LOCAFI+

Temperature assessment of a vertical member subjected to LOCAlised FIre
Dissemination

Grant Agreement n° 754072

6. Synthesis Fire resistance

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6.1. General Procedure

Step 1 : Definition of thermal loading

Step 2 : Thermal Analysis

Step 3 : Mechanical Analysis

The general procedure is step-by-step (Step 1 → Step 2 → Step 3) but, more accurately, the coupling should be in both directions. If this double coupling is not considered, the engineer must be aware of the associated assumptions !

- The deflections/displacements of a structural element may influence the development of the fire
- The deflections/displacements of a structural element may influence the thermal exposure
- The elevation of temperature in members may influence the absorbed energy absorbed in walls/floors
- Plasticity and cracking may induce generation of heat or heat leakage
- …

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6.2. Definition of fire scenario

6.2.1. Compartment fire

- Standard fire curve (ISO-834, Hydrocarbon,…)
- Natural fire curve (parametric curve according to Annex A of EN 1991-1-2, OZone software based on EN 1991-1-2 Annexes D and E)

6.2.2. Localised fire

- Fire scenario defined by engineer/authorities (diameter, RHR)

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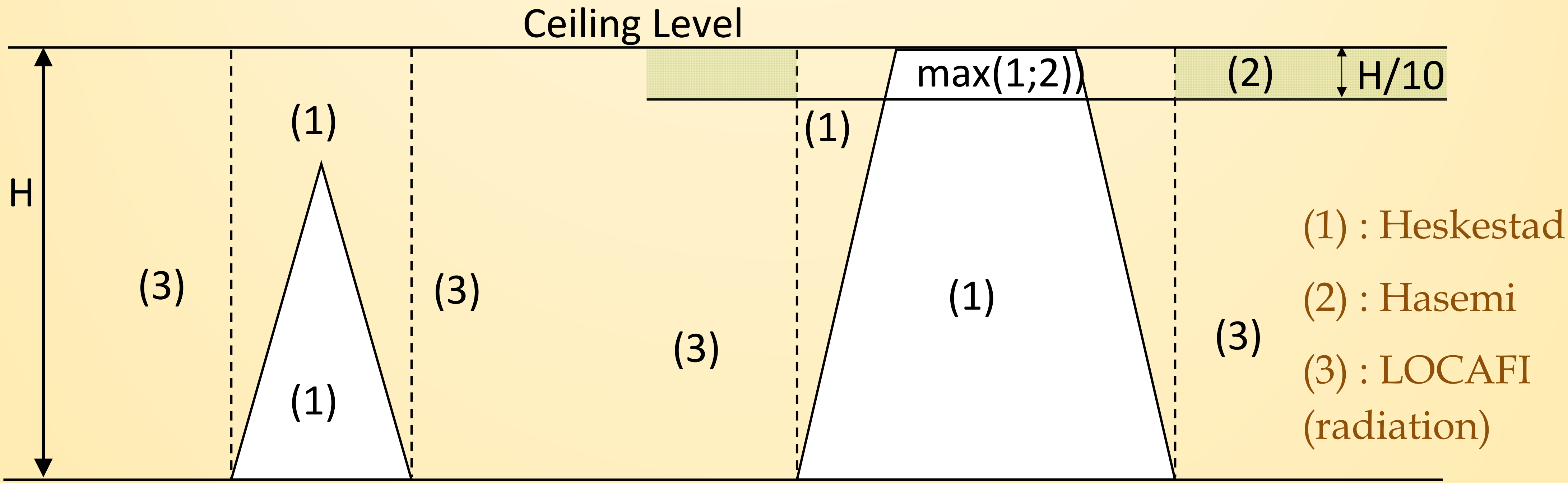
6.2. Definition of fire scenario

6.2.2. Localised fire



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[W.m-2]

6.3. Thermal analysis

6.3.1. Steady-state temperature

Steady-state temperature θ is the temperature at which the absorbed flux is equilibrated by the emitted (convective and radiative) fluxes

$$0 = \underbrace{\alpha_c(\theta - 20)}_{\text{Emitted net convective flux}} + \underbrace{\sigma\varepsilon[(\theta + 273)^4 - (20 + 273)^4]}_{\text{Emitted radiative flux}} - \underbrace{\varepsilon * \dot{h}_{m,r}}_{\text{Absorbed flux}}$$

In case of compartment fire, the mean incident radiative flux $\dot{h}_{m,r}$ must be replaced by $\dot{h}_{m,tot}$, including both convective and radiative fluxes.

$$\dot{h}_{m,tot} = min\left(\dot{h}_{m,r} + \dot{h}_{m,c}; 100000\right) \qquad [W.m^{-2}]$$

This simplified approach neglects the thermal inertia of the member

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6.3. Thermal analysis

6.3.2. Incremental procedure (uniform temperature)

The member temperature is calculated by stating the thermal balance of the member

$$\rho_a c_a(T)\frac{dT}{dt} = \frac{A_m}{V}\left[\varepsilon * \dot{h}_{m,r} + \alpha_c(20-\theta) + \varepsilon\left(\sigma(293^4 - (\theta+273)^4)\right)\right]$$

ρ_a, c_a, and A_m/V are density [kg.m^{-3}], specific heat [J.kg^{-1}.K^{-1}] and massivity [m^{-1}] of the member

EN 1993-1-2 imposes that the time step Δt is not higher than 5 seconds

In case of compartment fire, the mean incident radiative flux $\dot{h}_{m,r}$ must be replaced by $\dot{h}_{tot}$, including both convective and radiative fluxes.

$$\dot{h}_{m,tot} = min\left(\dot{h}_{m,r} + \dot{h}_{m,c}; 100000\right) \qquad \text{[W.m}^{-2}\text{]}$$

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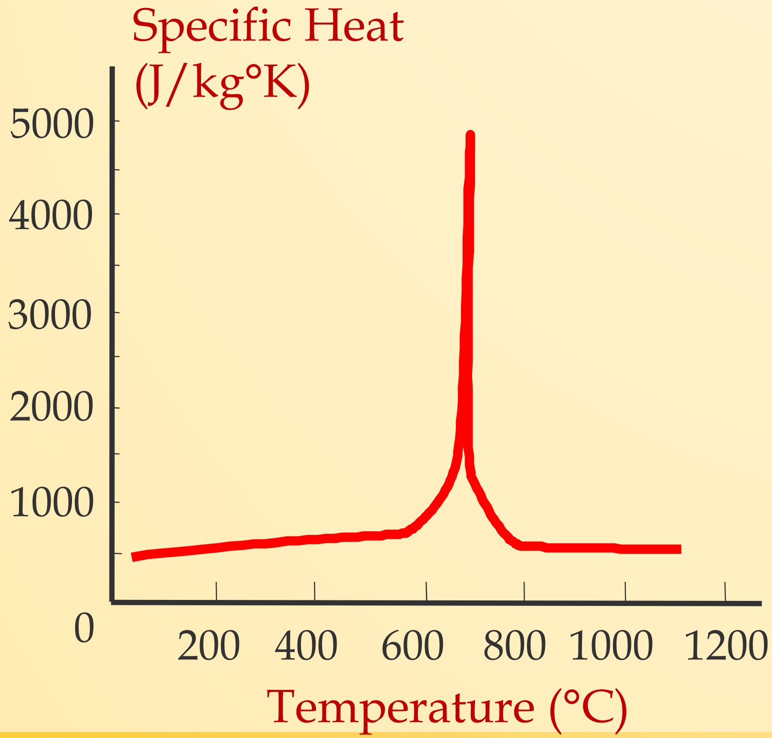
6.3. Thermal analysis

6.3.2. Incremental procedure (uniform temperature)



Volumic mass of steel : 7850 kg/m^3

Independent of temperature

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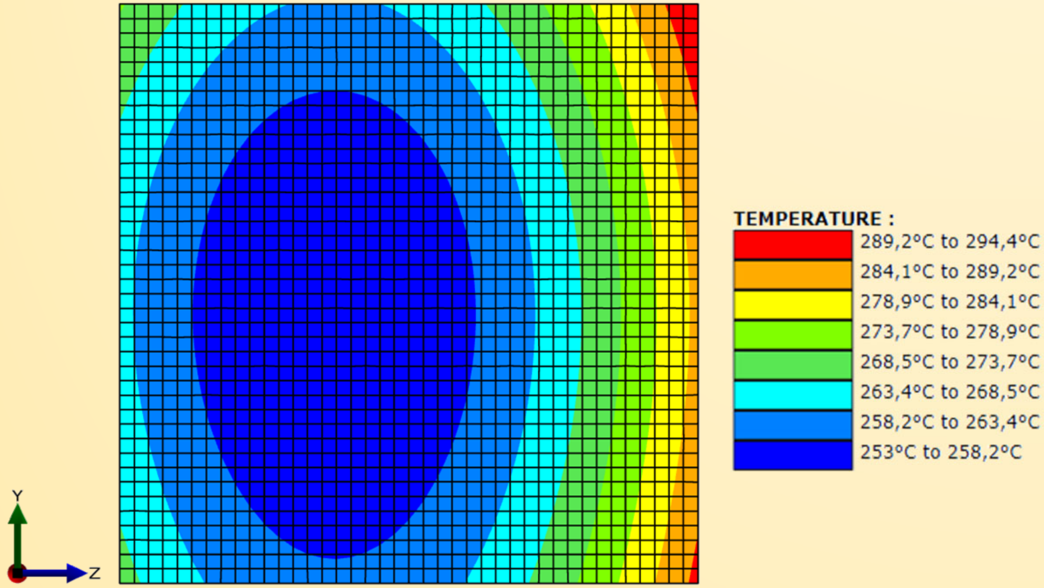
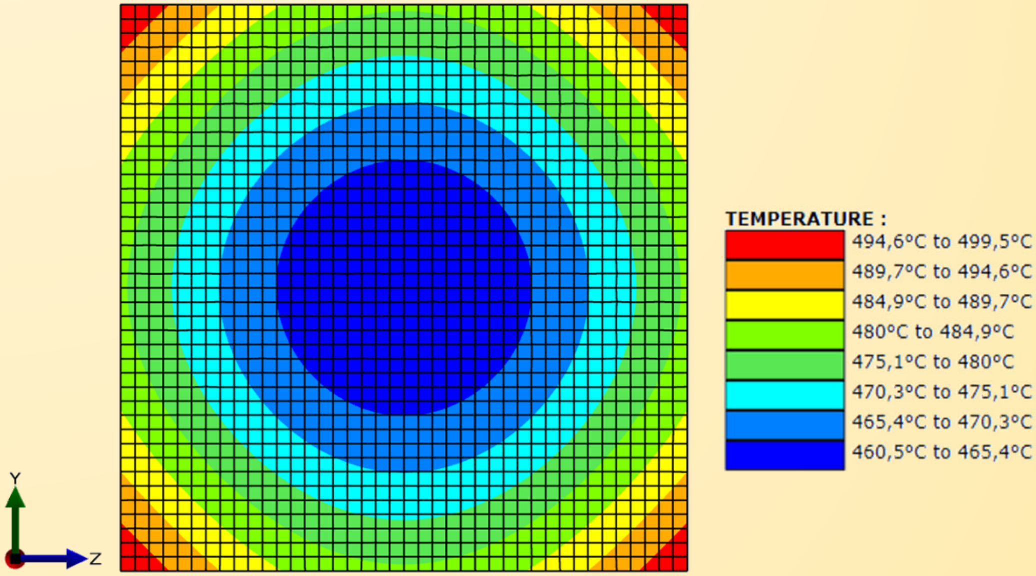
6.3. Thermal analysis

6.3.3. F.E. thermal analysis (non-uniform temperature)





Temperature distribution [°C] after 33 minutes for a 3.36 [m] column with a 130[mm]x130[mm] square cross section surrounded by 3 cars and 1 van at a) a height of 0.94[m] ; b) a height of 3.1[m]

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6.4. Mechanical analysis

6.4.1. General rules of EN 1993-1-2

Only load bearing function R of steel structures is covered by the design rules of the fire part of Eurocode 3

Load bearing function of a structure is satisfied only if during the relevant duration of fire exposure t

$$E_{fi,d,t} \leq R_{fi,d,t}$$

where $E_{fi,d,t}$: design effect of actions (Eurocodes 0 and 1)

$R_{fi,d,t}$: corresponding design resistance of the structure at instant t

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.1. General rules of EN 1993-1-2

<u>ULS Combination</u>

$$E_d = 1.35 * \sum_{j \geq 1} G_{k,j} + 1.5 * Q_{k,1} + 1.5 * \sum_{i \geq 2} \Psi_{0,i} Q_{k,i}$$

<u>ACC Combination</u>

$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1} Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i} Q_{k,i}$$

Note : Depending on the country, $\psi_{1,1}$ or $\psi_{2,1}$ should be used.

Actions	Ψ_0	Ψ_1	Ψ_2
Category A : domestic, residential areas	0.7	0.5	0.3
Category B : office areas	0.7	0.5	0.3
Category C : congregation areas	0.7	0.7	0.6
Category D : shopping area	0.7	0.7	0.6
Category E : storage areas	1	0.9	0.8
…	…	…	…

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.1. General rules of EN 1993-1-2

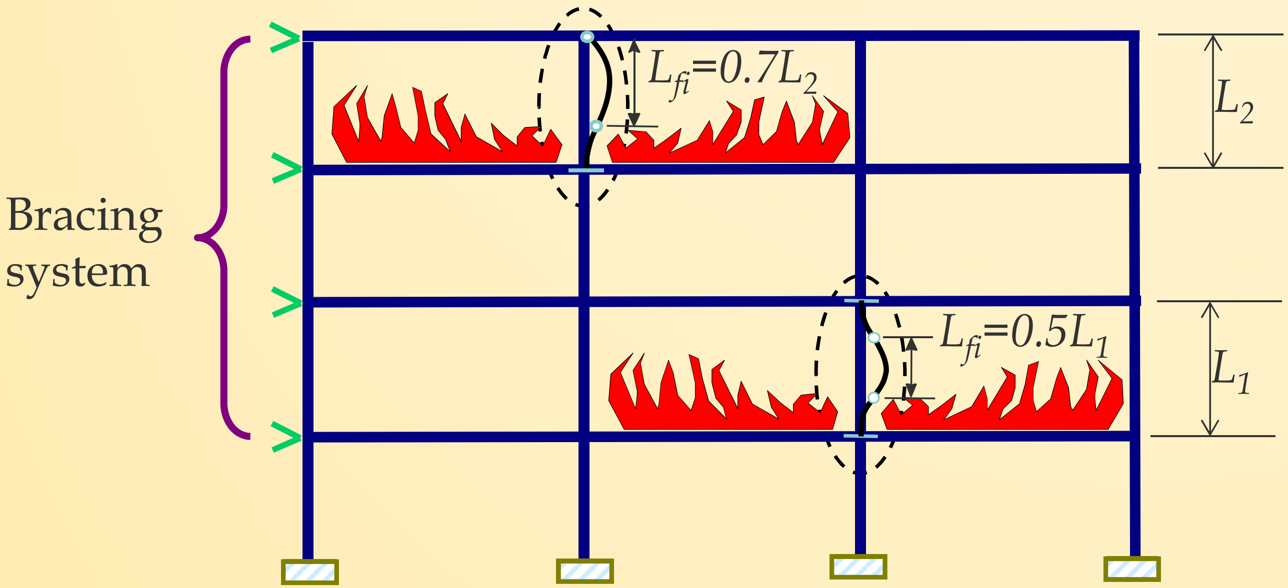
Partial factors of steel at elevated temperatures

Type of members	Cold design	Fire design
Cross-sections	$\gamma_{M0} = 1.0$	$\gamma_{M,fi} = 1.0$
Members with instability	$\gamma_{M1} = 1.0$	$\gamma_{M,fi} = 1.0$
Tension members to fracture	$\gamma_{M2} = 1.25$	$\gamma_{M,fi} = 1.0$
Joints	$\gamma_{M2} = 1.25$	$\gamma_{M,fi} = 1.0$

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.1. General rules of EN 1993-1-2



Conditions :

- Braced structures
- Continued or ends maintained columns
- Same fire resistance R between columns and floor members

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6.4. Mechanical analysis

6.4.1. General rules of EN 1993-1-2

Verification of fire resistance according one of the 3 following methods :

Temperature : $\theta_{cr,d} \geq \theta_d$

Most simple and commonly-used method, only valid for uniform T°

Load resistance : $R_{fi,d,t} \geq E_{fi,d,t}$

Feasible by hand calculation (reduced capacity at required time)

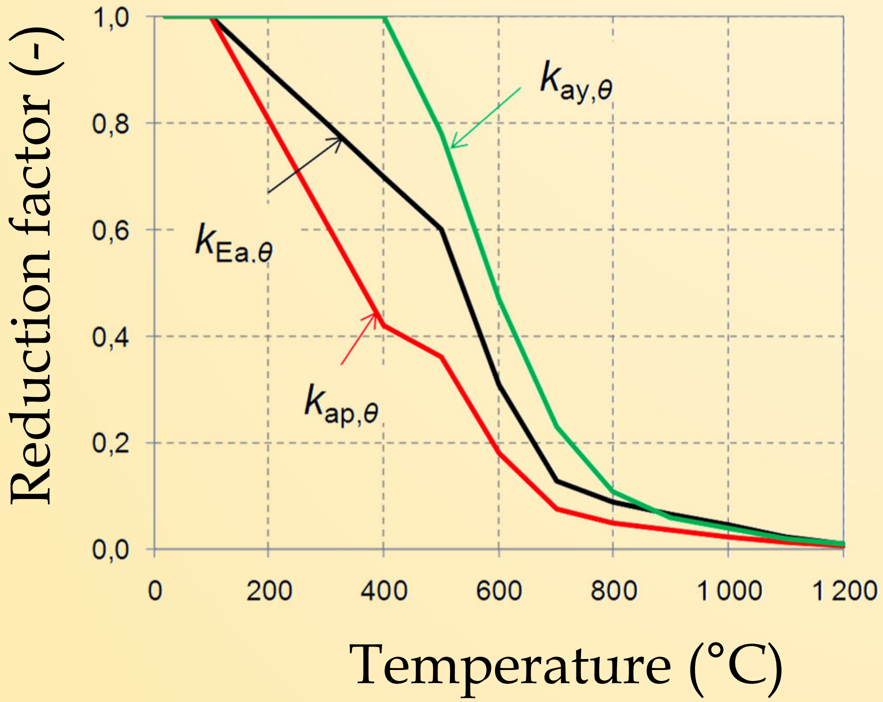
Time : $t_{fi,d} \geq t_{fi,required}$

Only feasible using advanced tools, like Finite Element Models

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.2. Analytical verification of column according to EN 1993-1-2



Temperature

$k_{y,\theta}$: reduction of yield limit

$k_{E,\theta}$: reduction of Young modulus

$k_{p,\theta}$: reduction of proportional limit

Current version of EN 1993-1-2 applies to steel grades S235 to S460

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.2. Analytical verification of column according to EN 1993-1-2

Temperature

Accidental combination loading

$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1}\, Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i}\, Q_{k,i}$$

Note : Depending on the country, $\psi_{1,1}$ or $\psi_{2,1}$ should be used.

$$E_d = 1.35 * \sum_{j \geq 1} G_{k,j} + 1.5 * Q_{k,1} + 1.5 * \sum_{i \geq 2} \Psi_{0,i}\, Q_{k,i}$$

Reduction factor for the level of loading

$$\eta_{fi} = \frac{E_{fi,d,t}}{E_d}$$

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.1. Analytical verification of column according to EN 1993-1-2

Temperature

$$\eta_{fi} = \frac{\gamma_{GA} G_k + \psi_{2.1} Q_{k.1}}{\gamma_G G_k + \gamma_{Q.1} Q_{k.1}}$$

Reduction factor for the level of loading

In structural fire design ACC design

γ_{GA} = 1.0 Permanent loads;

$\psi_{2.1}$ = 0.3 Combination factor; variable loads, offices

Ambient temperature ELU design

γ_G = 1.35 Permanent loads;

$\gamma_{Q.1}$ = 1.50 Combination factor; variable loads

Note : Depending on the country, $\psi_{1,1}$ or $\psi_{2,1}$ should be used.

$Q_{k,1}/G_k$	η_{fi}
0	0.74
1	0.53
2	0.46
4	0.41

EN 1993-1-2 recommends η_{fi} = 0.65 (except Category E, η_{fi} = 0.7)

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.2. Analytical verification of column according to EN 1993-1-2

Temperature

Accidental combination loading

$$E_{fi,d,t} = \sum_{j\geq 1} G_{k,j} + \Psi_{2,1}\, Q_{k,1} + \sum_{i\geq 2} \Psi_{2,i}\, Q_{k,i}$$

Note : Depending on the country, $\psi_{1,1}$ or $\psi_{2,1}$ should be used.

Reduction factor for the level of loading

$$\eta_{fi,t} = \frac{E_{fi,d,t}}{R_d} < \eta_{fi}$$

Ambient temperature design resistance

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.1. Analytical verification of column according to EN 1993-1-2

Temperature

Degree of Utilisation

$$\mu_0 = \left(\frac{E_{d,fi}}{R_{d,fi,0}} \right) = \eta_{fi,t} \left(\frac{\gamma_{M,fi}}{\gamma_{M0}} \right)$$

- Accounts for partial safety factors at room and elevated T° (normally both of them are 1.0)
- Allows a direct calculation of the critical T°
- In case the failure mode includes instabilities, the reduced non-dimensional slenderness is required

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.1. Analytical verification of column according to EN 1993-1-2

Temperature

$\bar{\lambda}_{fi,0}$	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
μ_0											
0.04	1000	977	949	913	880	839	787	742	696	678	659
0.06	900	885	866	837	795	756	700	679	656	630	602
0.08	860	839	811	785	749	697	674	647	616	588	564
0.10	820	797	780	752	703	677	648	614	585	557	527
0.12	792	777	755	719	685	656	622	588	559	526	474
0.14	775	757	730	694	668	636	597	567	533	487	373
0.16	758	737	705	681	652	615	580	546	507	408	
0.18	742	717	691	668	636	596	563	524	453		
0.20	725	698	680	655	619	582	545	503	384		
0.22	708	689	669	641	603	568	528	457			
0.24	696	679	658	628	591	554	511	406			
0.26	688	670	647	615	579	540	485				
0.28	679	660	636	602	568	526	446				
…	…	…	…	…	…	…	…				

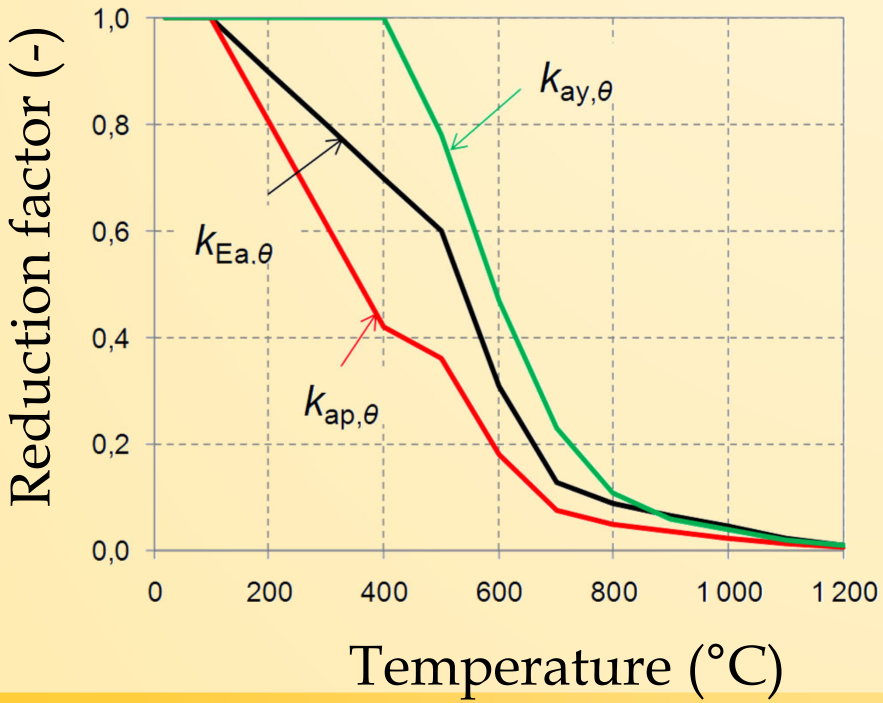
Critical temperature of steel members under instability using specific tabulated data based on:

- non-dimensional slenderness at instant 0
- and a specific load level $\mu_0 = N_{fi,d,t} / N_{pl,fi,0}$
- each steel grade has its own tabulated data

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.2. Analytical verification of column according to EN 1993-1-2



Load resistance

$k_{y,\theta}$: reduction of yield limit

$k_{E,\theta}$: reduction of Young modulus

$k_{p,\theta}$: reduction of proportional limit

Current version of EN 1993-1-2 applies to steel grades S235 to S460

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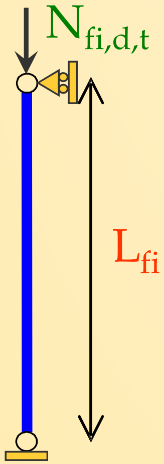
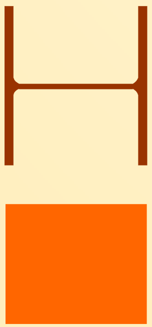
6.4. Mechanical analysis

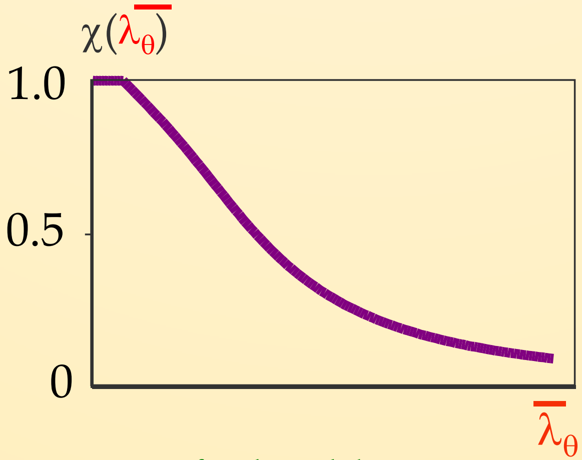
6.4.1. Analytical verification of column according to EN 1993-1-2

Load resistance





Section and temperature



Specific buckling curve

$$\alpha = 0.65\sqrt{\frac{235}{f_y}} \qquad \overline{\lambda_\theta} = \bar{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

$$\varphi_\theta = \frac{1}{2}\left[1 + \alpha\overline{\lambda_\theta} + \overline{\lambda_\theta}^2\right]$$

$$\chi_{fi} = \frac{1}{\varphi_\theta + \sqrt{\varphi_\theta^2 - \overline{\lambda_\theta}^2}}$$

$$N_{b,fi,t,Rd} = \frac{\chi_{fi}\, A\, k_{y,\theta}\, f_y}{\gamma_{M,fi}}$$

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.2. Analytical verification of column according to EN 1993-1-2

Load resistance

Accidental combination loading

$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1}\, Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i}\, Q_{k,i}$$

Note : Depending on the country, $\psi_{1,1}$ or $\psi_{2,1}$ should be used.

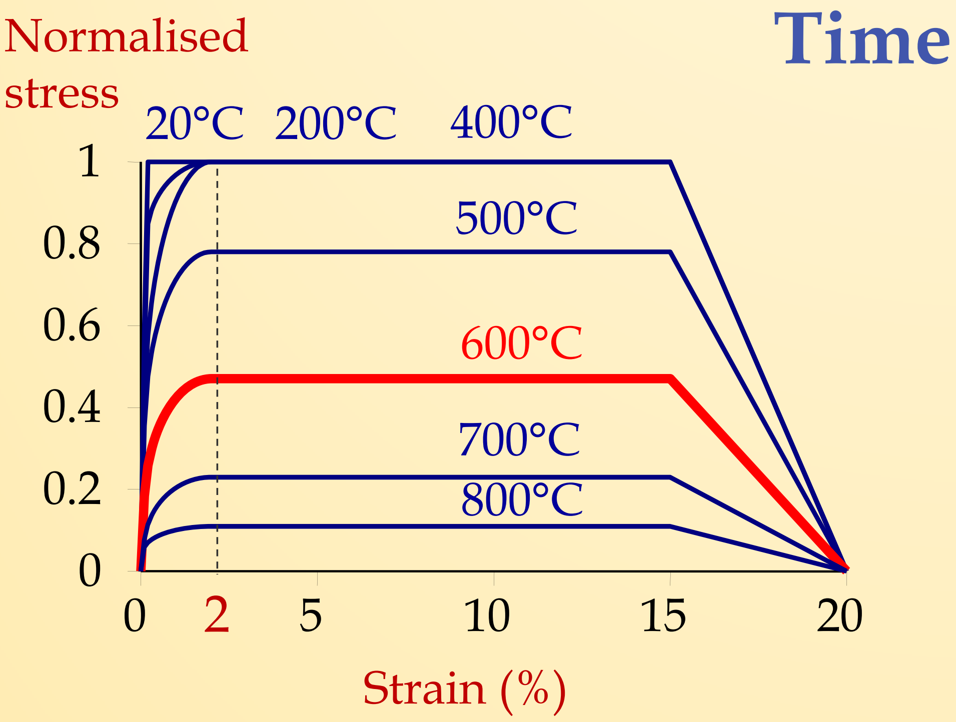
Design criteria

$$\mathbf{R_{fi,d,t} \geq E_{fi,d,t}}$$

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.3. Finite element analysis



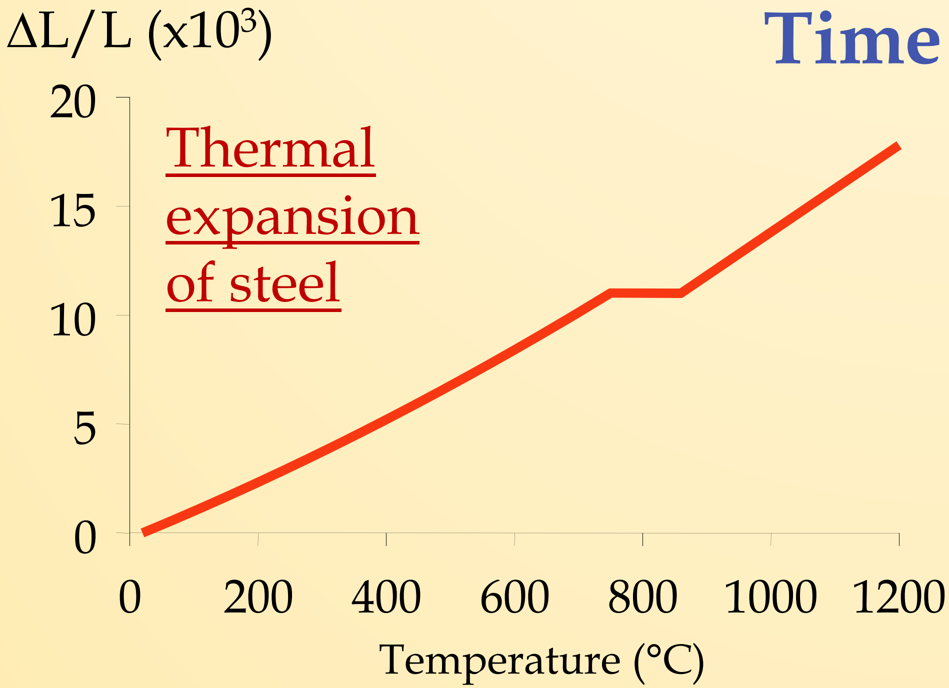
- Stress-strain diagram of steel is non-linear (elastic, parabolic, plateau, descending branch)
- Yield strength at 600°C reduced by over 50%

6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.3. Finite element analysis

Time



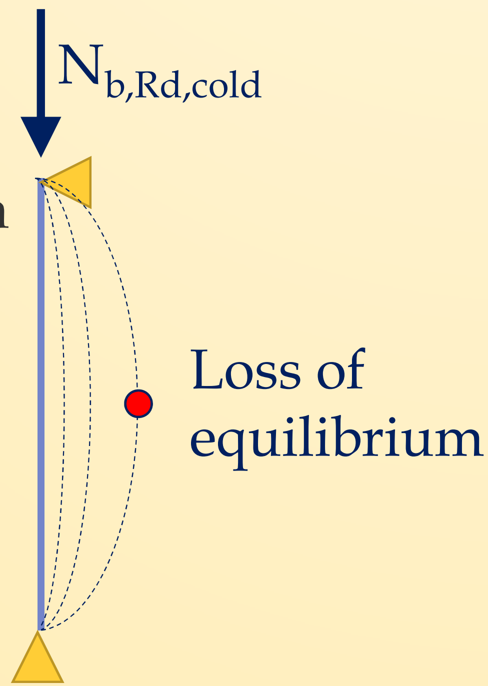
6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.3. Finite element analysis

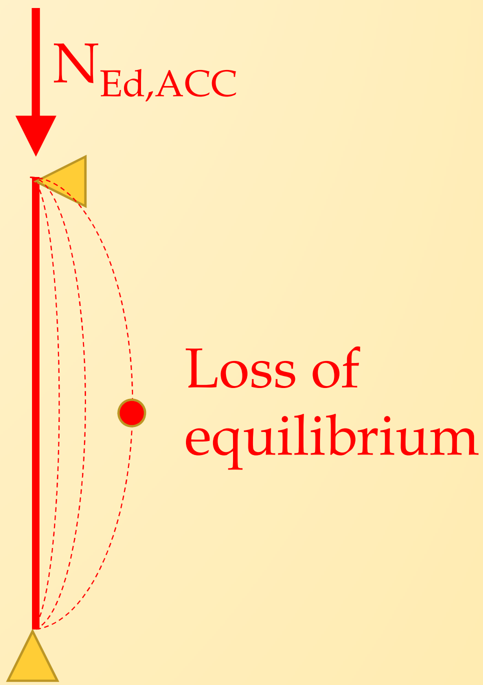
<u>Cold design</u>

- Initial imperfection
- Load increases until failure



<u>Hot design</u>

- Initial imperfection
- Initial loading
- Temperature increases until failure

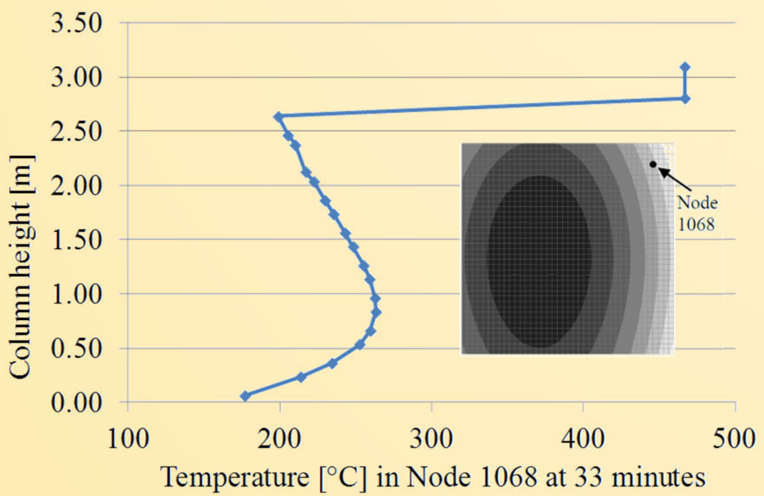


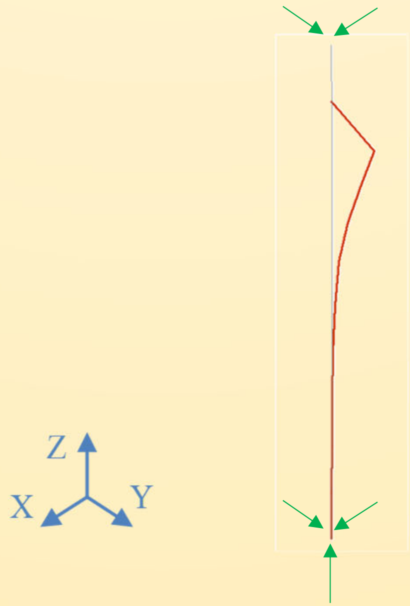
6. Synthesis Fire resistance

6.4. Mechanical analysis

6.4.3. Finite element analysis

Time





Left : Temperature distribution at Node 1068 after 33 minutes along a 3.36 [m] column with a 130[mm]x130[mm] square cross section surrounded by 3 cars and 1 van

Right : Displacement shape in failure (scale factor 1) of a 3.36[m] column with a 130[mm]x130[mm] square cross section surrounded by 3 cars and 1 van