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Response of Structure - Verification of SAFIR advanced calculation model through DIN EN 1991-1-2 procedure

Raul Zaharia
The "Politehnica" University of Timişoara – Romania

DIN EN 1991-1-2 (2010)

The document presents 11 verification examples assembled in Annex CC, concerning:

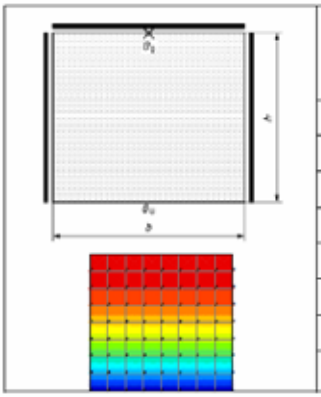
- heat transfer for different sections and material properties;
- temperature induced expansion for different material laws;
- internal forces and stresses induced by thermal action;
- fire resistance time.

These examples include steel, concrete and composite steel-concrete sections.

Each example offers a set of results and the acceptable tolerances for the results.

EXAMPLE 1

- Example 1 analyses the heat transfer in the cooling process of a square section with given material properties.
- The initial temperature of the section is 1000 °C. Three sides of the cross-section represent an adiabatic boundary, while the other side exchanges heat with a medium of which temperature is and remains equal to 0 °C.

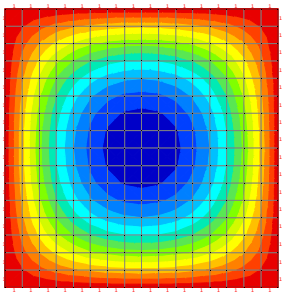


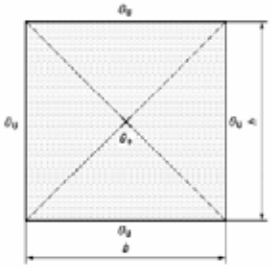
Time [s]	Calculated Temperature [°C]	Deviation [%] / [K]		Limit
0	1000	0	0	± 1 % and ± 5.0 K
60	998.6	-0.07	-0.7	
300	892.5	0.07	0.6	
600	719.1	0.20	1.4	
900	576.4	0.26	1.5	
1200	461.9	0.33	1.5	
1500	370.1	0.38	1.4	
1800	296.3	0.34	1.0	

- The limit deviations for the calculated temperatures in a selected point were satisfied for a 64 quad elements mesh (8*8).

EXAMPLE 2

- Example 2 analyses the heat transfer in the heating process of a square section with given material properties.
- The initial temperature of the section is 0°C and the section is plunged into a medium having 1000 °C.



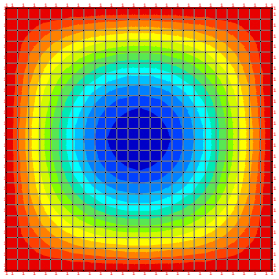


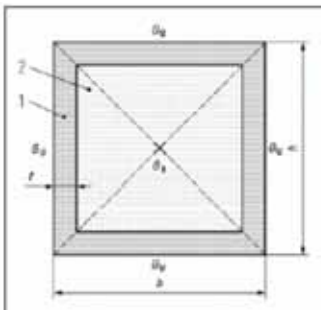
Time [min]	Calculated Temperature [°C]	Deviation [%] / [K]		Limit
30	32.5	-11.9	-4.4	for t ≤ 60 min ± 5.0 K for t > 60 min ± 3 %
60	132.5	-3.6	-4.9	
90	241.6	-1.2	-3	
120	362.6	0.4	1.5	
150	469.6	0.7	3.4	
180	559.7	0.9	4.9	

- The limit deviations for the calculated temperatures in the center point of the section were satisfied for a 576 quad elements mesh (24*24).

EXAMPLE 3

- Example 3 analyses the heat transfer in a *steel* hollow section with a thickness of 0.5mm, filled with a material for which the thermal properties are known, with an initial temperature of 0 °C, plunged into a medium having 1000 °C.



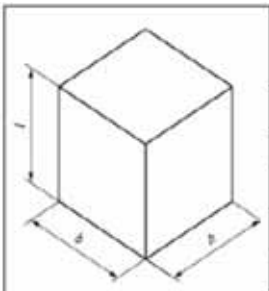


Time [min]	Calculated Temperature [°C]	Deviation [%]	Deviation [K]	Limit
30	337	-1.0	-3.5	± 1 %
60	721.7	0.6	4.6	
90	885.3	0.4	3.7	and
120	952.7	0.2	2.1	
150	980.5	0.1	1.2	± 5.0 K
180	992	0.0	0.3	

- The limit deviations for the calculated temperatures in the center point of the section were satisfied for a 324 quad elements mesh (18*18).

EXAMPLE 4

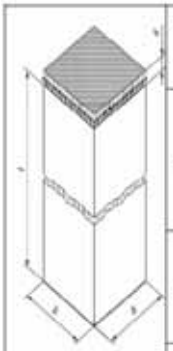
- Example 4 analyses the thermal induced expansion Δl of a steel element 100*100*100mm, at different values of homogenous temperature in the cross-section.



Θ [°C]	Reference Δl [mm]	Calculated $\Delta l'$ [mm]	Deviation [%]	Deviation [mm]	Limit
100	0.09984	0.10	0.16	0.00016	for Θ ≤ 300 °C ± 0.05 mm
300	0.37184	0.37	−0.49	−0.00184	
500	0.67584	0.68	0.61	0.00416	
600	0.83984	0.84	0.02	0.00016	
700	1.01184	1.01	−0.18	−0.00184	for Θ > 300 °C ± 1 %
900	1.18000	1.18	0.00	0.00000	

EXAMPLE 5

- Example 5 analyses the elongation of a cantilever with a height of 100 mm and a square cross-section made of steel or concrete, for different homogenuous temperature distributions at some given stress-strength ratios. For the steel cantilever, all results fit well within the prescribed limits, but some deviations may be observed for the concrete cantilever.



Θ °C	Stress/ Strength	Reference Δl [mm]	Calculated $\Delta l'$ [mm]	Deviation [%]/ $\Delta l' - \Delta l$	Limit [%]
20	0.2	−0.0334	−0.03	−10.18/ -0.0034	± 3
	0.6	−0.104	−0.10	−3.85/ -0.004	
	0.9	−0.176	−0.18	+2.27	
200	0.2	+0.107	−0.11	+2.80	
	0.6	−0.0474	−0.05	+5.48/ +0.0026	
	0.9	−0.2075	−0.21	+1.20	
400	0.2	+0.356	+0.36	+1.12	
	0.6	+0.075	+0.07	−6.66/ -0.005	

- It must be noted that the results are of very small values, the problem here being the number of digits that the software can provide. The differences in terms of absolute values are very small, the maximum value being 0.005 millimeters.

EXAMPLE 6

- The aim of Example 6 is to determine the load bearing capacity at different temperatures of the structural steel and concrete elements of Example 5.

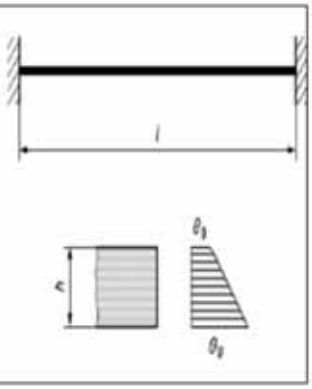
Θ [°C]	Calculated $N_{R,fi,k}$' [KN]	Deviation [%] / [KN]	Limit
20	-20.0	0	± 3 % and ± 0.5 KN
200	-19.0	0	
400	-15.0	0	
600	-8.99	-0.11/0.01	
800	-3.0	0	

- For steel, a perfect fit of the reference and calculated values was obtained. For concrete, only a slight difference for one case was obtained, which fits well within the limits.

EXAMPLE 7

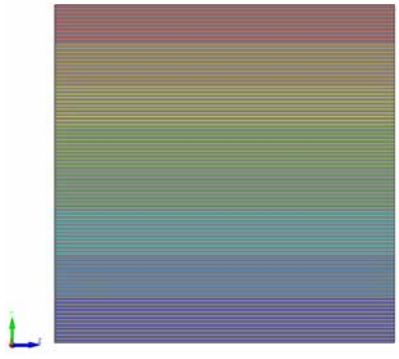
- In Example 7, for a fixed steel beam subjected to thermal loading and having a square cross-section of 100x100 mm, the calculation of the internal forces N and M as well as of the stress σ are demanded.
- Two cases of temperature distribution are considered: uniform temperature distribution of 120 °C in the section and linear variation of temperature on the height of the cross-section, of 20/220 °C in the top/ bottom fiber, respectively.

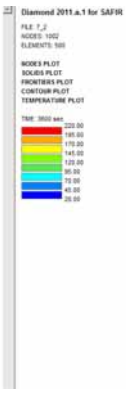
Temperature load case		Calculated value	Deviation [%]	Limit [%]
120/120	N [KN]	−2587	+0.08	N: ± 1 M: ± 1 σ: ± 5
	M[KNm]	0	0	
	σ [N/mm²]	−258.73	+0.09	
20/220	N [KN]	−2457	−2.15	
	M [KNm]	−40.35	+0.12	
	σ [N/mm²]	−478.60	−0.08	



- An analysis of the results reveals that only the axial force calculated by SAFIR for the 20/220 °C load case (done in SAFIR by imposing the corresponding temperatures on the top/ bottom frontiers) does not fit within the deviation limits, while all other values offer deviations which are extremely low compared to the limits (including for the stress, which considers the effect of the axial force).

EXAMPLE 7



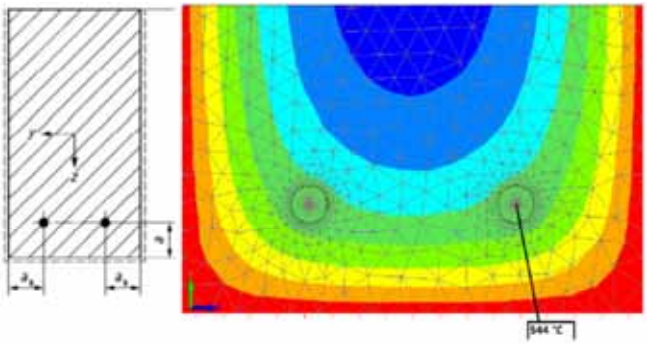


Temperature load case		Reference value X	Calculated value X'	Deviation [(X'−X)/X] x100 [%]	Deviation limit [%]
20/220	N_{Zw} KN	−2511	−2510	−0.039	N_{Zw}: ± 1 M_{Zw}: ± 1 σ_{Zw}: ± 5
	M_{Zw} KNm	−40.3	−40.50	+0.496	
	σ_{Zw} N/mm²	−479	−479.00	0	

- By dividing the height of the cross-section in 200 elements and by imposing in each element the corresponding temperature in order to obtain a linear distribution, all results fit within the deviation limits.

EXAMPLE 8

- Example 8 analyses a weakly reinforced simply supported concrete beam loaded with uniform distributed load, subjected to ISO fire on 3 sides.
- The purpose is to determine the necessary area for the two rebars S500, in order to reach the fire resistance of 90 minutes.

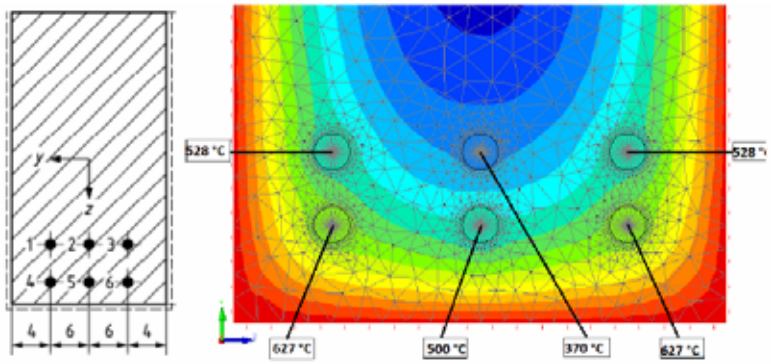


Fire resistance	Reference value As [cm²]	Calculated value As' [cm²]	Deviation [%]	Limit [%]
R90	3.56	3.77	+5.90	± 10

- A temperature of 544°C is obtained in the reinforcement, which presents a deviation of -3.2% from the reference value of 562°C. The limitation of the deviation refers only to the area of the reinforcement and this criteria is fulfilled.

EXAMPLE 9

- Example 9 is similar to Example 8, with the difference that in this case, the same concrete beam is strongly reinforced.

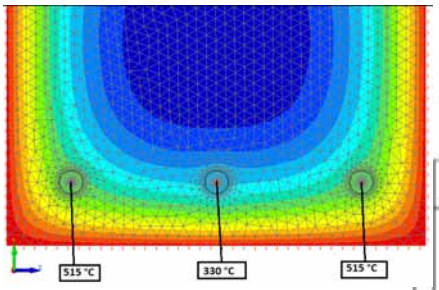


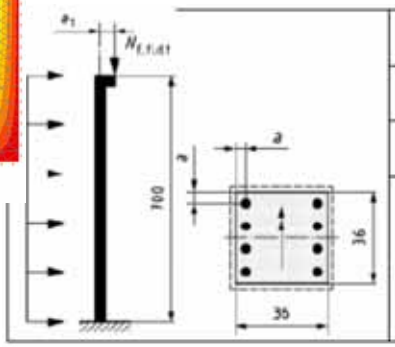
Fire resistance	Reference value As [cm²]	Calculated value As' [cm²]	Deviation [%]	Limit [%]
R90	9.76	9.28	-4.91	± 10

- For this case also, the criteria refers only to the area of the reinforcement, and it is fulfilled. The calculated temperatures in the rebars present a deviation that ranges between -0.54% and -4.76%, compared to the reference values.

EXAMPLE 10

- Example 10 analyses a reinforced concrete column loaded with a vertical load having an eccentricity and a uniformly distributed horizontal load, subjected to ISO fire on 4 sides.
- The reference results, for which a limit deviation is provided, are: the fire resistance time (93 minutes), the top horizontal displacement and the bending moment at the base of the column after a fire time t = 90 minutes.



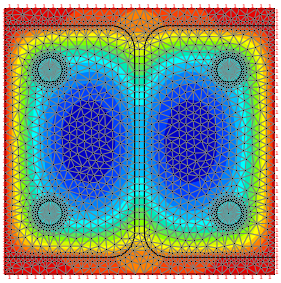


Requested results	Calculated value	Deviation [%]	Limit [%]
Failure time [min]	92	-1.08	± 3
Displacement [mm]	405	+6.30	± 15
Bending Moment [kNm]	74.93	-0.75	± 5

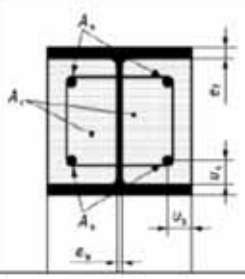
- The criteria are fulfilled for all the requested results. The maximum deviation of the calculated temperatures in the rebars is of -3.33% from the reference ones.

EXAMPLE 11

- The last example analyses a composite column with partially encased steel section, subjected to ISO fire on 4 sides. The column is centrically loaded and a parabolic imperfection with peak value of l/1000 is considered.
- The reference results, for which a limit deviation is provided, are: the fire resistance and the horizontal displacement at the mid-span of the column at t = 30 and 60 minutes.



Requested results		Reference value	Calculated value	Deviation [%]	Limit [%]
Failure time		92	88	−4.35	± 5
Displ. [mm]	30 min	4.40	4.44	+0.82	
	60 min	5.50	5.04	-8.18	



- The criterion is not fulfilled for the displacement corresponding to 60 minutes of ISO fire. This deviation is not consistent with the other results:
  - the displacement at 60 minutes is lower than the reference value (-8.18%), while for 30 minutes the displacement is slightly higher (+0.82%);
  - it would be expected that lower displacements lead to a higher failure time, which is not the case here, the calculated failure time being lower than the reference one.

CONCLUSIONS

- The results generally comply with the criteria and tolerances allowed by the DIN EN1991-1-2 procedure, thus demonstrating that SAFIR is a suitable advanced calculation model available for the structural analysis at elevated temperatures.

- For two examples, there are some deviations from the accepted limits:
  - for one example of a concrete element with very small dimensions, the deviation in the value of the elongation at elevated temperatures is due to the number of digits that SAFIR could provide for the displacements, for reference results with values smaller than one millimeter.
  - for the other example, only one reference value (displacement) was not within the limits, while the other value demanded for the displacement in the same point, at another time step, fulfilled the criteria with small deviations; there seems to be an inconsistency on the reference values for this example.

- It would be helpful to identify the origin of the procedure results.

- It must be mentioned that a program is not verified through the DIN procedure for many situations that may be considered in a structural fire analysis. For instance, for the thermal analysis, the effects of moisture or the presence of cavities in the cross-section are not covered by any example, while for the mechanical analysis only beam elements are considered. All examples are limited to 2D for both thermal and mechanical analysis.

Thank you for your attention !