TA - the new Frilo application for temperature analyses of rectangular and circular cross sections

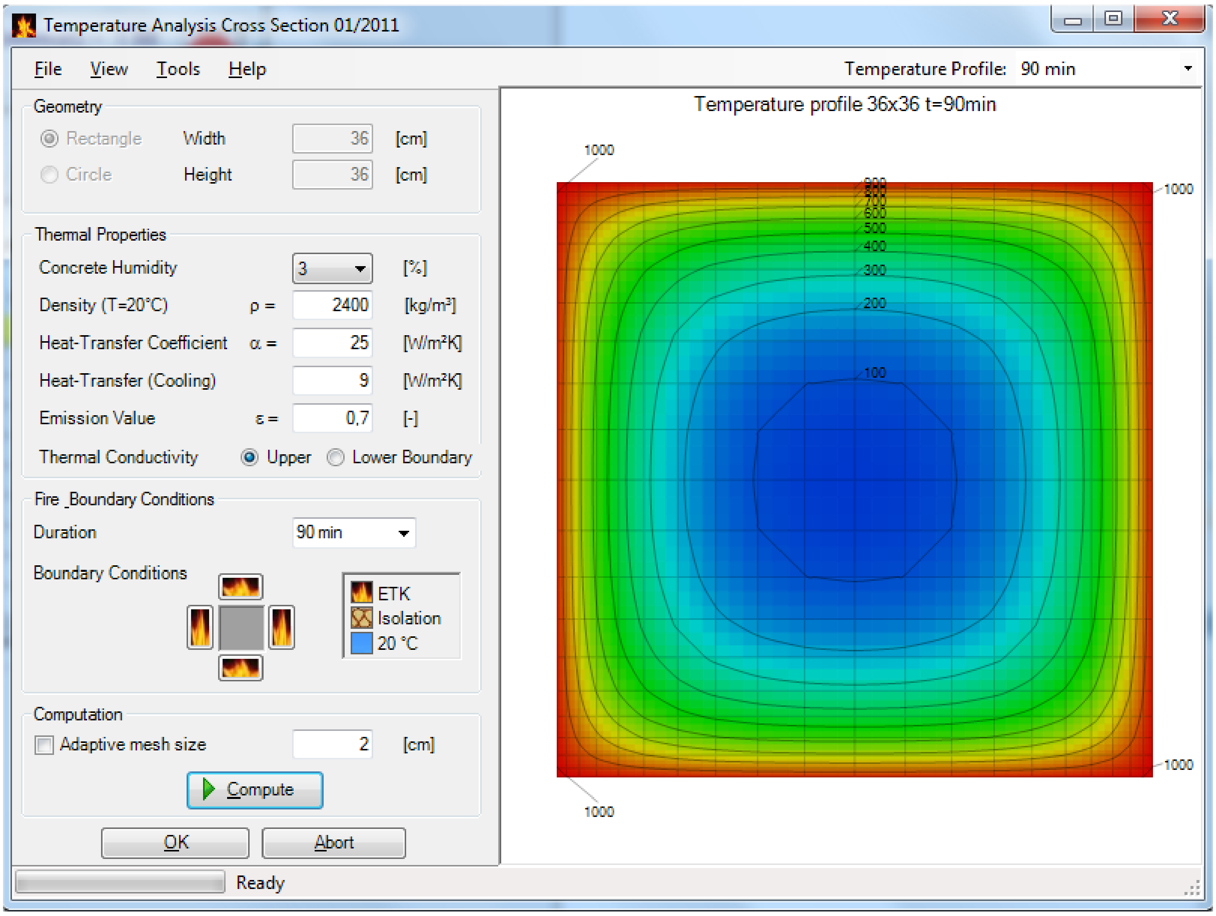
The TA application is used for the calculation of temperature fields in rectangular and circular concrete cross sections under fire exposure.

The fire load is taken into account via the standard temperature-time curve as per DIN EN 1991-1-1-:2010-12.

In terms of mathematics, the transient heat conduction in a solid body is described with a partial differential equation of second order. Since material properties such as heat conductivity, bulk density and specific thermal capacity depend on temperature themselves, the solution is obtained numerically with the help of the Finite Element Method.

Reinforcement is disregarded in temperature analyses of reinforced concrete cross sections, because the influence of the reinforcement steel is negligibly low (compare /3/4.3.2 (4)).

At the borders, thermal radiation and convection must be taken into account in addition.



Essential input parameters are:

- Component moisture — 1 - 3 %
- Bulk density of the concrete [T = 20° C] — ρ = 2200 - 2500 kg/m³
- Heat transfer coefficient — α_c = 25 W/(m²·K) for the exposed side as per /3/ 3.2.1 (2); α_c = 4…9 W/(m²·K) for the unexposed side as per /5/
- Emission value of the component surface — concrete: ε_m = 0.7 as per /1/ 2.2 (2)
- Thermal conductivity — concrete: between upper and lower limit

Comparison between the accurate temperature analysis and the temperature assessment on the basis of temperature profiles as per DIN EN Annex A

Until recently, the temperature profiles stated by DIN EN 1992-1-2 Annex A were used in fire safety analyses. The profiles were based on the following border conditions:

- Flame exposure on four sides in accordance with the standard temperature-time curve
- Specific heat $\varepsilon = 0.7$
- Component moisture 1.5 %
- Thermal conductivity with its lower limit
- Convective heat transfer coefficient $\alpha_c = 25$ W/(m²·K)
- Circular cross section, d = 300 mm and square cross section, h = 300 mm
- Fire resistances R30, R60, R90 and R120

These relatively inflexible assumptions required a typical design solution by approximation with other cross section sizes. The calculation was based on the assumption that the spacing of the temperature ISO-lines to the border in good approximation can also be used with larger or smaller cross sections. Therefore, the temperatures are slightly higher with larger cross sections (h > 30 cm), i.e. they are on the safe side. With smaller cross sections (h < 30 cm), the temperatures are slightly too low. The deviations become greater with increasing fire resistance.

The thermal analysis feature of the TA application assesses temperature fields accurately for any cross section dimensions and border conditions.

The comparison below shows the difference in temperature between the approximation and the more accurate method whereby the other border conditions remain unchanged. The temperatures in the corner bars are considered. The required reinforcement was calculated with the reinforced concrete column application B5 and the B5 hot design add-on module.

Standard cross section 30 cm

First, the results for a circular cross section with a diameter of 30 cm (C30) and a square with a side length of 30 cm (S30) are compared to each other. The dimensions are the default ones specified by Annex A.

The temperature in the reinforcement of the circular section and that in the corner bars with a spacing d_1= 3 cm in the rectangular cross section are compared to each other.

Cantilever column l = 3 m Reinforcement spacing d_1= 3 cm			**Approximation as per Annex A**		**Frilo TA application**			
					Grid 1 cm		**Grid 2 cm**	
Cross section	Fire resistance	N_{Ed} [kN]	T [°C]	req. A_s [cm²]	T [°C]	req. A_s [cm²]	T [°C]	req. A_s [cm²]
C30	R60	300	470	19.3	452	18.0	462	18.5
	R120	100	680	20.6	668	18.3		
S30	R60	300	612	22.9	610	22.7		
	R90	100	744	15.1	741	14.8	743	14.8
	R120	100	828	24.5	828	24.5		

The result of the thermal analysis depends also on the selected grid. The results match best with the temperature profiles as per Annex A if a coarser grid is used.

Smaller cross sections

Cantilever column l = 3m Reinforcement spacing d_1= 3 cm			Approximation as per Annex A		Frilo TA application Grid 1 cm	
Cross section	Fire resis-	N_{Ed} [kN]	T [°C]	req. A_s [cm²]	T [°C]	req. A_s [cm²]
C20	R60	100	470	15.2	500	16.2
S20	R60	100	612	18.5	611	18.5

With cross sections differing from the original dimensions, the deviations vary more or less as expected.

With smaller cross sections, the temperatures assessed in accordance with Annex A tend to be slightly too low due to the overestimated thermal capacity.

In the example, the temperatures on the squared cross section are identical for both methods whereas those on the circular cross section differ considerably by approximately 60 °C.

Larger cross sections

Cantilever column l = 6m Reinforcement spacing d_1= 5 cm				Approximation as per Annex A		TA application Grid 1 cm	
Cross section	Fire resistance	N_{Ed} [kN]	Reinforcement location	T [°C]	req. As [cm²]	T [°C]	req. A_s [cm²]
C60	R120	800		500	42.2	431	33.1
S60	R120	1000	Corner	615	55.8	614	52.3
			Middle	424		387	
R40X80	R120	1000 (H=50)	Corner	615	51.7	615	49.6
			Middle	424		394	

Due to the approach by approximation, the thermal capacity of larger cross sections is underestimated and the temperatures are slightly too high. On the S60 squared cross section, the differences are relatively low and range from 6 to 16 °C. The differences in the corner reinforcements (item E) are the lowest. They increase in the middle bar (item M) and in the interior of the cross section (item I).

On the C60 circular cross section, however, considerable deviations from 40 °C can be observed.

The examples show that the TA application produces more economic results in some cases and prevents uncertain results in others.

Temperature profiles with border conditions as per DIN EN 1992-1-2/NA: 2010-12

Germany's National Annex specifies other values than the border conditions stipulated for the temperature profiles in Annex A of the General Eurocode.

According to 3.3.3 (1), the upper limit of the thermal conductivity should be assumed.

The component humidity and the bulk density ρ are not specified as such but the assumption of k = 3 % and ρ = 2400 kg/m^3 for the assessment of the design diagrams with the simplified method as per Annex A can be interpreted as a kind of recommendation for a practice-oriented approach.

First, the influence of the parameters is examined individually for each parameter on the S30 cross section with R90 fire resistance. In the examination, the temperatures in the corner bar (point 1 (X_1 = 12 cm, Y_1 = 12 cm)) and the inner cross section (point 2 (X_2 = 7.5 cm / Y_2 = 7.5 cm)) are considered. The coordinates refer to the centre of the column.

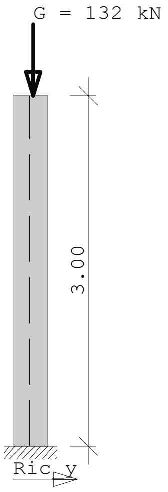
	Component moisture [%]	Density ρ [kg/m^3]	Conductivity λ	Temperature [^{0}C]		Difference to Annex A	
				Point 1	Point 2	Point 1	Point 2
Annex A	1.5	2300	λ_l	741	308		
	3	2300	λ_l	734	290	-7	-18
	1.5	2400	λ_l	732	297	-9	-11
	1.5	2300	λ_u	760	365	+19	+47

The examination reveals that higher component moisture produces lower temperatures and so does higher bulk density, whereas a higher limit of thermal conductivity produces higher temperatures.

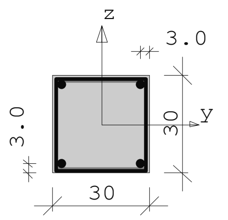
Fire resistance R90	Component moisture [%]	Density ρ [kg/m^3]	Conductivity λ	Temperature [^{0}C]		Difference to Annex A	
				Point 1	Point 2	Point 1	Point 2
Annex A	1.5	2300	λ_l	741	308		
NA Ger	3	2400	λ_u	746	337	+5	+30

When you compare the parameter sets of Annex A and Germany's NA, the following can be observed:
In the corner bar, the temperature increases only slightly by approximately 5 °C whereas, in the inner concrete cross section, it increases considerably by 30 °C.

The next step is to combine the influencing parameters in such a manner that a minimum and maximum steel temperature results for the corner bar. For a simple cantilever column, the effects on the hot design are demonstrated.



C 30/37 BSt 500 S(A)
Phi = 2.46
Reinforcement in the corners



	Component moisture [%]	Density ρ [kg/m^3]	Conductivity λ	Temperature [^{0}C]	Difference to Annex A	req. As [cm^2]
T_{max}	1.5	2300	λ_u	760	+22	25.28
T_{min}	3	2400	λ_l	726	-15	20.43

The maximum temperature specified in the table above corresponds also to the most unfavourable value stated in the German NA, unless the most favourable assumption of a high component moisture and a high density is considered to be justified as in the validation example CC 4.10 (in German) , for instance.

The minimum temperature can result in combination with other National Annexes (see the following page, e.g. Austria), if applicable, and if a favourable bulk density (high) and component moisture (high) are assumed. The resulting temperature values vary considerably which also affects the design results of course.

Temperature variations of such order can have considerable effects on the fire safety verifications. Therefore, the input parameters for the thermal analysis should be selected with utmost care.

Comparison of temperature profiles with the border conditions of various National Annexes

	Compo-nent moisture [%]	Density ρ [kg/m³]	Conductivity λ as per NA	Default λ in TA application	Tempera-ture [⁰C]	
Austria	1.5	2300	Standard λ_l High strength λ_u	λ_l λ_u	741 760	
UK	1.5	2300	Standard λ_l High strength λ_u	λ_l λ_u	741 760	
Netherlands	1.5	2300	Lime aggregate λ_l Gravel aggregate λ_u	λ_l λ_u	741 760	
Belgium	1.5	2300	Lime aggregate λ_l Gravel aggregate λ_m Lightweight concrete λ_n	λ_l λ_u λ_l	741 760 741	 *1 *2
Czech Republic	1.5	2300	λ_l ... λ_u	λ_l	741	*3
Germany	3	2400	λ_u	λ_u	746	

*1 According to the Belgian NA, a conductivity value λ_m between the upper and the lower limit applies with gravel aggregate. When using the upper limit, the results are on the safe side.

*2 According to the Belgian NA, a conductivity value λ_n below the lower limit applies with lightweight aggregate. When using the lower limit, the results are on the safe side.

*3 According to the Czech NA, the conductivity value is freely selectable within the limits of λ_l and λ_u. The default value is λ_l in accordance with the assumptions of Annex A.

Since specifications concerning the component moisture and the bulk density are not given with the exception of the German NA (see above), the assumptions forming the basis of the temperature profiles of Annex A are used .

Currently, a thermal conductivity beyond the limits λ_l and λ_u cannot be taken into account.

For reasons of comparison, the table above indicates the steel temperatures with the default settings of the application for the example S30/R90.

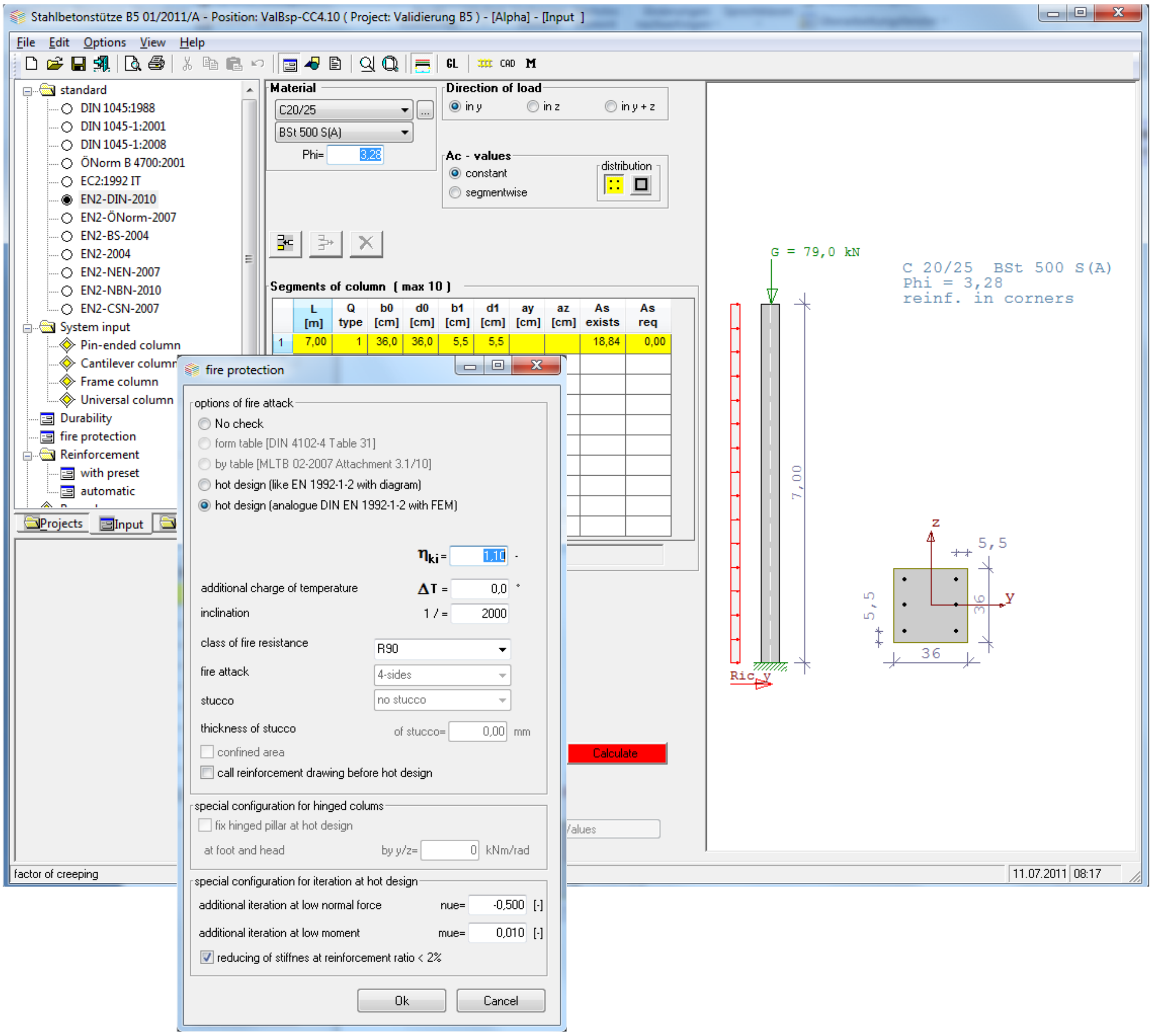
Application of TA in combination with other FRILO software

Fire safety analyses in accordance with DIN EN 1992-1-2/NA cannot be based on the temperature profiles of Annex A any longer. Since Germany's NA was introduced in the beginning of 2011 and the hot design is performed in accordance with the Eurocode in particular cases, the regulations of the NA apply also to the hot design.

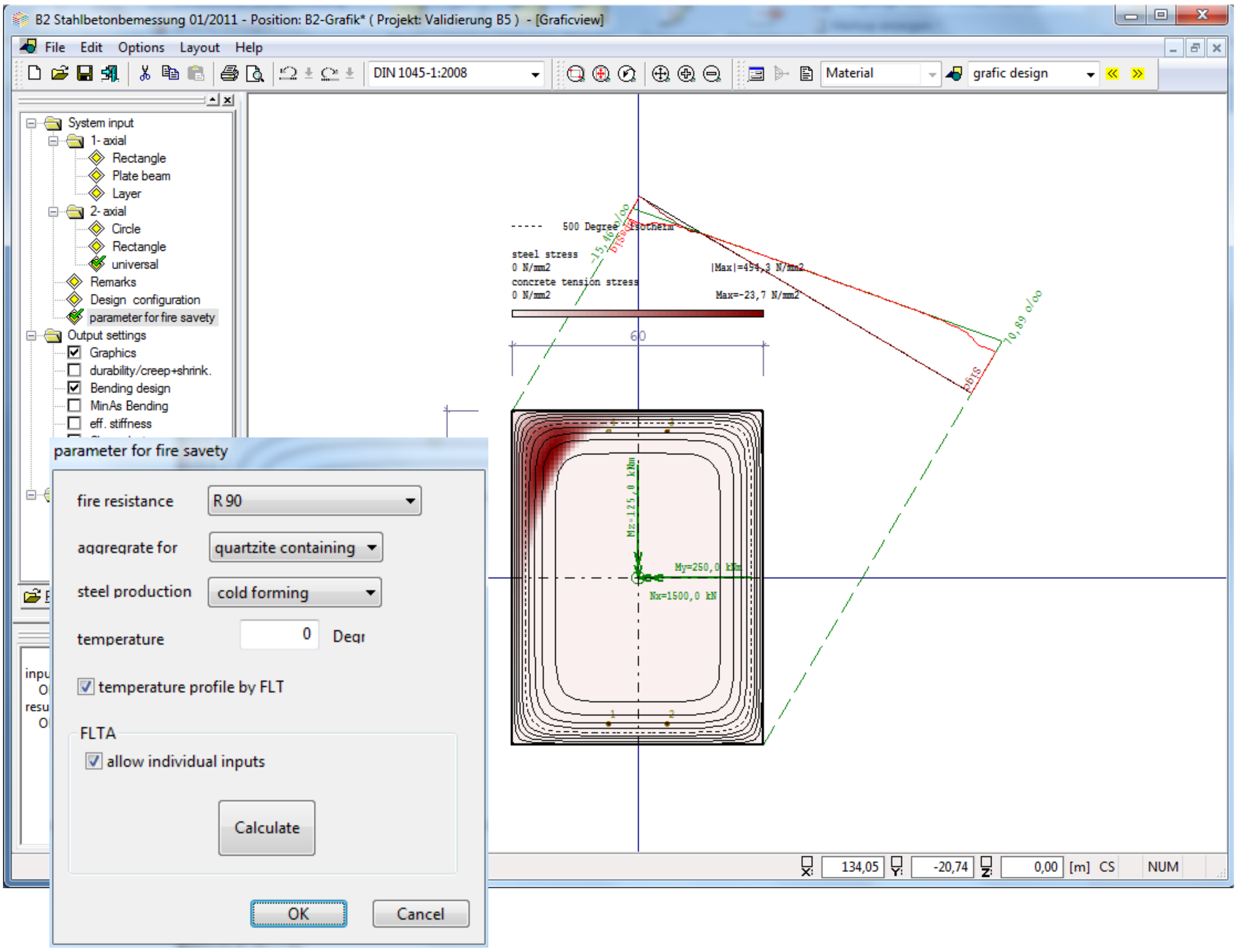
The new FRILO TA application allows the temperature assessment for rectangular and circular cross sections with any dimensions typical for reinforced concrete in accordance with Germany's NA and other National Annexes to the Eurocode.

Temperature analysis TA is available as optional add-on feature and currently implemented with the following applications:

B5 - fire safety analysis of columns in accordance with the general method



B2 - cross section design and stiffness assessment in the accidental design situation fire



Due to the great impact the assumptions have on the resulting temperature, the editing of the default thermal parameters in B2 requires the explicit confirmation of the experienced user.

Preview

In addition to flame exposure on four sides, future versions will provide options for exposure on one, two or three sides in the fire safety analysis of columns.

In principle, you can optionally take fire curves other than the standard temperature-time curve and natural fire models as per EN 1991-1-1 into account.

Currently, the application of natural fire models is only allowed in exceptional cases after coordination with the construction supervision authorities. We will see whether demand will arise in this respect.

Reference literature

/ 1 / DIN EN 1992-1-2:2010-12

/ 2 / D. Hosser, Grundlagen und Hintergründe der Heißbemessung,
in: Tagungsband der Gemeinschaftstagung „Eurocode 2 für Deutschland“

/ 3 / DIN EN 02/01/1991:2010-12