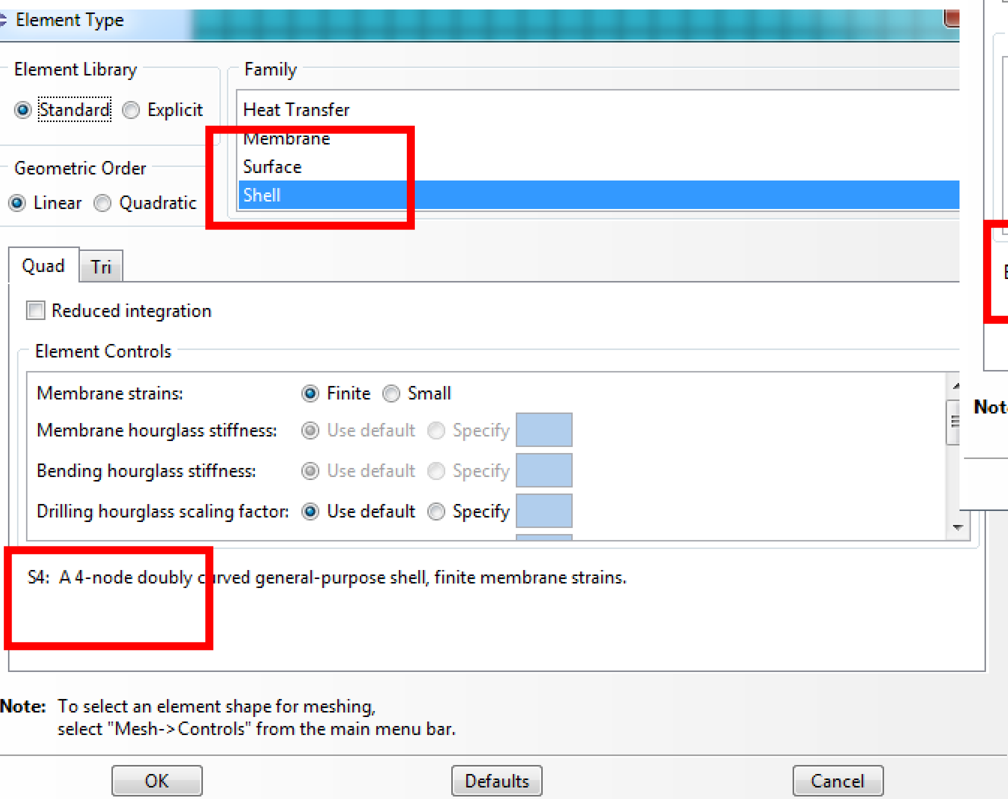
Numerical model

Structural analysis of composite slab

Mesh and finite elements:

Beams & → columns: B31 (0.3 m)





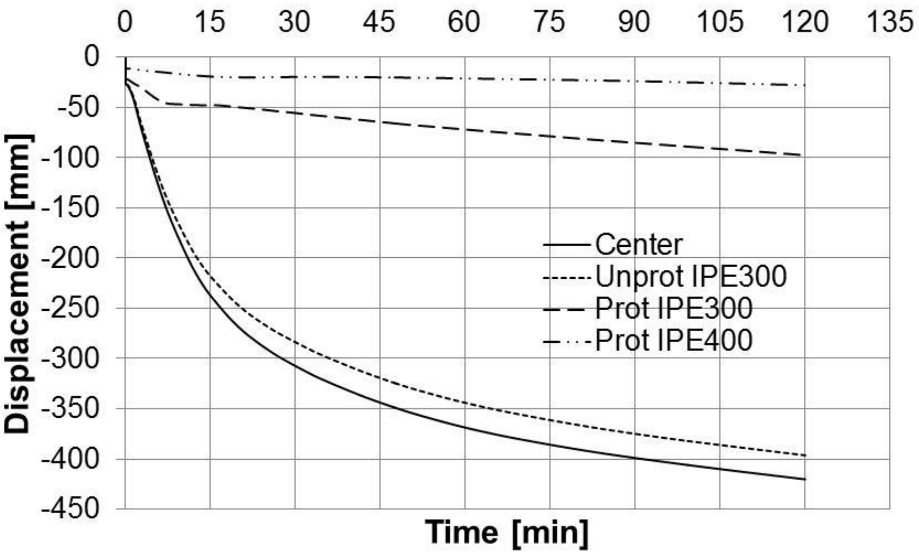
← Slab: S4 (0.3 m)

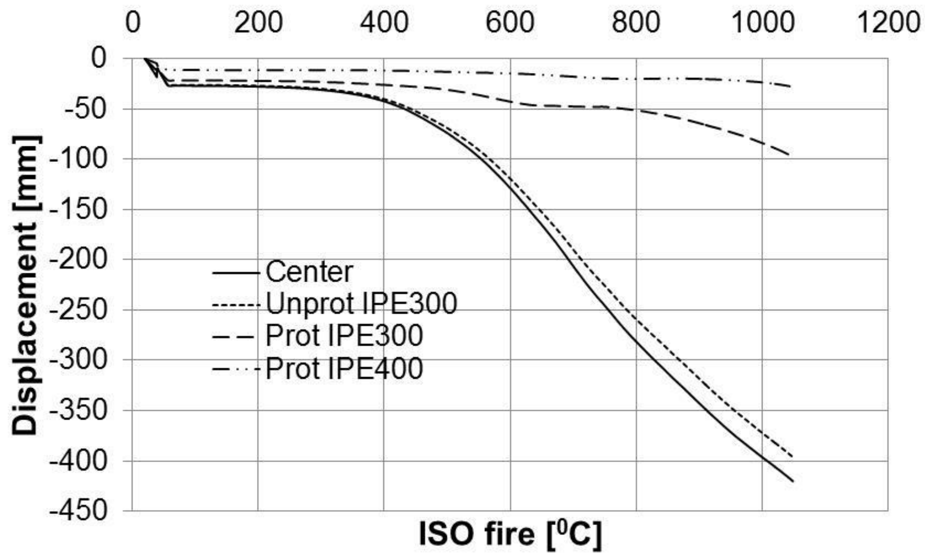
Numerical model - results

Structural analysis of composite slab

Results:

Displacements





With respect to time

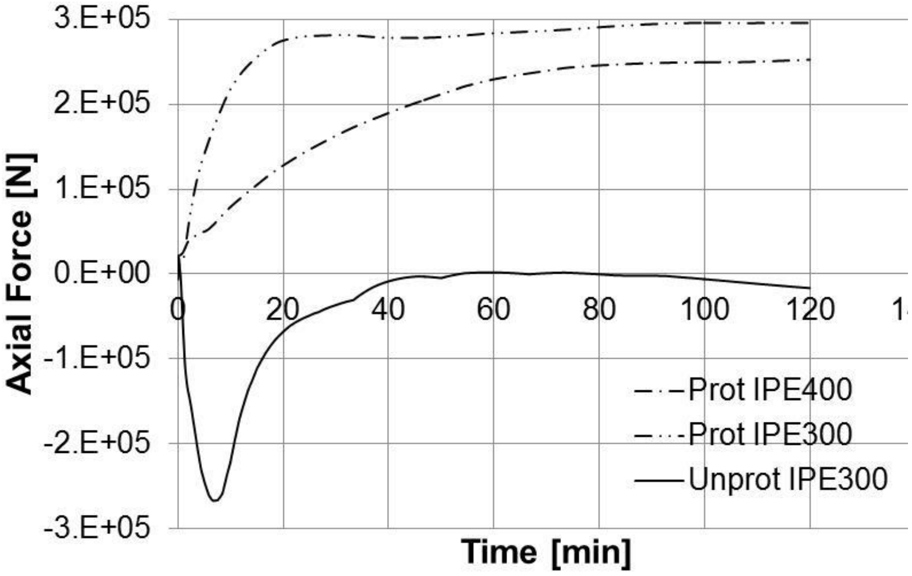
With respect to temperature

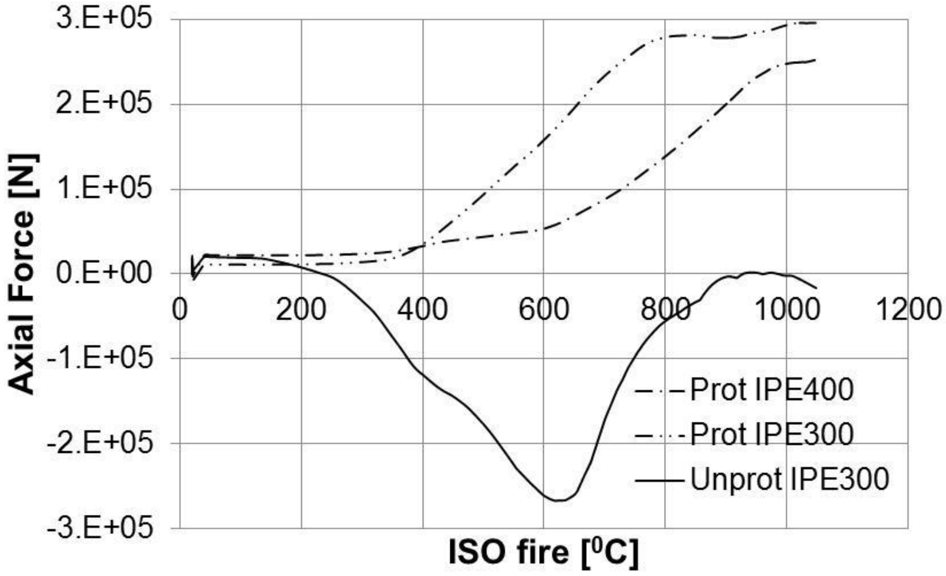
Numerical model - results

Structural analysis of composite slab

Results, other than obtained in experiment:

Axial force





With respect to time

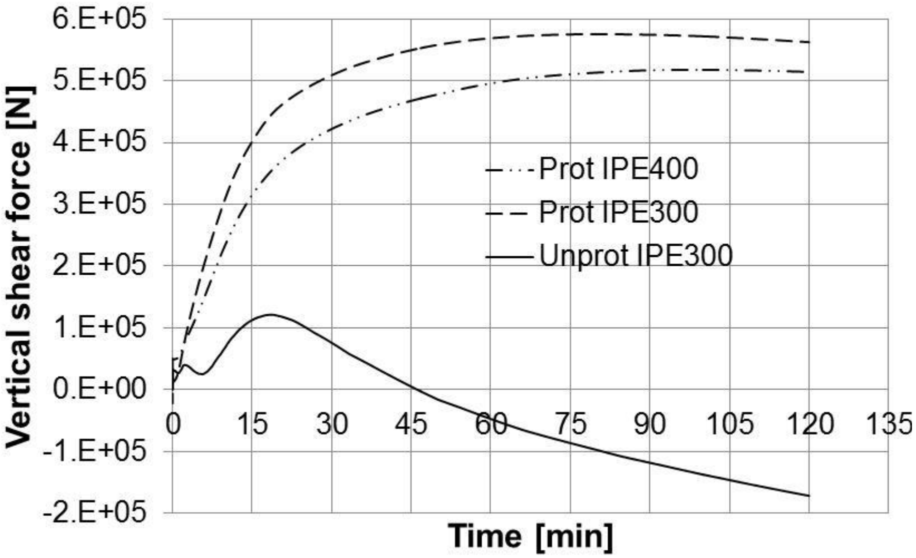
With respect to temperature

Numerical model - results

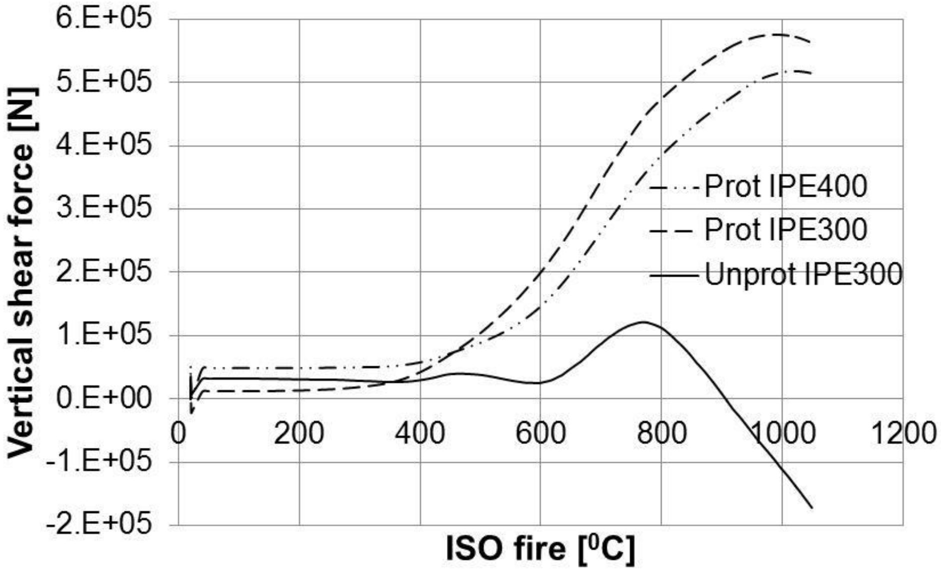
Structural analysis of composite slab

Results, other than obtained in experiment:

Vertical shear force



With respect to time



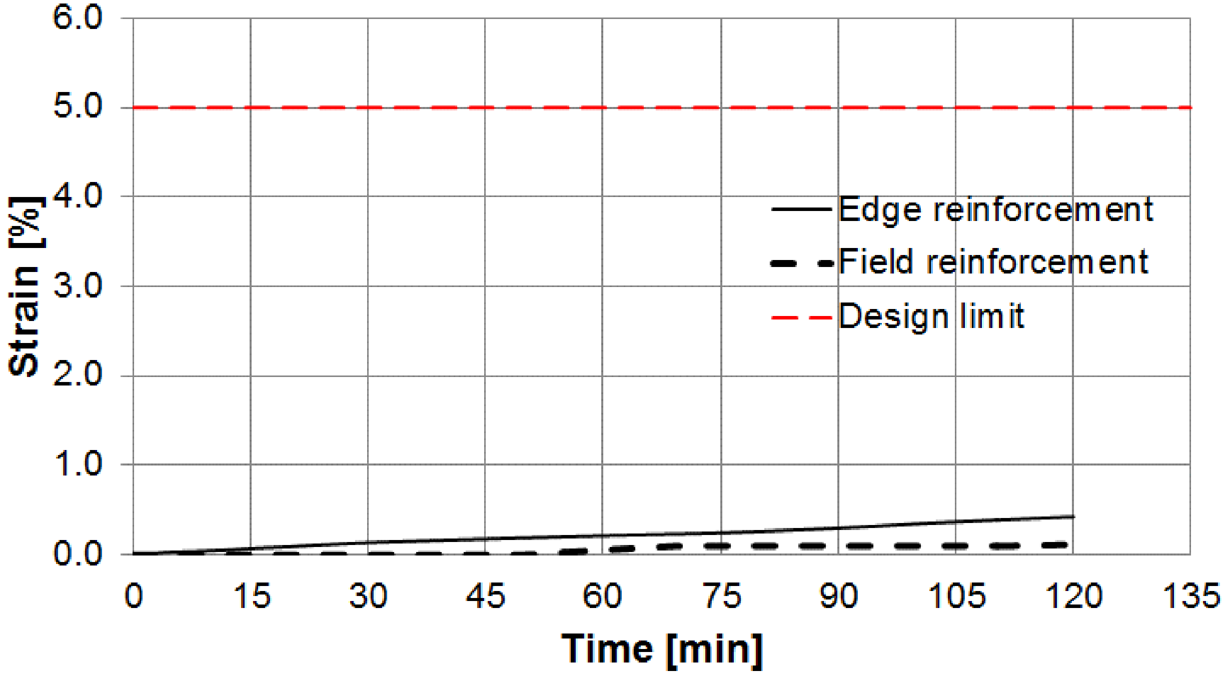
With respect to temperature

Numerical model - results

Structural analysis of composite slab

Results, other than obtained in experiment:

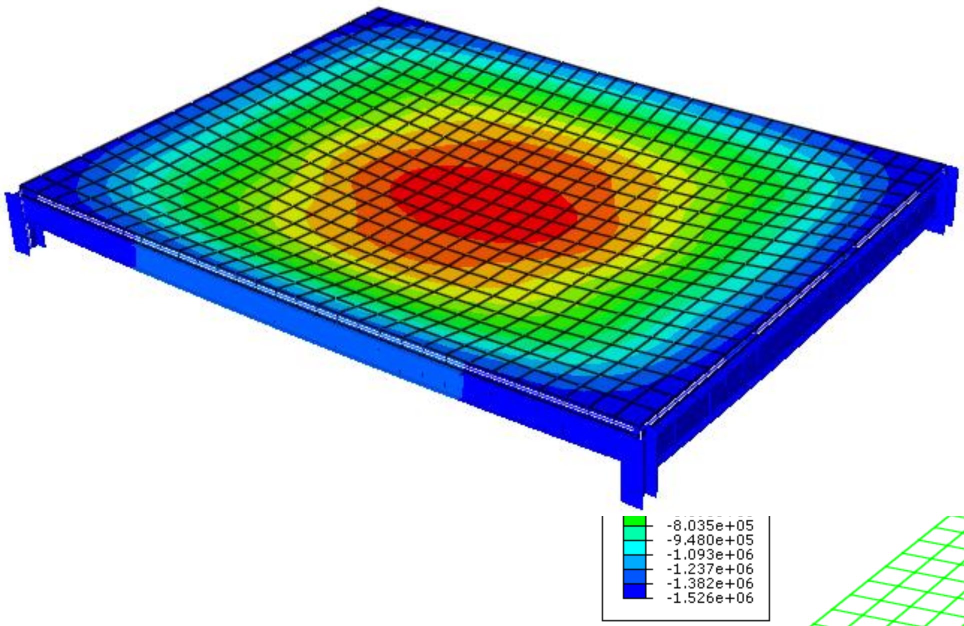
Reinforcement strain



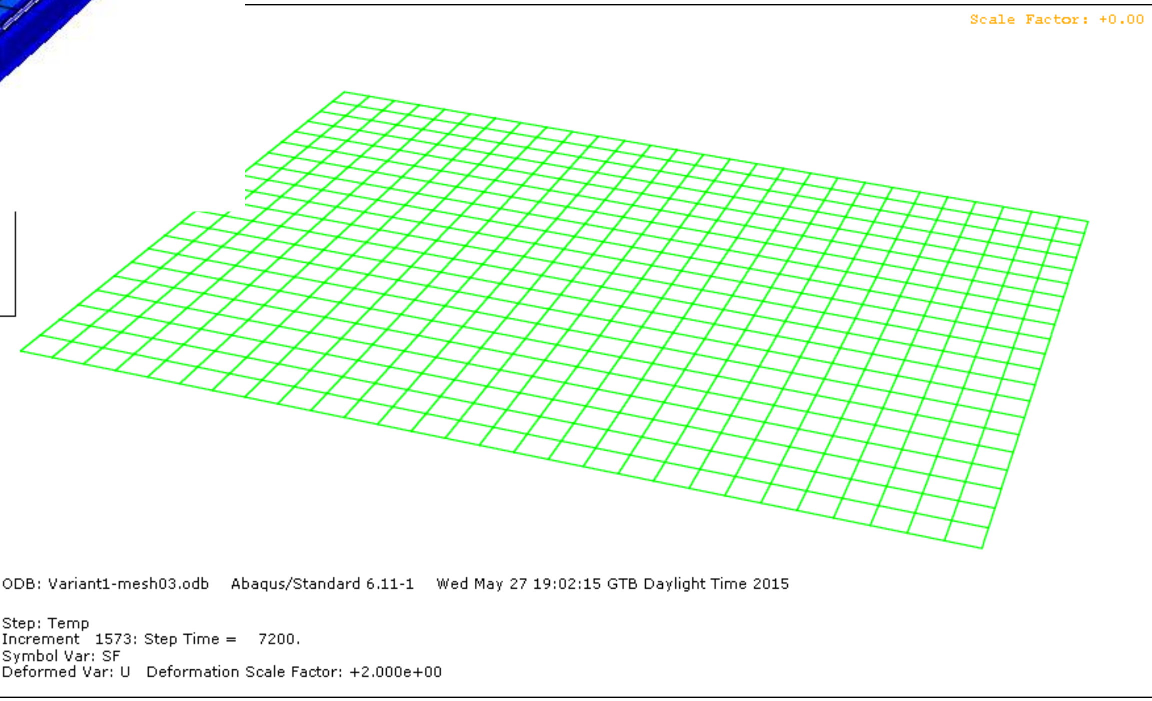
Numerical model - results

Structural analysis of composite slab

Deformed shape



Axial force



Numerical model - results

Mesh sensitivity study

Monitored variable: vertical displacement of the slab centre, U3

	Size [m]	Variable: U3 [cm]	Grid: h	Factor r	ε	Apparent order: p	Asympt solution	Extra-polated value	Approximate relative error	Extrapolated relative error	GCI_{12} [%]	GCI_{23} [%]
1	0.3	42.03	0.304	1.262	-0.27	4.160	42.20	42.20	0.0064	0.0039	0.49	0.84
2	0.4	41.76	0.383	-	-			-	-	-		
3	0.5	41.05	0.519	1.354	-0.71			42.04	0.0170	0.0067		

$$h = \left[\frac{1}{N} \sum_{i=1}^{N} (\Delta A_i) \right]^{1/2}$$

$$E_1 = \frac{\varepsilon}{r^p - 1}$$

$$\varepsilon = \frac{f_1 - f_2}{f_1}.$$

$$GCI = \frac{F_s\,|\varepsilon|}{r^p - 1} 100\%,$$

$$p = \frac{\ln\left(\dfrac{f_3 - f_2}{f_2 - f_1}\right)}{\ln(r)}$$

$$A_1 = \frac{f_1 - f_{h=0}}{f_{h=0}} \cong \frac{f_1 - f_2}{f_{h=0}} \frac{1}{r^p - 1},$$

h – representative value

N – number of elements

A_i – area of element “i”

r – refinement ratio (should have close values

ε – relative difference

A1 – relative error

p- order of convergence

GCI – grid convergence index

Conclusions

- A benchmark represents a step-by-step procedure for a thermo-mechanical analysis in a certain FEM computer program, here Abaqus;

- The procedure used in Abaqus was validated with the experimental results from the fire test, by means of the same numerical model, for which a complete input data was considered.

Bibliography

[1] R. Zaharia, C. Vulcu, O. Vassart, T. Gernay and J.M. Franssen, "Numerical analysis of partially fire protected composite slabs," *Steel and Composite Structures*, vol. 14, no. 1, pp. 21-39, 2013

[2] Florian Block, Fire Engineering in Practice – State of the Art in Performance-based Design, *COST TU904 – 2013 Training School – Naples 7th of June 2013*

[3] Fire Behaviour of Steel and Composite Floor Systems – FRACOF - http://www.macsfire.eu/uk-start.html

[4] Abaqus, Documentation Abaqus 6.11

[5] Dictionary.com

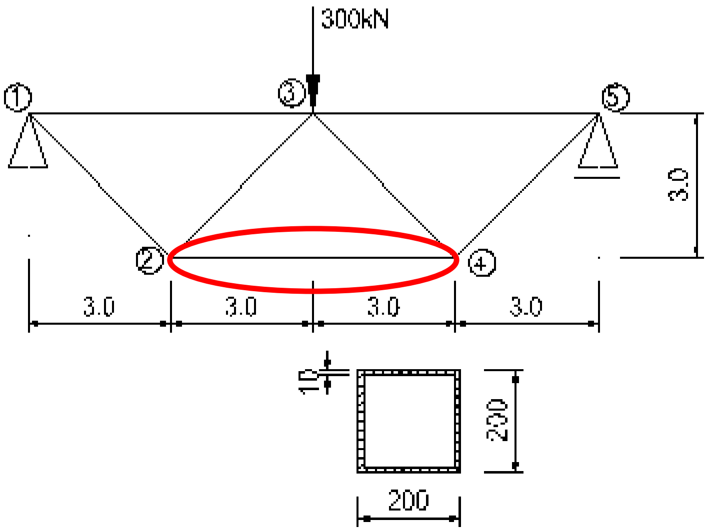
[6] Wald, F., Burgess, I., Kwasniewski, L., Horova, K. and Caldova, E. (ed.). 2014. *Benchmark studies-Verification of numerical models in fire engineering*, Prague: CTU Publishing House

[7]Bin Zhao, Mohsen Roosefid, and Olivier Vassart, "Full scale test of a steel and concrete composite floor exposed to ISO fire," in Structures in fire (Proceedings of the Fifth International Conference), Singapore, 2008, pp. 539-550

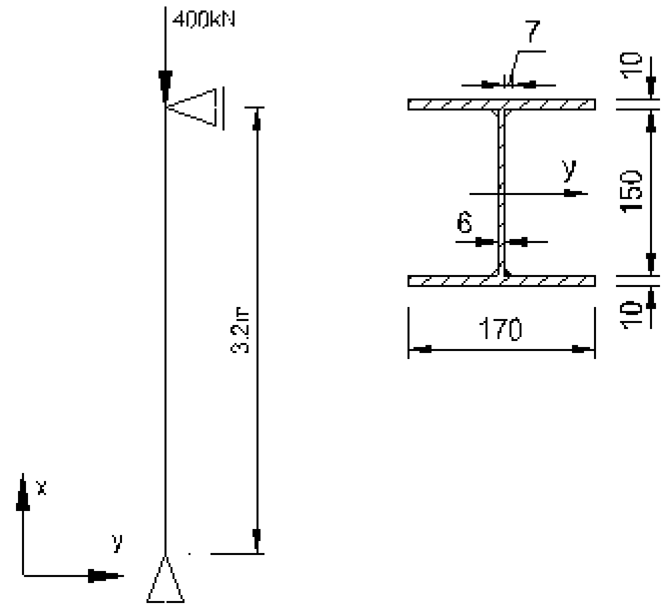
EN 1994-1-2 Eurocode 4 - Design of composite structures - Part 1-2: General rules - Structural fire design

Examples

Tensioned element



Compressed element



Bended element