ROBUST METHOD OF EXACT ANALYSIS OF REINFORCED CONCRETE COLUMNS IN FIRE

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ABSTRACT

The aim of this work is to bring the exact - Thermo-mechanical - analysis of reinforced concrete columns under fire exposure to the level of a structural engineering design office maintaining the high degree of scientific basis for the analysis.
The basic principles of mechanics involved in a thermo-mechanical analysis are the same as when designing a composite bridge deck with differential strains due to creep and shrinkage of the concrete plate element as against the steel member across the cross section. In the case of a column exposed to fire the differential material properties across the section which is temperature dependant and thermal strains inducing residual forces have to be resolved und considered while determining the bearing capacity of the column. The proposed method is based on the moment-curvature method and discretizes the temperature zones across the column section. This is done by defining the cross section of the column as a composite section. The section is divided into layers identical to the temperature fields determined with a 2D-Heattransformation analysis of the column section to be analysed. The EC2 has provided the basics for a scientific method of analysis which enables the structural engineer to estimate the safety level of the structural member under fire conditions. The proposed method of exact analysis uses commercial structural engineering software, to perform the geometric and material non linear analysis with thermal properties, the fire exposure can be 1 face to 4 faces heating and the column section shape is not restricted.
The steps involved are:

- 2D – Heat transfer analysis of the cross section with a given time temperature curve for the required fire rating time.
- Generating a composite column section with layers identical to the temperature fields and assigning the temperature dependant material properties to the layers of the composite section.
- Induce the thermal expansion due to temperature across the cross section of the composite zones in the longitudinal direction of the column.
- Model the column with the respective boundary conditions and perform a geometric and material non linear analysis.

Keywords: Thermal analysis; Thermal strains; Composite section

SOFTWARE

Sofistik Modules

HYDRA	A Finite element Heat transfer analysis programme
AQUA	General section definition module
GENF	System generation module
STAR3	A Space frame non linear analysis programme.

INTRODUCTION

Geometric and material non-linear analysis is the standard procedure in the stability analysis of slender reinforced concrete columns under compression.
The application of this procedure under fire conditions is complicated due to the temperature dependant non linear material properties of concrete and reinforcement steel. Numerical simulations with a FE-software is possible, however this method is time consuming and not practical for the use in a design office, and has hence been restricted for use at the research institutions.
This paper deals with the analysis of a reinforced concrete column under fire conditions according to the moment-curvature method using commercial engineering design office software STAR3 from the SOFISTIK package.
The column section is created as ***composite section*** consisting of zones identical to the temperature fields obtained from a 2D-Heattransfer analysis of the concrete column section. The zones are identified with individual Material properties which are temperature dependant und the reinforcing steel rebar's are assigned the temperature of the zone where the steel reinforcement is placed. The material properties and thermal strains are according to the EC 2 Temperature curves for concrete and steel.

MECHANICAL BASICS FOR THE ANALYSIS

Stress-Strain relationship for concrete and reinforcing steel under elevated temperatures according to EC 2

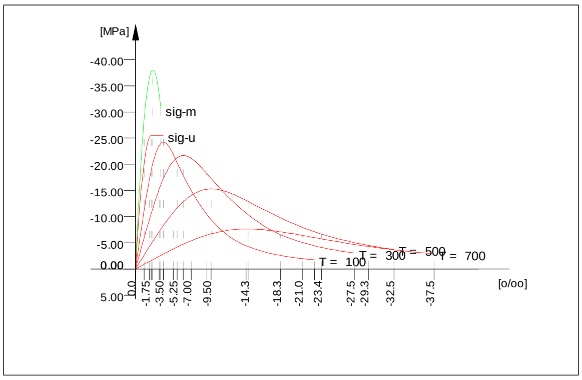


Fig 1: Stress-Strain relationship for concrete under compression under elevated temperatures according to EC 2

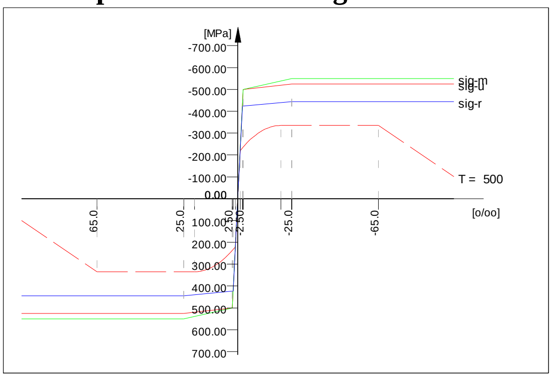


Fig 2 Stress-Strain relationship for reinforcing steel at elevated temperatures according to EC 2

Thermal expansion according to EC 2 for concrete

quarzhaltige Zuschläge:

für $20\ ^\circ C < \theta_c \leq 700\ ^\circ C$

$$(\Delta l/l)_c = (-1{,}8 \times 10^{-4}) + (9 \times 10^{-6} \times \theta_c) + (2{,}3 \times 10^{-11} \times \theta_c^{\,3})$$

für $700\ ^\circ C < \theta_c \leq 1\ 200\ ^\circ C$

$$(\Delta l/l)_c = 14 \times 10^{-3}$$

Eq.1

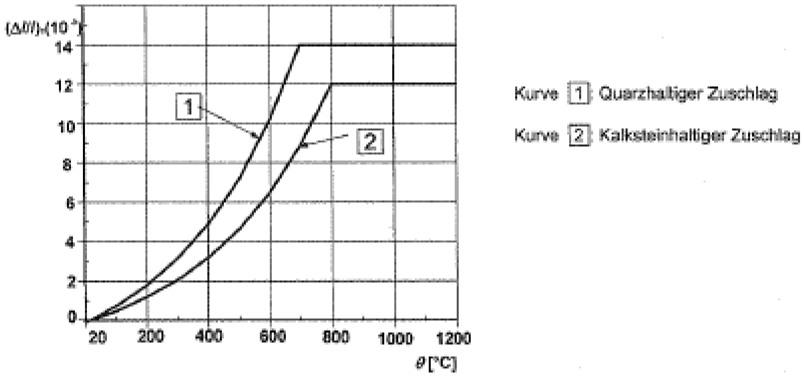


Fig 3: Thermal expansion of concrete according to EC 2

Thermal expansion according to EC 2 for reinforcing steel

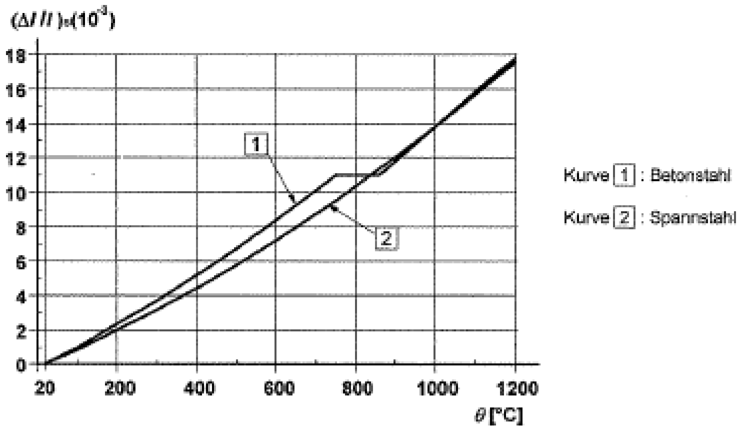


Fig3 Thermal expansion of reinforcing and pre-stressing steels according to EC 2

Betonstahl:

für $20\ ^\circ C < \theta_s \leq 750\ ^\circ C$

$$(\Delta l/l)_s = (-2{,}416 \times 10^{-4}) + (1{,}2 \times 10^{-5} \times \theta_s) + (0{,}4 \times 10^{-8} \times \theta_s^{\,2})$$

für $750\ ^\circ C < \theta_s \leq 860\ ^\circ C$

$$(\Delta l/l)_s = 11 \times 10^{-3}$$

für $\theta_s \geq 860\ ^\circ C$

$$(\Delta l/l)_s = (-6{,}2 \times 10^{-3}) + (2 \times 10^{-5} \times \theta_s)$$

Eq. 2

Beton:

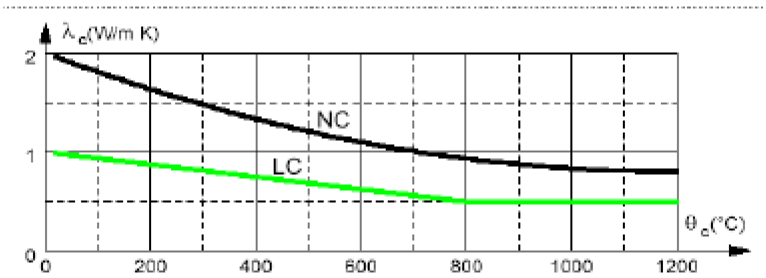


Fig 5 : Thermal conductivity of normal concrete and light concrete vs. Temperature

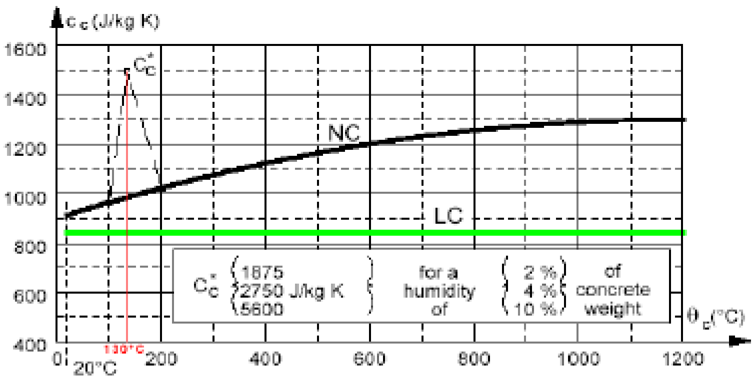


Fig 6 : Specific heat capacity of concrete

The FOURIER equation for heat transfer through a solid body is written as:

$$\frac{\delta T}{\delta t} = \frac{\lambda}{\rho C}\left(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2}\right) \qquad \text{Eq.3}$$

t - time
T - temperature
Thermal material properties (Temperature dependant)
ρ - density
C - Specific heat capacity
λ - Thermal conductivity

The heat flow calculation within a fire exposed concrete section is not a closed equation which can be solved since the thermal material properties C and λ are variables with temperature dependency and hence the heat flow calculation has to be performed with variables which are in turn temperature dependant, which is only possible with numerical methods.

BASICS OF MECHANICS AND DESIGN

Moment - curvature relationship M-N-κ

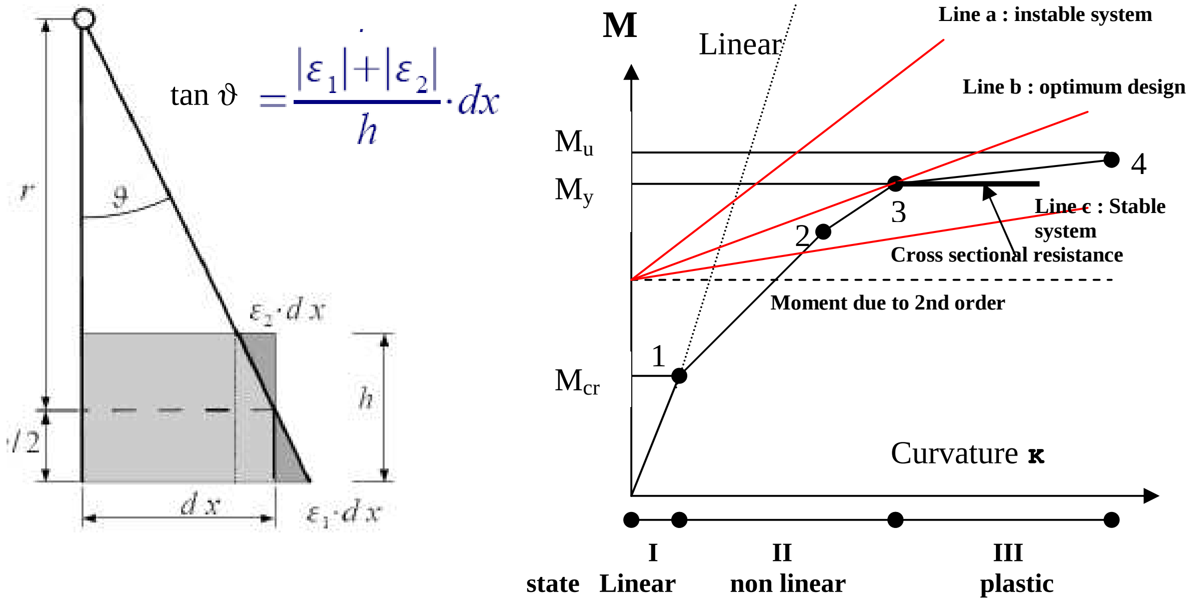


Bild 7: Moment-curvature relationship with a constant normal force

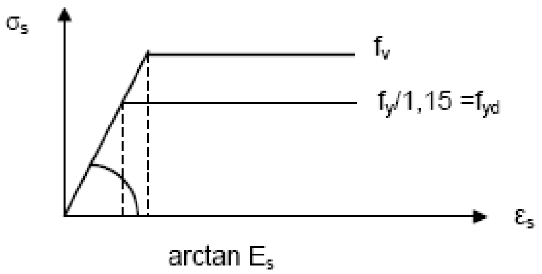
Point 1: M_{cr} : Crack moment – tensile strength of concrete exceded.

$M_{cr} = (f_{ctm} - N/A_c).W_c$

f_{ctm}	tensile strength of concrete
W_c	section modulus
A_c	Concrete section area

Point 2: yield point of compression reinforcement ε_s -2.17 °/oo

Point 3: yield point of tension reinforcement ε_s 2.17 °/oo



$$\varepsilon_s = \frac{500}{1{,}15}\cdot\frac{1}{200000} = 2{,}17\,‰$$

Fig 8: Stress-Strain relationship of reinforcing steel

Point 4: limit strain of concrete ε_{cu} -3.5 °/oo

Due to the non linear material behaviour of a reinforced concrete section the load deformation curve is constructed with the moment curvature relationship.

$$\frac{M}{EI} = \frac{\varepsilon_1 - \varepsilon_2}{h} = \kappa$$

Internal sectional resistance at normal temperautres

In the stability analysis of a reinforced concrete column, the bearing capacity is determined by resolving the internal resisting force by assuming a strain level for steel ε_s and fixing the limit strain for the concrete ε_{cu} . The possible thrust generated with this assumption is compared with the external action of axial force and moments due to second order effects. The ultimate load bearing capacity is determined when for a given vertical load the tension reinforcement yields and the limit strain for concrete has been reached, this thrust is known as the balance force N_{bal}. The maximum possible moment resistance for a section is governed by this balance force.
Under normal temperatures and for a symmetrically reinforced concrete section the balance force can be determined by assuming the strain plane as shown in fig. 9.

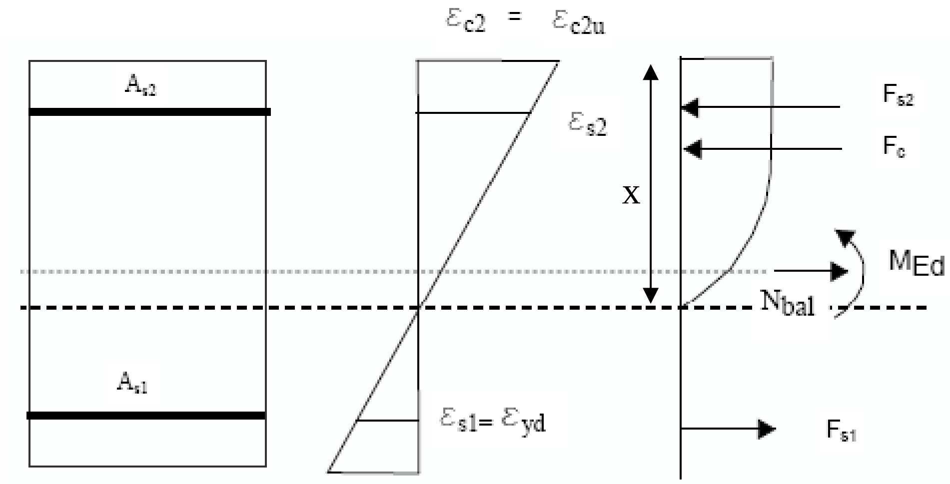


Fig 9: Internal resistance and bearing moment fort he assumed strain plane.

For the assumed strain plane of limit strain for concrete and yielding of tension reinforcement delivers the following balance force.

$$\Sigma N = 0$$

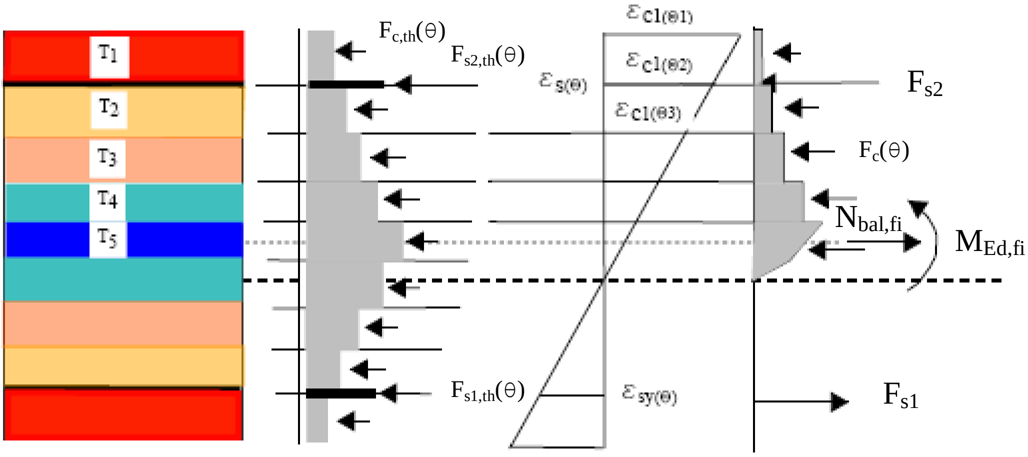
$$-N_{bal} + F_{s1} = F_{s2} + F_c \quad \text{Eq.4}$$

$F_{s1} = A_{s1}.f_y$ **tension reinforcement yields**
$F_{s2} = A_{s2}.f_y$ **compression reinforcement yields**

$F_c = \alpha_R.X.b.f_{cd}$ **concrete compression force**

Internal resistance at elevated temperatures

Under elevated temperatures the concrete and steel material properties are temperature dependant and the temperature varies across the cross section, in addition to this due the restraint of the thermal expansion of steel and concrete residual thrusts are generated which have to be resolved (Thermo-mechanical analysis).
The scientific basis for the thermo-mechanical analysis is documented in the EC 2, for further analysis the section is defined as a composite section with zones which are then assigned with the temperature dependant material properties.
The concrete zones for Temperatures $T_1 - T_5$ are assigned with the Material # Mat #1 – Mat#5, for the reinforcing steel the individual temperature dependant stress- strain curves are assigned.



Composite section with temperature dependant stress-strain relationship

$\varepsilon(\Theta) = 0$ and the residual thrust due to restraint of the axial elongation $F_{c,th}(\Theta)$, $F_{s1,th}(\Theta)$ $F_{s2,th}(\Theta)$

Stress-strain relationship under elevated temperatures and internal resistance at limit state. $F_c(\Theta)$, $F_{si}(\Theta)$

Fig10: Qualitative residual stress due to axial restraint force equiliabrium at elevated temperatures.

$$\Sigma N_{fi} = 0$$

$$-N_{bal\,fi} + F_{s1}(\Theta) - F_{s1,th}(\Theta) = F_{s2,th}(\Theta) + F_{s2}(\Theta) + \Sigma F_{c,th}(\Theta) + F_c(\Theta) \qquad \text{Eq.5}$$

$F_{s1}(\Theta)$ = Steel tension force at elevated temperature
$F_{s1,th}(\Theta)$ = compression force in steel due to restraint of thermal expansion (tension zone)
$F_{s2,th}(\Theta)$ = compression force in steel due to restraint of thermal expansion (compression zone)
$F_{s2}(\Theta)$ = Compression force of steel under elevated temperatures
$F_{c,th}(\Theta)$ = Residual compression force in concrete due to restraint of thermal expansion
$F_c(\Theta)$ = Compression force of concrete at elevated temperatures.

Strains

The total strain ε_{tot} under elevated temperatures contains the following components:

$$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{load} + \varepsilon_{creep} + \varepsilon_{tr} \qquad \text{Eq. 6}$$

ε_{th} thermal expansion

ε_{load} Load dependant strain

ε_{creep} Creep strain

ε_{tr} Transient strain

The EC 2 Stress – Strain curves under elevated temperatures include the high temperature creep strains, according to EC 2 Creep Strains during the fire can be neglected. The thermo mechanical analysis has to account for the ε_{th} and ε_{load}.

Thermal strains ε_{th}

Assuming the section remains in Plane and the axial elongation of the column is restraint internal thrust forces develop which vary across the section; the thrust maximum is at the centre of the column as the thermal expansion and Stress-Strain relationship are temperature dependant. Fig. 10 shows a qualitative form of the thrust across the section The thermal strains are induced as initial strains in the material law by shifting the stress-strain curve along the base line, such that the max. Thrust at zero strain is initially activated.

The thermal strains for concrete and reinforcement steels can be calculated according to the EC 2 values shown in equations 1 and 2.

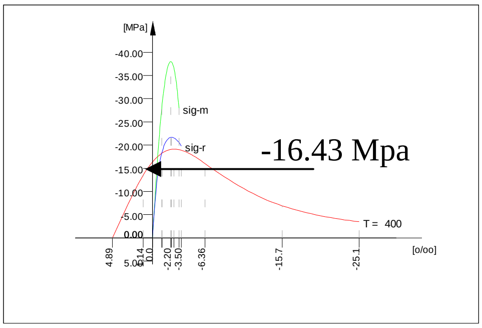


Fig 11: Material law with SHIFT for concrete at T=400 ° C

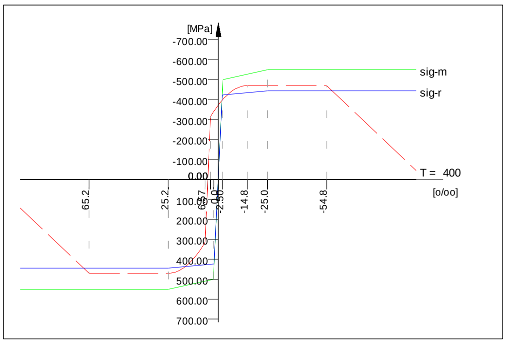


Fig 12: Material law with SHIFT for reinforcing steel at T=400 ° C

VERIFICATION CALCULATIONS

Heattransfer analysis of HYDRA

Calculation parameters:
2D – Heattransfer analysis for a concrete section of 300x300 mm .
Temperatur-Time curve : Standard temperature time curve according to ISO 834

$$\Theta g = 20+345*\log*(8*t+1) \qquad \text{Eq. 7}$$

Emissivity of concrete surface 0.4
Convective heat transfer coefficient on the hot surface α_c = 25 W/(m²K)
The validation is accomplished by comparing the temperature lines with those of the published EC 2 lines for a similar section and time.

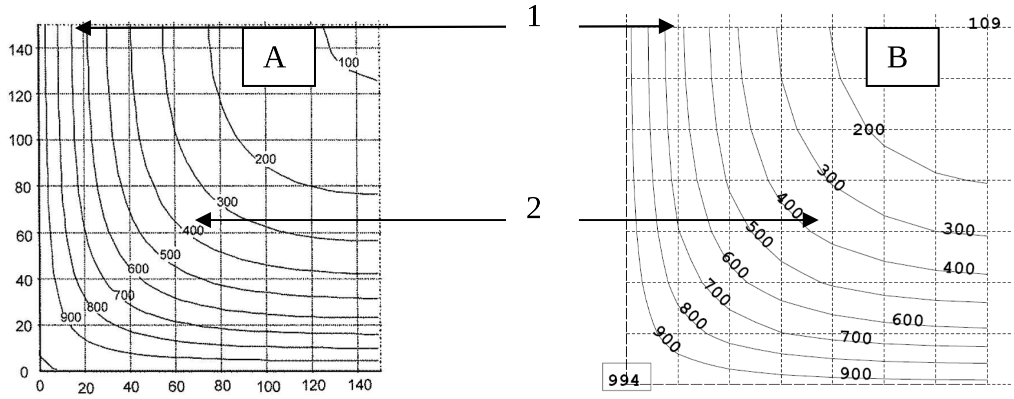


Bild 13: Temperature zones acc. to A) EC2 B) to HYDRA

Temperature zone comparison at:
Punkt 1 600 ° Line parallel to column side
Punkt 2 400 ° Line in the diagonal , reveals a good correlation.

Thermal strains of concrete and reinforcing steels.

Concrete thermal strain

In order to verify the shift action of the material law two tests are performed. Test 1 is restricting the expansion of the test column by applying an equivalent thrust force and test 2 is allowing a free expansion of the column.
The numerical test is performed on a test column 400 mm x 400 mm, for reasons of easy review the test column will be assigned only one material law, and the stress-strain curve for T=400 °C is chosen. At this temperature the thermal strain $\varepsilon_c(\theta)$ according to EC 2 is 4.89 °/oo and the respective pressure due to restraint for the section is 16.43 Mpa and results in a thrust force of 2.63 MN.
The numerical simulation for test 1 is performed for the column with an external force of 2.61 MN which shows zero strains as a result – see print out of the calculation.
For test 2 the resultant strain of 4.89 °/00 is shown in the print out.

Test 1: Sofistik print out with zero strain as a result of an equivalent external thrust force and shifted material law of concrete.

```
Parameter zur Dehnungsermittlung
Gleichgewichts-Iteration aller Schnittgrößen

Material Querschnitte mit Bruchabeitslinie ohne Sicherheitsbeiwerte
Material Bewehrungen  mit Bruchabeitslinie ohne Sicherheitsbeiwerte

MNr.  Anz.   Material-   max.Druck      bei     max.Zug       bei    tension-
      Temp  sicherheit   -spannung   Dehnung   -spannung   Dehnung  stiffening
                   [-]       [MPa]    [o/oo]       [MPa]    [o/oo]       [MPa]
  1     0        1.000      -19.13     -2.61        0.00      4.89        2.90
 10     0        1.000     -470.00    -54.80      470.00     25.20
Interaktion dünnwandige Normal- und Schubspannungen über Prandtl-Fließregel

Dehnungszustand
  Stab    x[m]  NQ   LF     e-o   ky/kz     x  zn/yn      Ni/Vi  Myi/Mzi Ey/Ez/G-EFF
                         [o/oo]  [1/km]   [m]    [m]       [kN]    [kNm]       [MPa]
     1   0.000   2   20   0.000   0.000 0.000 >+99.     -2621.5     0.00       28309
         0.167   2   20   0.000   0.000 0.000 >+99.     -2621.5     0.00       28309
         0.333   2   20   0.000   0.000 0.000 >+99.     -2621.5     0.00       28309
         0.500   2   20   0.000   0.000 0.000 >+99.     -2621.5     0.00       28309
         0.667   2   20   0.000   0.000 0.000 >+99.     -2621.5     0.00       28309
         0.833   2   20   0.000   0.000 0.000 >+99.     -2621.5     0.00       28309
         1.000   2   20   0.000   0.000 0.000 >+99.     -2621.5     0.00       28309
```

Strain = 0 under central axial load of 2.62 MN.

Test 2: Sofistik print out showing the resultant strain of 4.89 °/00

```
Parameter zur Dehnungsermittlung
Gleichgewichts-Iteration aller Schnittgrößen

Material Querschnitte mit Bruchabeitslinie ohne Sicherheitsbeiwerte
Material Bewehrungen  mit Bruchabeitslinie ohne Sicherheitsbeiwerte

MNr.  Anz.   Material-   max.Druck      bei     max.Zug       bei    tension-
      Temp  sicherheit   -spannung   Dehnung   -spannung   Dehnung  stiffening
                   [-]       [MPa]    [o/oo]       [MPa]    [o/oo]       [MPa]
  1     0        1.000      -19.13     -2.61        0.00      4.89        2.00
 10     0        1.000     -525.00    -25.00      525.00     25.00
Interaktion dünnwandige Normal- und Schubspannungen über Prandtl-Fließregel

Dehnungszustand
  Stab    x[m]  NQ   LF     e-o   ky/kz     x  zn/yn      Ni/Vi  Myi/Mzi Ey/Ez/G-EFF
                         [o/oo]  [1/km]   [m]    [m]       [kN]    [kNm]       [MPa]
     1   0.000   2   20   4.885   0.000 0.000 <-99.        -0.3     0.00       28309
         0.167   2   20   4.885   0.000 0.000 <-99.        -0.3     0.00       28309
         0.333   2   20   4.885   0.000 0.000 <-99.        -0.3     0.00       28309
         0.500   2   20   4.885   0.000 0.000 <-99.        -0.3     0.00       28309
         0.667   2   20   4.885   0.000 0.000 <-99.        -0.3     0.00       28309
         0.833   2   20   4.885   0.000 0.000 <-99.        -0.3     0.00       28309
         1.000   2   20   4.885   0.000 0.000 <-99.        -0.3     0.00       28309
```

Concrete strain 4.89 $°/_{00}$

Reinforcement steel thermal strain

In this case the concrete is assigned the material property at normal temperature and only the reinforcing steel is assigned the temperature dependant stress-strain curve of T=400 ° C. The iteration shows the expected convergence with a total strain of 5.198 $°/_{00}$ See Print out of the results.

Sofistik print out of the test of thermal strain for reinforcing steel induced through shifting of the material law along the base line.

```
Parameter zur Dehnungsermittlung
Gleichgewichts-Iteration aller Schnittgrößen

Material Querschnitte mit Brucharbeitslinie ohne Sicherheitsbeiwerte
Material Bewehrungen  mit Brucharbeitslinie ohne Sicherheitsbeiwerte

MNr.  Anz.   Material-   max.Druck      bei     max.Zug       bei    tension-
      Temp  sicherheit   -spannung   Dehnung   -spannung   Dehnung  stiffening
                   [-]       [MPa]    [o/oo]       [MPa]    [o/oo]       [MPa]
   1     0       1.000      -25.50     -2.00        0.00      0.00        2.00
  10     0       1.000     -470.00    -54.80      470.00     25.20
  11     1       1.000     -525.00    -25.00      525.00     25.00
Interaktion dünnwandige Normal- und Schubspannungen über Prandtl-Fließregel

Dehnungszustand
  Stab     x[m]  NQ    LF     e-o    ky/kz     x   zn/yn      Ni/Vi   Myi/Mzi Ey/Ez/G-EFF
                           [o/oo]  [1/km]    [m]    [m]       [kN]    [kNm]        [MPa]
     1    0.000   2    20   5.198   0.000 0.000 <-99.        -0.1     0.00        28309
          0.167   2    20   5.198   0.000 0.000 <-99.        -0.1     0.00        28309
          0.333   2    20   5.198   0.000 0.000 <-99.        -0.1     0.00        28309
          0.500   2    20   5.198   0.000 0.000 <-99.        -0.1     0.00        28309
          0.667   2    20   5.198   0.000 0.000 <-99.        -0.1     0.00        28309
          0.833   2    20   5.198   0.000 0.000 <-99.        -0.1     0.00        28309
          1.000   2    20   5.198   0.000 0.000 <-99.        -0.1     0.00        28309
```

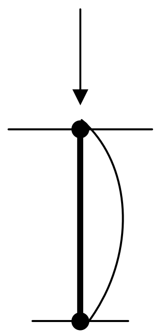
Steel strain 5.198 $^{\circ}/_{oo}$

Verification of the composite section.

The varying material properties of the concrete section in zones is defined in a composite section. The chosen composite section for the 90 min Fire rating analysis has 9 zones.
The Composite section is analysed with 9 normal temperature material properties and compared with the results of a standard cross section with one material property and one zone.

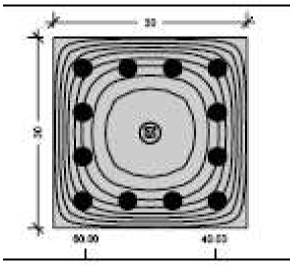
The test column with the following data is taken as a basis:

Concrete	C30
Reinforcement steel	Bst 500
Geometry	bxd=30x30 cm
Column height	H_{i}=3.40 m



Factored Design load under service conditions:

N^G = 2075 KN
N^Q = 800 KN
N_{ED} = 1.35x2075+1.5x800 ~ 4000 KN
Chosen reinforcement = 12Φ 28 = 73.92 cm²
Analysis is performed for a pinned supported column
Geometric and material non linear analysis; Pre camber acc. to DIN 1045 , V_o= l/400.
Safety factor for the materials γ_c=1.5 Concrete
γ_s=1.15 Steel



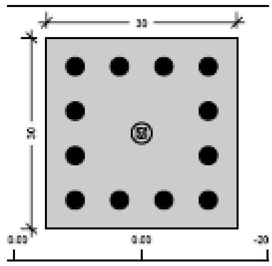


Fig 14.a Composite Section　　　　　　　　Fig 14.b Standard section

Results of the analysis with composite section :

MNr.	Anz. Temp	Material-sicherheit [-]	max.Druck -spannung [MPa]	bei Dehnung [o/oo]	max.Zug -spannung [MPa]	bei Dehnung [o/oo]	tension-stiffening [MPa]
1	0	1.500	-17.00	-2.00	0.00	0.00	2.90
2	0	1.500	-17.00	-2.00	0.00	0.00	2.90
3	0	1.500	-17.00	-2.00	0.00	0.00	2.90
4	0	1.500	-17.00	-2.00	0.00	0.00	2.90
5	0	1.500	-17.00	-2.00	0.00	0.00	2.90
6	0	1.500	-17.00	-2.00	0.00	0.00	2.90
7	0	1.500	-17.00	-2.00	0.00	0.00	2.90
8	0	1.500	-17.00	-2.00	0.00	0.00	2.90
9	0	1.500	-17.00	-2.00	0.00	0.00	2.90
11	0	1.150	-456.52	-25.00	456.52	25.00	

Erforderliche Bewehrung

Stab	x[m]	NQ	LF	Ni [kN]	Myi/Mzi [kNm]	e1/yn [o/oo	e2/zn / mm]	nue C/S	rel tra	As [cm2]	R
1	0.000	1	30	-4366.5	0.00	-2.04	-1.94	1.50	1.09	73.92	0
					0.00		6526	1.15			
	0.567	1	30	-4233.7	27.85	-2.37	-1.51	1.50	1.06	73.92	0
					0.00		1132	1.15			
	1.133	1	30	-4073.7	43.87	-2.60	-1.21	1.50	1.02	73.92	0
					0.00		860	1.15			
	1.700	1	30	-4021.7	49.10	-2.67	-1.11	1.50	1.01	73.92	0
					0.00		814	1.15			
	2.267	1	30	-4073.7	43.87	-2.60	-1.21	1.50	1.02	73.92	0
					0.00		860	1.15			
	2.833	1	30	-4233.7	27.85	-2.37	-1.51	1.50	1.06	73.92	0
					0.00		1132	1.15			
	3.400	1	30	-4366.5	0.00	-2.04	-1.94	1.50	1.09	73.92	0
					0.00		6526	1.15			

N_{bal} = 4021.7 KN , M_{ED} = 49.10 KNM, Relative bearing capacity 1.01 > 1.0

Verifikation - Vollquerschnitt/Verbundquerschnitt
NICHTLINEARER KNICKNACHWEISE DER STUETZE IM KALTZUSTAND, Verbundquerschnitt

Berechnung nach Theorie II. Ordnung Iteration 3 LF 30 Lastfaktor 1.00
----- K o n v e r g e n z e r r e i c h t -----

Genauigkeiten:	Absolut Vorhanden	Absolut Grenze	Relativ Vorhanden	Relativ Grenze
	(kN, kNm, m, rad)			(Prozent)
Kräfte	0.000E+00	3.974E+01		1.00
Momente	8.095E-02	4.852E-01		1.00
Verschiebungen	2.024E-05	1.213E-04		1.00
Verdrehungen	1.951E-05	1.333E-04		1.00

Schnittgroessen
Nichtlinearer Lastfall 30 Theorie II. Ordnung Iteration 3

Stab Nr	X [m]	N [kN]	V-z [kN]	M-y [kNm]	u-x [mm]	u-z [mm]	phi-y [mrad]
1	0.000	-4000.0	0.0	0.00	0.000	0.000	-13.423
	0.567	-4000.0	0.0	26.32	-0.590	6.579	-9.670
	1.133	-4000.0	0.0	43.08	-1.178	10.771	-5.039
	1.700	-4000.0	0.0	48.84	-1.768	12.209	0.000
	2.267	-4000.0	0.0	43.08	-2.358	10.771	5.039
	2.833	-4000.0	0.0	26.32	-2.947	6.579	9.670
	3.400	-4000.0	0.0	0.00	-3.536	0.000	13.423

N_{ED} = 4000 KN, M_2 = 48.84 KNM

Results of the analysis with a standard section:

Erforderliche Bewehrung

Stab	x[m]	NQ	LF	Ni [kN]	Myi/Mzi [kNm]	e1/yn [o/oo	e2/zn / mm]	nue C/S	rel tra	As [cm2]	R
1	0.000	2	20	-4347.3	0.00	-2.00	-2.00	1.50	1.09	73.56	0
					0.00			1.15			
	0.567	2	20	-4243.7	27.62	-2.31	-1.58	1.50	1.06	73.56	0
					0.00		797	1.15			
	1.133	2	20	-4084.8	43.51	-2.55	-1.26	1.50	1.02	73.56	0
					0.00		444	1.15			
	1.700	2	20	-4033.1	48.70	-2.63	-1.16	1.50	1.01	73.56	0
					0.00		389	1.15			
	2.267	2	20	-4084.8	43.51	-2.55	-1.26	1.50	1.02	73.56	0
					0.00		444	1.15			
	2.833	2	20	-4243.7	27.62	-2.31	-1.58	1.50	1.06	73.56	0
					0.00		797	1.15			
	3.400	2	20	-4347.3	0.00	-2.00	-2.00	1.50	1.09	73.56	0
					0.00			1.15			

N_{bal} = 4033.1 KN , M_{ED} = 48.70 KNM, Relative bearing capacity 1.01 > 1.0

Berechnung mit Vollquerschnitt QNR 2
NICHTLINEARER KNICKNACHWEISE DER STUETZE IM KALTZUSTAND, Vollquerschnitt

Berechnung nach Theorie II. Ordnung Iteration 3 LF 20 Lastfaktor 1.00
----- K o n v e r g e n z   e r r e i c h t -----

Genauigkeiten:	----- Absolut ------		------ Relativ ------	
	Vorhanden	Grenze	Vorhanden	Grenze
	(kN, kNm, m, rad)			(Prozent)
Kräfte	0.000E+00	4.000E+01		1.00
Momente	3.691E-02	4.830E-01		1.00
Verschiebungen	9.228E-06	1.208E-04		1.00
Verdrehungen	7.731E-06	1.327E-04		1.00

Schnittgroessen
Nichtlinearer Lastfall 20 Theorie II. Ordnung Iteration 3

Stab Nr	X [m]	N [kN]	V-z [kN]	M-y [kNm]	u-x [mm]	u-z [mm]	phi-y [mrad]
1	0.000	-4000.0	0.0	0.00	0.000	0.000	-13.274
	0.567	-4000.0	0.0	26.03	-0.595	6.508	-9.562
	1.133	-4000.0	0.0	42.61	-1.189	10.653	-4.986
	1.700	-4000.0	0.0	48.30	-1.784	12.076	0.000
	2.267	-4000.0	0.0	42.61	-2.380	10.653	4.986
	2.833	-4000.0	0.0	26.03	-2.974	6.508	9.562
	3.400	-4000.0	0.0	0.00	-3.569	0.000	13.274

N_{ED} = 4000 KN, M_2 = 48.30 KNM
The bearing capacity and the internal resisting forces are identical in both the cases, the non-linear thermo-mechanical analysis will be performed with the composite column.

THERMO-MECHANICAL STRUCTURAL ANALYSIS

2D-Heat transfer analysis with HYDRA till T= 90 min.

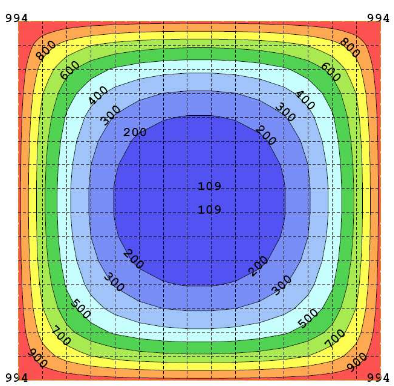


Fig 15: Temperature zones for T= 90 min acc. To ISO 834 Time – temperature curve, Section size 30x30 cm

Defining the composite section with varying material properties for steel and concrete With AQUA

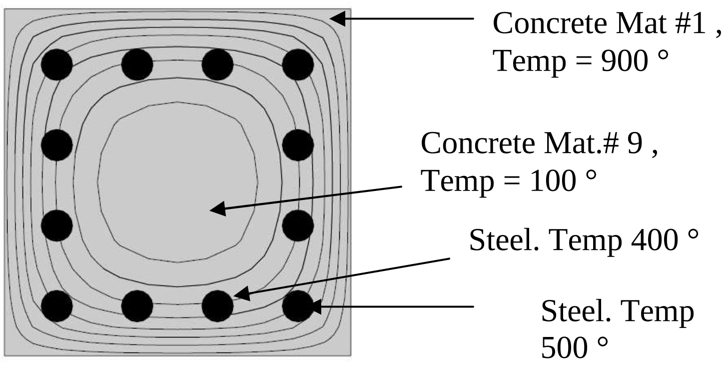
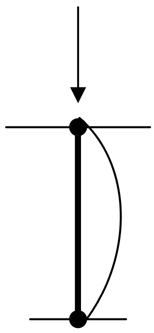


Fig 16 : Composite column section 30x30 cm

NON LINEAR THERMOMECHANICAL ANALYSIS WITH STAR3

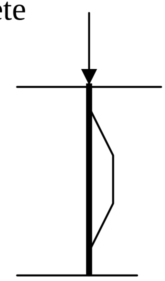
The reference column from the verification of composite section is analysed with material properties under elevated temperatures.

Concrete	C30
Reinforcement steel	Bst 500
Geometry	$b_x d$=30x30 cm
Column height	$H_{i=}$3.40 m



Factored Design load under service conditions:

N^G = 2075 KN
N^Q = 800 KN
N_{ED} = 1.35x2075+1.5x800 ~ 4000 KN
Chosen reinforcement = 12Φ 28 = 73.92 cm²
Analysis is performed for a pinned supported column
Geometric and material non linear analysis; Pre camber acc. to DIN 1045 , V_o= l/400.
Safety factor for the materials $\gamma_{c=}$1.5 Concrete
$\gamma_{s=}$1.15 Steel



Factored Load under fire condition:

N^G = 2075 KN
N^Q = 800 KN
$N_{ED,fi}$ = 1.0x2075+0.5x800 = 2475 KN

Under elevated temperatures for a column fixed at the top and bottom by a reinforced concrete slab, it can be assumed that the ends are fixed against rotation.
Geometric and material non linear analysis; Pre camber acc. to DIN 1045 , V_o= l/400.
Safety factor for the materials $\gamma_{c=}$1.30 Concrete
$\gamma_{s=}$1.00 Steel

Results of the thermo mechanical analysis:

System für Heißnachweis mit Verbundquerschnitt
NICHTLINEARER KNICKNACHWEISE DER STUETZE IM BRANDFALL

Berechnung nach Theorie II. Ordnung Iteration 13 LF 40 Lastfaktor 1.00

----- K o n v e r g e n z   e r r e i c h t -----

Genauigkeiten:	----- Absolut ------		------ Relativ ------	
	Vorhanden	Grenze	Vorhanden	Grenze
	(kN, kNm, m, rad)			(Prozent)
Kräfte	1.573E-07	9.037E+00		1.00
Momente	6.257E-02	9.622E-02		1.00
Verschiebungen	2.625E-05	5.259E-05		1.00
Verdrehungen	2.819E-05	4.049E-05		1.00

Schnittgroessen
Nichtlinearer Lastfall 40 Theorie II. Ordnung Iteration 13

Stab Nr	X [m]	N [kN]	V-z [kN]	M-y [kNm]	u-x [mm]	u-z [mm]	phi-y [mrad]
1	0.000	-2800.0	0.0	-29.81	0.000	0.000	-10.000
	0.567	-2800.0	0.0	-11.22	-0.413	6.640	-12.544
	1.133	-2800.0	0.0	7.47	-0.825	13.313	-9.809
	1.700	-2800.0	0.0	15.81	-1.238	16.294	0.000
	2.267	-2800.0	0.0	7.47	-1.650	13.313	9.809
	2.833	-2800.0	0.0	-11.22	-2.063	6.640	12.544
	3.400	-2800.0	0.0	-29.81	-2.475	0.000	10.000

$N_{ED,fi}$ = 2800 KN, $M_{2,fi}$ = -29.81/16.81 KNM

MNr.	Anz. Temp	Material-sicherheit [-]	max.Druck -spannung [MPa]	bei Dehnung [o/oo]	max.Zug -spannung [MPa]	bei Dehnung [o/oo]	tension-stiffening [MPa]
1	0	1.300	-18.63	-3.50	0.00	0.00	2.90
2	0	1.300	-17.65	-4.50	0.00	0.00	2.90
3	0	1.300	-16.67	-6.00	0.00	0.00	2.90
4	0	1.300	-14.71	-7.50	0.00	0.00	2.90
5	0	1.300	-11.77	-9.50	0.00	0.00	2.90
6	0	1.300	-8.83	-12.50	0.00	0.00	2.90
7	0	1.300	-5.88	-14.00	0.00	0.00	2.90
8	0	1.300	-2.94	-14.50	0.00	0.00	2.90
9	0	1.300	-1.57	-15.00	0.00	0.00	2.90
11	0	1.000	-335.00	-13.24	335.00	26.76	
12	0	1.000	-335.00	-13.24	335.00	26.76	
13	0	1.000	-335.00	-13.24	335.00	26.76	
14	0	1.000	-335.00	-13.24	335.00	26.76	
15	0	1.000	-470.00	-54.80	470.00	25.20	
16	0	1.000	-470.00	-54.80	470.00	25.20	
17	0	1.000	-470.00	-54.80	470.00	25.20	
18	0	1.000	-470.00	-54.80	470.00	25.20	

Erforderliche Bewehrung

Stab	x[m]	NQ	LF	Ni [kN]	Myi/Mzi [kNm]	e1/yn [o/oo	e2/zn / mm]	nue C/S	rel tra	As [cm2]	R
1	0.000	1	40	-2859.5	-30.45	-3.50	1.04	1.30	1.02	24.64	0
					0.00		404	1.00		49.28	1
	0.567	1	40	-3637.1	-14.57	-5.29	-2.33	1.30	1.30	24.64	0
					0.00		59	1.00		49.28	1
	1.133	1	40	-3491.7	9.31	-4.59	-1.42	1.30	1.25	24.64	0
					0.00		734	1.00		49.28	1
	1.700	1	40	-3056.2	17.26	-3.50	-0.03	1.30	1.09	24.64	0
					0.00		558	1.00		49.28	1
	2.267	1	40	-3491.7	9.31	-4.59	-1.42	1.30	1.25	24.64	0
					0.00		734	1.00		49.28	1
	2.833	1	40	-3637.1	-14.57	-5.29	-2.33	1.30	1.30	24.64	0
					0.00		59	1.00		49.28	1
	3.400	1	40	-2859.5	-30.45	-3.50	1.04	1.30	1.02	24.64	0
					0.00		404	1.00		49.28	1

$N_{bal,fi}$ = 3066.2 KN , $M_{ED,fi}$ = -30.46/ 17.26 KNM, Relative bearing capacity 1.09 > 1.0

CONCLUSION

$N_{bal,fi}$ = 3066.2 KN , $M_{ED,fi}$ = -30.46/ 17.26 KNM, Relative bearing capacity with 8.2 % reinforcement is 1.09 > 1.0
The ratio of design load under fire and the cold cross sectional resistance is
$N_{ED,fi}/N_{RD}$ = 2800/4000 = 0.7 .
This result is marginally better then the fire resistance proof according to the tabulated values of DIN 4102-T4. Where for a column of this nature the fire resistance is just about achieved by increasing the reinforcement to the max. of 9 %.
The analysis maintains the high degree of scientific basis of a thermo mechanical analysis with a relatively low computing effort. The extension possibilities of analysing structural members outside the tabulated values is the potential of this method.
Further validation of this analysis is in progress under the supervision of Dr.-Ing. Ekkehard Richter of the iBMB – Fire engineering department – Technical university of Braunschweig /Germany.
The results will be published at the conference.

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