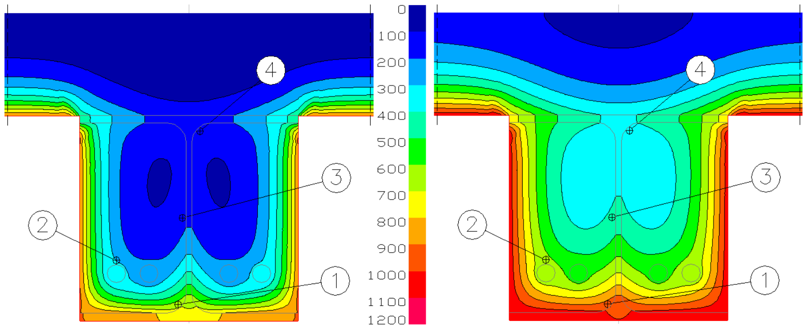
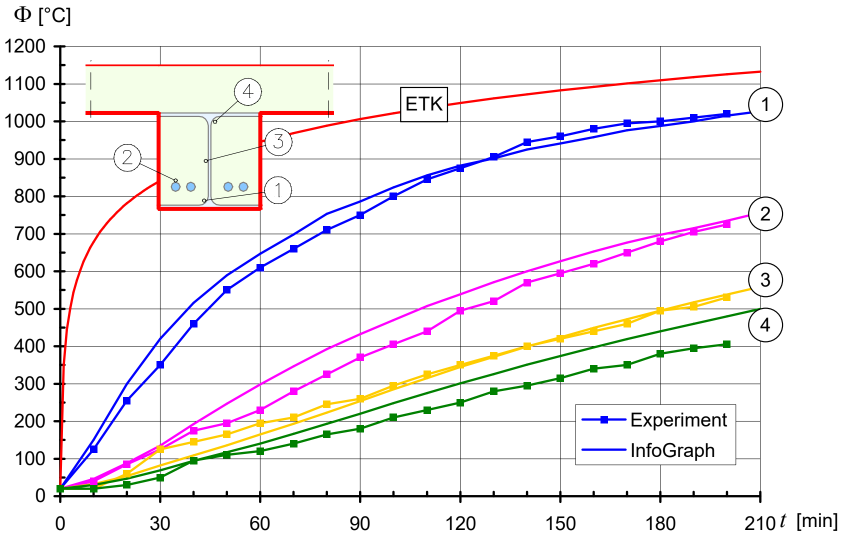
Structural Analysis for Fire Scenarios

for Steel, Concrete, Timber and Composite Structures according to Eurocode





InfoGraph

Software für die Tragwerksplanung

InfoGraph® Software uses Microsoft® MFC and Intel® MKL Libraries.

Title image: Temperature distribution for a composite girder after 60 and 90 minutes [°C].
Comparative analysis for: Fire Safety Check of Concrete-Encased Composite Components For Ultimate Fire Loads (Nachweis der Brandsicherheit von kammerbetonierten Verbundbauteilen über Grenzbrandlasten).
J. Upmeyer, Dissertation, TU Hannover, 2001.

Contents

Structural Analysis for Fire Scenarios

Area of Application

The structural analysis for fire scenarios allows the analysis of two- and three-dimensional beam and area structures within the *2D Frames*, *3D Frames* and *Finite Elements* program systems. Steel, reinforced concrete, timber and composite sections according to the following standards can be considered:

- EN 1992-1-2:2004+A1:2019 (Eurocode 2)
- EN 1993-1-2:2005+AC:2009 (Eurocode 3)
- EN 1994-1-2:2005+A1:2014 (Eurocode 4)
- EN 1995-1-2:2004+AC:2009 (Eurocode 5)

Steel sections, polygon sections and combinations of these as well as area sections can be used as section types. The following materials can be selected:

- Concrete according to DIN 1045-1, EN 1992-1-1, DIN EN 1992-1-1, OENORM B 4700 and SIA 262
- Construction steel according to DIN 18800 and EN 10025-2
- Steel with user-defined properties
- Timber according to EN 338:2016 and EN 14080:2013 (beams only)
- Freely defined material

The analysis can usually be divided up into the following steps:

1. Dimensioning the structure for standard actions

- Structural definition with statically effective sections.
- Determine the internal forces for the decisive load situations.
- Description of the action combinations according to the relevant national standard.
- Stress checks for structural steel members, determination of the reinforcement required for reinforced concrete members.

2. Thermal analysis to determine the section temperatures

- Definition of the determinant sections for fire scenarios (*Thermal analysis* function in the Section dialog).
- Determination of the effects of fire on the affected section boundaries.
- Calculation of the temperature profile in the section (using the *Thermal analysis* dialog or the *Section Temperatures* function in the *Analysis* menu).

3. Nonlinear system analysis for fire scenarios

- Specification of a decisive load case. Existing load cases are grouped together and weighted using the *Load group* load type.
- Addition of the *fire scenario* load type to the load case.
- Selection of this load case from the *Fire scenario* tab in the calculations settings for nonlinear system analysis.
- Selection of the reinforcement determined under item 1 (above), if relevant.
- Execution of the framework or FEM calculations to determine the load-bearing capacity for a fire scenario.

When different fire scenarios are to be investigated, the section boundaries can be allocated different fire effects under item 2. The individual fire scenarios are numbered in this case. Finally, a check load case should be generated under item 3 for each fire scenario. The respective numbers mentioned above are used in the *fire scenario* load type.

Calculation of Section Temperatures

This section describes the thermal analysis of the section temperatures due to the effects of fire.

Basics

The calculation of the temperature distribution for transient situations in solid bodies is carried out by solving the thermal conductivity equation as set out by Fourier. For the two-dimensional case considered here, this has the following form:

$$\rho \cdot c_p \cdot \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial y} \cdot \left(\lambda \frac{\partial \theta}{\partial y} \right) + \frac{\partial}{\partial z} \cdot \left(\lambda \frac{\partial \theta}{\partial z} \right) \tag{1}$$

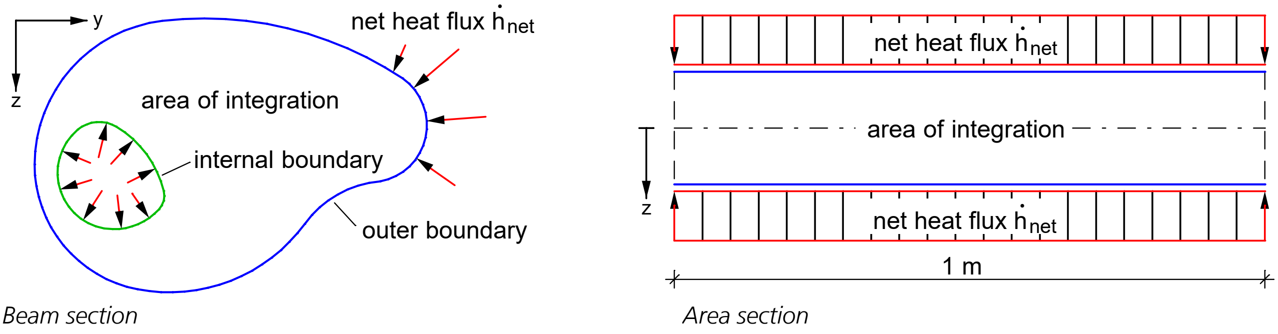
with

t	Time [s]
y, z	Local coordinates [m]

Functions of y, z, t

θ	Temperature [°C]
ρ	Apparent density [kg/m³]
c_p	Specific thermal capacity [J/(kg K)]
λ	Thermal conductivity [W/(m K)]

For area elements the thermal conductivity equation is reduced to the one-dimensional case with the coordinate z. A horizontal thermal conductivity cannot be taken into account. For this a solid model has to be used. Heat sources within the integration area are ignored for area sections. As all factors are dependent on time, the initial value problem needs to be solved in consideration of the boundary conditions. The temperature distribution in the area of integration at the time $t = 0$ is taken as the initial condition.



Beam section *Area section*

For the problem being considered here, the thermal actions will be primarily determined by the net heat flux $\dot{h}_{net}$ [W/m²] normal to the boundaries. This, in turn, comprises a convection and radiation component.

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \tag{2}$$

The convective component is calculated as follows:

$$\dot{h}_{net,c} = \alpha_c \, (\Theta_g - \Theta_m) \tag{3}$$

with

α_c	Coefficient of heat transfer [W/(m² K)]
Θ_g	Gas temperature in the region of the component under load [°C]
Θ_m	Temperature at the boundary of the component [°C]

In analysing of the convective component on the internal boundary of a section hole, during one time step, a mean gas temperature is assumed.

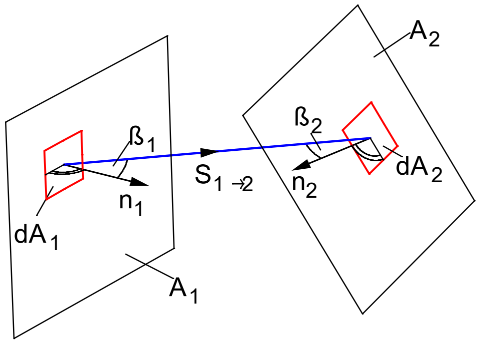
The net heat flux between two surfaces due to radiation is calculated as follows:

$$\dot{h}_{net,r} = \Phi \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot \sigma \cdot [(\Theta_1 + 273)^4 - (\Theta_2 + 273)^4] \tag{4}$$

with

Φ	Configuration factor
ε_1, ε_2	Emissivity of the component surfaces [-]
σ	Stephan-Boltzmann constant [= $5.67 \cdot 10^{-8}$ W/(m^2 K^4)]
Θ_1, Θ_2	Temperature at the component surfaces [°C]

The configuration factor is determined by the geometry of the surface, the distance between the surfaces and shadowing effects. The following figure shows the underlying parameters.



The configuration factor can be determined as follows:

$$\varphi_{1\to 2} = \frac{1}{\pi \cdot A_1} \cdot \int_{A_1} \int_{A_2} \frac{\cos\beta_1 \cdot \cos\beta_2}{s_{1\to 2}^2} \cdot dA_1 \cdot dA_2 \tag{5}$$

In the case of radiation due to fire follows:

$\Phi = 1$

$\varepsilon_1 = \varepsilon_m$	emissivity of the component surface [-]
$\varepsilon_2 = \varepsilon_f$	emissivity of the flame (here $\varepsilon_f = 1$) [-]
$\Theta_1 = \Theta_r$	effective radiation temperature of the fire (here $\Theta_r = \Theta_g$) [°C]
$\Theta_2 = \Theta_m$	surface temperature at the component boundary [°C]

The gas temperature Θ_g of a region of a fire is assumed to be known and is generally defined according to particular temperature-time curves.

The nonlinear boundary problem set by equations (1) to (5) cannot be solved in a closed form. Instead, the finite element method is used to solve the problem. In this case, Galerkin's method followed by partial integration is used to convert the boundary problem described above into a system of variation equations.
The program system uses compatible elements with a fully quadratic approach. This results in a high degree of accuracy, which is largely independent of the net geometry.

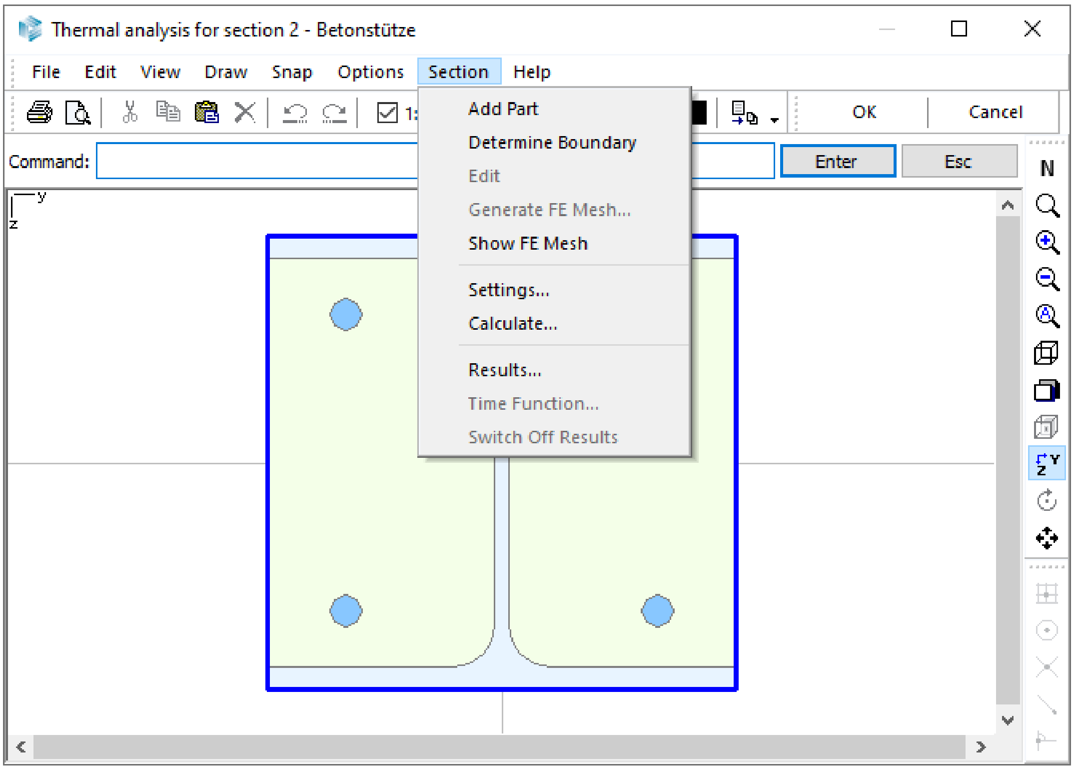
The element approach automatically satisfies the so-called 'adiabatic boundary conditions', meaning that thermal energy is only exchanged where boundary conditions are explicitly specified.

The nonlinear initial value problem is solved using time-step integration in conjunction with an incremental Newton-Raphson algorithm. After successful calculation, the temperature profiles for all times considered are available for further calculation.

Thermal Section

The input window shown below is accessed by way of the sections dialog and then the *Thermal analysis* function. The functions which are described below can be found in the *Section* and in the context menus:

Add part	Allows the section to be assembled from new and existing parts.
Determine boundary	Determines the boundary of a section assembled from parts and highlights it with a red line.
Edit	Starts the dialog for editing a selected section part or for determining the fire actions for the marked part of the section boundary.
Generate FE mesh...	Starts the dialog for specifying the mesh size of the element mesh used for thermal calculation.
Show FE mesh	Shows the element mesh for the thermal calculation. This mesh is automatically generated before each analysis, even when the display is switched off.
Settings...	Starts the dialog with the settings for thermal analysis.
Calculate...	Starts the thermal analysis in its own window and shows the temperature distribution for the last calculated time step.
Results...	Starts the dialog for selecting results calculated for different times.
Time function...	Starts the dialog with the illustration of a time function of the current result for a selected section point.
Switch off results	Switches off the representation of results.



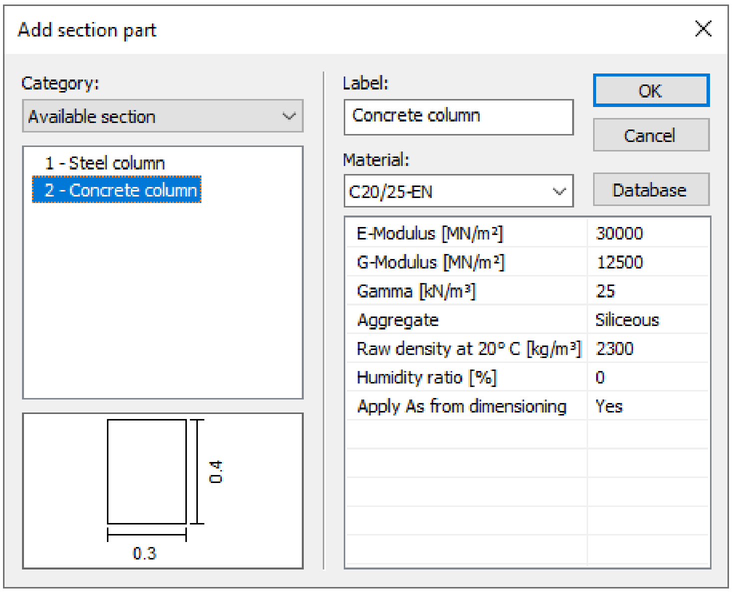
The thermal section can be assembled from any sectional components and, along with the representation of statically relevant parts, can also include, for example, thermal insulations.

The beam axes for the static analysis (fire scenario) are located at the origin (0; 0) of the thermal cross-section.

The central area of the area elements goes through z = 0.

Addition of Section Parts

The thermal section is defined by adding section parts. During this process, section parts added later overlap parts that were added previously. The order in which section parts are added therefore determines the geometry of the final section. When adding a cross-section with a hole, first a cross-section part with the shape of the outer polygon and the selected material type is created and then a cross-section part with the shape of the hole and the material type *Null*. Note, however, that a part in the background may not be completely overlapped by another part.



Category: Available section

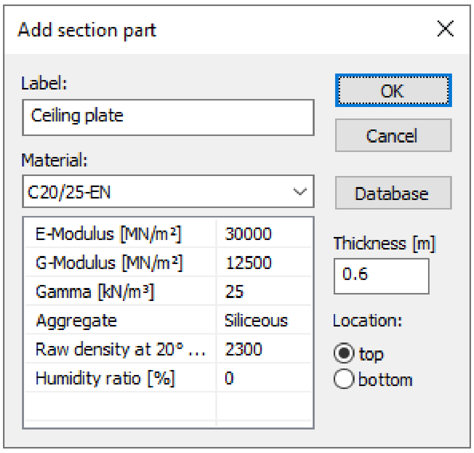
1 - Steel column
2 - Concrete column

Label: Concrete column

Material: C20/25-EN

E-Modulus [MN/m²]	30000
G-Modulus [MN/m²]	12500
Gamma [kN/m³]	25
Aggregate	Siliceous
Raw density at 20° C [kg/m³]	2300
Humidity ratio [%]	0
Apply As from dimensioning	Yes

or



Label: Ceiling plate

Material: C20/25-EN

E-Modulus [MN/m²]	30000
G-Modulus [MN/m²]	12500
Gamma [kN/m³]	25
Aggregate	Siliceous
Raw density at 20° …	2300
Humidity ratio [%]	0

Thickness [m] 0.6

Location:
● top
○ bottom

For area sections section parts of desired thickness can be added above or below existing section parts. The width of the section parts is always 1 m.

For beam sections the following categories of section parts may be added:

Category

- *Reinforcement bar*: is added as a section part and represented as a structural element and therefore influences temperature distribution (however, only makes sense for larger diameters).
- *New definition*: new definition of a polygonal section part which can also contain reinforcement. This is not represented as a structural element and has no influence on the temperature profile.
- *Steel profile*: steel profile from the section library.
- *Available section*: a section already defined in the project.

Material

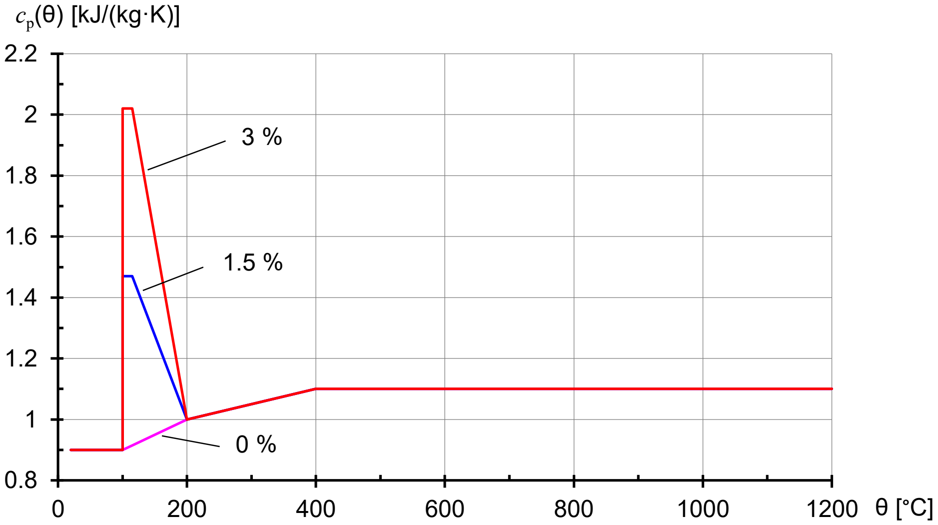
The section material together with its thermal and mechanical properties.

The *Apply As from dimensioning* option is used to specify that the selected reinforcing will be applied to the current section. This reinforcing is selected on the *Fire Scenario* tab in the nonlinear system analysis *Calculation Settings*. It is assumed that these reinforcing steel layers have no influence on the temperature distribution in the section and so the concrete temperature at their locations is assigned to them. The material can be saved in the *Igraph.dat* database for use in other structures.

The following specific material properties apply to the thermal analysis:

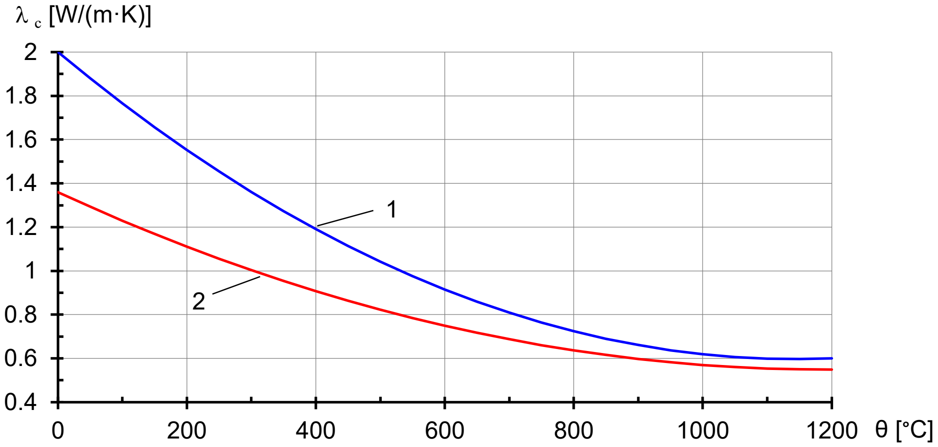
Concrete

All concrete section parts are automatically assigned the temperature-dependent *specific thermal capacity*, the *thermal conductivity* and the *raw density* as specified in EN 1992-1-2. According to DIN EN 1992-1-2/NA:2010-12 the upper limit function of the *thermal conductivity* in 3.3.3 (2) is used for DIN concrete. The lower boundary value is used for other kinds of concrete. The *humidity ratio* and *raw density at 20° C* can be specified by the user. For the *ÖNBeton* material user-defined progressions of the thermal properties can be described.

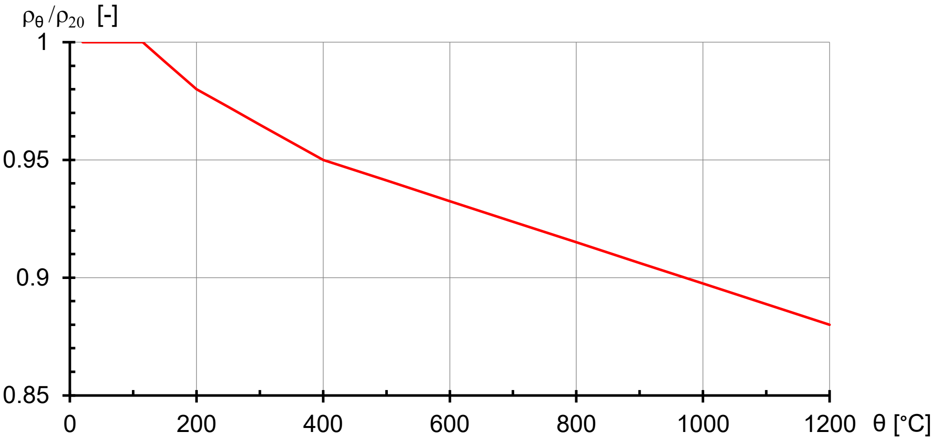


The specific heat capacity of siliceous and calcareous concrete $c_p(\Theta)$ *depending on the temperature (moisture content u = 0, 1.5 and 3 % by weight)*

Moisture contents between the values specified will be linearly interpolated.



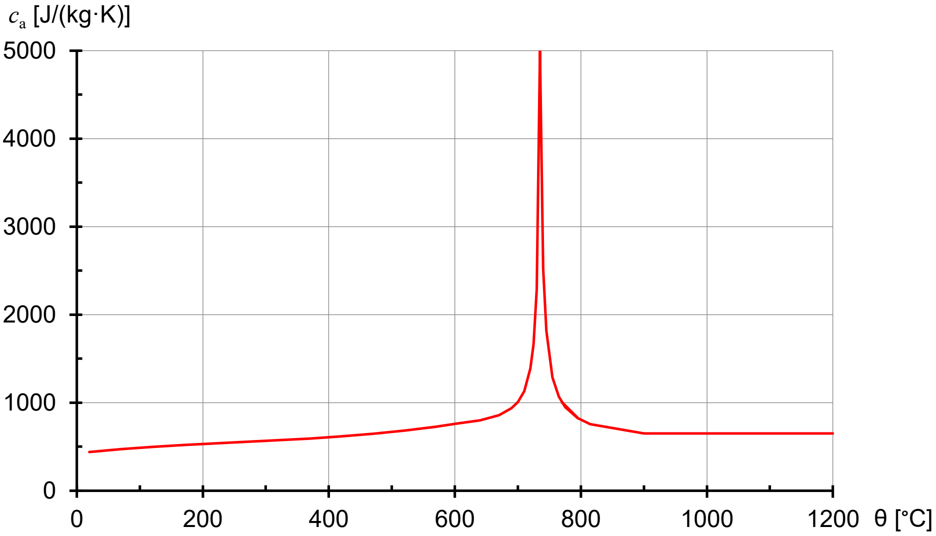
Temperature-dependent thermal conductivity
1: upper limit (DIN concrete); 2: lower limit



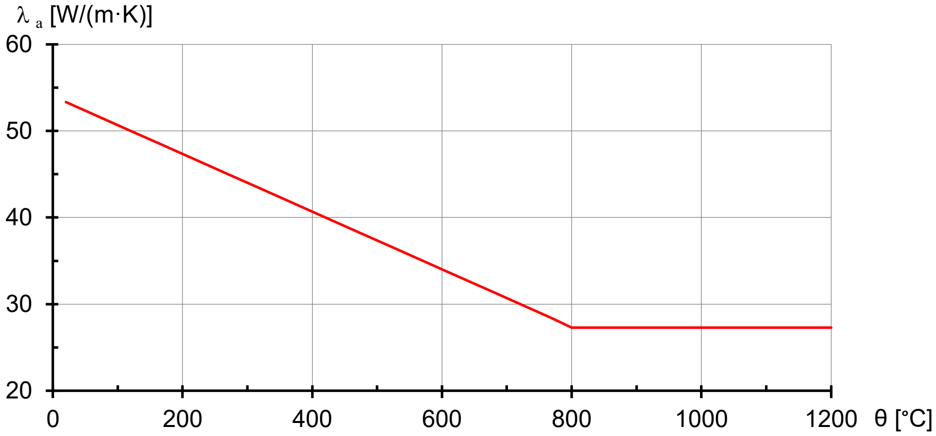
Temperature-dependent raw density ratio of concrete

Steel

All steel sections are automatically assigned the temperature-dependent *specific thermal capacity* and the *thermal conductivity* as specified in EN 1993-1-2.



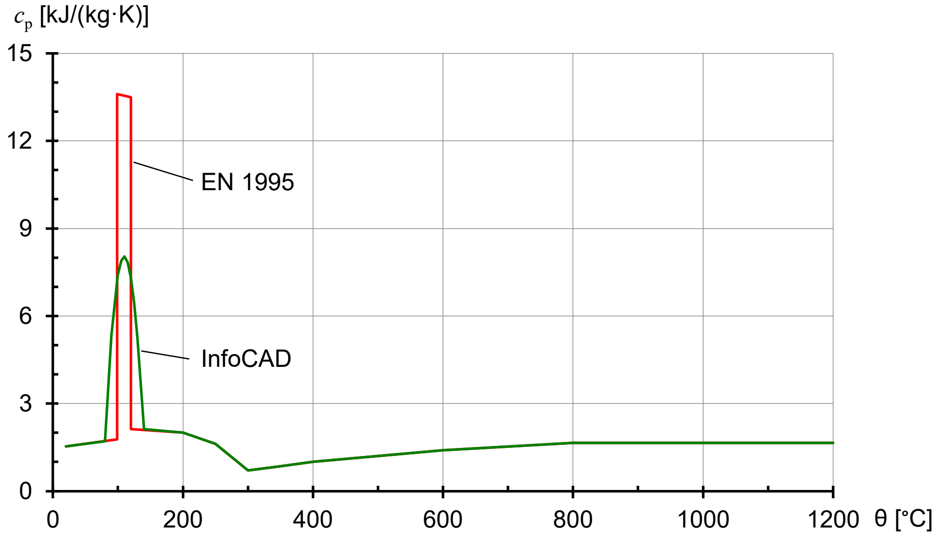
The temperature-dependent specific thermal capacity for carbon steel



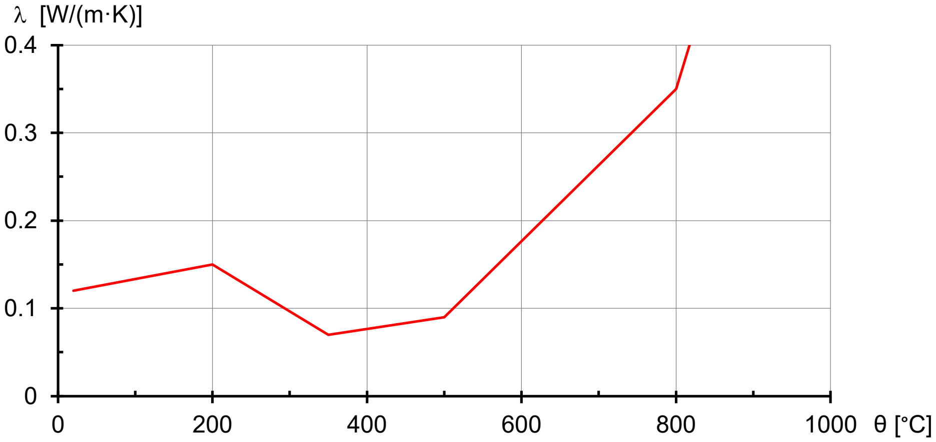
The temperature-dependent conductivity for carbon steel

Timber

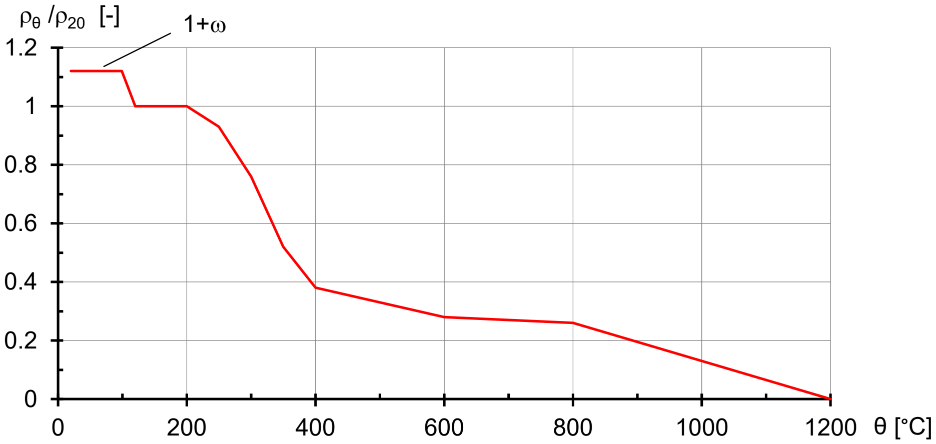
All timber section parts are automatically assigned the temperature-dependent *specific thermal capacity*, the *thermal conductivity* and the *raw density* as specified in EN 1995-1-2.



The temperature-dependent specific thermal capacity for timber



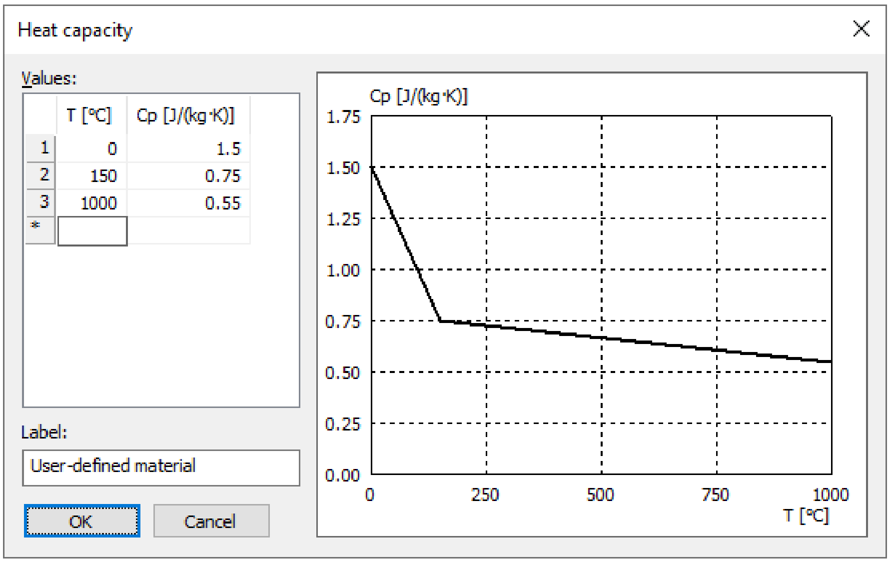
The temperature-dependent conductivity for timber



The temperature-dependent raw density ratio for timber with an initial moisture content ω of 12 %

User-defined material

User-defined section parts are used to specify, for example, insulating materials, where any temperature-dependent *specific thermal capacity*, *apparent density* and *conductivity* can be specified.



	T [°C]	Cp [J/(kg·K)]
1	0	1.5
2	150	0.75
3	1000	0.55
*		

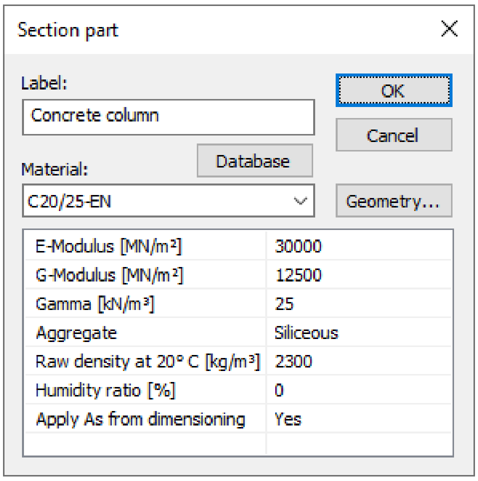
Label: User-defined material

User-defined thermal conductivity

'Null' Material type

Sections with this material type are excluded from analysis, which allows openings to be 'added' subsequently to a section.

Edit Section Parts



Label: Concrete column

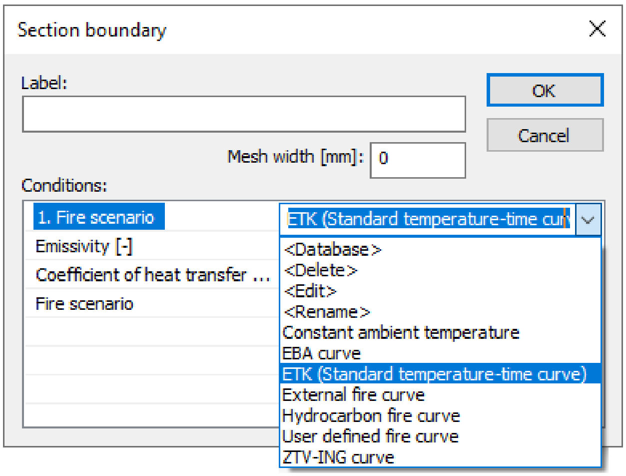
Material: C20/25-EN

E-Modulus [MN/m²]	30000
G-Modulus [MN/m²]	12500
Gamma [kN/m³]	25
Aggregate	Siliceous
Raw density at 20° C [kg/m³]	2300
Humidity ratio [%]	0
Apply As from dimensioning	Yes

The *Edit* function allows the material properties and thermal parameters of a selected section part to be changed. In addition, the geometry and reinforcement of section polygons can be modified.

Edit Section Boundaries

The section boundaries are specified after all the section parts have been added. This is automatically carried out using the '*Determine boundary*' command. Each of the resulting section boundaries can then be allocated the following properties. Edges at holes have the standard feature '*Inner radiation and convection*'.



Label:

Mesh width [mm]: 0

Conditions:

1. Fire scenario	ETK (Standard temperature-time cur
Emissivity [-]	
Coefficient of heat transfer ...	
Fire scenario	

Mesh width

The section boundary is divided with the chosen mesh width [mm]. If the mesh width '0' is chosen and a fire curve is assigned to the boundary the boundary is divided into pieces of about 20 mm.

Conditions

In order to be able to investigate different fire situations, different *fire scenarios* can be defined. The name and number of these scenarios can be changed by the user as required. The thermal calculations for each fire scenario are carried out separately. During calculation, actions whose number corresponds with the fire scenario number will be applied to the boundaries. Boundaries that have not been allocated actions for a particular fire scenario number are treated adiabatically.

The following properties can be specified for each fire scenario:

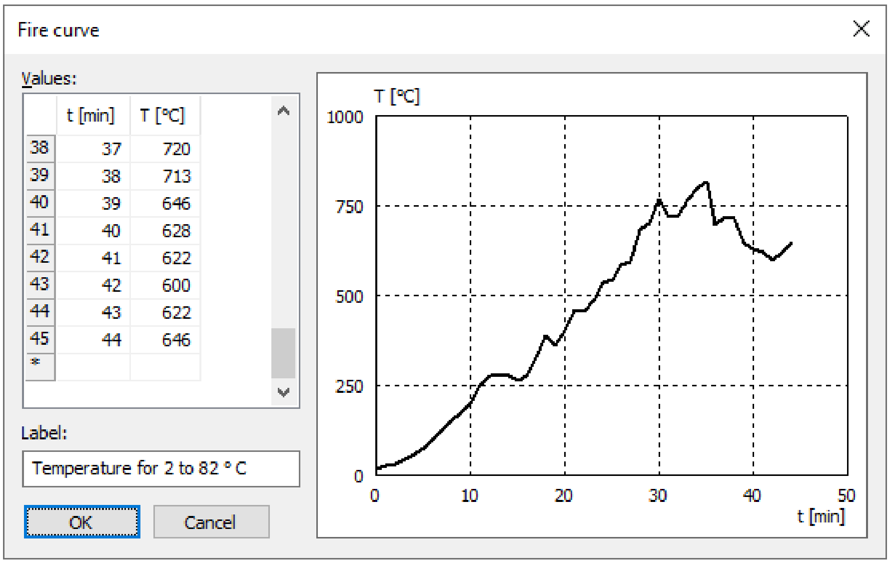
- Fire curve, e.g., *ETK (Standard Temperature-Time Curve)*
- *Coefficient of heat transfer [W/(m² K)]*
- *Emissivity [-]*

The convective coefficient of heat transfer can be taken from EN 1991-1-2, Appendix B.

The emissivity of concrete and construction steel surfaces should be determined according to EN 1992-1-2 or EN 1993-1-2, Chapter 2.2 (2) for a default value of 0.7. According to Appendix C of the standard, the emissivity for stainless steel should be set to 0.4.

The following fire curves can be used to determine the fire progression.

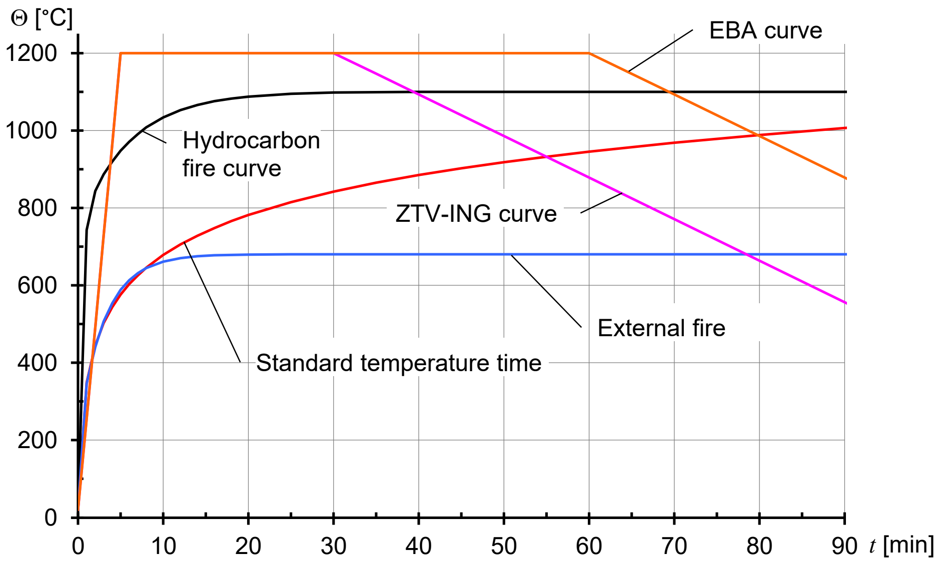
- *Constant ambient temperature*: The ambient temperature can be set (colored green).
- *EBA curve*: Fire curve according to EBA-Guideline (colored orange).
- *ETK (Standard Temperature-Time Curve)*: Fire curve according to EN 1991-1-2 or prEN 13501-2 (colored red).
- *External fire curve*: Fire curve according to EN 1991-1-2 (colored turquoise).
- *Hydrocarbon fire curve*: Fire curve according to EN 1991-1-2 (colored black).
- *User-defined fire curve*: Fire curve defined by the user (colored blue).
- *ZTV-ING curve*: Fire curve according to ZTV-ING Part 5 (colored purple).



	t [min]	T [°C]
38	37	720
39	38	713
40	39	646
41	40	628
42	41	622
43	42	600
44	43	622
45	44	646
*		

Label: Temperature for 2 to 82 ° C

User-defined fire curve

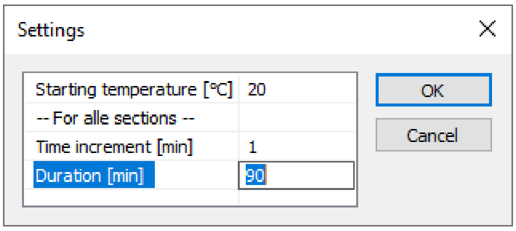


Fire curves according to EN 1991-1-2, ZTV-ING Part 5 resp. EBA-Guideline

Generate FE Mesh

The section geometry is determined by the added section parts and the boundary. The finite element mesh for the thermal analysis is then generated by the program based on this geometry. This mesh can be displayed by use of the '*Show FE mesh*' command. For beam sections the option *'Generate FE-Mesh'* allows the selection of the mesh width [mm] and the mesh angle [°] (smallest internal angle of elements). The FE-mesh affects the thermal analysis and also the subsequent mechanical analysis, because both use the same element mesh.

Settings for Thermal Analysis



Settings

Starting temperature [°C] 20

-- For alle sections --

Time increment [min] 1

Duration [min] 90

The initial temperature is used to set the initial conditions for the time-step calculation at time t = 0. This applies to the current section. At a temperature of 20°C there is no thermal expansion according to the standard.

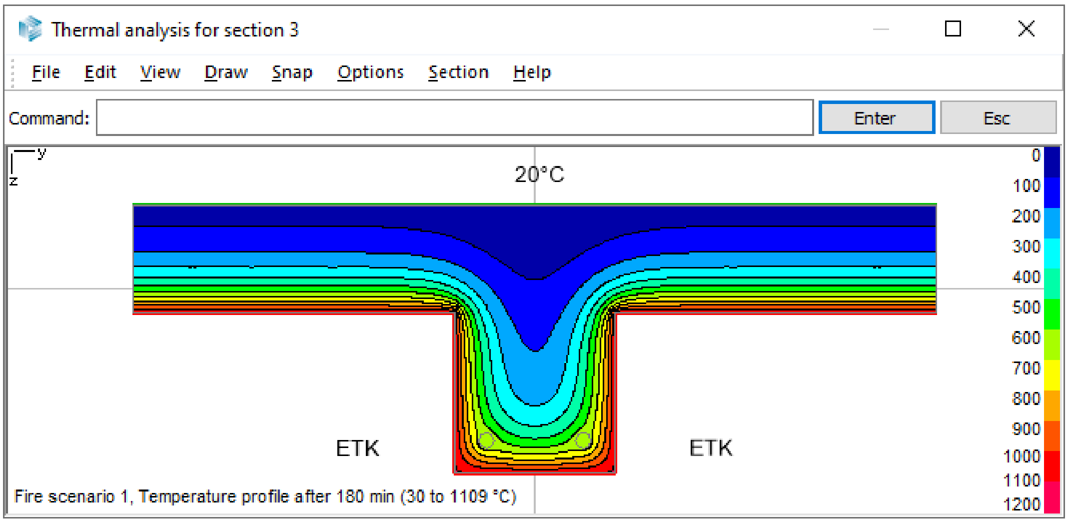
The time increment and duration apply for both the thermal and the mechanical analysis. For reasons of compatibility, both parameters are applied globally.
The size of the time step influences calculation accuracy; however, because of the computing time required, this should be set to a value smaller than 1 min in exceptional situations only.

Calculation of the Temperature Profile

The *Calculate* menu item in the editing window starts the calculation of the temperature profile for the current section over the required period of time. The *Section Temperatures* function in the main window's *Analysis* menu is used to start the collective calculation for all sections.

Display Results

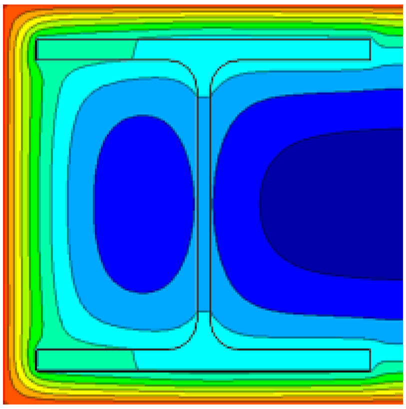
After calculating results, the temperature distribution for the last time step calculated will be shown. The results dialog can be used to show the temperature profile for each time investigated.



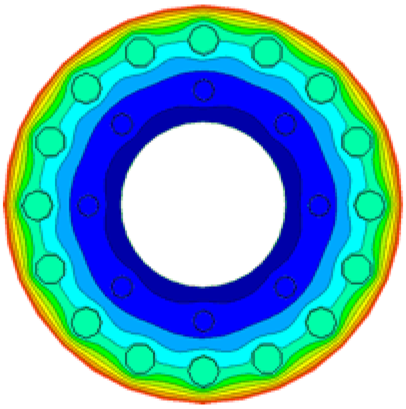
Thermal analysis for section 3

Fire scenario 1, Temperature profile after 180 min (30 to 1109 °C)

Temperature distribution from the standard temperature-time curve (ETK)



Composite section fired from three sides with one adiabatic boundary



Spun concrete column with steel reinforcing

Nonlinear Structure Analysis for Fire Scenarios

Points to be considered when applying nonlinear systems to fire scenarios are explained below. The general theoretical principles are explained in the *Nonlinear Structural Analysis* chapter.

Basics

The nonlinear representation of fire is to be carried out in accordance with the '*Advanced calculation method*' of the EN 1992-1-2, EN 1993-1-2 and EN 1995-1-2 standards. This procedure assumes that the mechanical and thermal analyses can be carried out independently of one another. The basis for these calculations is the temperature profile previously determined as part of the analysis of the thermal section. This basis corresponds with the '*Calculation of section temperatures*' chapter.

As the most important factors are dependent on time and temperature, a time-step calculation is always carried out with '*Nonlinear system analysis for fire scenarios*'. In this situation, all sections for which a thermal analysis is available will be treated according to the procedure specified in EN 1992-1-2, EN 1993-1-2 and EN 1995-1-2. The thermal section will be used for all section-related integrations. Should no temperature profile be available for a thermal section, then the fire analysis is to be carried out at an assumed normal temperature (20°C) as laid out in EN 1992-1-2, EN 1993-1-2 and EN 1995-1-2. The properties of the basic section will be applied for all other sections. Section parts of the thermal section that are made neither from steel nor reinforced concrete nor timber are ignored in the mechanical analysis. As only very little is known about the shear load performance in fire scenarios – in particular for reinforced concrete sections – calculations are currently based on the shear and torsional stiffness of the basic sections.

The program calculates according to nonlinear elasticity theory, where loading and unloading follow the same path.
A possible strength increase of concrete or timber in the cool-down period is not considered.

On the resistance side, the material property partial safety factors for fire scenarios are set to $\gamma_{M,fi} = 1.0$ within the program.

On the (user-defined) action side, the following action combinations are to be considered for fire scenarios according to EN 1990 (Eurocode 0):

$$\sum_{j\geq 1} G_{k,j} \text{"+"}\ P \text{"+"}\ A_d \text{"+"}\ (\psi_{1,1}\ \text{or}\ \psi_{2,1}) \cdot Q_{k,1} \text{"+"} \sum_{i>1} \psi_{2,i} \cdot Q_{k,i}$$

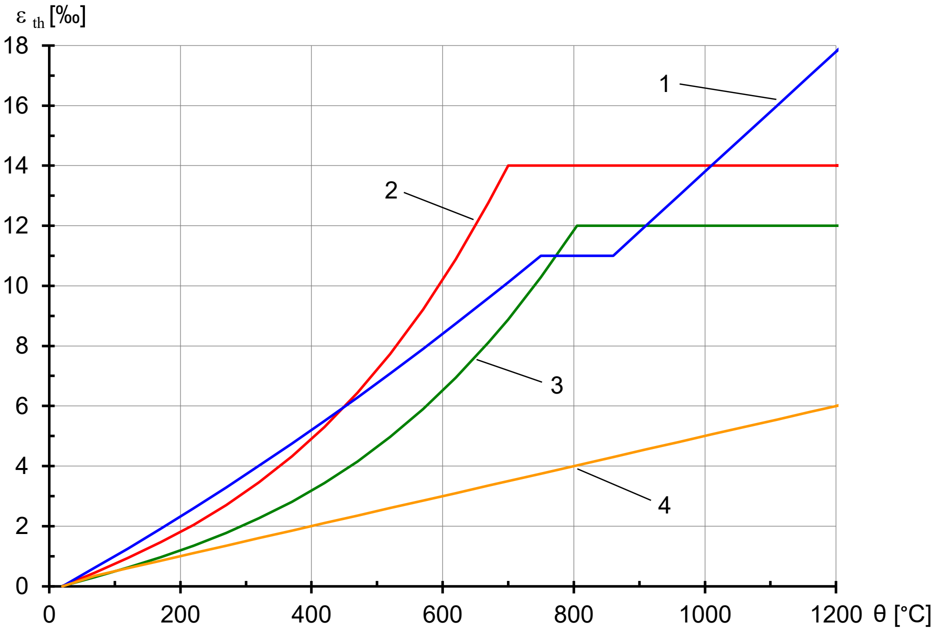
where A_d specifies the thermal expansion and the thermal effects on the material properties. The strain approach is:

$$\varepsilon_s = \varepsilon - \varepsilon_{th}$$

with

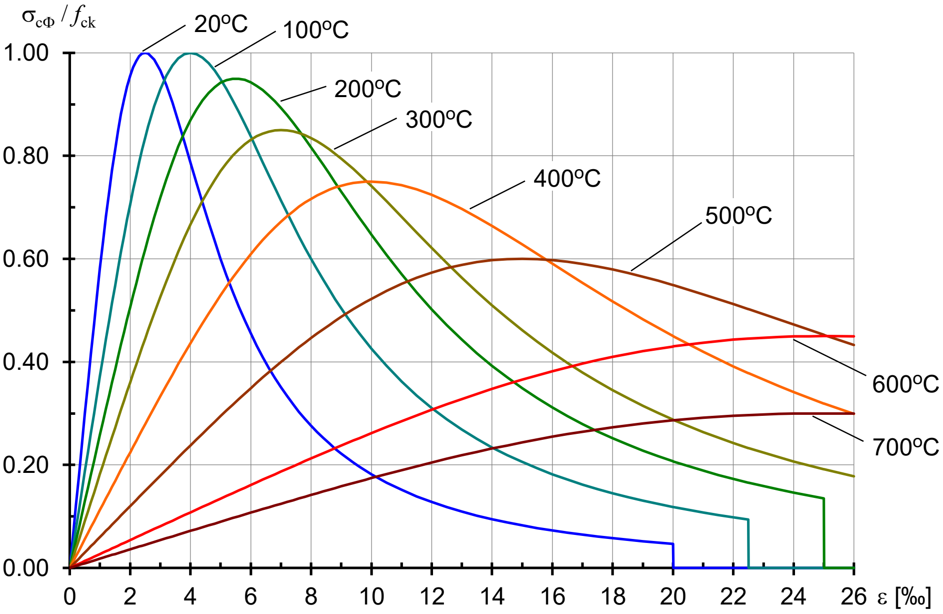
ε	Total strain
ε_s	Stress-creating strain
ε_{th}	Thermal strain

The following diagram shows the variation in thermal expansion for steel and concrete against temperature.



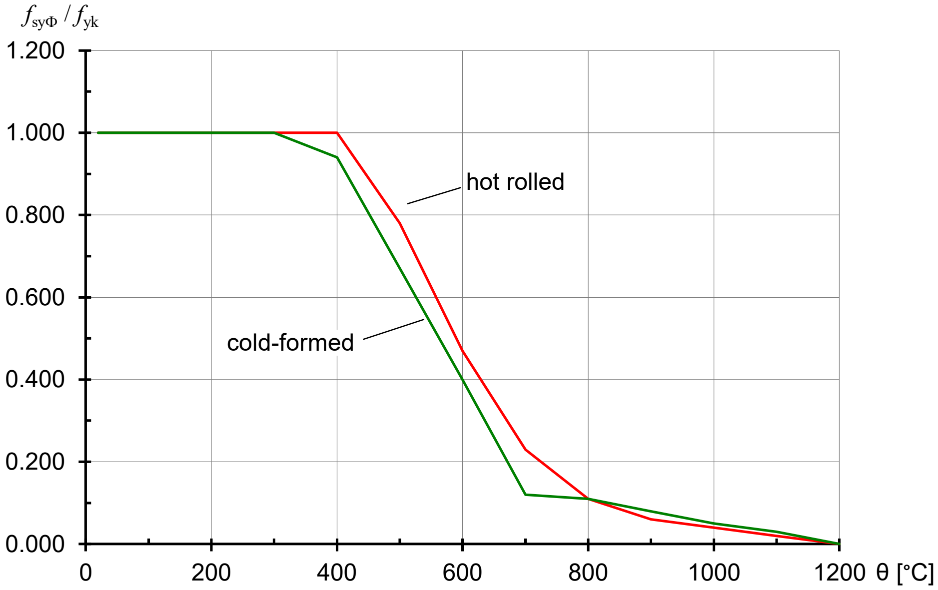
Thermal expansion (1:steel; 2:concrete with siliceous aggregate; 3:with calcareous aggregate; 4: timber)

The dependency of the stress-strain curves for concrete on temperature is clearly shown in the following diagram. Any tensile strength for concrete is ignored for fire scenarios according to EN 1992-1-2 (section 3.2.2.2).



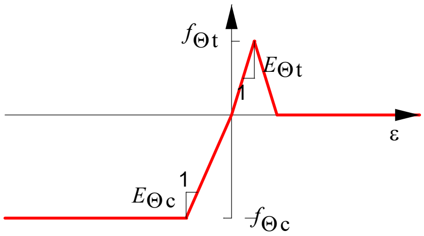
Related stress-strain curves for concrete with siliceous aggregate

The stress-strain curves for steel are also temperature dependent. They are derived from Figure 3.3 and Table 3.2a of EN 1992-1-2. The reduction in strength at higher temperatures is demonstrated in the following diagram.

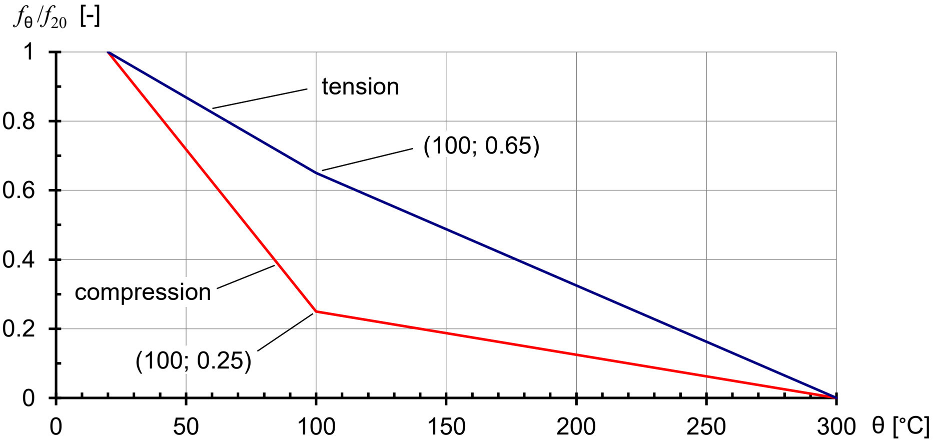


Reduction in strength of reinforcing and construction steel at higher temperatures

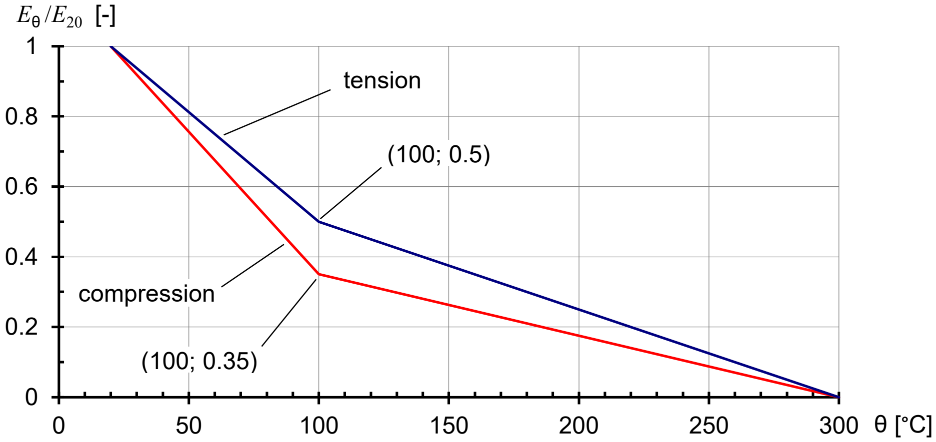
The stress-strain behavior of timber at increased temperatures is not specified in EN 1995-1-2. At the same time the consideration of the nonlinear material behavior is postulated. Therefore the following stress-strain curve with softening in the tensile zone and a bi-linear curve in the compression zone is used for frameworks. The strengths $f_{\Theta t}$, $f_{\Theta c}$ and the moduli of elasticity $E_{\Theta t}$, $E_{\Theta c}$ correspond to EN 338:2016 and EN 14080:2013 with consideration of the temperature-dependent decrease of strength. With this especially for construction members stressed by bending the resistance is underestimated compared to the design procedure according to EN 1995-1-2, Chapter 4.2. The reason for that are the lower compressive and tensile strengths ($f_{\Theta t}$, $f_{\Theta c}$) of the advanced calculation method compared to the average bending strength f_m used by the simplified check.



Stress-strain curve of timber



Decrease of strength of timber for increased temperatures



Decrease of elasticity modulus of timber for increased temperatures

Framework theory assumes that sections remain planar. The nonlinear thermal strain distribution over the section results in a similar nonlinear distribution of stress-creating strains. The stresses calculated here are integrated to internal forces over the section using the element mesh. The nonlinear strain state is varied as long as necessary during the equilibrium iteration through the addition of linear strain states until equilibrium is achieved. This method is implemented in the program as the standard algorithm.

An alternative procedure is based on the so-called '*Equivalent Temperature*'. In this case, the nonlinear temperature distribution determined in the thermal calculations is linearized using a regression level before the analysis is carried out. While this approach fully complies with the framework theory, the influence of the stiffness distribution of the whole framework on the position of the regression level cannot be determined; therefore, this method does not satisfactorily take into account the thermal effects, in particular for reinforced concrete structures.

Area structures are calculated using a sandwich model analogous to the non-linear analysis under normal temperature (see '*Non-linear system analysis > area elements*'). Thereby the biaxial structural behavior of reinforced concrete is taken into account. For area structures made of steel the Raghava yield criterion with the temperature dependent strengths is used as a basis. Area structures made of timber cannot be analyzed.

Load Case Definition

A decisive load case must be defined for nonlinear analysis of fire scenarios. The following procedure for doing this is recommended:

- Grouping and weighting existing load cases using the *load group* load type.
- Selection of the second-order theory if geometrical nonlinearity should be considered in addition to physical nonlinearity.
- Addition of the *fire scenario* load type to the load case. The numbering of the fire scenario is based on the numbering in the *Thermal Analysis* dialog.

When different fire scenarios are to be investigated, a new load case must be created for each scenario.

Analysis Settings

The following settings are made on the *Fire Scenario* tab in the *Settings* for the nonlinear analysis of the menu item *Analysis - Settings*.

Consider the following load cases

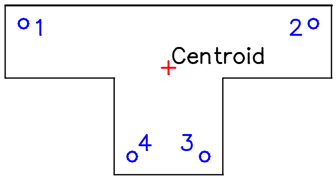
The load cases to be analyzed and described above are to be entered in the left-hand selection field.

Constantstiffness

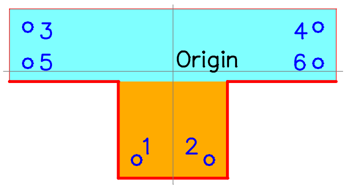
The iteration is done with a constant stiffness matrix. If the switch is not set, then the '*Newton Raphson method*' is used.

Start reinforcement

Reinforcement is incorporated in the *analysis for fire scenarios* in a different manner to the analysis under standard load conditions. The initial reinforcement according to the dimensions of the reinforced concrete corresponds with the reinforcing steel layers in the basic section. The embedded steel layers in the thermal section are generated by copying or redefining the section parts. This means that matching with the initial reinforcement in the basic section can only be carried out by comparing coordinates. In the example below, layers 1 to 4 are geometrically assigned when the '*Apply As from dimensioning*' option is activated. It must be ensured that the centroid of the basic section coincide with the origin of the thermal section.



Basic section



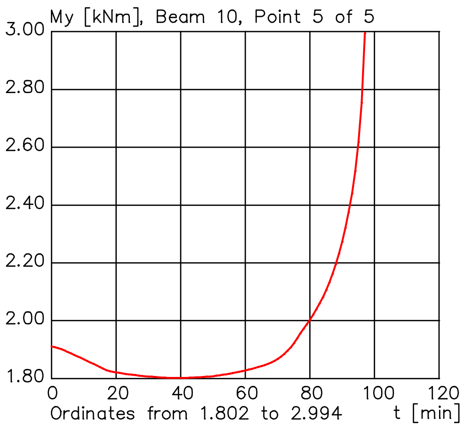
Thermal section

For the calculation of area elements the reinforcing steel layers of the basic section are always used. They are assigned to the thermal section depending on their height. Therefore, the center line of the thermal concrete section should be located on the zero line (z=0) and the thickness of the basic section should coincide with the thickness of the thermal concrete section.

Results

The deformations, internal forces and support reactions for the selected time steps are saved in the database for the check load cases selected in the settings dialog.

Additionally, for beams with thermal section the stress distribution of the section is stored at the result markers.



Variation of the bending moment M_y at a beam node over time

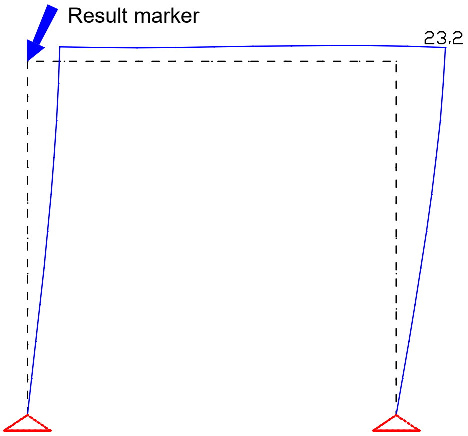
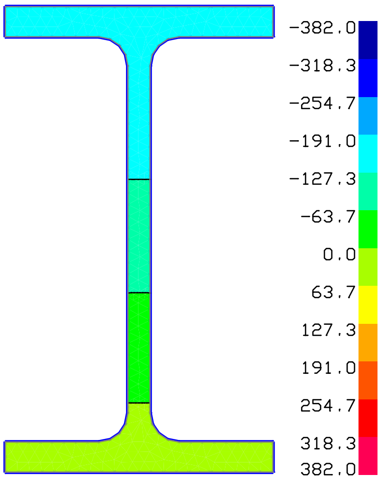
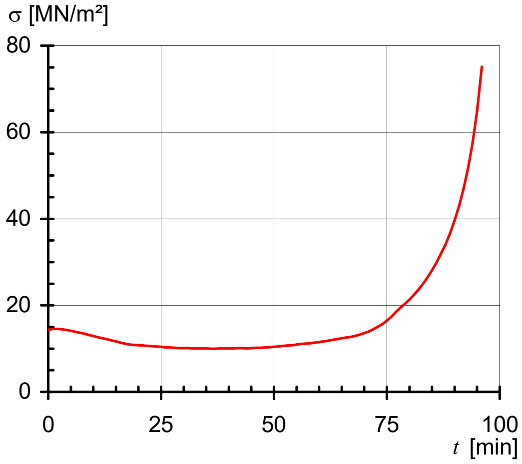


Illustration of the node displacements u [mm] for t = 90 min



Distribution of the stress σ_x [MN/m²] at the result marker for t = 90 min



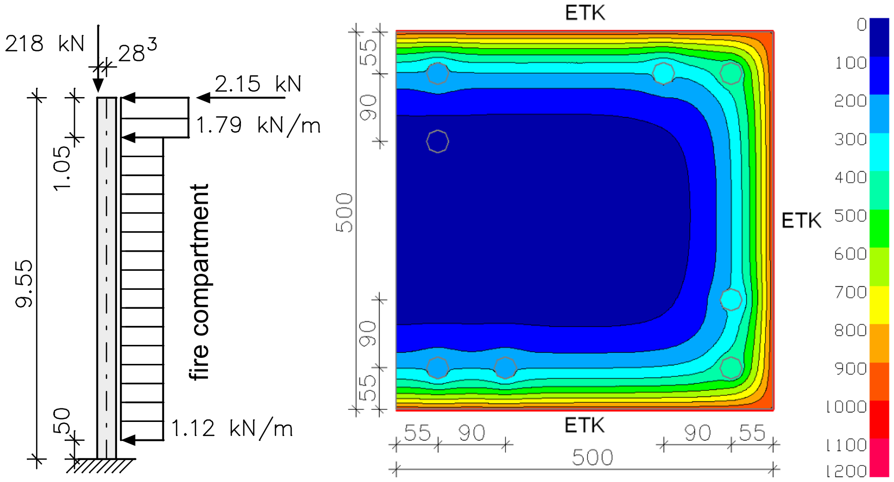
Stress curve σ_x at the result marker in the middle of the cross-section bottom edge

Examples

The following example analyses are intended to demonstrate the range of applications possible with this program system and at the same time provide results that are validated experimentally.

Gable Column

The following gable column was analyzed by *Richter*. The underlying static system together with the associated material parameters is shown below. The beam division corresponds to the load figure.



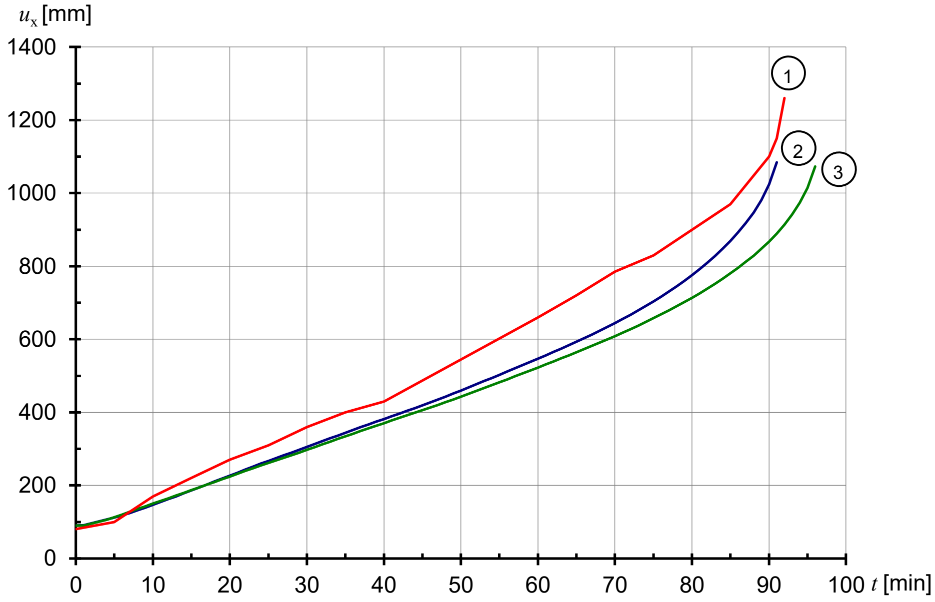
The system with loads and dimensions, section view and temperature profile after 90 min.

Material parameters:

Concrete: C30/37-EN, raw density at 20°C 2300 kg/m³, humidity ratio 0 %, Siliceous aggregate, α_c = 25 W/(m² K), ε_m = 0.7

Reinforcing steel: BSt 500 S (A), 8 ∅ 28 (hot-rolled), Axis distance from edge u = 55 mm

The calculations were carried out assuming flame exposure from three sides according to the standard temperature-time curve (ETK). Geometrical and physical nonlinearities were accounted for in the time-step analysis. Depending on the type of model used to represent the reinforcement, system failure occurred after 91 min (curve 2) or after 96 min (curve 3). For curve 3 the existing reinforcement was represented as structural elements. This influenced the temperature distribution, as can be readily seen on the temperature profile shown. In both cases the required R90 fire resistance class could be met.



Horizontal Load-displacement curves for the column head

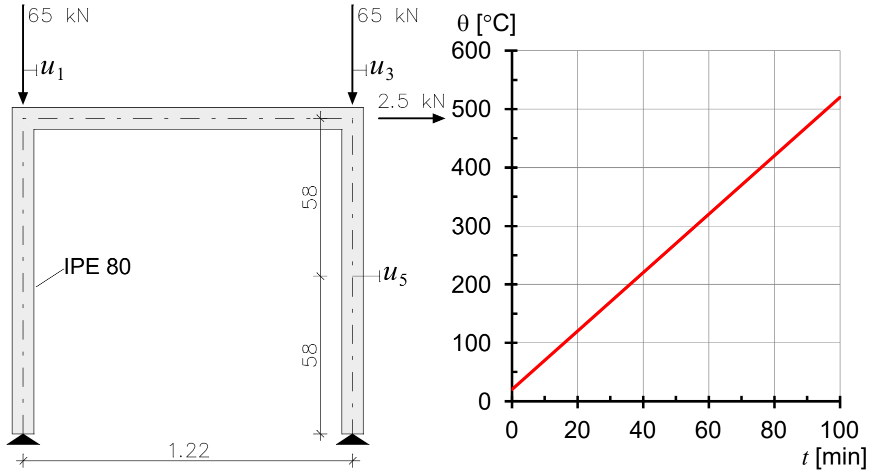
1: *Richter: Structural Design for Fire Safety, Institute for Building Materials, Concrete Construction and Fire Protection, Techn. University of Braunschweig (IBMB TU Braunschweig), Example 6*

2: *InfoGraph: Temperature profile without consideration of reinforcement*

3: *InfoGraph: Temperature profile with consideration of reinforcement*

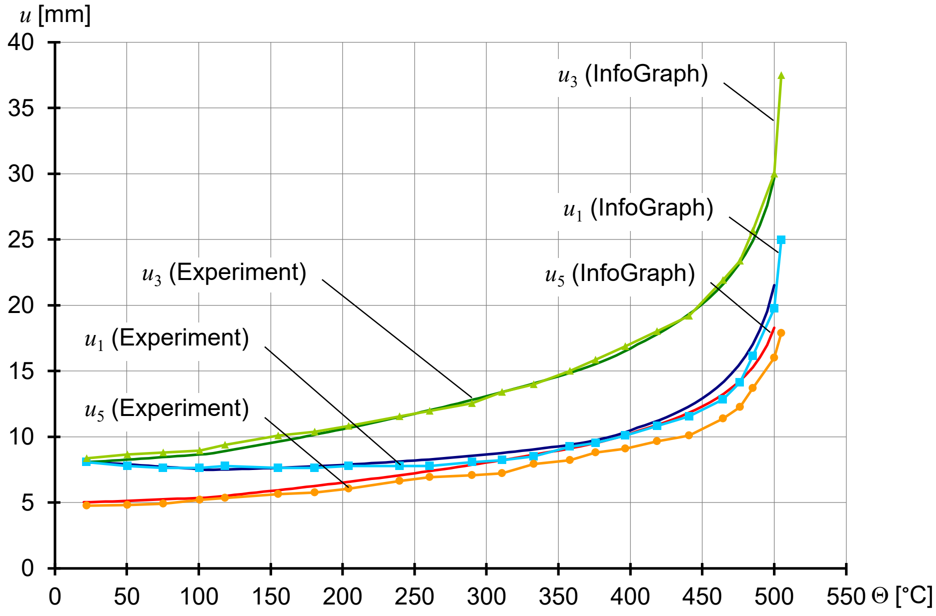
Steel Frame

The large model frame shown below (Trial EGR 1c) was experimentally and analytically researched by *Rubert* and *Schaumann* in 1985. In the fire tests, a uniform temperature increase rate of approx. 5 K/min was achieved. According to the test report, deviations from the ideal geometry were negligible. All material characteristics were determined experimentally. As these are not fully documented, the load utilization $1/\upsilon_u = 0.55$ and the system slenderness ratio $\lambda_{sys} = 0.93$ were taken account of when calibrating the system at normal temperature. Using a jointed foot support and a tenfold division of the columns resulted in a slightly increased load utilization factor of *0.57*. This difference was eliminated by applying a very small elastic foot restraint (*8.5* KNm/rad).



The system with loads and dimensions, section view and temperature profile.

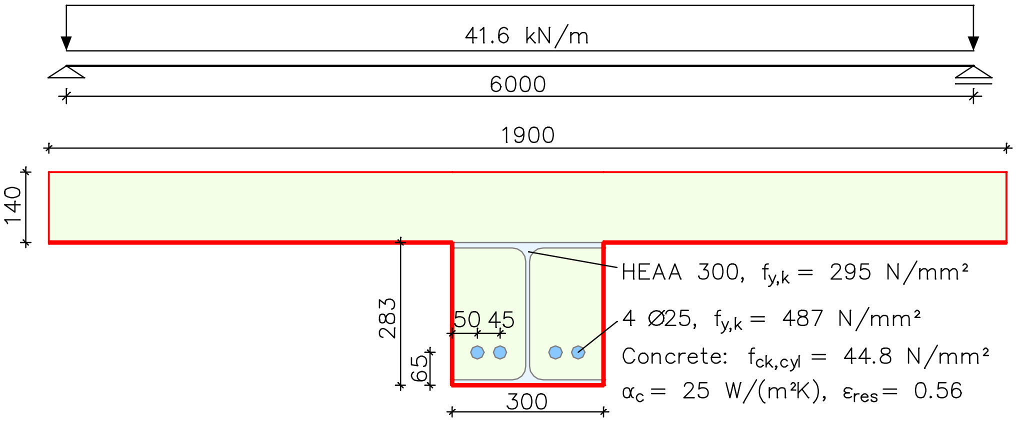
The temperature-displacement curves measured in the test for the points 1, 3 and 5 are shown in the following diagram alongside the calculated results. The curves show a very good correlation over the whole temperature range.



Experimental and comparative theoretical temperature-displacement curves

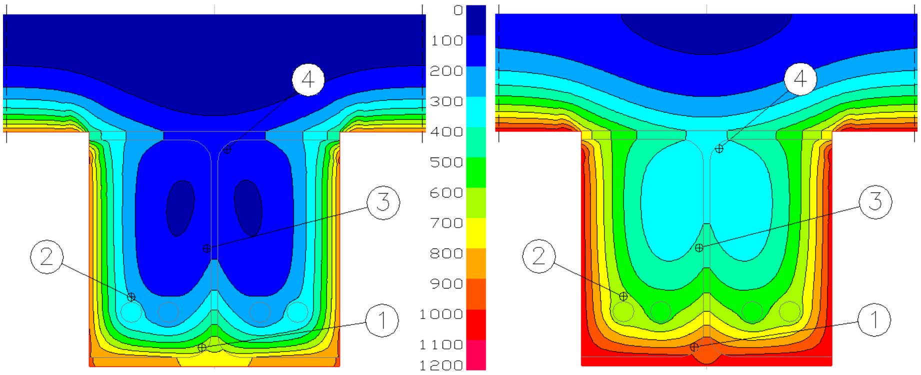
Composite Girder

The results presented here were taken from Upmeyer's dissertation completed at the University of Hannover in 2001 and describe the results of *fire tests on concrete-encased composite girders*. The static system consisting of 10 beams is shown below together with the associated material parameters.

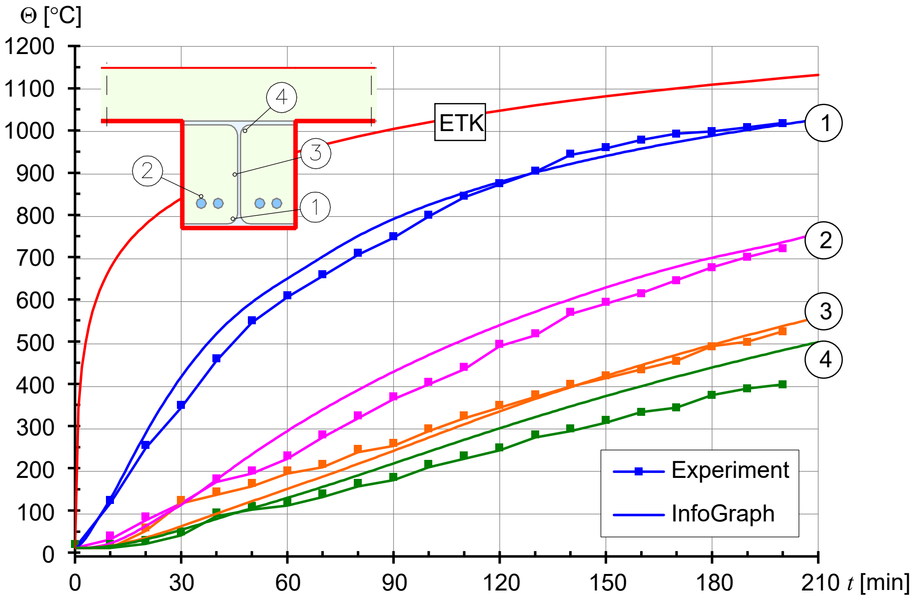


System with sections, loads and dimensions [mm]

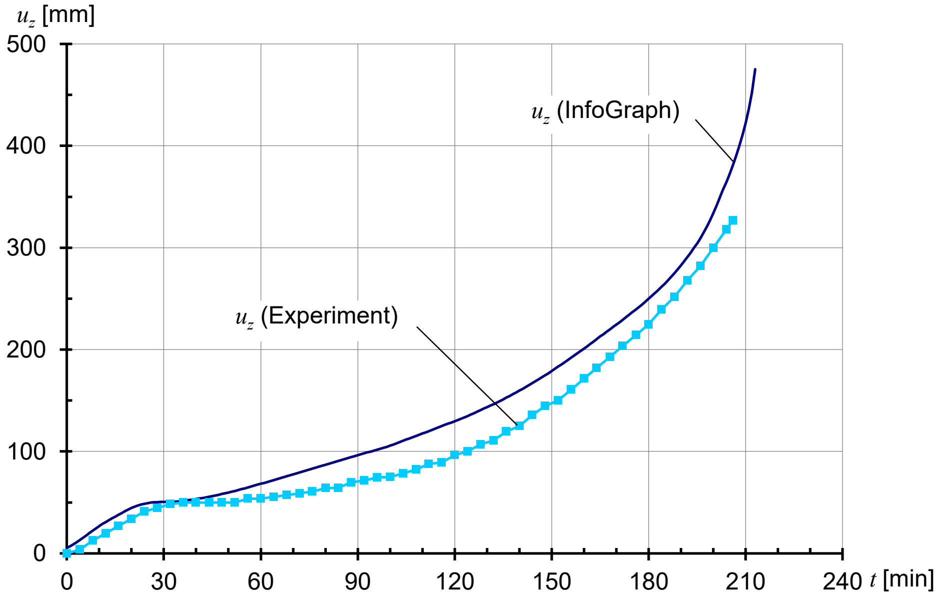
Component temperatures measured at four points are available along with the curves of displacement against time for the girder mid-point. The calculated development of the temperatures correlates strongly with the experimentally measured values. A single significant difference occurs at measuring point 4. This could either come from a variation in the moisture content of the concrete or in inaccuracy of the thermal conductivity resulting from bolts in the cold plate region of the girder which were not included in the model. In addition the exact position of the thermal elements is not known. This is particularly noticeable at measuring point 1 because of the large temperature gradient.



Temperature profile after 60 min and 150 min [°C]



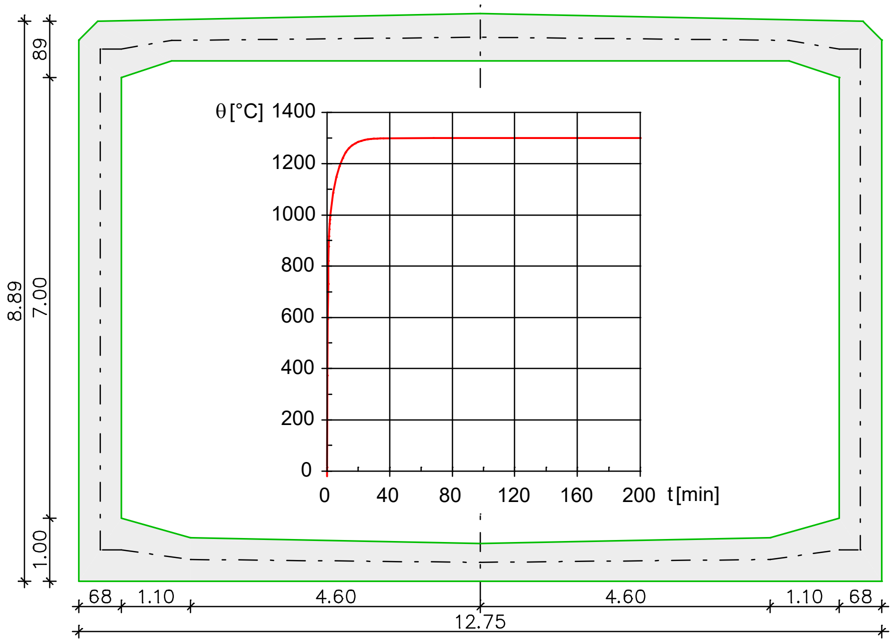
The good correlation between the calculated and measured curves for displacement against time and the time of failure are shown in the next diagram.



Midspan bending over time

Tunnel Structure

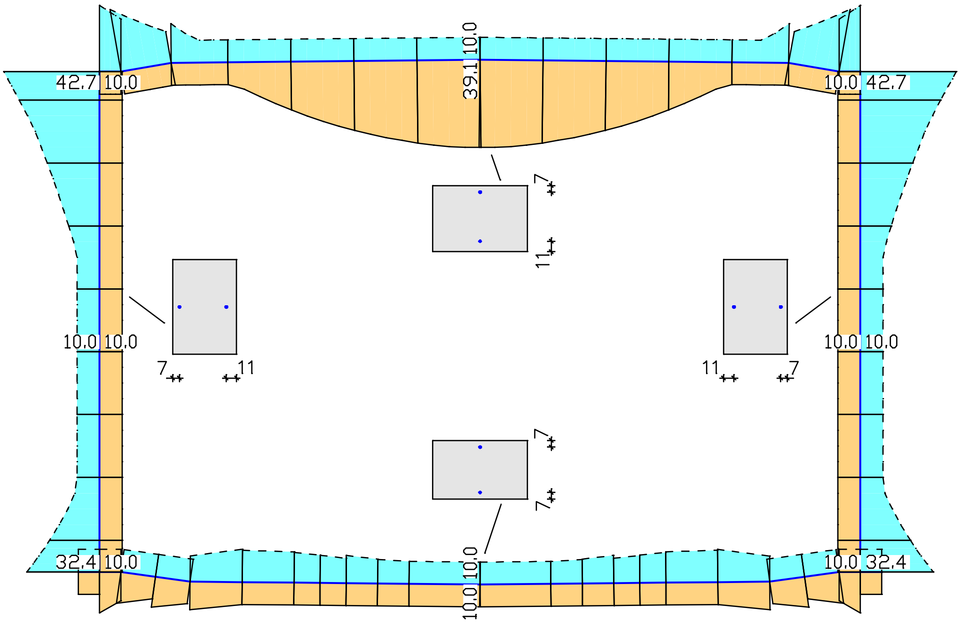
The following description of a tunnel structure are taken from the 'Fire Resistance of Fiber, Reinforced and Prestressed Concrete' ('Brandbeständigkeit von Faser-, Stahl- und Spannbeton'). Here, the internal forces and deformation after 180 min of fire exposure were investigated.



System with dimensions and temperature curve

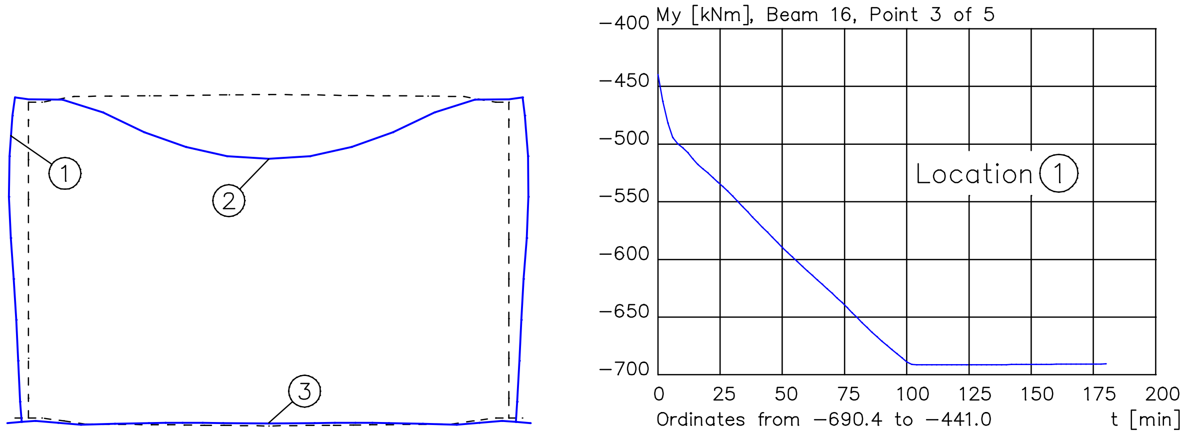
The base of the tunnel structure is flexibly bedded. The extensive section, material and load parameters are not relevant for the purposes of this description. Alongside the loads caused by fire, the action combination consists of dead load, buoyancy and fill forces as well as pressure from surrounding water and earth and traffic loads. The assumed temperature curve is shown above. The thermal section is geometrically identical with the basic section. Therefore the existing reinforcement could be automatically taken over. The reinforcing is distributed as shown below.

The handling of a similar model is also shown in the video (German language) "*https://download.infograph.de/video_de/Stahlbetonrahmen%20im%20Brandfall.mp4*".

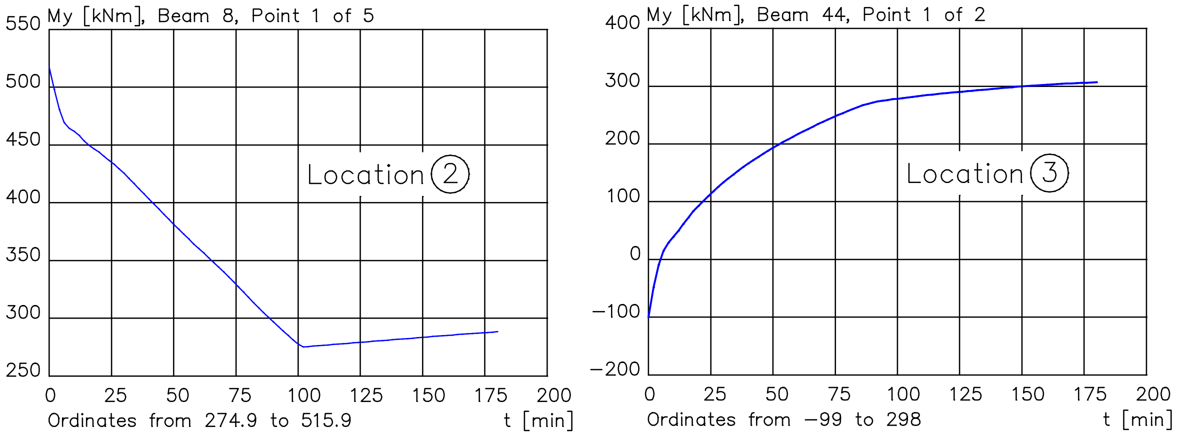


Distribution of reinforcement [cm²/m]

The combined loads result in negative moments being created in the regions around the frame corners. This means that the temperature of the tensile reinforcement is within the normal range. The lower reinforcement in the region around the horizontal frame member (location 2) is decisive for the load-bearing capacity. Because of the large overlap of 11 cm, after 180 min a temperature of approx. 250 °C was reached. This did not result in any significant reduction in strength.



Diagrams showing exaggerated deformation of the frame after 180 min and the moment curve over time



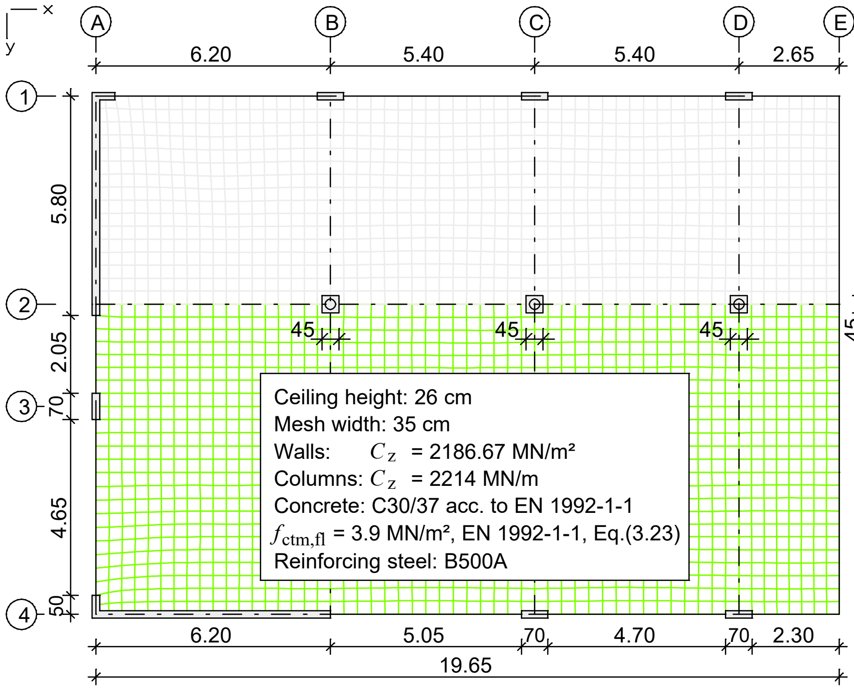
Moment curves over time

The moment curves show that after approx. 100 min a plastic joint forms at location 1 in the tunnel structure. The system as a whole is, however, still stable after 180 min. However, a different load situation would result in concrete flaking off in the region around the horizontal frame member (location 2). The higher temperatures would then extend further into the section and failure of the span reinforcement would lead to failure of the whole system.

Ceiling Slab Under Fire Exposure

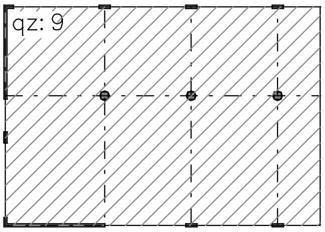
This example shows a ceiling slab, which has been analyzed before in the manual chapters *EN 1992-1-1 Design* and *Nonlinear structural analysis*. It shall be verified that the slab resists a fire exposure of 90 minutes.

In the **first calculation step** a thermal analysis of the ceiling slab is carried out for fire exposure (standard temperature-time curve) at the bottom of the slab.

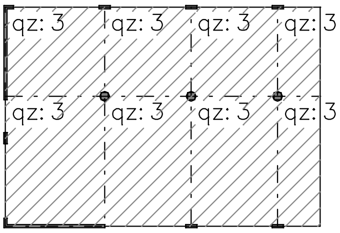


Ceiling height: 26 cm
Mesh width: 35 cm
Walls: C_z = 2186.67 MN/m²
Columns: C_z = 2214 MN/m
Concrete: C30/37 acc. to EN 1992-1-1
$f_{ctm,fl}$ = 3.9 MN/m², EN 1992-1-1, Eq.(3.23)
Reinforcing steel: B500A

Loads



Load case 1,
G permanent loads [kN/m²]



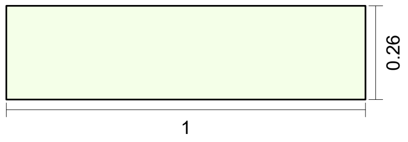
Load case 2 to 9,
Q field 1 to 8 [kN/m²]

Element system and loads from
"Beispiele zur Bemessung nach Eurocode 2 – Band 2: Ingenieurbau"

Thermal section 1 - Ceiling slab

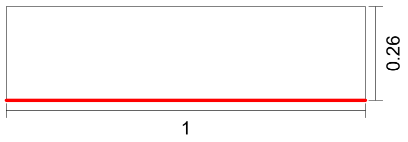
Starting temperature = 20 °C; Time increment = 1 min; Duration = 90 min

1. Part - (Section 1)



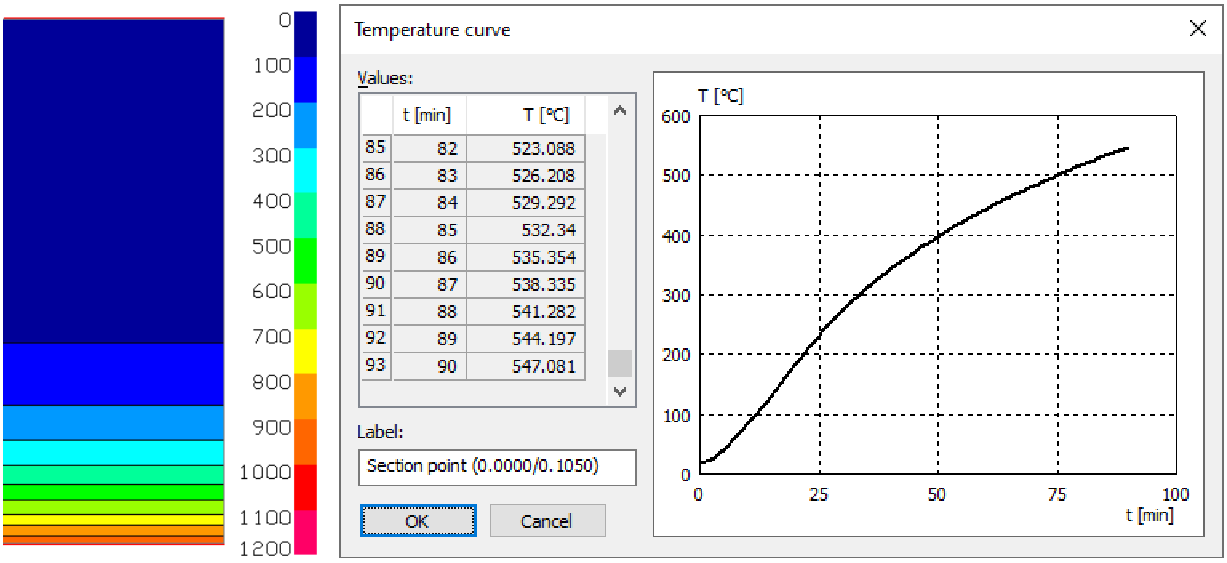
Material	C30/37-EN
E-Modulus [MN/m²]	33000
G-Modulus [MN/m²]	13800
Gamma [kN/m³]	25
Aggregate	Limestone-containing
Raw density at 20° C [kg/m³]	2300
Humidity ratio [%]	3
Apply As from dimensioning	Yes

1. Fire scenario - (Section 1)



ETK (Standard temperature-time curve)	
Emissivity	0.7
Coefficient of heat transfer	25 W/(m²·K)

The following figure documents the results.



Temperature curve

Values:

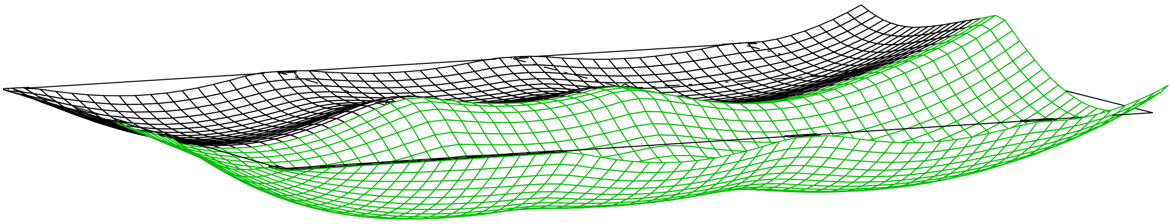
	t [min]	T [°C]
85	82	523.088
86	83	526.208
87	84	529.292
88	85	532.34
89	86	535.354
90	87	538.335
91	88	541.282
92	89	544.197
93	90	547.081

Label: Section point (0.0000/0.1050)

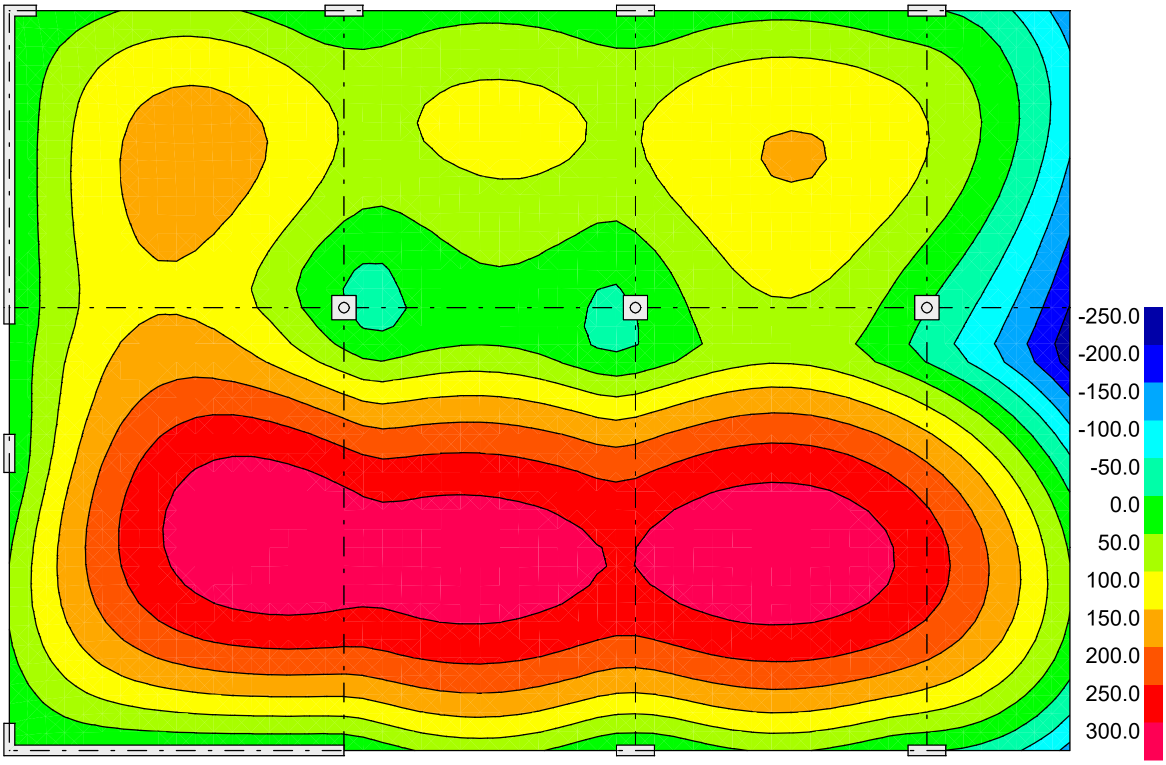
Temperature curve after 90 min at the section and over the time at the location of the lower reinforcement layer

In the **second calculation step** a nonlinear analysis for the fire scenario is carried out. As in the above-mentioned example, the longitudinal reinforcement from a previously performed design is taken as a basis.

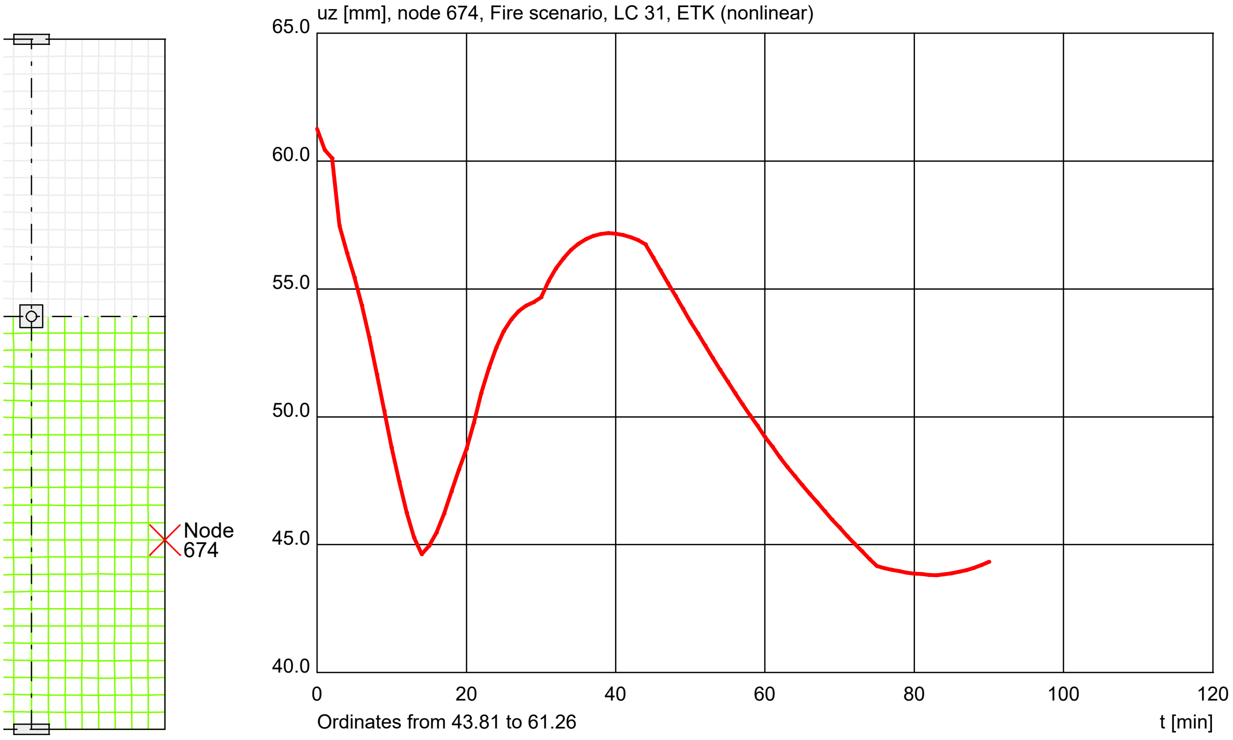
In consideration of the nonlinear material behavior in fire scenarios the load-bearing capacity can be verified for 90 minutes for the accidental combination with one fold dead load and 50% of the traffic load, because equilibrium could be reached in every time-step.



Deformation figure after 90 min with 5-fold superelevation



Color gradient of deformations u_z [mm] after 90 min under fire exposure (ETK)



Deformations u_z of node 674 under fire exposure (ETK)

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