

Support for applications in fire design

### Benchmark studies on composite floors and composite columns subjected to elevated temperature

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### **Overview**

Introduction

Reference case

Validation

Benchmark model

Input data

Numerical model details

Results

Conclusions





### **Advanced calculation models:**

- shall provide a realistic analysis of structures exposed to fire. They shall be based on fundamental physical behavior in such a way as to lead to a reliable approximation of

the expected behavior of the relevant structural component under fire conditions

Section 4.4.4 of EN 1994-1-2

Validation of advanced calculation models

- A verification of the calculation results shall be made on basis of relevant test results

- The critical parameters shall be checked, by means of a sensitivity analysis, to ensure that the model complies with sound engineering principles

### 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.



**Benchmark:** a standard or reference by which  $other(\underline{s})$  can be measured or judged [5]







FRACOF fire test - Setup



9



FRACOF fire test - Setup





#### Composite floor

Real-scale specimen



**FRACOF** fire test

Beam to slab connections



Secondary beams IPE300

Primary beams IPE400

Full shear connection !

#### FRACOF fire test - Connections

| Secondary beam     Primary beam       Double angle web cleats     Flexible end plate     Double angle web cleats       Image: Cleat second                                | Beam to                    | Beam to beam       |                            |
|---|----------------------------|--------------------|----------------------------|
| Double angle web cleats     Flexible end plate     Double angle web cleats       Image: Contrast of the second se | Secondary beam             | Primary beam       | Dealli to bealli           |
|   | Double angle web<br>cleats | Flexible end plate | Double angle web<br>cleats |
|   |                            |                    |                            |



Secondary beams:  $f_y$ =311 N/mm<sup>2</sup> Primary beams:  $f_y$ =423 N/mm<sup>2</sup> Reinforcing steel mesh:  $f_y$ =594 N/mm<sup>2</sup> Concrete cylinder compressive strength:  $f_c$ =36.7 N/mm<sup>2</sup>









### Validation

Displacement

with respect to time

with respect to temperature



Central Point-test

 $\rightarrow$  Protected IPE300-test



Temperature



with respect to time

with respect to temperature

### **Benchmark model**

Materials properties

# <u>Consideration:</u> only strength of materials is affected by temperature!!! (EN 1994-1-2)

Thermal analysis

| Material | Density<br>[kg/m <sup>3</sup> ] | Conductivity<br>[W/m K] | Specific heat<br>[J/kg K] |
|----------|---------------------------------|-------------------------|---------------------------|
| Steel    | 7850                            | 40                      | 550                       |
| Concrete | 2400                            | 0.9                     | 1050                      |

#### Mechanical ananlysis

| Steel | E<br>[N/m²] | ν   | σ <sub>y</sub><br>[N/m²] | α<br>[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<br>[N/m²] | ν   | f <sub>c</sub><br>[N/m²] | f <sub>t</sub><br>[N/m²] | α<br>[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<sup>2</sup>
- selfweight: 3280 N/m<sup>2</sup>

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

### - 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]

### - Basics

### Settings

### <u>ABAQUS has no settings for</u> <u>units system</u>

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

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

| 🖶 Edit Mode  | l Attributes                          |  |  |  |
|--|---------------------------------------|--|--|--|
| Name:  | TempIPE300-Bench                      |  |  |  |
| Model type:  | Standard & Explicit                   |  |  |  |
| Description:   | /                                     |  |  |  |
| 🔲 Do not us  | e parts and assemblies in input files |  |  |  |
| Physical Co  | onstants                              |  |  |  |
| Absolute   | zero temperature: -273.15             |  |  |  |
| Stefan-B   | oltzmann constant: 5.67E-008          |  |  |  |
| 🔲 Universa   | I gas constant:                       |  |  |  |
| Specify a  | coustic wave formulation:             |  |  |  |
| Restart Se   | ubmodel                               |  |  |  |
| Note: Specify these settings to reuse state data from a previous analysis of this model. |                                       |  |  |  |
| 🔲 Read dat   | a from job:                           |  |  |  |
| Restart Loca   | ition: 'Ġʻ                            |  |  |  |
| Step nam   | 1e:                                   |  |  |  |
| Restart from the end of the step   |                                       |  |  |  |
| Restart from increment, interval, iteration, or cycle:                                   |                                       |  |  |  |
| I and terminate the step at this point   |                                       |  |  |  |
| and complete the step  |                                       |  |  |  |
|  | OK Cancel                             |  |  |  |

Temperature field for secondary, unprotected beams



### Temperature field for secondary, unprotected beams

📥 Abagus/CAE 6.11-1 - Model Database: G:\Abagus work\Postdoc Praga\Benchmark\de lucru.cae [Viewport: 1] ■ File Model Viewport View Edit Add Tools Plug-ins Help \*? | ビェゴ 戸 ビュビュゴ 美 1 2 3 4 🎄 🕀 🕈 🔍 🖾 輝 🗋 🗃 🖩 🖶 🗄 🗗 🗇 i 🕞 All Module: 🚊 Part Model: TempIPE300-Bench IPE300 -Part: T Model Results - 🔹 🗈 🗞 🍟 🚝 Model Database + \*\* H ¥ Gradient-shell TempIPE300  $\bigcirc$ E TempIPE300-Bench 🛛 🕒 Parts (1) 1) C ⊟ IPE300 C A 🖻 📇 Features (1) Shell planar-,∕,|→ 🗁 Sets **A** N Nurfaces Skins +…⊦ <mark>≯</mark>> Stringers E Section Assignments (1) el. b Orientations L # Layups A A S Engineering Features Ē 1 H Mesh  $\prod f(x)$ 🗄 🌾 Materials (1) Calibrations A) (\* 🗄 🥵 Sections (1) Profiles K 🔗 Assembly Steps (2) La La ⊕ ∽ Initial н. н H -----Field Output Requests (1) History Output Requests H Time Points Edit the section sketch Done ALE Adaptive Mesh Constraints

Create part: 2D shell planar

### Temperature field for secondary, unprotected beams

Define material:

- conductivity
- specific heat

- density

| lur |   | dary, unprotected beams  |              |
|-----|---|--|--------------|
|     | Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus   | s work\Postdoc Praga\Benchmark\de lucru.cae [Viewport: 1]  | in market in |
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|     | Model Results Material Library  | Module: Property Model: TempIPE300-Bench Part: IPE300  |              |
| al: | Model Database<br>Gradient-shell<br>TempIPE300<br>TempIPE300-Bench<br>Materials (1)<br>S235<br>Calibrations<br>Sections (1)<br>Profiles<br>Sections (1)<br>Profiles<br>Sections (1)<br>Profiles<br>Sections (1)<br>Steps (2)<br>Sections (2)<br>Steps (2)<br>Sections (1)<br>Steps (2)<br>Sections (1)<br>Assembly<br>Sections (1)<br>Steps (2)<br>Sections (1)<br>Steps (2)<br>Sections (1)<br>Sections (2)<br>Steps (2)<br>Sections (1)<br>Sections (2)<br>Sections | <ul> <li>Edit Material</li> <li>Name: S235</li> <li>Description:</li> <li>Material Behaviors</li> <li>Conductivity</li> <li>Density</li> <li>Specific Heat</li> <li>Specific Heat</li> <li>Type:  Constant Volume Constant Pressure</li> <li>Use temperature-dependent data</li> <li>Number of field variables: 0</li> <li>Data</li> <li>Specific Heat</li> <li>1 550</li> </ul>   |              |

### Temperature field for secondary, unprotected beams

Define section property:

- Solid homogeneous



### Temperature field for secondary, unprotected beams

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Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus work\Postdoc Praga\Benchmark\de lucru.cae [Viewport: 1]
File Model Viewport View Instance Constraint Feature Tools Plug-ins Help ?

Create instances: - IPE300

Model: TempIPE300-Bench Module: Assembly Step: 🖨 Initial Model Results 🖣 韋 🗈 🗞 🍟 Model Database 14 Gradient-shell \_\_\_\_\_ TempIPE300 ť r<sup>2</sup> TempIPE300-Bench 🗄 🕒 Parts (1) 100 🗄 🌾 Materials (1) Calibrations li, Ito, 🗄 🥵 Sections (1) 2 Assembly -+== **L** IPE300-1 (XYZ) 🗄 🃇 Features (1) X by Sets 2/ 🐛 Nurfaces Connector Assignments Genering Features 🗄 🖧 Steps (2) E Field Output Requests (1) History Output Requests Ht Time Points ALE Adaptive Mesh Constraints Interactions (2) Haraction Properties - X ŧ١. Contact Controls Contact Initializations Constraints Connector Sections

### Temperature field for secondary, unprotected beams

#### Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus work\Postdoc Praga\Benchmark\de lucru.cae [Viewport: 1] Eile Model Viewport View Step Output Other Tools Plug-ins Help ★? 🗅 🦰 🖥 🚔 ANT 1 + C 4 Define steps: 🖓 🗐 i 🚱 🗖 🌆 i 🚱 Step: Step: - Heat transfer Module: 🖨 Step Model: TempIPE300-Bench • Model Results - 🕈 🗈 🗞 🍟 🚝 Model Database •+= 🛅 📥 Edit Step Gradient-shell **1** Name: ISOfire TempIPE300 📥 Edit Step Type: Heat transfer E TempIPE300-Bench <u>h</u> Name: ISOfire 🗄 🕒 Parts (1) Basic Incrementation Other Type: Heat transfer TR -Description: S Calibrations Basic Incrementation Other **b**, **b**, 🗄 🥵 Sections (1) Response: 🔘 Steady-state 🔘 Transient Type: Automatic Fixed Profiles (XYZ) Time period: 7200 Maximum number of increments: 10000 # 本 Assembly NIgeom: Off 21 I. Steps (2) Initial Minimum Maximum ⊕ ← Initial 0.072 5 Increment size: 1 End step when temperature change is less than: Field Output Requests (1) History Output Requests Max. allowable temperature change per increment: 20 His Time Points Max. allowable emissivity change per increment: 0.1 ALE Adaptive Mesh Constraints 1 Interactions (2) Haraction Properties Contact Controls Contact Initializations Constraints Connector Sections 🗄 牙 Fields Amplitudes (3) Loads L BCs Predefined Fields (1) OK Cancel 🕮 Remeshing Rules OK Cancel

### Temperature field for secondary, unprotected beams

Define fire curve:

- Amplitude



### Temperature field for secondary, unprotected beams

Define interactions:

- Convection (surface film condition)



### Temperature field for secondary, unprotected beams

📥 Abagus/CAE 6.11-1 - Model Database: G:\Abagus work\Postdoc Praga\Benchmark\de lucru.cae [Viewport: 1] 토 File Model Viewport View Interaction Constraint Connector Special Feature Tools Plug-ins Help 🏌 i 🗋 🦰 🔚 🚔 ALINC Model: TempIPE300-Bench Step: 🖹 ISOfire Module: --Model Results F 韋 🗈 🗞 🍟 11 🛅 🚝 Model Database Gradient-shell ₽. İ. TempIPE300 E TempIPE300-Bench - 🛅 🗄 🕒 Parts (1) 1 🖉 X Edit Interaction S Calibrations 1 i. 🗄 🥵 Sections (1) Name: Emisivity Profiles Type: Surface radiation 1 🗄 🎎 Assembly Step: ISOfire (Heat transfer) ± of Steps (2) P E Field Output Requests (1) Surface: (Picked) History Output Requests 🖶 🛅 Radiation type: 
To ambient 
Cavity approximation (3D only) Ht Time Points X RP f(x)Emissivity distribution: Uniform sh Constraints Interactions (2) 0.7 **Emissivity:** + Convection Ambient temperature: 1 Emisivity ... 4 A Interaction Properties Ambient temperature amplitude: | FOC-ISO-C (XYZ) Contact Controls \* OK Cancel Contact Initializations 2/ 美 Constraints Connector Sections ⊕ *F* Fields Amplitudes (3) Loads BCs 🗄 🖶 Predefined Fields (1) ← X Fill out the Edit Interaction dialog Remeshing Rules

Define interactions: - Radiation

(surface radiation)








### Temperature field for secondary, unprotected beams





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

Temperature field for protected beams

Beam elements sections are defined function of a reference line



### Temperature field for protected beams

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

- amplitude
- gradient



### Temperature field for protected beams

| 💠 Edit Amplitude     | ×                  |  |  |  |
|----------------------|--------------------|--|--|--|
| Name: MainBeamTemp   |                    |  |  |  |
| Type: Tabular        |                    |  |  |  |
| Time span: Step time | e 🔻                |  |  |  |
| Smoothing: () Use s  | olver default      |  |  |  |
| Speci                | ify:               |  |  |  |
| Amplitude Data B     | aseline Correction |  |  |  |
| Time/Frequer         | ncy Amplitude      |  |  |  |
| 1 0                  | 20                 |  |  |  |
| 2 7200               | 114.4              |  |  |  |
|                      |                    |  |  |  |
| ОК                   | Cancel             |  |  |  |

Amplitude is function of reference line temperature obtained by linear interpolation



Temperature field for protected beams

Determination of gradient

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



x - gradient  $\theta_{ref}$  - temperature at reference line level,  $d_2$  - distance from reference line to a point along direction 2;  $\theta_2$  - temperature at distance  $d_2$ 

### Temperature field for protected beams



#### 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

$$\begin{split} h_{eff} &= h_1 + 0.5 \ h_2 \! \left( \frac{\ell_1 + \ell_2}{\ell_1 + \ell_3} \right) \\ h_{eff} &= h_I \! \left[ 1 + 0.75 \left( \frac{\ell_1 + \ell_2}{\ell_1 + \ell_3} \right) \right] \end{split}$$

$$\begin{array}{c} h_{eff} \neq & & & \downarrow \\ \hline & \downarrow \\ \hline & \downarrow \\ \ell_1 \\ \ell_3 \end{array} \end{array} \begin{array}{c} \downarrow \\ h_3 \\ \hline & h_1 \\ h_2 \\ \hline & h_2$$

for 
$$h_2/h_1 \le 1,5$$
 and  $h_1 > 40$  mm

for 
$$h_2/h_1 > 1,5$$
 and  $h_1 > 40$  mm

#### Temperature field for concrete slab



#### Temperature field for concrete slab

Define material: -conductivity -specific heat -density

| <u>File M</u> odel Vie <u>w</u> port <u>V</u> iew Mat <u>e</u> rial | Section    | <u>P</u> rofile  | le <u>C</u> omposite <u>A</u> ssign Specia <u>l</u> Feat <u>u</u> re <u>T</u> ools Plug-ins <u>H</u> elp <b>N</b> ? |              |
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| i 💦 All 💽 🖣   🚱   |            |                  |   |              |
| Model Results Material Library                                      | Mod        | lule: 🏮 F        | Property Variant1-thermal-mesh03 Part: Slab   | •            |
| 🛢 Model Database 🛛 🛓 🛍 🇞  | · 🖗 🖉 E    |                  | 🖶 Edit Material   |              |
| Variant1-mesh03-w-o expansion                                       | ^ <b>.</b> |                  | Name: Concrete  |              |
| Variant1-mesh03-w-o pressure     Variant1 mesh04                    | 1          |                  | Description   |              |
| Variant1-mesh04   | I          |                  | beenplon  |              |
| Variant1-mesh06   | m 🖦        |                  | C Material Behaviors  |              |
| Variant1-thermal  | 8          | <sup>n2</sup> n1 | Conductivity  |              |
| Wariant1-thermal-mesh015  |            |                  | Density   |              |
| Variant1-thermal-mesh02   | - ₽        |                  | Specific Heat   |              |
| Variant1-thermal-mesh03   |            |                  |   |              |
| B Parts (1)   |            |                  |   |              |
|   | =          |                  | General Mechanical Thermal Other  |              |
| Colibertions  |            |                  | Tanan Tanan Tanan Tan   |              |
| 🗈 🤹 Sections (1)  | <u> </u>   | <u> </u>         | Conductivity  |              |
| Profiles  | <u> </u>   |                  | Type: Isotropic   |              |
| 🕀 🎎 Assembly  | +          | 1                | Use temperature-dependent data  |              |
| ⊕ o <sup>c</sup> te Steps (2)                                       |            | ≁ ∥              |   |              |
| Here History Output Requests (1)                                    |            |                  |   |              |
| Time Points   | -+-        |                  | Data  |              |
| ALE Adaptive Mesh Constraints                                       | -~~·       |                  | Conductivity  |              |
|   | 100        | _≫_              | 1 0.9   |              |
| - 🔁 Interaction Properties  | (XYZ)      | ±                |   |              |
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#### Temperature field for concrete slab

🚔 Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus work\Postdoc Praga\Benchmark\Fracof-Benchmark.cae [Viewport: 1] 🔄 File Model Viewport View Material Section Profile Composite Assign Special Feature Tools Plug-ins Help A? i (0) (0) | ● 🔚 📰 i 📺 x 🎽 💭 İŻ x Č x Č z z Č ł, Ž, 1 – 2 – 3 – 4 – Å i 🕂 ् 🔍 🖾 🖬 77 🖬 🚔 AA C All Model: Variant1-thermal-mesh03 👻 Part: 🌲 Slab Module: Property Model Results Material Library 1 2 2 • σε Model Database X 📥 Edit Section Define section: Variant1-mesh03-w-o expansion Ĵ. Name: Slab ..... Wariant1-mesh03-w-o pressure -thickness Type: Shell / Continuum Shell, Homogeneous Variant1-mesh04 1·L 🗖 Variant1-mesh05 Section integration: 
O During analysis 
O Before analysis Variant1-mesh06 -material "2n Basic Advanced Variant1-thermal Variant1-thermal-mesh015 Thickness ₽, + Variant1-thermal-mesh02 -integration Shell thickness: 
 Value: 0.12 Variant1-thermal-mesh03 0 🗄 🕒 Parts (1) Element distr rule / f(x) € 🖉 Materials (1) Nodal distribution: 匣 Calibrations 🗄 🏂 Sections (1) -integration li, lt Σe Material Concrete 2 Thickness integration rule: 
 Simpson Guss Profiles points 🗄 🎎 Assembly Thickness integration points: 13 🚔 + ⊕ of Steps (2) Options: 🖕 🗄 🚰 Field Output Requests (1) History Output Requests 2 OK Cancel His Time Points ALE Adaptive Mesh Constraints 100 (without 🖶 Interaction Properties (XYZ) Contact Controls 21 i reinforment, yet) **Contact Initializations** Constraints Connector Sections

### Temperature field for concrete slab

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| Set Model Database  | li   |  |   |  |  |  |  |
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| + Profiles  | <u> 1</u> : 1:   |  |   |  |  |  |  |
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| Slab-1  | - <del>1</del>   |  |   |  |  |  |  |
| Features (1)  | <b>L</b>   |  |   |  |  |  |  |
| E Sets  | (1)(2)   |  |   |  |  |  |  |
| 🔊 🔍 Surfaces  | +  |  |   |  |  |  |  |
| Connector Assignments   |  |  |   |  |  |  |  |
| Genering Features   |  |  |   |  |  |  |  |
| Hota Steps (2)  |  |  |   |  |  |  |  |
|   |  |  |   |  |  |  |  |
| Time Points   |  |  |   |  |  |  |  |
| 📙 ALE Adaptive Mesh Constraints   |  |  |   |  |  |  |  |
| Interactions (4)  |  | Y  |   |  |  |  |  |
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| A Contact Controls  |  | × ×  |   |  |  |  |  |
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|   | <ul> <li>Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus</li> <li>File Model Viewport View Instance Ca</li> <li>All  Model Results </li> <li>Model Database All  Model Database </li> <li>Variant1-thermal-mesh03 Parts (1) Calibrations Sections (1) Portiles Sections (1) Features (1) Features (1) Sets Surfaces Connector Assignments Engineering Features Sourfaces Field Output Requests (1) History Output Requests Time Points ALE Adaptive Mesh Constraints Time Points ALE Adaptive Mesh Constraints Contact Initializations Contact Initializations Constraints</li></ul>   | Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus work\Postdoc Praga\Bence<br>File Model Viewport View Instance Constraint Feature Ioo<br>Model Results<br>Model Results<br>Model Database<br>Variant1-thermal-mesh03<br>Model Database<br>Variant1-thermal-mesh03<br>Model Calibrations<br>Se Sections (1)<br>Profiles<br>Sections (1)<br>Field Output Requests br>Time Points<br>ALE Adaptive Mesh Constraints<br>Contact Controls<br>Contact Controls<br>Constraints | Abaquy/CAE 6.11-1 - Model Database: G:Abaqus work/Postdoc Praga/Benchmark/Eracof-Benchmark.cae [Viewport: 1]<br>File Model Viewport View Instance Constraint Feature Iools Plug-ins Help N?<br>Model Results<br>Model Results<br>Model Results<br>Model Database<br>Variant1-thermal-mesh03<br>Step<br>Sections (1)<br>File Sections (2)<br>File Sections (3)<br>File Connect Constraints<br>File ALE Adaptive Mesh Constraints<br>File Interactions (4)<br>Interactions (4)<br>File Interactions (4)<br>File Interactions (4)<br>File Contact Initializations<br>Constraints |  |  |  |  |

#### Temperature field for concrete slab

Define heat transfer step: -transient

-time



#### Temperature field for concrete slab

|  | 💠 Edit Interaction              |                          | 🖨 Edit Interaction          |                        | ×   |
|--|---------------------------------|--------------------------|-----------------------------|------------------------|-----|
|  | Name: Conv-heated               |                          | Name: Conv-unheated         | 7                      |     |
| Define interactions:                                       | Type Surface film condition     |                          | Type: Surface film conditi  | on                     |     |
|  | Step: FocISO (Heat transfer)    |                          | Step: FocISO (Heat transf   | er)                    |     |
| convection for heated                                      | Surface: (Picked) 📘             |                          | Surface: (Picked) 📘         |                        |     |
| and unheated sides   | Definition: Em                  | nbedded Coefficient 👻    | Definition:                 | Embedded Coefficient 💌 | f(> |
|  | Film coefficient: 25            |                          | Film coefficient:           | 9                      |     |
| radiation for heated and                                   | Film coefficient amplitude: (In | istantaneous) 💌          | Film coefficient amplitude: | (Instantaneous)        | Ъ   |
| unheated side  | Sink definition: Un             | niform 💌                 | Sink definition:            | Uniform 🔻              | 8   |
|  | Sink temperature: 1             |                          | Sink temperature:           | 20                     |     |
|  | Sink amplitude: Fo              | c-ISO-C                  | Sink amplitude:             | (Instantaneous)        | Ъ   |
| 🕂 Edit Interaction   | Edit Interaction                |                          | К                           | Cancel                 |     |
| Nam : Rad-heated   | Name Rad-unheated               |                          |                             |                        |     |
| Type Surface radiation                                     | Type: Surface radiation         |                          |                             |                        |     |
| Step: FocISO (Heat transfer)                               | Step: FocISO (Heat transfer)    |                          |                             |                        |     |
| Surface: (Picked) 📘  | Surface: (Picked) 📘             |                          |                             |                        |     |
| Radiation type:  To ambient Cavity approximation (3D only) | Radiation type: 💿 To ambient 🔘  | Cavity approximation (3D | only)                       |                        |     |
| Emissivity distribution: Uniform $f(x)$                    | Emissivity distribution:        | Uniform 💌 f              | (x)                         |                        |     |
| Emissivity: 0.7  | Emissivity:                     | 0.7                      |                             |                        |     |
| Ambient temperature: 1                                     | Ambient temperature:            | 20                       |                             |                        |     |
| Ambient temperature amplitud :: Foc-ISO-C                  | Ambient temperature amplitude   | (Instantaneous) 🖌 🖡      | $\mathbf{b}$                |                        |     |
| OK Cancel  | ОК                              | Cancel                   |                             |                        |     |
|  |                                 |                          |                             |                        |     |

### Temperature field for concrete slab

Define initial temperature: -predefined field – constant through region

| W ADdu  | US/CHE UI   | 1-1 - INIOUE  |  | ise: O:V     | Huaqua     | WOIK (F | ostuoc     | riaya\ot   | encriman   | K/FIGCOP                     | -benchim                   | arkicae               | Inem          | pore r       | 1          |   |      |           |    |          |     |   |   |
|---|---|---|--|--------------|------------|---------|------------|--|--|------------------------------|----------------------------|-----------------------|---------------|--------------|------------|---|------|-----------|----|----------|-----|---|---|
| 🖻 <u>F</u> ile  | <u>M</u> odel   | Vie <u>w</u> port   | View   | <u>L</u> oad | <u>B</u> C | Predet  | fined Fie  | l <u>d</u> L <u>o</u> a  | d Case   | Feat <u>u</u> re             | e <u>T</u> ools            | Plug                  | -ins          | <u>H</u> elp | <b>h</b> ? |   |      |           |    |          |     |   |   |
| : 🗋 🖻   | 7 🖩 🖷   | : Ø (   | 3 💋  | 1            | 00         | 0       | <u>, i</u> | Ì́Ľ¥.  | хŮГ  | ۲ کې ۲                       | z z ł                      | , 1 χ                 | 2             | 3            | 4 🙏        | ÷ | C    | 0         |    | <b>1</b> | : ≣ | 昌 | Ē |
|   |   | All   |  |              | Ø.         | 100     | (Cr.       |  |  |                              |                            |                       |               |              |            |   |      |           |    |          |     |   |   |
| Model   | Results   |   |  |              |            | Mod     | ule: 📮 l   | .oad   | •  | Mode                         | l: 📮 Varia                 | ant1-the              | ermal-        | mesh         | )3         | - | Step | : 📮 Initi | al | -        |     |   |   |
| 🚰 Mo  | del Databas   | e   | <b>•</b>   | È.           | 5 🍟        | Ľ       |            | 0  |  |                              |                            |                       |               |              | _          |   |      |           |    |          |     |   | _ |
|   | ariant1-the<br>G  | rmal-mesh(<br>(1)   | )3   |              | *          | L       |            |  |  |                              |                            |                       |               |              |            |   |      |           |    |          |     |   |   |
| 8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8<br>8 | Mater<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Section<br>Profile<br>Section<br>Calibr<br>Section<br>Calibr<br>Section<br>Calibr<br>Section<br>Calibr<br>Section<br>Calibr<br>Mater<br>Histor<br>Listor<br>Calibr<br>Mater<br>Histor<br>Calibr<br>Histor<br>Calibr<br>Histor<br>Calibr<br>Histor<br>Calibr<br>Calibr<br>Histor<br>Calibr<br>Calibr<br>Histor<br>Calibr<br>Calibr<br>Histor<br>Calibr<br>Calibr<br>Histor<br>Calibr<br>Calibr<br>Histor<br>Calibr<br>Calibr<br>Calibr<br>Histor<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calibr<br>Calib | (1)<br>rations<br>(1)<br>rations<br>ons (1)<br>es<br>nbly<br>(2)<br>Output Req<br>ry Output R<br>Points<br>daptive Me<br>ctions (4)<br>ction Prope<br>act Controls<br>act Initializa<br>traints<br>ector Sections<br>itudes (5)<br>fined Fields | uests (1)<br>equests<br>sh Const<br>erties<br>tions<br>ons | traints      | Ш.         |         |            | Edit<br>Name:<br>Type:<br>Step:<br>Regior<br>Distrib<br>Section<br>Magni | Predefin<br>T-initi<br>Temp<br>Initial<br>n: (Picke<br>ution:<br>n variatic<br>tude: | ned Field<br>ial<br>eerature | Direct sp<br>Constan<br>20 | ecificati<br>t throug | ion<br>h regi | ion          |            |   | f(x) |           |    |          |     |   |   |
|   | - 🔣 Optin   | nization Tas  | ks   |              |            |         |            |  |  | ОК                           |                            |                       |               | Car          | ncel       |   |      |           |    |          |     |   |   |

### Temperature field for concrete slab

### Define mesh and finite elements: DS4 (0.3 m)

| Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus                              | s work\Postdoc Praga\Benchmark\Fracof-Benchmark.cae [Viewport: 1]  |      |
|--|--|------|
| <u>File</u> <u>M</u> odel Vie <u>w</u> port <u>V</u> iew <u>S</u> eed Mesh | h <u>A</u> daptivity Feat <u>u</u> re <u>T</u> ools Plug-ins <u>H</u> elp <b>\?</b>  |      |
| 🗋 🗃 🖶 🖶 🗗 🗗 🔰 🗉 👁 👁  | D 🗢 🔚 🏬 🗓 🖾 🖾 🖾 🏹 🏃 1 -2 -3 -4 - 📐 🕀 🔿 🔍 🔯 輝 🗄 🗸   | 1    |
| i 🕞 All 🕞 📮 i 🚱 🗀  |  |      |
| Model Results  | Module: Mesh Model: Variant1-thermal-mesh03 Object: Assembly Part: S   | ilab |
| 🚝 Model Database 🔄 🖨 🗞 🍟   |  |      |
| □ Variant1-thermal-mesh03  |  |      |
| Parts (1)  |  |      |
| Calibrations   | Element Type   |      |
| Sections (1)     Profiles  | Element Library Family   |      |
| ⊕ 🍰 Assembly<br>⊕ 🖧 Steps (2)  | Standard O Explic : Heat Transfer Article Arti |      |
| Field Output Requests (1)     History Output Requests     Time Points      | Geometric Order<br>Linear O Quadratic  |      |
| →  | Cuad Tri   |      |
| - 🔁 Interaction Properties   | Element Controls   |      |
| Contact Initializations  | (XYZ) There are no applicable element controls for these settings.   |      |
| <ul> <li>Constraints</li> <li>Gonnector Sections</li> </ul>                | 「御見し」  |      |
| T Fields   | 1.1%   |      |
| Amplitudes (5)   |  |      |
| Loads  |  |      |
| BCs  | ×  |      |
| T-initial  | DS4: A 4-node heat t ansfer quadrilateral shell.   |      |

#### Temperature field for concrete slab









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* 



### Structural analysis of composite slab

Add the reinforcement of the concrete slab



#### Structural analysis of composite slab

Define "profiles" for the wire elements and orientation



#### Structural analysis of composite slab

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



### Structural analysis of composite slab

Define steps for analysis:

-<u>for mechanical</u> loading

-for temperature influence

Both steps are "Static, General"

| J I   |   |
|---|---|
| 🖶 Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus | s work\Postdoc Praga\Benchmark\Fracof-Benchmark.cae [Viewport: 1] |
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| All 🔽 🖬 🕞 🗖                                     |   |
| Model Results                                   | Module: Step Variant1-mesh03 Step: Load                           |
| Model Database                                  |   |
| Variant1-mesh03                                 | Contraction of the step   |
| ⊕ Parts (4)                                     | Name: Load  |
| ⊕ 🖉 Materials (4)                               | Type: Static, General   |
| 🛛 🗑 Calibrations                                | Basic Incrementation Other  |
| 🗄 🥵 Sections (4)                                | Description:  |
| Profiles (3)                                    |   |
| Assembly  | 1 Ime period: 1   |
| Down Steps (3)                                  | (XYZ) 👬 Nigeom: On 🦯  |
| toad  | Automatic stabilization: None                                     |
| temp  |   |
| a 🐘 Field Output Requests (2)                   |   |
| History Output Requests                         | Edit Step   |
| Time Points                                     |   |
| ALE Adaptive Mesh Constraints                   | Name: Load  |
| Interactions                                    | Type: Static, General   |
| H Contraction Properties                        | Basic Incrementation Other  |
| Contact Controls                                |   |
| Constraints (1)                                 | Type:   Automatic  Fixed  |
| Connector Sections (1)                          | Maximum number of increments: 100                                 |
| ⊕ <i>F</i> Fields                               | Initial Minimum Maximum   |
| ⊕ 🅂 Amplitudes (5)                              |   |
| Loads (1)                                       | Increment size: 0.05  |
| ⊕ 📙 BCs (3)                                     |   |
| 🕀 🕒 Predefined Fields (5)                       |   |
| ← Щ Remeshing Rules     ←                       | OK  |
|   |   |

### Structural analysis of composite slab

Define steps for analysis:

-for mechanical loading

-<u>for temperature</u> <u>influence</u>

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| Model Results Module: Step Variant1-mesh03 Step: Temp   |
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| 🕞 Variant1-mesh03   |
| Parts (4)   |
|   |
| B Sections (4)  |
| B Profiles (3)  |
| Time period: 7200   |
| E (XYZ) t Nigeom: On  |
| ⊕ ∽ Initial   |
| 🗄 🚥 Load 🗸 🖓 🚑 Automatic stabilization: None 💽  |
|   |
| Edit Step   |
| History Output Requests   |
| Br ALE Adaptive Mesh Constraints  |
| Interactions  |
| Finteraction Properties   |
| Contact Controls  |
| Type:      Automatic      Fixed   |
| 🗄 🕣 Constraints (1)   |
| Connector Sections (1)  |
| 🖲 🗲 Fields Initial Minimum Maximum  |
| Amplitudes (5)  |
|   |
| DCS (5)   |
|   |
| ✓ III → OK Cancel   |

### Structural analysis of composite slab

#### Define mechanical interactions between slab and beams: constraints

| 🚔 Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus work\Postdoc Praga\Benchmark\Fracof-Benchmark.cae [Viewport: 1]  |
|--|
| Eile Model Viewport View Interaction Constraint Connector Special Feature Tools Plug-ins Help ★?   |
| ! D  |
| Model Results Module: Tinteraction Variant1-mesh03 Variant1-mesh03   |
| Varianti-metho3   Image: Stab-grinzi   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Type: Tie   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi   Image: Stab-grinzi < |
| Or Cancer  |

### Structural analysis of composite slab

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Model Results

Model Database

Variant1-mesh03

🗄 🕒 Parts (4)

ANT

All

R

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



E File Model Viewport View Interaction Constraint Connector Special Feature Tools Plug-ins Help

Module:

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Type: Join 🥖

Edit Connector Section

Name: SectiuneConector

Connection type diagram: 🔅

Available CORM: None Constrained CORM: U1, U2, U3

1?

A

2 3 4

#### Structural analysis of composite slab

Define Amplitudes :

-temperature of unprotected beams,

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



#### Structural analysis of composite slab





### Structural analysis of composite slab

#### Predefined fields: 🚔 Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus work\Postdoc Praga\Benchmark\Fracof-Benchmark.cae [Viewport: 1] summer in the second in File Model Viewport View Load BC Predefined Field Load Case Feature Tools Plug-ins Help **\?** ◎ 🔘 🗢 🔚 🎫 🖄 🖓 🖓 🖾 🖄 🕹 📜 🗄 🚊 🗐 i 🗋 🗃 🔜 🚔 A00 🕜 : 🔓 🥅 -Initial temperatures Module: 🖹 Load Model: Variant1-mesh03 ▼ Step: 🖨 Temp • Model Results (entire structure) 🖣 韋 🗈 🗞 🍟 Model Database LL 🛅 History Output Requests X 🚔 Edit Predefined Field H Time Points -Gradients through La ALE Adaptive Mesh Constraints Prot-IPE400 Name: L 🖬 Interactions Temperature Type: L H Interaction Properties III. beam section Temp (Static, General) Step: Contact Controls <u>18</u>, 1+ Region: (Picked) 📐 Contact Initializations 2 (protected beams) Distribution: **Direct specification** Connector Sections (1) -+13 • • F Fields Gradients through beam section Section variation: Amplitudes (5) 4 Reference magnitude: 1 -Constant through Æ 🗄 🕒 BCs (3) Amplitude: MainBeamTemp (XYZ) E Predefined Fields (5) N1 gradient: 21 region (unprotected Prot-IPE300 N2 gradient: -3.2757 Derot-IPE40 T-initial Note: The gradient method cannot be used for beam) Temp-IPE300-unprot elements with thermal degrees of freedom Temp-Slab Remeshing Rules Optimization Tasks -From thermal L Sketches OK Cancel Variant1-mesh03-w-o expansion

-From thermal analysis data base (slab)

### 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)



(slab)

### Structural analysis of composite slab



### Structural analysis of composite slab

Support conditions: Boundary conditions:

- columns

-longit. direction -transv. direction



Variant1-mesh05

Variant1-mesh06

Variant1-thermal

### Structural analysis of composite slab

Ξ File Model Viewport View Load BC Predefined Field Load Case Feature Tools Plug-ins Help Support 〒100 🜑 🖱 🏣 🗄 ビュゴ 兵 ビュゴ 美 (1 2 3 4 🕹 🕀 🍼 🔍 🗟 🔱 目 昌 🎒 💋 🚺 ì 🚰 🖥 🚔 AAA All conditions: Module: 🖨 Load -Model: Variant1-mesh03 • Model Results - - E B 🚝 Model Database LL 📰 Boundary 23 Edit Boundary Condition History Output Requests L 📖 His Time Points Name: XBeam conditions: ALE Adaptive Mesh Constraints 🍆 🛄 Displacement/Rotation Type: 1 Interactions Step: Temp (Static, General) 🖶 Interaction Properties - columns Region: (Picked) Contact Controls li, I+, Contact Initializations CSYS: (Global) Constraints (1) 1 -longit. direction Method: Specify Constraints Connector Sections (1) 13.0 + F Fields Distribution: Uniform Amplitudes (5) **L V** U1: -transv. directior 🗄 💾 Loads (1) BCs (3) U2: (XYZ) 🗄 Stalpi 🔲 U3: 21 1 🗄 XBeam radian UR1: 🗄 YBeam 🗄 🔚 Predefined Fields (5) radian UR2: 🗓 Remeshing Rules radian **V** UR3: 0 Optimization Tasks Sketches -A Amplitude: (Ramp) Variant1-mesh03-w-o expansion Variant1-mesh03-w-o pressure Variant1-mesh04 Note: The displacement value will be

🚔 Abaqus/CAE 6.11-1 - Model Database: G:\Abaqus work\Postdoc Praga\Benchmark\Fracof-Benchmark.cae [Viewport: 1]

maintained in subsequent steps.

Cancel

OK
## **Numerical model**

### Structural analysis of composite slab

📥 Abagus/CAE 6.11-1 - Model Database: G:\Abagus work\Postdoc Praga\Benchmark\Fracof-Benchmark.cae [Viewport: 1] Ξ File Model Viewport View Load BC Predefined Field Load Case Feature Tools Plug-ins Help Support #00 ) 菺 🖥 🚔 AI conditions: ▼ Model: Variant1-mesh03 🔹 Step: 📮 Temp Module: 🚊 Load Model Results - - E B Boundary 🚝 Model Database 止 📰 X Edit Boundary Condition History Output Requests Ht Time Points Name: YBeam conditions: ALE Adaptive Mesh Constraints L 🗖 Type: Displacement/Rotation Interactions Step: Temp (Static, General) 🔛 🛄 Interaction Properties - columns Region: (Picked) £ Contact Controls <u>1. I.</u> Contact Initializations CSYS: (Global) € Constraints (1) 1 -longit. direction Specify Constraints Method: 🗄 🐻 Connector Sections (1) • Fields Distribution: Uniform Amplitudes (5) 1 4 🔲 U1: -transv. directior 🗄 陆 Loads (1) BCs (3) V U2: 0 (XYZ)  $\mathbf{A}$  Stalpi 21 I 🔲 U3: XBeam UR1: radians 🗄 YBeam Description: Example: Examp radians UR2: Remeshing Rules **UR3**: radians Optimization Tasks L Sketches -A Amplitude: (Ramp) Variant1-mesh03-w-o expansion Variant1-mesh03-w-o pressure Variant1-mesh04 Note: The displacement value will be Variant1-mesh05 maintained in subsequent steps. Variant1-mesh06 OK Cancel Variant1-thermal



### Structural analysis of composite slab

### Results: Displacements



With respect to time

With respect to temperature

Structural analysis of composite slab

### Results, other than obtained in experiment: Axial force



Structural analysis of composite slab

### Results, other than obtained in experiment: Vertical shear force



With respect to temperature

Structural analysis of composite slab

Results, other than obtained in experiment: Reinforcement strain





Mesh sensitivity study

### Monitored variable: vertical displacement of the slab centre, U3

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

 $h = \left[\frac{1}{N}\sum_{i=1}^{N} (\Delta A_i)\right]^{1/2} \qquad E_1 = \frac{\varepsilon}{r^p - 1}$   $\varepsilon = \frac{f_1 - f_2}{f_1}. \qquad GCI = \frac{F_s |\varepsilon|}{r^p - 1} 100\%,$   $p = \frac{\ln\left(\frac{f_3 - f_2}{f_2 - f_1}\right)}{\ln(r)}$   $A_1 = \frac{f_1 - f_{h=0}}{f_{h=0}} \cong \frac{f_1 - f_2}{f_{h=0}} \frac{1}{r^p - 1},$ 

N – number of elements

 $A_i$  – area of element "i"

r – refinement ratio (should have close values

- $\epsilon$  relative difference
- A1 relative error
- p- order of convergence
- GCI grid convergence index

## **Conclusions of composite slab benchmark**<sup>81</sup>

 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.

## **Verification example**

- By comparison to existing experimental tests
- German annex EN1991-1-2
  Comparison examples

There are 11 examples analyzing :

- heat transfer for different material properties
- elongation of elements
- forces and stresses
- fire resistance time

For each example there are given results and their error tolerances

# Example 11 - DIN1991-1-2

## Parabolic longitudinal path –

### midspan imperfection L/1000

|   |                 | 1/h/b  | cm           | 400 / 30 / 30   |  |
|---|-----------------|--|--------------|-----------------|--|
| Dimensione                              |                 | Us   | mm           | 50              |  |
| Dimensions                              |                 | ef   | mm           | 19              |  |
|   |                 | ew   | mm           | 11              |  |
| Buckling length                         |                 | <i>I</i> 0,fi                                    | cm           | 200             |  |
| Load                                    |                 | <b>N</b> E,fi,d,t                                | KN           | -1700           |  |
| Concrete C25/30<br>(3 % moisture (by ma | ss))            | <i>f</i> ck(20°C)                                | N/mm²        | 25              |  |
| Reinforcing steel S 50                  | 0               | <i>fyk</i> (20°C)                                | N/mm²        | 500             |  |
| Structural steel S 235                  |                 | <i>fak</i> (20°C)                                | N/mm²        | 235             |  |
|   |                 | Concrete a.                                      |              |                 |  |
| Stress – strain curve                   |                 | Reinforcing                                      | steel b.     | DIN EN 1994-1-2 |  |
|   |                 | Structural st                                    | eel          |                 |  |
| Temperature load                        |                 | ETK (four sid                                    | les)         | DIN EN 1991-1-2 |  |
| Heat transfer coeffici                  | ent             | α  | W/(m² × K)   | 25              |  |
| Emissivity                              |                 | Em   |              | 0.7             |  |
| Thermal and                             | Concrete        | $\lambda, \rho, c_{p, \varepsilon}$ th,c         |              | DIN EN 1994-1-2 |  |
| physical material properties            | Steel           | $\lambda$ , $\rho$ s, $C$ a, $\mathcal{E}$ th,s, | €th,a        | DIN EN 1994-1-2 |  |
| a. Containing mainly                    | quartzite aggre | egate and density p                              | o=2400 kg/m³ |                 |  |

b. Hot-rolled





# Analysis

#### **Previous verification using SAFIR**

- 2D beam elements
- For displacement at 60 minutes the criterion is not fulfilled

| Requested<br>results |           | Reference | Calculated | Deviation | Limit | A  |
|----------------------|-----------|-----------|------------|-----------|-------|----|
|                      |           | value     | value      | [%]       | [%]   |    |
| Failure time         |           | 92        | 88         | -4.35     |       | A, |
| Displ.               | 30<br>min | 4.40 <    | 4.44       | +0.82     | ± 5   | 5  |
| լոույ                | 60<br>min | 5.50      | 5.04       | -8.18     |       |    |

The result is not consistent with the other values:

- at 30min the displacement is bigger than the reference value while for 60 minutes the displacement is smaller than the reference value
- For smaller displacement it is expected longer resistance time; but for this case the fire resistance is smaller

## **Model - Abaqus**

**Material properties** 



# Model

**Part definition** 



# Model

**Concrete model** 

Piecewise stress-strain



Large tensile stress for concrete

Smeared concrete



-elongation & BC problems

Damaged plasticity concrete



# Model

#### **Boundary conditions**

### Fully fixed -surface

## Fully fixed -node





# Analysis

Thermal analysis - 2D - verification

Grid Convergence Index (GCI) for temperatures at 90min



# Analysis

#### **Structural analysis**

Sequentially coupled analysis

Thermal analysis

 3D solid – DC3D8:
 An 8-node linear heat transfer brick

Mechanical analysis

- 3D solid C3D8R: An 8-node linear brick, reduced integration, hourglass control

Fully coupled analysis

Thermal and mechanical analysis

 3D solid – C3D8T
 An 8-node thermally coupled brick, trilinear displacement and temperature

## **Results**

### Fully coupled analysis



# **Results**

The results do not fulfill 2 criterion: fire resistance time and

| displacemen | ABAQ    | QUS       | Reference<br>value<br>X | Calculated<br>value<br>X' | Deviation<br>[%] | Limit<br>[%] |
|-------------|---------|-----------|-------------------------|---------------------------|------------------|--------------|
|             | Failure | time      | 92                      | > 87                      | -5.43            |              |
|             | Displ.  | 30<br>min | 4.40                    | 4.56                      | +3.52            | ± 5          |
|             | [mm]    | 60<br>min | 5.50 <                  | 7.82                      | +42.16           |              |

It can be observed that, as is case of SAFIR analysis, fire resistance time is smaller than the reference value. On the other hand, displacement for 60 minutes is higher than the reference value (still, the Abaqus results are consistent since for a smaller resistance time there is a corresponding larger deflection for the column, with respect to the reference value).

| SAFI    | R         | Reference | Calculated | Deviation | Limit |
|---------|-----------|-----------|------------|-----------|-------|
| Failure | time      | 92        | 88         | -4.35     |       |
| Displ.  | 30<br>min | 4.40      | 4.44       | +0.82     | ± 5   |
| լոորյ   | 60<br>min | 5.50      | 5.04       | -8.18     |       |

## **Conclusions for composite column**

- Extra information needed for the calculation model
- Mechanical interaction between elements - unknown
- Concrete model difficult to define
- Analysis time long
- What happens after debonding? –thermal condition

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